Natural Resource Management and Policy

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Handbook of Bioenergy Economics and Policy: Volume II

Modeling Land Use and Greenhouse Gas Implications

Springer

Natural Resource Management and Policy

Volume 40

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Madhu Khanna · David Zilberman
Editors

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Editors
Madhu Khanna
Department of Agricultural and Consumer Economics
University of Illinois at Urbana-Champaign
Urbana, IL
USA

David Zilberman
Department of Agricultural and Resource Economics
University of California at Berkeley
Berkeley, CA
USA

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Contributors

Robert H. Beach Agricultural, Resource & Energy Economics and Policy Program, RTI International, Research Triangle Park, NC, USA

Géraldine Bocquého LEF, AgroParisTech, INRA, Nancy, France

Rafael Silva Capaz Institute of Natural Resources, Federal University of Itajubá, Itajubá, Brazil

Miguel Carriquiry Universidad de la República, Montevideo, Uruguay

Xiaoguang Chen Research Institute of Economics and Management, Southwestern University of Economics and Finance, Chengdu, China

Luciane Chiodi Bachion Agroicone, São Paulo, Brazil

Maria Paula Vieira Cicogna Polytechnic School, University of São Paulo, São Paulo, Brazil

Xiaoxue Du Department of Agricultural and Resource Economics, University of California at Berkeley, Berkeley, CA, USA

Jennifer B. Dunn Energy Systems Division, Argonne National Laboratory, Argonne, IL, USA

Alla A. Golub Department of Agricultural Economics, Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA

Ben Gordon Department of Agricultural and Resource Economics, University of California at Berkeley, Berkeley, CA, USA

Jeongwoo Han Energy Systems Division, Argonne National Laboratory, Argonne, IL, USA

Leila Harfuch Agroicone, São Paulo, Brazil

Thomas W. Hertel Department of Agricultural Economics, Center for Global Trade Analysis, Purdue University, West Lafayette, IN, USA

Gal Hochman Department of Agriculture, Food and Resource Economics, Rutgers University, New Brunswick, NJ, USA

Mark Horridge Centre of Policy Studies, Victoria University, Melbourne, VIC, Australia

Scott Kaplan Department of Agricultural and Resource Economics, University of California at Berkeley, Berkeley, CA, USA

Madhu Khanna Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Liang Lu Department of Agricultural and Resource Economics, University of California at Berkeley, Berkeley, CA, USA

Bruce A. McCarl Department of Agricultural Economics, Texas A&M University, College Station, TX, USA

Ruiqing Miao Department of Agricultural Economics and Rural Sociology, Auburn University, Auburn, AL, USA

Márcia Azanha Ferraz Dias de Moraes (USP—ESALQ, Department of Economics, Administration and Sociology), University of São Paulo, São Paulo, Brazil

Marcelo Melo Ramalho Moreira Agroicone, São Paulo, Brazil

André Meloni Nassar Agroicone, São Paulo, Brazil

Luiz Augusto Horta Nogueira Institute of Natural Resources, Federal University of Itajubá, Itajubá, Brazil

Michael O'Hare Goldman School of Public Policy, University of California at Berkeley, Berkeley, CA, USA

Richard J. Plevin Institute of Transportation Studies, University of California at Davis, Davis, CA, USA

Deepak Rajagopal Institute of the Environment and Sustainability, University of California at Los Angeles, Los Angeles, CA, USA

Luciano Rodrigues (USP—ESALQ, Department of Economics, Administration and Sociology) and Specialist with Extensive Experience on the Sugarcane Industry and Ethanol Market in Brazil, Applied Economics at the University of São Paulo, São Paulo, Brazil

Steven K. Rose Electric Power Research Institute, Washington, DC, USA

Joaquim Seabra UNICAMP, Campinas, São Paulo, Brazil

Joaquim Bento de Souza Ferreira Filho Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo, São Paulo, Brazil

Michael Traux Department of Agriculture, Food and Resource Economics, Rutgers University, New Brunswick, NJ, USA

Michael Wang Energy Systems Division, Argonne National Laboratory, Argonne, IL, USA

Xi Yang Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Yuquan W. Zhang Agricultural, Resource & Energy Economics and Policy Program, RTI International, Research Triangle Park, NC, USA

David Zilberman Department of Agricultural and Resource Economics, University of California at Berkeley, Berkeley, CA, USA

Bioenergy Economics and Policy in US and Brazil: Effects on Land Use and Greenhouse Gas Emissions

Madhu Khanna and David Zilberman

1 Overview

The biofuel industry has expanded since the start of the millennium. This expansion was due to the desire to reduce dependence on foreign oil, to mitigate greenhouse gas (GHG) emissions from the transportation sector and enhance rural economic development. Brazil emerged as an early leader in biofuel production, producing 3 billion gallons of sugarcane ethanol in 2000 followed by the US producing 1.6 billion gallons from corn ethanol. Production expanded in both countries in the following decade but much more significantly in the US which overtook Brazil as the leading producer of ethanol in the world and shifted from an importer of biofuels from Brazil to becoming an exporter of biofuels to Brazil. US production rose to about 14 billion gallons in 2014 while production of sugarcane ethanol in Brazil increased to about half of that.

There is a large body of literature that aims to address the economic, political and technological aspects of the biofuel sector. The first volume of the *Handbook of Bioenergy Economics and Policy* broadly covered the major economic and policy issues associated with biofuel and bioenergy. This second volume focuses on three major issues.

M. Khanna (✉)
Department of Agricultural and Consumer Economics,
University of Illinois at Urbana-Champaign, Urbana, IL, USA
e-mail: khanna1@illinois.edu

D. Zilberman
Department of Agricultural and Resource Economics,
University of California at Berkeley, Berkeley, CA, USA
e-mail: zilber11@berkeley.edu

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First, what led to this over fourfold increase in total biofuel production in the two countries? What role did market forces versus policy incentives play in explaining these trends? Both the US and Brazil have had a mix of policy incentives to support biofuel production over the last two decades. In particular, both countries have relied on a biofuel mandate to accelerate blending of biofuels with gasoline beyond the levels that would have been supported by the market. Were supply-side factors, such as, limits to availability of land or feedstocks and high costs of production, or demand-side factors, such as, the technical feasibility of blending biofuels with gasoline responsible for the plateauing or even declining trend in biofuel production observed in recent years in these two countries? Did the interaction of biofuel policies with other policies create further incentives or barriers for the growth of the biofuels sector? Several chapters in this book address these issues.

Second, as biofuel production from food crops in the two countries expanded, concerns about the increasing diversion of cropland to biofuel crop production and the conversion of noncropland to crop production have grown. These changes in land use have implications for both food prices and for GHG emissions as carbon stored in soils is released when land is converted to agricultural production. This has led to considerable skepticism about the potential for biofuels to lead to GHG savings relative to fossil fuels. Life cycle analysis has been used to assess the GHG impacts of biofuels. Life cycle analysis of the GHG emissions accounts for all emissions associated with the production of biofuel, including production of fertilizers and other inputs used to produce the feedstock, transport the feedstock to the bio-refinery and conversion of the feedstock to biofuel at the refinery. The direct life cycle emissions are expected to be relatively small with the next generation of biofuels produced from cellulosic biomass from crop and forest residues and dedicated energy crops. These feedstocks require fewer carbon intensive inputs in the process of production. Energy crops can also sequester a large amount of carbon in the soil and make the resulting biofuel a net sink for carbon rather than a source (Dwivedi et al. 2015; Hudiburg et al. 2016). In addition to these direct emissions, emissions can also be generated indirectly due to changes in land use caused by biofuel-induced changes in crop prices and changes in fossil fuel use caused by biofuel-induced changes in fuel prices. Estimating the extent to which the food price increases and land use changes are caused by biofuels and would not have occurred anyway is complicated since it relies on economic models to simulate effects with and without biofuels. The outcomes of economic models are dependent on their structure, parametric assumptions, and scenarios simulated (Khanna and Crago 2012). Various chapters in this book describe improved methods for modeling the transformation of land from one use to another.

Third, the transition to second generation biofuel will require a shift toward new crops that are yet to be grown commercially. The nascent commercial scale production of cellulosic biofuels that emerged in 2014 has relied largely on crop residues for feedstock. Large scale production using energy crops has yet to occur due to high costs of production, large capital requirements, and riskiness of production. Dedicated energy crops differ from the annual crops used for biofuels because they are typically perennials with a lifespan of at least 10–15 years and a lag of 1–5 years between planting and harvestable yield. What type of incentives will be required to induce farmers to switch from an annual crop with well-developed markets and subsidized crop insurance to an energy crop with thin market demand that require a long-term commitment of land to recover investment value? The rich literature on technology adoption suggests that there are mechanisms that can induce farmers to make long-term investments in risky crops, including various types of contracts between farmers and feedstock refiners and government policies such as subsidies and crop insurance that can protect both farmers and the refiners. Furthermore, adoption of biofuel policy may be constrained by credit availability, which may call for other forms of intervention. There is paucity of research on adoption of second generation biofuels and mechanisms that will induce it and we aim to fill this gap.

The chapters in this book provide an economic framework to explore the issues discussed above in greater detail. The chapters are grouped into three sections. The first section describes the market forces and policy incentives that have contributed to the development of the biofuel industry in the US and Brazil.

Biofuels emerged as an infant industry whose high costs of production required high market prices or policy incentives that level the playing field with their functionally equivalent fossil fuels. These chapters describe the type of biofuel policies pursued in US and Brazil, differences in the structure of the fossil fuel industry and the fossil fuel pricing policies and the differing role of the government in providing demand-side incentives for biofuel production in the two countries. It analyzes the implications of these different approaches for the outcomes over time in the two countries.

The second section describes the methodological and conceptual issues involved in assessing the direct and indirect life cycle GHG emissions and land use change associated with biofuel production. Chapters in this section describe the life cycle approach to GHG accounting, the rationale for including GHG emissions due to direct and indirect land use change and the role of life cycle analysis in assessing compliance with biofuel policies in the US and the European Union (EU). It also discusses issues that arise in modeling land use change. Approaches ranging from stylized models to partial domestic models to global general equilibrium models are presented. These chapters describe the conceptual considerations that should be incorporated and empirical strategies utilized by modelers to represent the determinants of land use change due to biofuels, the mix of biofuels, and feedstocks likely to be produced under alternative policy scenarios and their global impacts on food and fuel prices. These chapters also assess the extent to which biofuel policies in the US and Brazil lead to land use change, the type of land use change likely to occur and its economic and environmental consequences.

The last section includes chapters that discuss the issues related to developing a supply chain for cellulosic biofuel feedstocks, including the contractual arrangements needed to induce biomass production. It includes chapters that review the existing literature on contact design and incentives for technology adoption and discuss the factors likely to influence farmer willingness to produce bioenergy crops and the policies needed to overcome the barriers to do so.

Like Volume 1 of the Handbook, this volume will be of value for academic audiences and policy analysts and for decision makers in industry and non-government organizations that are interested in understanding the economic impacts of biofuels and their implications for land use, GHG emissions, energy, and food prices. It will be a useful reference for scholars seeking a review of the current state of knowledge and a comparative understanding of the biofuel industry in the two leading producers of biofuels in the world, US and Brazil. The book provides comprehensive coverage of not only issues that have affected the development of the first generation of biofuels but also challenges facing the development of the next generation of biofuels. This volume will also be of interest to practitioners and managers in industry and agriculture who seek to understand the conceptual and practical issues associated with implementation and use of bioenergy and economic and policy dimensions of a growing bioeconomy. Policy makers will find useful insights on the economic consequences of various policy alternatives to support biofuel production. Scholars with an interest in renewable energy policy and its effects on agriculture, trade, economic development, resource economics, and public policy will appreciate the comparative analysis of US and Brazil biofuel policies.

Similar to Volume 1, this book should also be attractive for educational purposes, for use as a textbook for courses and curricula associated with the emerging field of bioenergy economics. As universities develop more specialized curriculum centered around bioenergy, this book could serve as a supplementary reading to familiarize students with applications of economic tools to analyze the economic and environmental implications of bioenergy development and policies.

2 Market and Policy Incentives for Biofuel Production in the US and Brazil

Chapter "US Biofuel Policies and Markets" by Hochman, Traux, and Zilberman discusses the suite of biofuel policies established in the US, including the biofuel mandate, the tax credit, and the import tariff to enable the infant biofuel industry to develop. They compare the implications of these policies for food and fuel prices and the costs of these policies to consumers, producers, and the government. This chapter also describes the various indirect effects that biofuel production generate in the food and fuel markets because they affect food and fuel prices. These include, among others, the positive and negative indirect effects of biofuels, including the land use change effect, the fuel rebound effect, and a balance of trade effect. The chapter concludes by discussing the demand-side challenges to expanding ethanol production due to the blend wall in the US.

Chapters "The Sugarcane Industry and the Use of Fuel Ethanol in Brazil: History, Challenges and Opportunities," "Incentives and Barriers for Liquid

Biofuels in Brazil," and "Prospects for Biofuel Production in Brazil: Role of Market and Policy Uncertainties" trace the development of the biofuel industry in Brazil. Chapter "The Sugarcane Industry and the Use of Fuel Ethanol in Brazil: History, Challenges, and Opportunities" by Moraes, Rodriguez, and Kaplan describes the early stages of the development of the biofuel sector in Brazil and the institutional factors that helped Brazil support not only increased production of ethanol but also develop the infrastructure needed for its supply to consumers and the purchase of flex-fuel cars that would enable its consumption by consumers. The military regime in Brazil together with the state owned oil company Petrobras enabled the development of an integrated supply chain for biofuels that included production by mills, distribution, and transportation as well as price incentives for biofuels and ethanol-operated cars that made biofuels appealing to fuel consumers in the 1980s. The chapter also discusses the post-deregulation period in the 1990s, the design of a new institutional feedstock pricing arrangement between sugarcane growers and mills to ensure fair remuneration to each group and the growth in demand for flex-fuel cars which facilitated market-based incentives for production and consumption of ethanol.

Brazil has been able to establish a biofuel industry that sells ethanol in two forms: anhydrous ethanol which is pre-blended with gasoline (to form gasohol) and 100% ethanol (hydrous ethanol) that fuel consumers can blend as they choose depending on its price competitiveness with the pre-blended fuel whose price depends in part on the price of gasoline. The government has regulated the domestic price of ethanol to prevent it from fluctuating with the international price of oil in order to limit inflationary pressures in Brazil. In recent years, the domestic price of gasoline has remained below the international price. This together with the lowering of the federal tax on gasoline has adversely affected the competitiveness of sugarcane ethanol. In Chapter "Incentives and Barriers for Liquid Biofuels in Brazil," Nogueira and Capaz focus on the post-2005 period of development of the sugarcane ethanol industry and describe the adverse effect of government interventions in the gasoline market on the ethanol industry. In contrast, support through mandates and other financial incentives provided by the government for development of the biodiesel industry to benefit small farmers in less developed rural areas has led to exponential growth of the biodiesel industry. The chapter explains the contrast between biodiesel versus ethanol markets and the policy toward gasoline versus diesel markets.

In Chapter "Prospects for Biofuel Production in Brazil: Role of Market and Policy Uncertainties" Cicogna, Khanna, and Zilberman discuss the role of market and policy uncertainties in limiting incentives for investment in sugarcane ethanol production in Brazil. Fuel taxes and tax credit for ethanol have played an important role in improving the competitiveness of hydrous ethanol. Ethanol production costs have been increasing over time while the tax on gasohol has been declining. Fluctuations in these taxes and in the mandated blend rate have also added to uncertainty about future demand for ethanol and limited incentives for investment. This policy uncertainty has been accompanied by market uncertainties about the price of ethanol, due to the absence of futures markets for ethanol. This chapter discusses various options for mitigating market uncertainties, including mechanisms for storage of ethanol, diversifying the revenue stream by producing co-generated electricity and cellulosic biofuels as co-products with sugarcane. It concludes by discussing the prospects for cellulosic biofuel production in Brazil.

3 Land Use and Greenhouse Gas Effects of Biofuel Production in the US and Brazil

Chapter "Biofuel Life-Cycle Analysis" reviews the methodology for life cycle analysis of biofuels and its application for different biofuel pathways and the issues associated with estimating direct and indirect land use change emissions due to biofuels. Dunn, Han, Seabra, and Wang discuss various methodological choices, such as the techniques for handling biofuel co-products, and range of estimates for the GHG intensities of ethanol from corn, sugarcane, stover, switchgrass, and miscanthus. They also describe how life cycle analysis is used to determine compliance with regulations in various countries and how estimates of the carbon intensities of a biofuel differ across countries, feedstocks and with the inclusion of land use change emissions. They show the extent to which estimates of land use change emissions, in particular, vary considerably across studies.

Assessing the indirect land use effects of biofuels necessitates reliance on economic models that make a number of assumptions about the behavior of agents, market structure and elasticities of supply, demand and transformation of land from one use to another. General equilibrium models, in particular, rely on the assumption that the elasticities are constant over time and across large regions within a single agro-ecological zone. In Chapter "Effect of Biofuel on Agricultural Supply and Land Use," Zilberman, Rajagopal, and Kaplan question the assumptions that the elasticity of land use change with respect to agricultural prices is constant over time. The authors develop a stylized dynamic model framework to show that the responsiveness of land allocation between agricultural and environmental uses varies depending on changes in demand for agricultural and environmental goods, environmental regulations, and the evolution of the relationships between output, land use, and variable input use over time. Moreover, the observed land use changes and the observed changes in cropland rents in the US in recent years indicate that cropland acreage at the extensive margin is fairly inelastic (Barr et al. 2011). Relatively large changes in land rents in recent years have been accompanied by very small changes in aggregate crop acreage. Although this before and after biofuels comparison of land use change is different from the analysis of with and without biofuels at a point in time done by general equilibrium models, it does suggest a divergence between the observed phenomenon and the simulated behavior. This calls into question the data and modeling assumptions being made by the large scale static CGE and multi-market models such as those by Searchinger et al. (2008).

Golub, Hertel, and Rose demonstrate this in Chapter "Global Land Use Impacts of U.S. Ethanol: Revised Analysis Using GDyn-BIO Framework," by developing a dynamic computational general equilibrium (CGE) version of the GTAP model and using it to compare the land use effects of a 15 billion gallon mandate with those from a static CGE model. They examine the extent to which use of a dynamic model leads to a decline in land use effect of biofuels it allows for increased possibilities for intensification of production in the agricultural and forestry sectors, growth in crop yields over time and changes in demand and supply elasticities over time.

In Chapter "Land Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy," Chen and Khanna use a dynamic partial equilibrium model, BEPAM (Biofuel and Environmental Policy Analysis Model) which is an integrated model of the agricultural and transportation sectors to compare the land use and GHG effects of the RFS with those of the RFS combined with alternative biofuel policies, such as a volumetric tax credit, an LCFS and a carbon tax. They model the potential to produce both first generation biofuels, advanced biofuels, and cellulosic biofuels from a wide range of feedstocks. Their analysis compares the implications of two indirect effects of biofuel policies on GHG emissions—the indirect land use effect and the fuel market rebound effect. They use the spatially explicit nature of the BEPAM structure to show the spatial pattern of production of feedstocks for cellulosic biofuels and how it varies with the policy incentives provided. Their analysis provides another estimate of the extent to which total land use can be expected to respond to changes in crop prices. It also shows how the effectiveness of using land to mitigate GHG emissions varies across the policies considered.

In Chapter "Modeling Bioenergy, Land Use, and GHG Mitigation with FASOMGHG: Implications of Storage Costs and Carbon Policy," Beach, Zhang, and McCarl use the dynamic partial equilibrium model FASOMGHG to examine the optimal mix of feedstocks to meet the RFS while taking into account the differential need for storage of biomass for different feedstocks. They analyze the extent to which energy crops have a smaller need for storage because they have a longer harvest window as compared to an annual biomass crop like corn stover. The inclusion of storage costs in the model affects the economic incentives to produce energy crops instead of crop residues. Similar to Chen and Khanna in the previous chapter, they also examine the effect of the addition of a carbon price to the RFS on the mix of feedstocks and the extent to which it shifts the mix toward low carbon energy crops instead of crop residues.

In Chapters "Empirical Findings from Agricultural Expansion and Land Use Change in Brazil" and "Land Use Change, Ethanol Production Expansion and Food Security in Brazil" we turn our attention to land use changes in Brazil due to sugarcane ethanol production. Harfuch, Bachion, Moreira, Nassar, and Carriquiry present an updated version of the partial equilibrium BLUM (Brazil Land Use Model) model that more accurately models land use change at the intensive and extensive margins. Instead of keeping the land supply elasticity as a constant, the authors present a modified structure of the model in which the land supply elasticity varies with the extent to which current agricultural land use diverges from that in base period. This implies that as land is increasingly converted to agriculture, further changes in land use become more inelastic. Changes in land use at the extensive margin (between agriculture and forestry) in the model occur in response to changes in the weighted average return to agriculture. The revised model relies on observed land use transition data to determine the weights to be attached to different activities so that activities directly responsible for deforestation are assigned a higher weight. The improved model also increases the ease of pasture intensification. They discuss the implications of these changes for the effect of increased production of sugarcane ethanol for land use change and show how it affects the indirect land use change related GHG intensity of sugarcane ethanol in Brazil.

In Chapter "Lessons from the ILUC Phenomenon," O'Hare and Plevin discuss the conceptual challenges posed by indirect land use change for GHG emissions accounting for biofuels and its implications for policy. They note that the indirect effects of biofuels depend on the policy used to promote biofuels and that these effects are uncertain and model dependent. The authors also point out that models are simplifications of the global economy and discuss the need to make policy choices while recognizing the uncertainties that will remain in estimating the exact magnitude of the indirect land use change effect. An important consideration that is often overlooked in estimating this magnitude is the timing of the different emissions over the life cycle of the biofuel. The indirect land use change effect occurs at the onset of the conversion of noncropland to crop production while other emissions associated with the production of biofuel crops and the savings due to displacement of fossil fuels are annual effects that occur over time in the future. The chapter discusses various options for incorporating the effect of this difference in timing of emissions on the climate system in accounting for the GHG effect of biofuels.

4 Feedstocks for Cellulosic Biofuels: Production Risks and Risk Management

Large scale and sustainable production of cellulosic biofuels will require a dedicated feedstock. These feedstocks present new crop choices and/or production systems for farmers with uncertainties about yields, costs and returns. Studies analyzing the costs of producing dedicated energy crops and cellulosic biofuels typically assume that crop yields are known with certainty, that farmers are risk neutral, have low discount rates and do not have any credit constraints; the fixed costs of establishing energy crops can therefore be amortized over the lifespan of the crop. Macro-models implicitly assume that biomass will be sold on the spot market and its price will fluctuate with demand and supply. In practice, farmers are likely to require long-term contracts and an assurance of demand before they will be willing to convert land from an annual crop to an energy crop.

Khanna, Zilberman, and Miao discuss the various factors likely to influence the adoption of energy crop feedstocks for biofuels in the chapter "Innovation in Agriculture: Incentives for Adoption and Supply Chain Development for Energy Crops". Using miscanthus and switchgrass as examples of promising energy crops they describe the key biophysical features of these crops such as yield and lifespan as well as the farm and farmer characteristics that are likely to affect the economics of the energy crop adoption decision. Heterogeneity in these features across spatial locations and across farmers can be expected to lead to spatial variability in the pattern of energy crop production across the rain-fed US.

In the chapter "Effects of Liquidity Constraints, Risk and Related Time Effects on the Adoption of Perennial Energy Crops" Bocqueho delves deeper into the role of liquidity constraints, risk aversion and time preferences on the incentives to adopt an energy crop. She examines the empirical evidence on the effects of these factors on technology adoption and presents a model to analyze the effects of liquidity constraints on a farmer's adoption decision. She describes survey evidence on the perceptions of risk of producing energy crops by farmers in France. The chapter also discusses other factors such as the irreversibility of the adoption decision, intertemporal fluctuations in income and reduced flexibility of changing the allocation of land that has been planted under a perennial crops as other barriers to energy crop production.

In the Chapter "Contracting in the Biofuel Sector" Du et al. address the issue of contracting for the production of biomass feedstocks. Biomass production from perennial energy crops imposes a number of risks for farmers because markets for it are thin, costs of transporting them long distance are high and a 10 to 15 year lifespan requires long term commitment of land to it to recover the initial investment. There is a large literature examining the incentives for farmers to enter into marketing or production contracts due to risk aversion, transactions costs and thin markets. This chapter reviews this existing literature and then discusses the design of contracts for biomass feedstocks.

5 Summary

The corn and sugarcane ethanol industries have grown rapidly in recent decades and reached a high degree of maturity in both the US and Brazil. Policy has played a critical role in both countries in enabling the infant industry to develop. However, production levels of both types of ethanol have stalled recently in both the US and

Brazil although for different reasons. Although Brazil has lagged behind the US in the volume of biofuel production, it has achieved much greater penetration of ethanol in its fuel mix because it was able to simultaneously develop the infrastructure to distribute 100% ethanol and induce a shift in the vehicle fleet to include an increasing share of flex-fuel vehicles. In contrast, in the US, biofuel consumption has hit a blend wall because of inadequate ability to distribute or consume higher blends. Brazil, on the other hand, has provided inadequate incentives for new investments in biofuel production because government policies have reduced the competitiveness of biofuels relative to gasoline. The first section of the book describes the policy incentives as well as the market and policy barriers for increased biofuel production in the US and Brazil.

Expansion of biofuel has raised concerns about the GHG savings they can lead to and their adverse implications for land use and food prices. Models estimating indirect land use changes due to biofuels rely on a number of parametric assumptions and their outcomes are dependent on model structure. Chapters in Sect. 2 of the book presents the improvements made in existing models to enable them to have a more flexible structure that better captures the evolution in the responsiveness of land supply to prices over time. This section of the book also includes chapters that take a prospective look at the land use and GHG implications of the cellulosic biofuel mandate in the US.

The last section of the book examines the factors that will influence farm-level decisions about producing dedicated energy crops for cellulosic biofuels. It describes the effects of risks and uncertainties associated with perennial energy crop production and the role of liquidity constraints in creating disincentives for energy crop production. These chapters highlight the need for developing contractual arrangements between farmers and the refinery to develop the supply chain needed to support cellulosic biofuel production.

The chapters in this book will familiarize readers with the latest conceptual analysis and developments in numerical models to assess the land use and GHG implications of biofuels. They describe the suite of biofuel policies implemented in the US and Brazil and describe the intended and unintended effects these policies have had on the development of the biofuel industry in these two countries. Finally, the chapters in this book discuss the economic issues that will affect farm-level production of energy crops and the development of a supply chain for the next generation of biofuels.

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Part I
Market and Policy Incentives for Biofuel Production in the US and Brazil

US Biofuel Policies and Markets

Gal Hochman, Michael Traux and David Zilberman

Abstract The United States has established various policies to support a transition to biofuels from fossil fuels as part of its strategy to achieve energy security and independence. These policies include mandates, tax credits, and import tariffs aimed at developing the nascent biofuel industry. To compare the impact of various energy sources requires a comprehensive understanding of both direct and indirect effects. This chapter discusses some of the indirect effects, including land use change, fuel rebound effect, and balance of trade effect. It finds that due to the ubiquity of energy, indirect effects impact numerous markets and that an already noncompetitive energy market that is capital intensive exacerbates the challenge of introducing biofuels. While first-generation biofuels contributed to rural development and reduced dependency on imported fuel sources, they have failed to reduce GHG emissions significantly. Introduction of advanced biofuels is challenged by the blend wall in the US and high costs, there is much opportunity for them to contribute significantly to energy security but also reducing GHG emissions.

Keywords Balance of trade · Benefit and costs · Biofuels · Energy security · Greenhouse gases · Policy · Risk

1 Introduction

For years now, the United States has been attempting to find a way to have energy security and independence (Yergin 2006). With decades of net importation of petroleum and natural gas, the idea of developing a source of energy from the staple crop

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G. Hochman (✉) · M. Traux
Department of Agriculture, Food and Resource Economics, Rutgers University,
New Brunswick, NJ, USA
e-mail: gal.hochman@rutgers.edu

D. Zilberman
Department of Agricultural and Resource Economics,
University of California at Berkeley, Berkeley, CA, USA
e-mail: zilber11@berkeley.edu

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of corn seemed to be a promising way to achieve energy security and independence from fossil fuels (Lapan and Moschini 2009). It was believed that with improving technology in both biofuel production, and agricultural techniques, producing ethanol would become competitive with imported petroleum, allowing the market to help develop the infant industry. After years of stagnant development for ethanol fuels (the 1980s and 1990s), the United State government developed policies aimed at promoting the use and production of ethanol to compete with gasoline.

The government established a biofuel mandate in 2005, which required a minimum amount of ethanol to be blended with transportation fuel (the Energy Policy Act of 2005[1]). It also implemented the now repealed tax credit, and import tariff, which together were supposed to protect the domestic industry by making foreign ethanol more expensive and less competitive with the domestically produced corn ethanol. Although these policies were intended to benefit the domestic energy sector and provide a variety of competitive fuel sources for consumers, the infant industry led to unintended consequences as it developed. While the biofuel industry has matured, the adverse effects of its growth are causing policy makers to reconsider if the benefits outweigh the side effects (Hochman and Zilberman 2016, and references therein).

Land use and rising food prices have caused the most concerns for policy makers, with food prices increasing 2.7% annually[2] since the implementation of these policies. The amount of available land for agriculture transitioned to producing ethanol crops affects the cost of other staple crops now no longer being produced at the same levels (Hertel et al. 2010; Chen et al. 2012a; Roberts and Schlenker 2013).

Although initially not a direct goal of the enacted policies, greenhouse gas (GHG) emissions were explicitly introduced into the regulation in May 2009 (Renewable Fuel Standard—RFS2) and were expected to contribute to the development of low carbon fuel sources. Research into GHG emissions from burning ethanol has shown mixed results against the supposed benefits of ethanol fuels (Hochman and Zilberman 2016), with some research showing that ethanol fuel worsen the problem of GHGs in the atmosphere (Hertel et al. 2010).

Although the environmental benefits of current crop-based biofuels are much more limited than initially thought and the cost of producing advanced biofuels much higher than many hoped, biofuels did affect the U.S. balance of trade and contributed to its reduction in recent years (Hochman and Zilberman 2016). The rest of the chapter begins by describing the biofuel industry (Sect. 2). This is followed by a discussion of biofuel policies in the U.S. (Sect. 3) and a summary of the policy instruments used (Sect. 4). The U.S. biofuel policy has affected commodity markets and international trade that are discussed in Sect. 5. We conclude with Sect. 6.

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[1] The Energy Policy Act of 2005 is available at http://energy.gov/sites/prod/files/2013/10/f3/epact_2005.pdf.

[2] See USDA Food Price Outlook website, available at http://www.ers.usda.gov/data-products/food-price-outlook/ (viewed: January 21, 2016).

2 Biofuel Production

Biofuels are seen as an energy source that could help reduce the United States reliance on fossil fuels, and the amount of GHGs emitted into the atmosphere. The many advantages of biofuels include lower GHG emissions intensity, domestic availability, renewability, higher combustion efficiency, lower sulfur, and aromatic content and biodegradability (Hertel et al. 2010). The disadvantages of biofuels include lower energy efficiency and its contribution to air pollution (Brown 2008). However, because the perception was that the benefits outweigh the costs and because of the high cost of production of biofuels relative to fossil-based fuels, governments instituted policies that promoted the industry's growth.

The most efficient country (in terms of fuel yields per unit land) in the world at producing ethanol is Brazil, using sugarcane as a source of ethanol (Demirbas 2009). The majority of this sugar cane is grown in Mato Grosso, Sao Paulo, and Parana, along with other eastern-coastal states within the country (see Fig. 1).

There are many different reasons believed to be responsible for Brazil's success with ethanol production. Sugarcane itself is a more efficient crop than other sources, with it being seven times more efficient than corn in terms of fuel yield per unit land (Crago et al. 2010). Brazilian sugarcane ethanol has a production cost that is, on average, 24% lower than United States corn ethanol, mainly because it is possible to produce 45% more ethanol per unit of land from the sugarcane plant than from corn (Crago et al. 2010). In addition, the tropical weather of Brazil provides a more suitable climate for sugarcane (Crago et al. 2010).

The Untied States is the second most efficient country at producing biofuel, relying heavily on corn ethanol (Hochman and Zilberman 2016). The majority of corn comes from the "corn belt" region, which is composed of Iowa, Illinois, Indiana, Southern Michigan, Western Ohio, Eastern Nebraska, Eastern Kansas, Southern Minnesota, and Northern Missouri. This region is the most suitable for corn production in the United States because of the vast, flat fields naturally available in the Great Plains (Miller et al. 2009). Figure 3 depicts the top four U.S. corn ethanol producing states in 2013. These regions are the most productive in terms of corn production, mainly because of the naturally nutrient rich soil, and the long growing season (Miller et al. 2009) (Fig. 2).

Corn is used as a primary source of feed for livestock production. Corn also uses more land per unit of ethanol compared to sugarcane (Bundy 2007). While sugarcane has an energy balance of 8.3–10.2, corn only has a balance of 1.3–1.6 (Bundy 2007), meaning higher energy input is required to produce the same amount of energy for corn when compared to sugarcane. This also means the productivity of the land is higher in Brazil than in the United States. In Brazil, there is roughly 355 million hectares (Mha) of land available for agricultural production, with 3.6 Mha dedicated for ethanol production in 2006 (Bundy 2007). In the United

Fig. 1 Brazil's regions. *Source* Ezilon Maps, available at ezilon.com

States, there is 270 Mha available for agricultural use, with 10 Mha dedicated to ethanol production in 2006 (Crago et al. 2010).[3]

Europe produces biodiesel primarily from sugarbeet and is the most expensive of the top three-ethanol producers in the world. This stems from poor growing conditions in Europe, along with the lower energy content of sugarbeets [see ebb-eu.org (viewed: January 22, 2016)]. Figure 4 depicts the top sugarbeet producing nations in 2011. The entire European Union allocated 8.6 million tons of sugar beet to biodiesel in 2011, yielding the most biodiesel produced in the world [see ebb-eu.org (viewed: January 22, 2016)].

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[3] See also Demirbas (2009).

Fig. 2 The map of the United States. *Source* Ezilon Maps, available at ezilon.com/maps

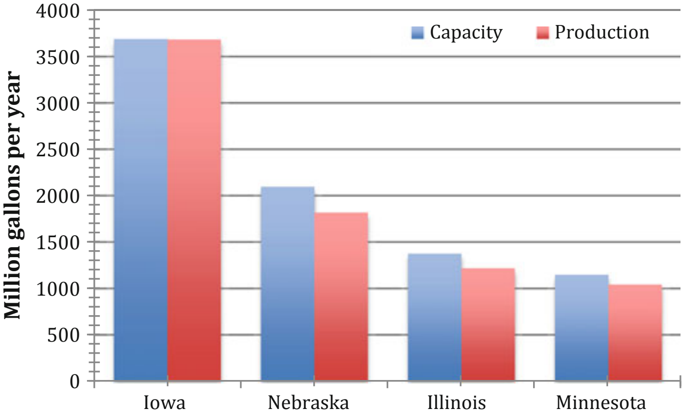
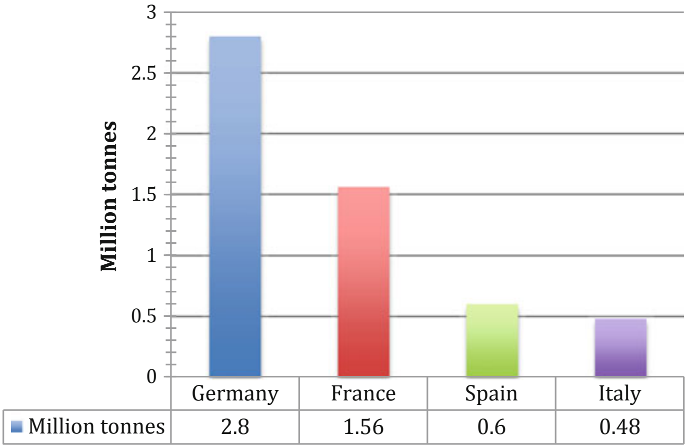


Fig. 3 Top four U.S. corn ethanol producing states in 2013 [see neo.ne.gov (viewed: January 10, 2016)]



	Germany	France	Spain	Italy
■ Million tonnes	2.8	1.56	0.6	0.48

Fig. 4 Top European sugar beet producers in 2011 (*Source* European Biodiesel Board)

3 U.S. Biofuel Policy

In pursuing energy security, the United States began developing policies that would promote the production and consumption of biofuel in the early 2000s. Since the United States is the biggest producer of corn in the world, policy makers saw the use of the crop as a promising path for a sustainable fuel source. Corn is also one of the most energy dense crops that the United States produces and thus believed to be a crop suitable for competition with gasoline (Gardner and Tyner 2007; Gallagher et al. 2003; Rajagopal et al. 2007; Cui et al. 2011). In 2000, the United States produced 1.65 billion gallons of corn-based ethanol; this was before any significant policies were put into place at the federal level to promote its use. In 2008, after two prominent laws were passed in 2005 and 2007, production rose to 9 billion gallons (Lapan and Moschini 2009).

3.1 The U.S. Biofuel Mandate

The Energy Policy Act of 2005 took the first noticeable step towards building the biofuel industry in the United States by requiring a specific amount of ethanol to be consumed as fuel. It was followed by the Energy Independence and Security Act of 2007 (EISA 2007), which established the Renewable Fuel Standard (RFS) that set the apportioned mandated quantity for the different feedstock. The RFS was updated in 2010 (RFS2) to differentiate among different types of renewable feedstock, depending on whether it was cellulosic biofuel, biomass-based diesel, advanced biofuel, or renewable fuels. This mandate is implemented by assigning a Renewable Identification Number (RIN) to each unit of biofuel, which can be bought or sold to and from other fuel blenders after the fuel attached to the RIN is bought by the blender. This encourages some blenders to produce more ethanol mixed fuel than they are required to, with the opportunity to trade RINs and earn money from their competitors. If a blender does not purchase enough biofuel to meet their required mandate, they are able to purchase the RIN from other blenders who produce a surplus amount of biofuel. This system is similar to a cap-and-trade policy, which limits SO_2 and CO_2 emissions (Thompson et al. 2009).

The Energy Policy Act of 2005 initially set the RFS mandate at a total of 4 billion gallons in 2006, with an increase in the mandate to a total of 7.5 billion gallons in 2012. With the adoption of the Energy Independence and Security Act of 2007, the mandated levels were increased from a total of 9 billion gallons in 2008, to a total of 36 billion gallons in 2022. The 2022 mandated level has an implicit cap of 15 billion gallons for corn ethanol, with a minimum of 16 billion gallons from cellulosic biofuels.[4]

The RFS was updated in 2010 to include language that suggests that its goals were to reduce GHG emissions and minimize the contribution of transportation fuel to global climate change (RFS2). The update defined advanced biofuels as those that achieve a reduction to life cycle GHG emissions intensity (including emissions from direct and indirect land use change) by at least 50%, cellulosic biofuels as those that reduce life cycle GHG emissions intensity by at least 60% while conventional biofuels need to achieve a reduction in life cycle GHG emissions by at least 20%. Another stated objective of RFS2 was to decrease gasoline consumption by at least 20% by 2020 and by 30% by 2030 (Sorda et al. 2010).

The implications of the volumetric mandate on fuel prices are a topic of much controversy (Hochman and Zilberman 2016). Because the mandate requires fuel blenders to blend a minimum amount of ethanol in the fuel sold to distributors, a binding mandate may force blenders to bid higher than is economically viable based on the market price for biofuels. That is, the demand for the fuel is not set on the economic market, but by governmental policy (de Gorter and Just 2009a; Thompson et al. 2009). However, others have argued that the introduction of biofuels yields lower crude oil prices (Hochman and Zilberman 2016, and references therein) and thus lowers the price of fuel at the pump.

3.2 The Volumetric Ethanol Excise Tax Credit

The Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 were accompanied by a Volumetric Ethanol Excise Tax Credit (VEETC), or feed in tariff, for blenders to purchase biofuels and an import tariff on foreign biofuels, which incentivized purchase of domestic biofuels to promote the country's infant industry. The VEETC was created by the American Jobs Creation Act of

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[4] See U.S. EPA ruling available at http://www.epa.gov/otaq/fuels/renewablefuels/index.htm.

2004 and applied through December 2010. It was extended for one year by the Renewable Fuels Reinvestment Act (RFRA). Initially, the tax credit allowed ethanol blenders the opportunity to claim a $0.51 credit for every gallon of ethanol used in the blending process (Sorda et al. 2010). The 2008 Farm Bill reduced the VEETC from $0.51 to $0.45 per gallon. While the tax credit expired on December 31, 2011, the American Taxpayer Relief Act of 2012 (Pub. L. 112-240) retroactively extended certain fuel tax credits till December 31, 2013, which included biodiesel and renewable biodiesel (Pub. L. 112-240; sec. 405), as well as cellulosic (Pub. L. 112-240; sec. 404).

In general, the use of tax credits to promote biofuels is viewed as being very costly to the taxpayer, and causing negative effects on social welfare (Lapan and Moschini 2012; de Gorter and Just 2009b, 2010; Chen et al. 2012a). The biggest complaint is that a tax credit increases the consumption of fuels by lowering the real cost of the gasoline. This reduction in cost causes a higher consumption rate, making any reduction to GHG emissions difficult to obtain (Khanna et al. 2008). The tax credit is also viewed as an incentive for refineries and blenders to bid up the price of ethanol above that of gasoline. Blenders and refineries are accused of bidding up the price in order to receive the full amount of the tax credit, with a lower price offering a lower credit amount. By bidding the cost higher than the real market value, blenders, and refineries indirectly cause the price of corn to rise throughout its supply chain. Beside the already mentioned increase to corn prices caused by blenders and refiners bidding up the cost of ethanol, the taxpaying public is responsible for providing the tax credit to the fuel producers. It is estimated that the tax credit has cost the United States $2.4 billion in 2006, and $5 billion in 2010. For biodiesel, the credit is estimated to cost taxpayers $1.4 billion in 2008 (Sorda et al. 2010).

3.3 Trade Restrictions

Beginning in the 1980s until 2011, U.S. ethanol producers were protected by a 54 cent per gallon import tariff. Historically, the motivation for the import tariff was to offset the federal tax credit that applied to ethanol regardless of country of origin. These policies together made the purchase of domestic biofuels cheaper than Brazilian sugarcane ethanol. Most of this support was discontinued after 2011, aside from the mandate. A removal of the import tariff was expected to reduce the domestic price for United States ethanol by 13.6%, and reduce the domestic market share for corn ethanol by 3.7%. The removal of the import tariff, along with the biofuel tax credit was expected to reduce ethanol consumption by 2.1% and the price of ethanol by 18.4% (Cui et al. 2011).

On January 1, 2012 the U.S. eliminated the 54 cents per gallon import tariff imposed on ethanol imports followed by the 45 cents per gallon corn ethanol tax credit to blenders. Overall, the two top world producers and exporters of ethanol, the U.S. and Brazil, now provide free access to their conventional biofuel markets.

4 Combining Biofuel Policies

From 2007 to 2022, Chen et al. (2012a) simulated a scenario with only an RFS mandate in the United States and showed that the expected net social welfare gain relative to the business-as-usual would be \$110 billion to \$132 billion. However, if a tax credit is provided then, relative to an RFS alone, social welfare declines to between \$79 billion and \$118 billion over the 2007–2022 period. The incremental gain of a tax credit and RFS regime, relative to the RSF alone, is between 8.45 billion gallons and 26.15 billion gallons across the various scenarios. Put differently, the incremental welfare cost of the tax credit is between \$2.65 and \$9.84 per liter of ethanol.

Hertel et al. (2010) argue that the combination of biofuel mandates, tax credits, and import tariffs have caused a 10% rise in corn prices, which leads to a reduction of food consumption across the world. The rise in corn prices is believed to contribute to a 42% reduction in the amount of corn grown for feed, leading to other crops substituting for corn and higher prices for these competing crops. With an increase in crop prices, the livestock which consume these products also saw an increase in price, contributing to a decrease in demand for livestock by $\sim$31% as a result of higher cost of production.

While food prices are increasing and demand is declining, crop yield increases continue. There has been 0.4% increase in crop yields since the policies have come into effect, leading to a 2.8% increase in agricultural production intensification.[5] This rise in production has resulted in a reduction in coarse grain imports to the United States by 17%, while reducing the countries coarse grain land reserves 4% (Hertel et al. 2010). For more on the benefits of GMO and its impact on yield, see Barrows et al. (2014).

5 Biofuel Policies, Markets, and the Environment

In 2012, CO_2 emissions in the United States accounted for 17.89% of the world's fossil fuel emissions, with 5636.74 mmt emitted (http://www.eia.gov). Biofuels are seen as a way to reduce this number. Although biofuels reduce CO_2 emissions, Nitrous Oxide (NO_x) emissions rise with the use of biofuels, and an increase in NO_x by approximately 10% is expected from pure biodiesel (i.e., B100) and a 2% increase for a 20% biodiesel/80% petrodiesel mix (i.e., B20) (Brown 2008). This has increased the NO_x concentration in the atmosphere from 1.86 to 2.23%, with each pound of NO_x emitted being 300× per pound stronger than each pound of CO_2 emitted [see https://www.epa.gov/climatechange/ghgemissions/gases/n2o.html (viewed: January 12, 2016)]. The U.S. EPA calculates the annual GHG emissions of corn-based ethanol to be 39 gCO_2e/MJ, compared to 92 gCO_2e/MJ annual

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[5] See also Bennett et al. (2015).

emissions for gasoline, however these calculations do not account for the market-mediated effect of the introduction of biofuels, such as indirect land use changes.

With the implementation of biofuel policies, the United States expected beneficial outcomes, with energy security being paramount. However, these policies have created numerous economic and environmental side effects. There is an overwhelming consensus that the policies have caused increases in food prices of about $0.61 on average—about 20% at current prices (Hochman and Zilberman 2016). There is also an agreement that these policies have caused a negative effect on current land use, with 40–45% of land being used for the production of corn for biofuel instead of food/feed use (Zilberman et al. 2013).

The most debated unintended consequences of the United States biofuel policy have been adverse land use and an increase in food prices. These two problems have caused researchers to look into the benefits of biofuel policies, and to decide if they are worth promoting in the future, and which changes should be made to ensure the policies have a positive impact rather than a negative one on the social welfare (Zilberman et al. 2012, 2013).

5.1 Indirect Land Use Change

Biofuel policies may cause farmers to change the use of their land by either changing their current cropland for production of energy crops, or by farmers increasing the amount of land used to produce crops for either food or fuel. The introduction of biofuels contributed to increased demand for land, and thus to deforestation, which further increases the cost of reducing CO_2 (Timilsina and Sherestha 2010). Concerns about the effects of biofuels on deforestation led regulators, particularly CARB, to assign biofuels a GHG emissions intensity taking account of the indirect land use changes associated with their production when evaluating their compliance with the biofuel policies.[6]

With the current biofuel policies in place, the United States is expected to increase coarse grain acreage by 10%, representing a 0.8% increase to agricultural land use in 2015 (Cui et al. 2011). This increase will reduce current forest and pasture land by 3.1%. In the European Union, there is an expected 10% increase in oilseed acreage, which will increase the European Union's cropland area by 40% as food crop land increases to make up for energy crop land conversion. The European Union will see a reduction in forest and pasture land by 4.9% (Cui et al. 2011). The demand for feedstock is responsible for 75–80% of this increase in land use (Demirbas 2009).

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[6] See U.S. Environmental Protection Agency's website at http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm.

U.S. coarse grain output has increased by roughly 1.25–2.49%, which is mainly attributed to an increase in land use in the United States assuming 2006 figures and a 1-billion-gallon increase in U.S. ethanol demand (Keeney and Hertel 2009). For every 1 billion gallon increase in the United States ethanol fuel mandate, there has been a 0.35% decrease in forest cover, a 0.53% decrease in pasture cover, and a 0.10% increase to cropland. For the 0.10% increase to cropland, there has been a 1.66% increase in coarse grain land usage, while other crops have decreased in production. Land under oilseed decreased by 1.44%, sugarcane by 0.64%, other grains by 1.31%, and a 0.34% decrease to all other agricultural crops, globally (Keeney and Hertel 2009). The decrease in the supply of these crops caused an increase in their price, resulting in the United States spending more for these crops. The increased demand for imports has also affected land use in other countries, with Canada having a 0.14% increase in crop land, which has caused a 0.105% decrease in forestland, and a 0.17% decrease in pastoral land. The same findings were shown for Latin American countries, Brazil, and Asian Pacific and Oceania (Keeney and Hertel 2009). Chen et al. (2012b) argue that the U.S. biofuel mandate is responsible for a 16% increase in corn acreage in the United States in 2022. This increase is met by a reduction in soybean and other crop production (Chen et al. 2012b). The global harvested area was expected to increase in 2015 by 15.6 Mha because of the EU and U.S. biofuel mandate; the projected increase is much smaller (11.5 Mha) if corn coproducts are incorporated (Taheripour et al. 2009).

In 2004, only 1% of the total world cropland was dedicated to biofuel production. Brazil has led the way among countries dedicating a share of cropland for biofuel crops, with sugarcane being produced on 5.6 million ha, or approximately 10% of the country's cropland. For the world at large, there is approximately 13.5 billion ha of land available, with forest covering 4.2 billion ha, and cropland and pasture covering 5 billion ha. Of the 5 billion ha, only 1.6 billion ha are cropland, 2 billion ha are poor quality land with low crop yield and high degradation, and the rest are urban with too poor quality for agricultural use. These sites provide benefits in the form of biodiversity conservation, carbon sequestration, and natural water filtration, and since these play such an important role in the natural environment, they are likely zoned for protection (Chakravorty et al. 2009).

However, concerns regarding the indirect land use changes are shrouded with uncertainty (Zilberman et al. 2013) and caution need to be applied when applying these methodologies. Koltz et al. (2014) showed that estimates of the change in GHG emissions due to a unit expansion in biofuel varies significantly with the amount of biofuel in the economy and with the policy instituted.

5.2 *Food Versus Fuel Concerns*

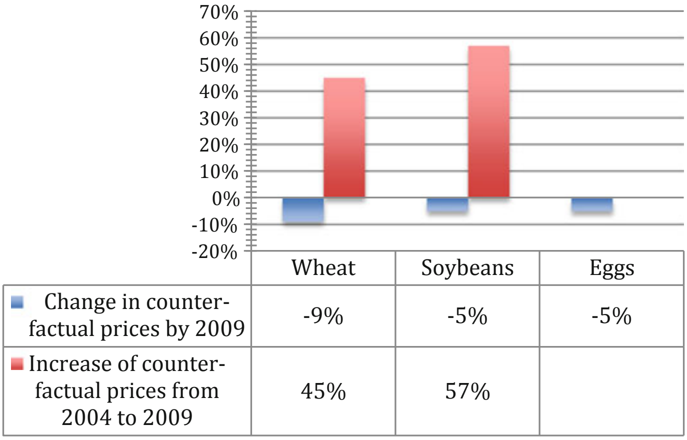
One of the most recognizable complaints about the current biofuel policies has been the relationship between biofuel production and an increase in food commodity prices. From 2000 to 2007, there was an average price increase for food crops of

30% (Rosegrant 2008). This figure is adjusted depending on what factors are being considered; with future expected prices factored into some studies, and the coproducts and inventories being considered in others (Hochman et al. 2011b). There is a wide range of estimates for the increase in food price from 2000 to 2008 is anywhere from 23 to 72%, with biofuel production being the major cause of the increase (Timilisina and Shrestha 2010). Zilberman et al. (2013) argue that there has been an increase of 20–30% in food commodity prices from 2001 to 2008, with factors such as food and feed demand, higher energy prices, a weaker dollar, and increase in biofuel production accounting for about 50% of the increase (see also Hochman et al. 2011a). Hochman and Zilberman's (2016) meta-analysis suggests that the introduction of corn -ethanol contributed on average to an increase of $0.61 in the food commodity price, which at current prices amounts to an increase of about 20%.

There are different ways researchers have estimated how much food prices will change in the future, and how they have changed since the inceptions of various policies. Some look at how price increase will be affected if the biofuel mandates levels are increased the way they are supposed to until 2022. Under this view, corn prices are expected to increase 7.1% per bushel, while soybean prices are expected to increase 2.85% (Babcock 2011). Eggs, beef, poultry, and other food goods have the smallest price increase, with only 1.1%, or $0.02, compared to current policies (Babcock 2011). Other studies argued that rice will increase 39% compared to 1990–2000 policies, while wheat will have a 22% increase compared to these same 1990–2000 policies (Rosegrant 2008).

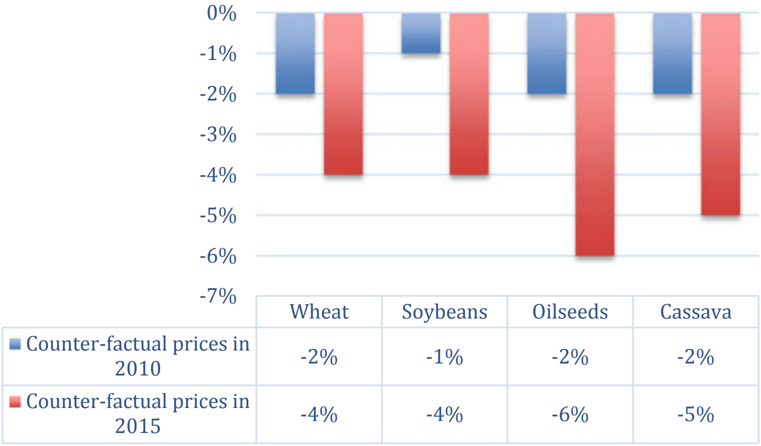
Without an increase in the biofuel mandate levels, and a halt at 2007 mandate levels, food prices were expected to be reduced by 14% by 2015 (Timilsina and Shrestha 2010). Rosegrant (2008) performed a similar exercise and concluded that if the mandates were frozen at 2007 levels, there would be a decrease in food cost by 6% by 2010, and 15% by 2015. For corn, if left at 2004 policy levels, by 2009 there would have been a decrease in prices of 21%. This would also reduce ethanol production approximately 11%, as long as demand for oil and price stay constant up until 2022 (Babcock and Zhou 2013). For other food products, a freeze of the mandate levels would also cause the price to increase at a lower rate than if the subsidies were to increase to 2022 levels (Figs. 5 and 6).

As mentioned before, these findings do not take into consideration the use of corn coproducts, which if taken into consideration, will result in these numbers being less dramatic. By not including coproduct usage in the findings, the United States has a 19.8% increase in food cost, with the EU (11.0%) and Brazil (9.8%), also showing significant food price increases. However, once the coproducts are included, the United States has an increase of food cost of 13.0%, with the EU (5.6%), and Brazil (7.9%) also showing a reduced amount of the increase in food prices (Taheripour et al. 2009).



	Wheat	Soybeans	Eggs
🟦 Change in counter-factual prices by 2009	-9%	-5%	-5%
🟥 Increase of counter-factual prices from 2004 to 2009	45%	57%	

Fig. 5 If biofuel mandate was left at 2004 level, what are the counterfactual prices in 2009 (Babcock 2011)



	Wheat	Soybeans	Oilseeds	Cassava
🟦 Counter-factual prices in 2010	-2%	-1%	-2%	-2%
🟥 Counter-factual prices in 2015	-4%	-4%	-6%	-5%

Fig. 6 Counterfactual Prices in 2010 and 2015 if biofuel mandate were frozen at 2007 level (Rosengrant 2008)

5.3 *Indirect Fuel Use*

Discussions have also looked into the effect indirect fuel use changes have on the amount of GHGs emitted into the atmosphere (Hochman and Zilberman 2016, and references therein). These indirect fuel use changes may increase or decrease greenhouse gas intensity of biofuels, depending on the various factors. These factors include policy attributes, current and future market conditions in fuel markets, and direct greenhouse gas intensity of biofuel related to oil (Rajagopal et al. 2011).

5.4 The Organization of Petroleum Exporting Countries (OPEC) Effect

The behavior of OPEC, a cartel of nations, is different from that of a standard cartel or competitive markets, and this leads to differences in predictions of the OPEC response to changes in supply and demand of crude oil. These different conclusions regarding indirect fuel effect depend on the industrial organization of the fuel markets. Hochman et al. (2011) showed that when computing change in GHG emissions due to the introduction of biofuels, the cartel-of-nations model results in the largest decrease in emissions compared with the standard cartel and the competitive models. That paper shows that the differences are large and that the rebound effect (whereby substituting gasoline with biofuels yields a reduction in fuel prices and thus more fuel consumption) is more than 7% larger under the competitive model.

The cartel-of-firms model (Hochman et al. 2011b) also affects the calculations of the impact of biofuels on food commodity prices. Hochman et al. (2010) analyzed the multiple contributions of biofuels to the increase in food commodity prices within a multimarket framework that includes the OPEC effect, namely, OPEC is modeled as a cartel of nations. These authors show that the introduction of alternatives such as biofuels affects OPEC choices, and that OPEC stabilizes prices and mitigates the upward pressure biofuel created on food commodity prices. The paper concludes that while cartel and competitive models overestimate the effect of biofuels on fuel prices, they underestimate the effect of the introduction of biofuels on the environment.

5.5 The Indirect Coproduct Effect

Barrow et al. (2012) identified an indirect effect of biofuels that results from decreased supply of petroleum coproducts, namely, the indirect coproduct effect (ICE). The ICE represents the change in greenhouse gases associated with the displacement of petroleum coproducts that are eliminated or replaced with reduction in petroleum-based fuels. This study assesses the order of magnitude of the ICE effect and finds that it is likely to reduce the greenhouse gas emissions intensity associated with biofuels and thus serve to offset the negative effect of indirect land use changes. Their numerical analyses suggest that when the ICE is included in the life cycle analysis, corn-based ethanol easily meets minimum requirements for renewable fuel credits under the RFS.

5.6 *The Indirect Food Effect*

The indirect food effect captures the market-mediated effect from the introduction of biofuels that contribute to the reduction of the GHG emissions from food, as land switches from producing feedstock for food to producing feedstock for fuel. This effect suggests that the life cycle approach that incorporates the indirect land use change recognizes the impact of market-mediated adjustments in an asymmetric manner: while biofuels are credited for market-mediated incremental GHG emissions attributed to land expansion, biofuels are not credited for market-mediated effect that reduced the GHG emissions of food production (Zilberman et al. 2013).

5.7 *The Balance of Trade Effect*

An important reason for promoting domestic production of biofuels (and natural gas) is the increasing deficit in the United States balance of trade over the last few decades. The introduction of ethanol led the United States to save about US$100 billion (Hochman et al. 2013). Historical data suggests that the increase in ethanol consumption from 2005 to 2011 equaled in volume 67.25% of the decline of finished motor gasoline consumption (Hochman et al. 2013). Both the introduction of biofuels and the new developments in natural gas substantially improved the United States balance of trade.

The primary sources of energy before the promotion of biofuels were, and still are coal, natural gas, and petroleum products. For coal, the United States has been a net exporter since at least 1955. In 1955, the United States imported just 0.008 Q Btu, while exporting 1.465 Q Btu. The trend has continued every year with every year more coal being exported than imported (Fig. 7). The most coal the United States

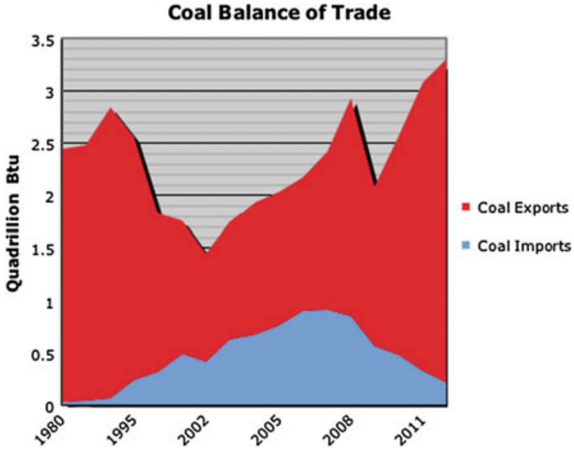


Fig. 7 Coal imports and exports

imported was in 2007, with 0.909 Q Btu purchased from other countries, and 1.507 Q Btu exported. In 2012, the United States exported the greatest quantity in one year at 3.088 Q Btu with 0.212 Q Btu imported [see www.EIA.org (viewed: 447 December 20, 2015)].

For natural gas, the US has consistently imported more than it exported. In 1955, the United States imported 0.011 Q Btu, while exporting 0.049 Q Btu, which is the last time the country has exported more natural gas than imported. This imbalance reached its peak in 2007, which was the year the United States imported the most natural gas at 4.723 Q Btu, while exporting 0.830 Q Btu. The gap has decreased since 2007, with 2012 seeing the United States exporting its highest amount at 1.633 Q Btu, but still importing 3.216 Q Btu (Fig. 8). However, combining coal and natural gas, the U.S. became a net exporter in recent years, with a dramatic break in the existing trend since 2007 (Fig. 9).

Natural gas was 26.9% of U.S. primary energy consumption in 2012, producing 22,902 billion cubic feet, which was 19.74% of the world's total production. The United States was also the world's leading consumer of the product, consuming 24,383 billion cubic feet, or 20.54% of the world's total consumption. Although the

Fig. 8 Natural gas

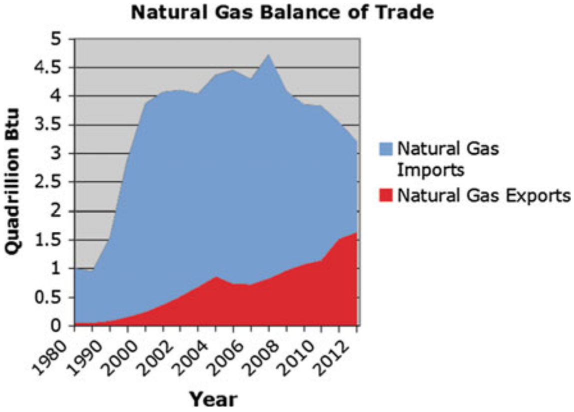
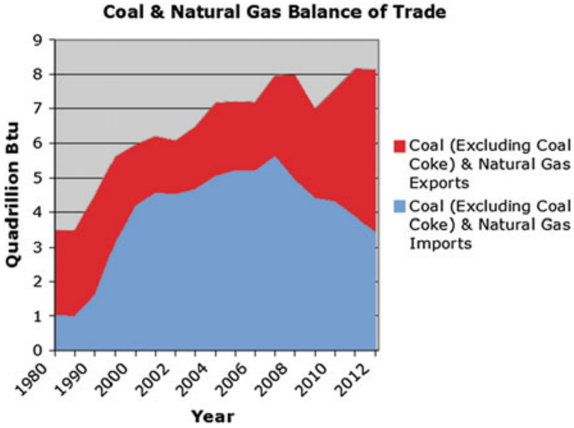


Fig. 9 Net exports of coal and natural gas in B Btu (2007)



industry has been in a recent domestic boom, the United States still has a net trade deficit of 1962 billion cubic feet of natural gas [see www.EIA.org (viewed: December 20, 2015)].

Recent trends indicate that the rise in natural gas will continue for the near future. Proven reserves of U.S. wet natural gas rose by 31.2 trillion cubic feet (Tcf) in 2011, which set a new record for the amount available at 348.8 Tcf. This led the total proven reserves for the U.S., "wet, dry, and shale", to increase by 9.8%, with the states of Texas, Wyoming, Louisiana, Oklahoma, and Pennsylvania having substantial gains in proven reserves. Pennsylvania reserves have increased by roughly 90% in 2011, contributing 41% of the nation's total increase. Texas accounted for an additional 32% of the nation's increase in wet natural gas reserves. For shale gas production, a substantial increase has taken place since 2010, when only 5.4 Tcf were produced, with 97.4 Tcf of reserves. In 2011, there was 8.0 Tcf for production, and an increase in reserves to 131.6 Tcf.[7] Natural gas production is pushing coal into foreign markets, yielding a drastic change in the United States balance of trade. While the introduction of a cleaner energy source results in less GHGs emitted in the U.S., the United States is becoming a major exporter of GHGs.

A similar trend in the energy trade balance of petroleum is observed, albeit for different reasons. The United States has been a net importer of petroleum since at least 1955, when 2.752 Q Btu were imported to only 0.774 Q Btu exported. This gap in imports and exports increased until 2005, when the imports totaled 29.169 Q Btu, which is the most ever imported, while exports for that same year totaled 2.442 Q Btu. The gap has since shrunk, with 2012 United States imports totaling 23.371 Q Btu, while exports were at a record high, at 6.493 Q Btu. At the same time, the United States regulatory environment introduced the Energy Policy Act of 2005 and later of 2007, as well as phased out the use of Methyl Tertiary Butyl Ether (MTBE) and replaced it with ethanol as an oxygenator for reformulated gasoline. While the U.S. is still a net importer of crude oil, it has become a net exporter of petroleum products in 2012 (Fig. 10).

These trends for crude oil and petroleum products, with the import/export gap of petroleum products reversing in 2012, can be seen to correlate with the introduction of biofuel policies (Figs. 11a, b).

This decrease in the net trade gap can be, at least partly, attributed to the biofuel mandate increase, which required a larger percentage of the nation's fuel source to be composed of biofuel products. The United States accounted for nearly 21% of the world's petroleum total use in 2012, with 35.3% of its primary energy source coming from petroleum. The dependence on foreign petroleum was a major deciding factor for policy makers to develop legislation that promoted the production and consumption of biofuels (Lapan and Moschini 2009). Proven reserves of crude oil increased in 2011, mainly because of new discoveries in Texas, Gulf of Mexico, Alaska, California, and North Dakota. For U.S. tight oil reserves, over

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[7] The effective recovery factor used to calculate current proven reserves reflects: (i) a probability factor; (ii) prior experience in how production occurs; and (c) current resources in the play.

Fig. 10 Crude oil and petroleum products

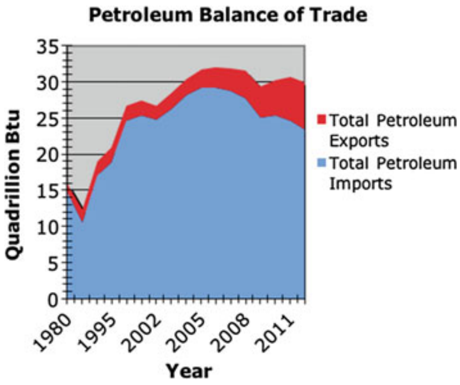
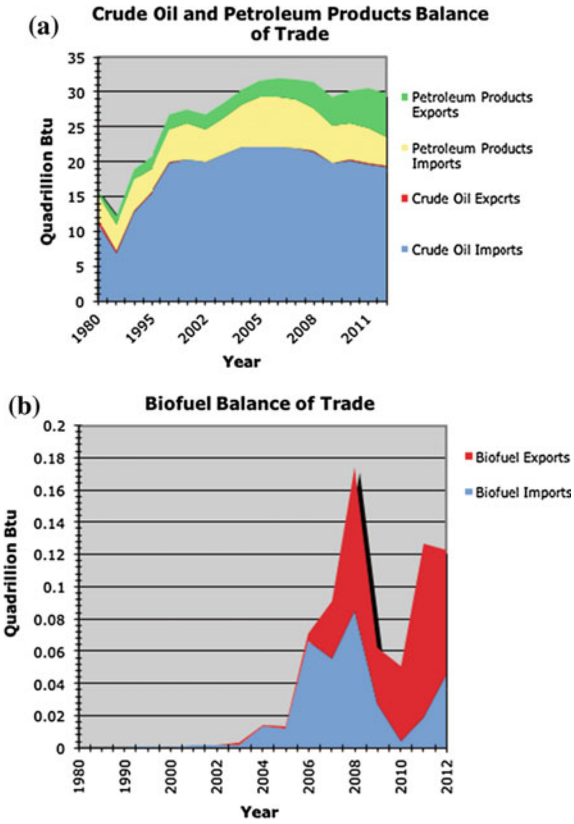


Fig. 11 **a** Crude oil and petroleum. **b** Biofuel production and consumption



90% in 2011 came from four plays, the Bakken Play with 2 billion barrels, Eagle Ford Play reserve which is estimated at almost 1.3 billion barrels, and the Niobrara and Barnett Play, with a combined total of 126 million barrels [www.EIA.org (viewed: December 10, 2015)]. The recent changes in proven reserves are attributed mostly to new discoveries, and to horizontal drilling and hydraulic fracturing—technologies that came into being toward the beginning of the new millennium (Yergin 2006). Although the introduction of current biofuels did not lead to large savings in GHG emissions, it did result in a large impact on the U.S. balance of trade. Similar conclusions can be made for natural gas and shale gas.

6 Demand for Biofuel and the Blend Wall

Currently, any biofuel produced in the U.S. that is above the 10% blend limit needs to be reallocated to a higher blend mixture (e.g., E85), or exported for foreign consumption. However, U.S. demand for flex fuel vehicles does not warrant significant investments in E85 infrastructure. In 2011, the U.S. Energy Information Administration estimated that the U.S. is using nearly all the ethanol it can under the 10% blend wall (U.S. Energy Information Administration 2012). Some see the approaching of the blend wall as a consequence of the infrastructure limitations for higher blend fuels, such as transportation equipment, facilities, the availability of flex fuel vehicle options, and the failure of wholesale distribution systems (Zhang et al. 2010).

The blend wall has become a recent concern due to the decline in demand for gasoline (Snow 2013) and the expansion of the biofuel industry. The ability to export biofuels can serve as a short term option to the blend wall, due to 95% of all ethanol produced having been consumed domestically for the past decade, with the exception of 2006. However, there will still remain a need to increase the demand for higher blend mixtures in the U.S. (Zhang et al. 2010; EIA 2011)

There are 3.24 million flex fuel vehicles currently owned and operated in the United States as of 2015 [see www.EIA.org (viewed: 447 December 20, 2015)]. In the absence of policy, this is not sufficient to justify an increase in investments for flex fuel infrastructure. A station owner would need to invest between $50,000 and $200,000 to add a flex fuel tank to their station (Braeutigam 2009).

As more ethanol is forced into the higher blends of ethanol, ethanol prices will see a decline, relative to gasoline prices (Zhang et al. 2010). Depending on how responsive the blend wall shift is to higher blends, the total petroleum gasoline consumption may increase or decrease with a positive shift in the blend wall (Qiu et al. 2014). The response to the blend wall shift centers around the position of demand curve for ethanol blends above E10.

Due to the small size of the E85 market, some oil companies argue that there is no demand for ethanol beyond the blend wall, while ethanol producers argue that there may be demand, but the limits to the E10 + market have prevented expansion of ethanol consumption (Babcock and Pouliot 2013). The blend wall can serve as an effective constraint on demand for greater ethanol production, however, if producers are able to supply higher blend levels then demand will continue to meet supply (Tyner 2010). Consumption of 1 billion gallons of E85 is possible as long as the blended fuel price match a 6% reduction in fuel costs (with the assumption of

E10 price being $3.60/gallon), and costs decrease further as more E85 is consumed (Babcock and Pouliot 2013). The literature expressed several other concerns with extending the blend wall (Qiu et al. 2014). Some have argued that extending the blend wall will cause a deceleration of flex fuel vehicle adoption, and an increase in total petroleum gasoline demand (Zhang et al. 2010; Foster et al. 2011). Automakers are concerned about the lack of durability testing for higher levels of ethanol blends in cars already on the road, and will not provide extended warranties to consumers that consume fuels beyond the E10 limit (Braeutigam 2009). This indicates that the blend wall might not be as much of a physical barrier, as it is a political-economic barrier (Zhang et al. 2010).

7 Biofuels, Risk Management, and the Contractual Environment

Agriculture and energy markets are inherently volatile leading to periods of high profits punctuated with periods of busts. Volatility in the staple food markets can induce periods of boom and bust in the ethanol markets (Hochman et al. 2008). Thus, biofuel policies have caused farmers to be concerned over the availability of insurance for energy crops. Miao and Khanna (2014) argue that farmers are reluctant to switch over to energy crops because they believe the risk associated with them is not worth the reward of production. Insurance programs could decrease the risk premium that refineries need to pay farmers to grow energy crops, thus reducing production costs and increasing biofuel competitiveness with gasoline and other fossil fuels. However, Miao and Khanna (2014) show that subsidizing crop insurance is less effective at promoting miscanthus in the U.S. than an establishment of cost sharing subsidy. The authors show that the cost-effective energy crop insurance subsidy rate is 0% while the cost-effective establishment subsidy rate is 100%. Comparing these outcomes to the no policy intervention, crop insurance reduces the total costs of meeting the 1 billion gallon mandate by only 0.3% yet the establishment of cost-share subsidy reduces the cost by 34% albeit at the cost of growing miscanthus in less productive counties (because of incentives to diversify the crop portfolio).

Du et al. (2014) argue that when the supply of the contracted feedstock (in our case, energy crop) is uncertain, the supply of biofuel to the biorefineries will be less than under certainty and more capital will be allocated to internal production of the feedstock. Yang et al. (2015) show that the best contract arrangements are very different for farmers in different circumstances

- For a farmer with lower land quality, and a higher degree of risk aversion, farmers will be more willing to lease their land to the refinery for biomass production. This means the farmer who owns the land is guaranteed to earn a reasonable income, and the refinery who signs the lease to grow on the land takes the risk associated with growing energy crops.

- A farmer with low land quality and a low degree of risk aversion is more willing to grow energy crops themselves with a revenue sharing contract signed with the refinery.

Yang et al. (2015) show that biorefineries are more likely to prefer a more vertically integrated system, and grow its own energy crop when biomass yield and price risks are high to avoid paying high risk premiums to a risk averse farmer. Refineries are also likely to prefer to be more vertically integrated when variability in returns to crop production is high and risk averse farmers are more willing to choose leasing land for energy crop production. The biorefinery is likely to have the biggest risk for loss if they only offer a revenue sharing contract. Yang et al. (2015) assume that the choices for refineries are to offer

- a long-term lease with the landowner at a fixed rental rate per acre,
- a fixed price contract for a given quantity of biomass delivery by independent producers, and
- a price indexed to profitability of biofuel production for refineries.

The authors then show that the best choice for the refinery is to lease the land and undertake vertically integrated production.

8 Concluding Remarks

The calculation of GHG emissions of biofuels is based on life cycle analysis, which accounts for emissions throughout the biofuel supply chain. But because biofuel policies impact markets in subtle ways, they result in numerous indirect effects and thus question the current use of lifecycle analysis in regulating biofuels (Khanna and Crago 2012; Zilberman et al. 2013). Because energy is ubiquitous, introducing alternatives to fossil fuels (i.e., biofuels) results in myriad indirect effects that impact numerous markets. A noncompetitive energy market that is very capital intensive further convolutes the effect of the introduction of biofuels on markets. Regulation should either account for the various effects, or disregard them and simply require that biofuels meet a stricter standard than fossil fuels and that the standard becomes stricter with time.

A second conclusion that emerges from our analysis is that current generation biofuels failed to deliver in key areas: the emission benefits are much more limited than initially expected, and the cost of advanced biofuels much higher than many hoped. However, current biofuels did contribute to rural development and substantially affected the U.S. balance of trade—helping the U.S. become less energy dependent and reducing the U.S. trade deficit. This suggests much potential for advanced biofuels, which can potentially result in significant contribution to GHG savings. The challenge, however, remains to reduce their cost, which currently is prohibitively high.

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The Sugarcane Industry and the Use of Fuel Ethanol in Brazil: History, Challenges, and Opportunities

Márcia Azanha Ferraz Dias de Moraes, Luciano Rodrigues and Scott Kaplan

Abstract Brazil is an international pioneer in biofuels, with more than 40 years of experience in the production and use of sugarcane ethanol. This paper describes institutional factors that contributed to the development of the biofuel industry, including the military regime and state-owned Petrobras in the 1970s and 1980s, the post-deregulation period in the 1990s, and changes in the 2000s, including new institutions targeting feedstock pricing arrangements and the growth in demand for flex-fuel cars, which allowed for market-based incentives. State intervention allowed the industry to overcome barriers of infrastructure, a transportation network, development of ethanol-powered vehicles, and output price stability and credit support. The paper concludes with key lessons from Brazilian ethanol production. While Brazil initially supported ethanol production in an effort to replace petroleum, it is now incentivizing expansion of a consumer market to address environmental and climate problems. Government support has allowed for efficient allocation of byproducts and positive impacts on the labor market, and agricultural sector in general. Still improvements in stability and predictability of the institutional environment are important for future growth. The lessons from Brazil provide insight into the challenges of biofuels in other countries attempting to replace fossil fuels with renewable resources.

Keywords Ethanol industry challenges · Flex fuel cars · Free market environment · Long term fuel polices · Energy matrix

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M.A.F.D. de Moraes (✉)
(USP—ESALQ, Department of Economics, Administration and Sociology),
University of São Paulo, São Paulo, Brazil
e-mail: mafdmora@usp.br

L. Rodrigues
(USP—ESALQ, Department of Economics, Administration and Sociology)
and Specialist with Extensive Experience on the Sugarcane Industry and Ethanol Market
in Brazil, Applied Economics at the University of São Paulo, São Paulo, Brazil

S. Kaplan
Department of Agricultural and Resource Economics, University of California
at Berkeley, Berkeley, CA, USA

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1 Introduction

Brazil is internationally recognized as a pioneer in biofuel, with more than 40 years of experience in producing sugarcane ethanol and using it on a large scale. The Brazilian National Ethanol Program (Programa Nacional do Álcool—Proacool or PNA) was launched in 1975 with substantial support from the State in both its creation and implementation, which certainly enabled the program's development.

The sugarcane supply chain used to be greatly affected by administrative state control. Since 1930, the government fixed prices for sugarcane, sugar, and ethanol, set production quotas for each production plant, and was responsible for exports, among other initiatives.

The profound institutional changes that took place starting in late 1980s altered the role played by the State in the sugarcane supply chain. The modifications included the transition from the strongly authoritarian military regime to a democracy as well as the promulgation of a new Federal Constitution in 1988, which shifted the State from direct intervention to a more regulatory role.

Moreover, the Brazilian economy was opened to foreign markets in the 1990s and in 1995 became a member of the World Trade Organization, both of which significantly impacted the country's industrial and commercial policy. Beginning in the late 1990s, Brazil drastically reduced state interference in the sugarcane production chain, and producers began to operate in a competitive, free market environment. These changes led to significant efficiency gains in both agricultural and industrial productivity, increasing the industry's competitiveness. Under this system, not only did social and environmental impacts gain importance, but also the competition between different fuels (ethanol and gasoline).

The Brazilian sugarcane industry faced several political changes since the launch of Proalcool. Significant institutional and technological movements have altered the course of the biofuel industry and promoted deep changes in the sector. Understanding of this long process is critical in identifying new opportunities and challenges of the industry in Brazil and abroad, and may also be useful for countries that already have or are considering implementing programs promoting ethanol-based fuels.

In this chapter, we present the history of Proalcool (Brazilian National Ethanol Program—PNA) and the main changes that occurred in the sugarcane industry during the government intervention period, including the Proalcool crisis in the late 1980s. The state withdrawal of the sugarcane supply chain was a long process, and deeply changed the relationships between the main stakeholders: sugarcane, sugar, and ethanol producers. The post-deregulation period (from 1999 to the present) is analyzed focusing on the changes in the grower/mill relationship and the new model for sugarcane payment (called CONSECANA). We also present the growth of the Brazilian share in the world sugar market as well as changes in the ethanol market, including the influx of foreign capital, the introduction of flex-fuel cars, and the competition between ethanol and gasoline in the free market environment. Finally, we explore the lessons from the Brazilian experience and future challenges for ethanol.

2 The Ethanol Program and Changes in the Sugarcane Industry During the Period of Government Intervention

2.1 The Brazilian National Ethanol Program

The Brazilian National Ethanol Program (PNA or Proalcool) was launched during the military regime in November 1975 (Brasil 1975). The program aimed to produce 3 billion liters of ethanol annually by 1980, which was achieved and increased to about 11 billion liters in 1985 (MAPA 2013).

Two phases stand out in the PNA implementation process. The first one starts with the onset of the program in November 1975 and lasts until 1978. It required gasoline to contain 20% anhydrous ethanol, implemented a policy that ethanol distilleries were to be attached to sugar mills, and involved the automotive industry in the production of ethanol-run cars. The ethanol production in this period grew approximately 349%: from 555 million in 1975 to 2.5 billion liters of ethanol in 1978 (MAPA 2013). The second phase of PNA (from 1979 to 1983) is related to large-scale production of hydrous ethanol to be used in cars that ran exclusively on this fuel. From 1980 to 1983, ethanol production soared from 3.7 billion to 7.8 billion liters (MAPA 2013).

In PNA's first phase, the government gave many incentives to ethanol producers, such as agricultural and industrial financing, product acquisition guaranteed by the Sugar and Ethanol Institute (Instituto do Açúcar e do Álcool—IAA), and fixed prices considering the parity of 44 L of ethanol for every 60 kgs (one bag) of standard raw sugar (which corresponds to the coefficient of conversion of sugar into ethanol), i.e., the anhydrous ethanol would be acquired by the IAA at a price equivalent to 44/60 cents of the price of a kilogram of standard raw sugar.[1]

In the second phase, support to producers and to consumption was reinforced. Ethanol production was stimulated by the reduction of the parity of a 60 kgs bag of sugar to 38 L of ethanol. Consumers were granted the following incentives that encouraged the consumption of the hydrous ethanol: (i) the maximum selling price of ethanol was capped at 66% of the gasoline price; (ii) a 50% price reduction on the Flat Road Tax (Taxa Rodoviária Única[2]); (iii) Taxi vehicles were exempted from the Industrialized Products Tax (Imposto sobre Produto Industrializado—IPI); (iv) a 5% reduction in the Industrialized Products Tax for cars running on ethanol as well as exemption from both the Tax on Operations Regarding the Trading of

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[1] Fuel ethanol prices were fixed by the government using sugar prices as a basis, so that it would be indifferent for the producer to manufacture either sugar or ethanol from the same raw material (sugarcane).

[2] Tax falling on vehicles' register and annual license, to be charged previously to the vehicle's register or annual license renewal. The amount charged used to be calculated on the total value of the vehicle: 7% for those run on gasoline and 3% for ethanol-run ones.

Goods (Imposto sobre Circulação Mercadoria—ICM) and the Tax on Fuels and Lubricants (Imposto Único sobre Combustíveis e Lubrificantes—IUCL).[3]

Analysis of Proalcool should combine two markets—sugar and petroleum—that stimulated the development and the achievement of the national policy for fuel ethanol. Increases in petroleum prices as a result of policies from the Organization of Petroleum Exporting Countries (OPEC) resulted in its prices soaring 225% between October 1973 and January 1974. The effects on the Brazilian trade balance were substantial, culminating with a deficit of US$4.69 billion dollars in 1974 (Santos 1993). The inflation rate increased by 122.6% in one year, from 15.5 to 34.5%. These events turned out to be fundamentally significant in decisions regarding energy policies to be adopted by the government. At the same time as the steep increase in energy prices, sugar producers faced an overproduction crisis, with declining prices both on the national and on the external sugar markets, where prices plummeted from US$0.55 per pound to US$0.12 per pound, depressing the industry's profitability (Moraes and Zilberman 2014). Thus, fuel ethanol became an important way for the government to reduce petroleum imports and improve the country's macroeconomy by stabilizing inflation rates and improving balance of trade. Ethanol production would also allow sugar producers to direct part of the sugarcane used in the sugar production into the new market of fuel ethanol.

The second phase of Proalcool started with the second petroleum economic crisis during the first half of 1979. From 1976 to 1978 there was relative stability in the petroleum market, which was followed by a period where OPEC members—mainly Saudi Arabia, Iran, and Iraq—disputed petroleum market control, disagreeing on prices and on volumes to be exported. In 1979 there were various price increases, notably seen in the spot market of Rotterdam where the price of a barrel of petroleum increased from US$12.58 at the end of 1978 to US$36.80 by the end of 1979. From 1978 to 1979, the value of Brazilian importation grew by 32%, mainly due to petroleum, which nearly tripled the balance of trade deficit to US$3.2 billion and increased the net external debt by 27% (reaching US$40.2 billion). At that time, according to Moraes and Zilberman (2014), Brazilian foreign dependence on petroleum was 41.6% compared to 43.6% in the energy crisis of 1973. The inflation rate in 1978 had already outstripped the barrier of 40% a year, and after the economic crisis it soared to 77% in 1979 (Santos 1993).

Many of the problems in the second phase of Proalcool originated from those in the first phase, namely (i) long periods of time needed to approve distillery projects' legal proceedings; (ii) the absence of monetary correction in loans offered to the distilleries[4]; (iii) distribution and warehousing of ethanol; (iv) insufficient prices of ethanol paid to producers; (v) resources for financing the expansion of plantations and industrial capacity; (vi) a fragmented decision-making structure, and

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[3] For more details, see Moraes (2000) and Moraes and Zilberman (2014).

[4] Due to slow legal proceedings for the projects approval and high inflation rates, at the time when projects were approved the amount requested had lost its value, and therefore it was not sufficient for the implementation of investments any longer.

(vii) development of technology for engines running exclusively on ethanol. Along with these was the difficulty to get the automobile industry involved in Proalcool (Santos 1993).

The lack of infrastructure for ethanol warehousing and distribution was the most serious problem faced by PNA at the end of the first phase of the program. According to Santos (1993), it was necessary to create a chain of warehousing tanks and collection centers, as well as a transportation system (pipes and also railway, highway, and cabotage systems) to transport ethanol from mills and distilleries to collection centers, from which it would be taken to mixing centers. In March 1980, a resolution from Ethanol National Council (Conselho Nacional do Álcool—CNAL) established that the means of transport to be used for hydrous ethanol should be primarily pipes, followed by cabotage, railways, and highways, given that the latter could not be used for distances over 300 km. This decision benefited Petrobras,[5] as it already had a wide transportation system available (oil pipes, tankers, and trucks) for petroleum products, whereas the fuel distributors had only trucks. In August 1983, Decree No. 88626 established that Petrobras could purchase and distribute the necessary volume of ethanol to supply the demand and the emergency stocks by means of its distribution system.

Santos (1993) points out that by the end of 1983, Petrobras was very near to holding a monopsony on ethanol, as it was already authorized to buy about 50% of total ethanol consumption (considering both anhydrous and hydrous ethanol, given that in São Paulo and the surrounding areas this percentage reached 100%). In addition, Petrobras bought not only the government's emergency stocks, but also 100% of the distilleries' excess production. On top of this, it controlled a significant share of tank collectors (23.5% of the total warehousing capacity), and the largest chain of hydrous ethanol filling stations in the country.

Because of Petrobras, the problems of distribution and tanking–considered to be bottlenecks for the implementation of the program–were solved, and in 1980 filling stations across the country received permission from the National Petroleum Council (Conselho Nacional do Petróleo-CNP) to install ethanol pumps. The number of stations equipped for selling hydrous ethanol grew rapidly: on December 31, 1980, 3587 filling stations sold both gasoline and hydrous ethanol, and by the end of 1982 it increased to 10,009 stations (Santos 1993). According to ANP (2013) there are currently over 32,000 filling stations selling both gasoline and hydrous ethanol in Brazil.

Under the supervision of the Industrial Technology Agency (Secretaria de Tecnologia Industrial—STI), belonging to the Ministry of Industry and Commerce, the Aeronautics Technical Center (Centro Técnico da Aeronáutica—CTA), an agency from the Ministry of Aeronautics, together with the automobile industry developed the necessary technology for cars to run on hydrous ethanol. In 1978, after the problems of storage and distribution had been overcome by the

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[5] At that time, Petrobras was a state-owned company and, legally, had a monopoly on the oil sector in Brazil. Currently, it is partially owned by the state.

government, car manufacturers joined PNA, and the largest ones (Volkswagen, Ford, G.M., and Fiat) began producing vehicles running on ethanol in the same year.

Many of the resources needed for the success of Proalcool stemmed from the country's budgetary endowments and positive results in the trading of anhydrous ethanol mixed in gasoline (Santos 1993). In March 1976, through Resolution No. 304/76, the Brazilian Federal Reserve Bank (Banco Central) stipulated the regulations of Proalcool industrial operations. It established that resources for financing installations or for updating or enlarging ethanol distilleries would come from either the trading of fuel ethanol or from government allowances from the National Monetary Committee (Conselho Monetário Nacional). According to Belik (1992), the biggest part of the resources for PNA's credit came from the Monetary Budget of the Country, where agricultural funding (Rural Proálcool) as well as resources for the acquisition or enlargement of the industrial units (Industrial Proalcool) originated. These resources were provided by the Brazilian Federal Reserve Bank (Banco Central) through the General Fund for Agriculture and Industry (Fundo Geral para Agricultura e Indústria—FUNAGRI).

During the second phase of Proalcool there were also demand incentives distributed by the government, aiming to expand the use of hydrous ethanol. Some of these incentives included (i) lower prices for ethanol (initially fixed at 66% of gasoline prices) than gasoline, (ii) a discount on the Flat Road Tax (Taxa Rodoviária Única) for vehicles running on ethanol, (iii) a longer financing term for the purchase of ethanol-run cars, and (iv) open filling stations for ethanol during the weekends (as they were closed for gasoline). However, in May 1980, ethanol car production targets were far behind schedule, which caused hydrous ethanol stocks to increase to a point where they exceeded warehousing capacity, resulting in the liberation of ethanol exportation to Japan and to the United States.

Resolution CNE[6] No. 14, passed in March 1982, established measures aiming to help the recovery of the ethanol market, which included (i) lowering the maximum ratio between ethanol and gasoline prices from 65 to 59%, (ii) increasing the IPI of gasoline-run cars and reducing it for cars run on ethanol, and (iii) installing densimeters at filling stations so that consumers were able to check the quality of the ethanol. As for car prices, the automobile industry agreed to sell cars run on ethanol for the same price as those run on gasoline (despite the higher production costs) as a means of encouraging the consumption of cars run on ethanol (Santos 1993).

Consumers' responses to the incentives and disincentives introduced to the Program show the importance of consumers for the success of the PNA. Figure 1 shows how sales of ethanol-run and gasoline-run cars have evolved. At the end of 1982, the ethanol car market was booming, representing 38% of total passenger car sales. In December 1982 alone, this rate reached 67%. From 1983 to 1989, sales of ethanol-run cars represented 90% of the overall car sales in Brazil. However, beginning in 1989 this proportion started to decrease, which can most likely be

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[6] Comissão Nacional de Energia—CNE (National Energy Commission).

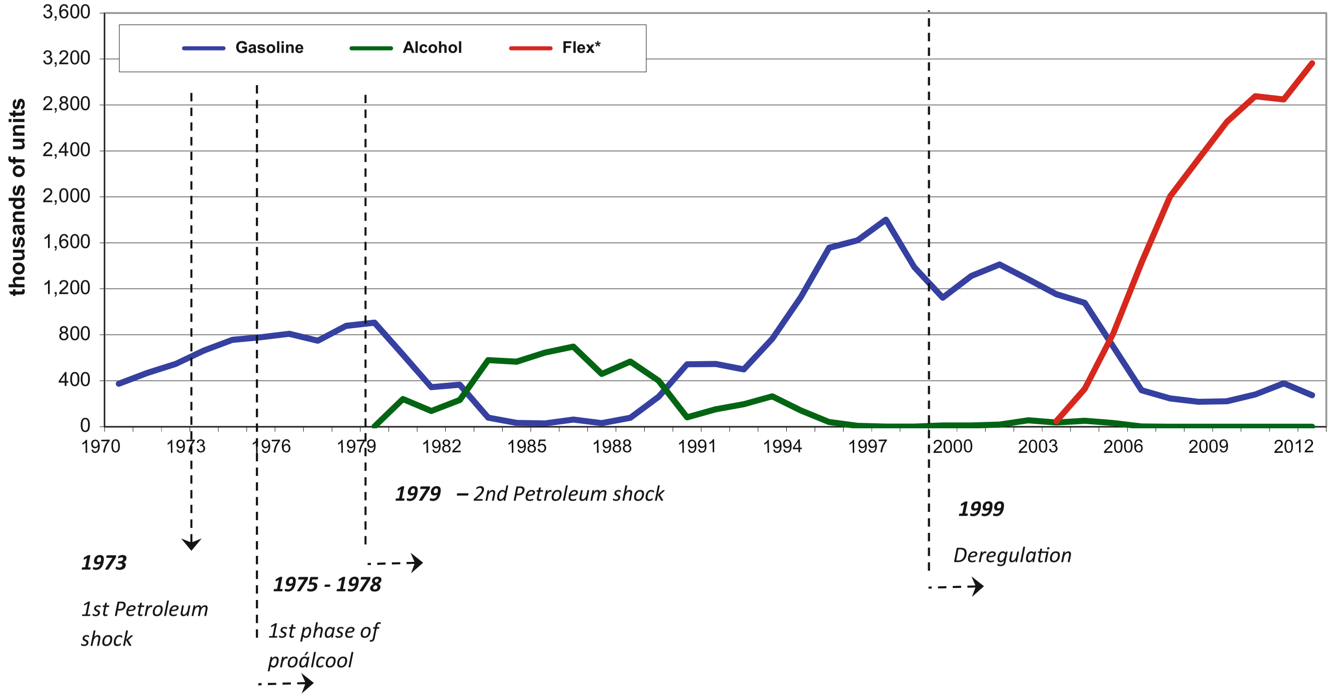

Fig. 1 Domestic sales of auto-vehicles (automobiles and other small-sized vehicles) by type of fuel, 1970–2012. *Source* Prepared by the authors using data from ANFAVEA 2005 (from 1970 to 2004) and UNICA (2013) (after 2004). *Flex-fuel: Either gasoline or ethanol, or any mix of gasoline/ethanol in a single tank of fuel

attributed to the ethanol shortage crisis that occurred at the time, and by 1990, ethanol-run car sales were only 11% of total car sales. Because of the ethanol shortage, there were long lines at filling stations in 1990. This led to a reversion in consumer behavior, and ethanol car sales, which represented 90% of overall sales for 4 years consecutively, started to decline in 1988, as illustrated in Fig. 1. The decrease in demand for ethanol-run cars and the economic crisis faced by the country actually balanced out the market for ethanol. In 2000, the proportion of ethanol-run car to total car sales dropped to less than 1%.

2.2 Proalcool Crisis

While ethanol car sales were booming and ethanol usage was at an all time high during the period from 1983 to 1989, in 1986 officials commissioned a reassessment of the Proalcool program. According to Santos (1993), international petroleum prices started to decline in January 1986. While the growing internal production of ethanol lessened the country's dependence on imported petroleum, the government prioritized inflation and public deficit controls, leaving the expansion of the Program to occur by increasing productivity in agricultural and industrial activities, as government loans for expanding installed capacity had been suspended. The depletion of official resources was evidence of the difficulty of the government in continuing to intervene in the ethanol sector. Moreover, conflicts between producers and the government showed the need for a new model of government intervention.

In October 1987, due to the financial deficit from ethanol commercialization, Petrobras stopped buying ethanol supplies that exceeded its demand. This significantly reduced payments to producers, although the norms established in Decree No. 94541 on July 1, 1987 (Brasil 1987) determined that the company must continue to buy emergency stocks and exceeding volumes. The measures adopted by Petrobras resulted in problems for ethanol producers, who complained about the gap in prices between ethanol and petroleum. These factors caused the stagnation of both sugarcane and ethanol production, represented by the poor harvest of 1985/1986, yet consumption grew by 12% (Moraes 2000).

As stated by Santos (1993), by the 1989/90 harvest about 28 autonomous distilleries had closed down, which meant a reduction in supply of about 500 million liters of ethanol. In the same year, remaining sugarcane suppliers and even ethanol producers threatened to halt production. Besides this, conflicts between sugarcane suppliers and ethanol producers aroused, related to the payment of this product. The circumstances were aggravated even further when Petrobras radically reduced its ethanol stocks, which generated a retail supply shortage; by the end of 1989, consumers faced long lines at the pump.

In order to alleviate the supply crises, the government took several measures: a reduction of anhydrous ethanol contents (from 22 to 13%) in the gasoline–ethanol mix, importation of methanol, and the replacement of anhydrous ethanol by MTBE (methyl tertiary butyl ether). The ethanol supply crises of 1989 and 1990 demonstrated Petrobras' strong dependence on anhydrous ethanol (which was and still is mixed with gasoline), and so at the time the company defended the use of MTBE as a substitute product. Yet, while the conflict between Petrobras and ethanol producers grew, environmental issues associated with MTBE emerged, as sugarcane ethanol is considered more environmentally friendly than MTBE. However, at that time, the positive externalities associated with ethanol were not considered, and in August 1990, Brazil's president Fernando Collor recognized the limits of ethanol as a substitute to petroleum derivatives. But instead of extinguishing Proalcool, he chose to maintain production of ethanol from the existing production capacity.

The early 1990s brought with it the opening of the Brazilian economy to external markets and Federal Government financial difficulties, which led to the exhaustion of the existing state intervention model in the sugarcane production chain. The deregulation of this production chain occurred simultaneously with major institutional changes in Brazil, as described below.

2.3 Deregulation of Sugarcane Production Chain

The deregulation of the sugarcane production chain was slow and gradual, beginning in the early 1990s and ending in 1999 when the state opted to have a strictly regulatory role in the industry. The main impacts of such a change were that prices of sugarcane, sugar, and ethanol started to be determined in a free market, mills, and distilleries no longer had sugar and ethanol production quotas, and government support for fuel ethanol was discontinued.[7]

It is important to compare the institutional environments at the beginning of Proalcool and in the late 90s. In the late 1990s, the political regime in force was (and continues to be) democratic, and the Brazilian Congress had a decisive role in public policy decisions. In 1975, the military regime led to centralized decisions. The present Federal Constitution (1988) impedes State interventionist action, and now the country's economy is immersed in a globalized market, subject to the rules of the World Trade Organization (WTO). From the reform implemented by President Fernando Collor in Brazil, a new institutional apparatus was established for the decision-making policy on ethanol and sugar that fell within a context of economic liberalization of the country as a whole and was supported by the Federal Constitution of 1988.

In March 1996, following the broader logic of the government policy to remove price controls on the fuel sector, Finance Minister Pedro Malan issued Directive No. 64, establishing that several commodities "…are subject to the government policy of price liberalization… sugarcane prices, including freights, supplied to mills and autonomous distilleries all over the country, standard crystal sugar prices, ethanol prices for all types of fuel and non-fuel ends, and all types of residual

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[7] For a detailed description of this process see Moraes (2000) and Moraes and Zilberman (2014).

molasses prices, in the producing units" (Brasil 1996). However, there were three delays before the total liberalization of the sugarcane production chain took place, and finally on February 1, 1999, the system of liberalized prices was installed, both for sugarcane and for all of the products in the sugar–ethanol agro-industry. The liberalization occurred during a time when there was overproduction of both sugar (nationally and internationally) and ethanol, consequently leading to a negative impact on prices. The industry thus faced a serious financial crisis, culminating with the closing of many industrial units in 1999.

Free market pricing led to competition between sugar and/or ethanol mills, leading them to seek new strategies to cut costs and increase efficiency in order to ensure survival in this new environment. In addition, the mills also implemented new production organization and management practices, resulting in a more professional company management system. The new management approaches and the recognition by the companies that the more Brazil participates in international trade, the greater the need for labor laws corresponding to those of sugar producers in developed countries (in order to create a similar operating environment), which has led to greater compliance in labor and environmental laws. The competitive environment has also redefined the production organizational structure, which has undergone a consolidation process through mergers and acquisitions, including the introduction of foreign capital in the sector, which is discussed in more detail later in this chapter.

2.4 Evaluation of Proalcool

The success of PNA can be evaluated by analyzing its goals, as stated in Decree No. 76593. Santos (1993) evaluates Proalcool considering the three goals identified during the first phase of the program, which introduced ethanol–gasoline mixed fuel: (i) improving the balance of payment, (ii) reducing the country's dependence on imported petroleum, and (iii) creating a new market for the sugarcane industry.

According to the author, the goal of creating a new market for the sugarcane industry was achieved. From 1975 to 1983, Brazilian production of ethanol increased from 555 million to 7.95 billion liters and the ethanol production capacity increased from 904 million to 11.1 billion liters per harvest (Fig. 2). In the early 1970s, more than 96% of total ethanol production was as a byproduct of the sugar production process; in the 1986/87 harvest, more than 60% of sugarcane grown was used in the production of ethanol.

The expansion of sugarcane production is a direct result of the evolution of ethanol and sugar production. It is important to observe the gains in productivity attained within the evolutionary period: in 1975, sugarcane productivity (in tons per hectare) was 46.8 t/ha, in 1980 it improved to 56.09 t/ha, in 1990 the productivity was 61.49 t/ha, and since 2009 it has remained at about 80 t/ha (MAPA 2011). In the Center-south region of the country, the agricultural productivity of sugarcane has reached about 85 t/ha (UNICA 2013). These productivity leaps were a consequence of public and private investments in research.

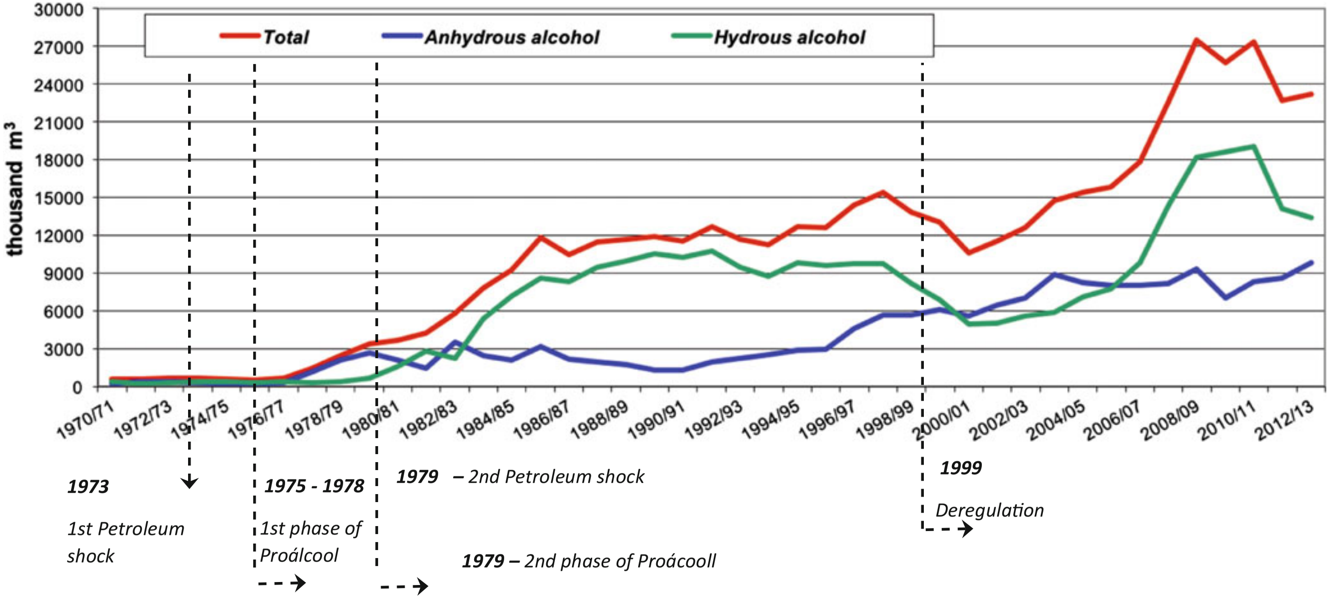

Fig. 2 Historical evolution of ethanol production in Brazil, from harvests in 1970/71–2012/13. *Source* Prepared by the authors using data from UNICA (2013)

Brazil's ethanol expansion scheme has also reduced their dependence on other energy sources, most notably petroleum. The increase in the consumption of fuel ethanol as a percentage of the total consumption of liquid fuels is staggering. Santos (1993) shows that in 1975 ethanol represented 0.2%, while in 1985 it grew to 12.4%. In the transportation sector (where all the ethanol is consumed), its contribution evolved from 0.4% in 1975 to 15.4% in 1985. That is, not only did the country's dependence on foreign energy decrease, but the relative consumption of renewable resources increased as well. Nastari et al. (2005) estimate that from 1975 to 2004, the use of ethanol led to the substitution of nearly 230 billion liters of gasoline.

As for the net exports savings, Santos (1993) finds the gains under Proalcool to be modest. From 1977 to 1985, Brazil's expenditures on net petroleum imports were US$64.8 billion, and estimates indicate that a total of US$6.9 billion was saved on these imports (10.7% of the total cost of petroleum). On the other hand, Nastari et al. (2005) have calculated the value of ethanol (hydrous and anhydrous) in gasoline equivalent, using the price of the gasoline in the world market (Rotterdam). According to the authors, from 1976 to 2004, ethanol used for fuel purposes led to savings of US$60.74 billion in gasoline imports (in real 2005 USD). When interest on the foregone external debt is considered (estimated at the prime rate plus 2% per year), the authors found that accumulated savings equal US $121.26 billion.

3 The Post-deregulation Period and the Free Market Environment

As seen in the previous sections, the withdrawal of the federal government from the sugarcane industry was a long and contentious process. When the federal government removed itself in the late 1990s, conflicts over distribution arose. This new environment required players in the industry to learn to cope with the conditions imposed by a free market, in which production efficiency and product competitiveness are two of the most important factors to being successful. In this section, we will describe the main changes observed in the sugarcane production chain and on sugar and ethanol markets in the post-deregulation period.

3.1 Changes in the Growers/Mills Relationship and a New Model for Sugarcane Payment

The deregulation process caused considerable concern not only among the owners of sugarcane mills, but also among the sugarcane suppliers, who until the deregulation of the industry had traded sugarcane on the basis of official prices dictated by the government. Different from many other crops, sugarcane has specific characteristics that make the relationship between suppliers and mills more complex. The necessity of harvesting the plant during a specific period of the year, the impossibility of storing its raw material, the high cost of transporting cane for long distances, and the fact that sugarcane is a semi-perennial crop (after being planted it remains in the field for about five years) creates the need for a mutual dependency between mills and sugarcane suppliers, which must be located near an industrial plant.

Therefore, the removal of price controls called for a new form of remuneration for sugarcane, which was to take the place of the previous system of prices tabulated by the government. As a result, in mid-1997 a technical and economic bipartisan committee was formed in the state of São Paulo in order to develop a new system of remuneration for sugarcane suppliers and to provide minimum standards for the relationships among the suppliers and mill owners, given that the government would no longer be establishing sugarcane prices. The committee, consisting of representatives of sugarcane suppliers nominated by the *Organização dos Plantadores de Cana do Estado de São Paulo* (ORPLANA, São Paulo State Sugarcane Growers Association) and representatives of the sugarcane industry nominated by the *União da Indústria de Cana-de-Açúcar* (UNICA, Brazilian Sugarcane Industry Association), was named the *Conselho dos Produtores de Cana-de-Açúcar, Açúcar e Álcool do Estado de São Paulo* (CONSECANA-SP, São Paulo State Council of Sugarcane, Sugar, and Ethanol Producers), and marked the establishment of a new sugarcane remuneration system. This model was implemented in the state of São Paulo at the end of the 1990s, and established standards and procedures for the remuneration of sugarcane suppliers by industrial facilities. It became the benchmark in the state of São Paulo after the deregulation (similar models have also been established in other sugarcane-producing states).

The CONSECANA-SP is a nonprofit and nongovernmental association. It is a private system of self-management, currently composed of equal numbers of representatives from two associations: ORPLANA, representing the interests of sugarcane suppliers, and UNICA, defending the interests of the processing plants. Adherence to the CONSECANA-SP model is voluntary. However, in practice, the vast majority of plants and suppliers use the model in order to determine the price of sugarcane delivered by suppliers. The set of rules established for evaluating sugarcane quality, assessing market prices, and, subsequently, determining the price of sugarcane is published in the CONSECANA-SP Procedure Manual.[8]

As defined by the CONSECANA-SP, the value of sugarcane is based on two variables: the amount of Total Recoverable Sugar (TRS) in the stalks of the sugarcane delivered by the producers, and the selling prices of sugar and ethanol on the domestic and foreign markets, which define the price of the TRS. The amount of TRS per ton of sugarcane represents the sugars (glucose, fructose, and sacarose) in

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[8] More details regarding Consecana can be found in Consecana Manual available in www.unicadata.com.br and in Moraes et al. (2014).

the sugarcane stalks that is converted into ethanol and sugar. The concentration of TRS in sugarcane is determined by laboratory tests performed on samples of sugarcane taken from each truckload delivered by suppliers. The calculations and procedures used in the analysis as well as the equipment and reagents approved for use in these processes are detailed in the CONSECANA-SP Procedure Manual.

The second element necessary for determining the price of sugarcane is the price of the TRS, which is established for each plant based on (i) the average prices of sugar and ethanol sold by mills in the São Paulo state to domestic and foreign markets, (ii) the share of the cost of sugarcane in the total cost of production of sugar and ethanol, and (iii) the volumes of sugar and ethanol produced in each plant. In order to establish the price of sugarcane as a raw material, the billing prices of ethanol and sugar are researched by the *Centro de Estudos Avançados em Economia Aplicada* (CEPEA, Center for Advanced Studies in Applied Economics), a research institution external to the model that is affiliated with the University of São Paulo, which ensures impartiality in the collection of such information.

The prices collected by the CEPEA are converted to TRS prices using several considerations, including the contribution of the cost of sugarcane to the overall production costs of sugar and ethanol as well as parameters based on the chemical equations and the efficiencies of the industrial process (Moraes and Zilberman 2014). Currently, the CONSECANA-SP model assumes that the cost of sugarcane accounts for 59.5% of the total production cost of sugar. Therefore, the model currently dictates that 59.5% of the selling price received by sugar mills be paid out to sugarcane suppliers. In the case of ethanol production, that proportion is 62.1%. The model is designed to assign a price to sugarcane that is proportional to the selling price received by the industry for the end product: increases or decreases in the average revenue obtained by production facilities in the state of São Paulo are automatically applied to the price of sugarcane, at 62.1 and 59.5% for ethanol and sugar, respectively.

Finally, the determination of the average per-kilogram TRS price at each processing facility is obtained at the end of each crop season by weighing the volume of each of the nine product class/target market combinations produced by a given facility during the harvest season. A facility that produces no sugar, for example, should only use ethanol prices to determine the average TRS price. Therefore, the per-kilogram TRS price will differ among facilities and among harvest years. We summarize the logic of the model based on the flowchart in Fig. 3.

Of course, the CONSECANA-SP model reduces transaction costs and minimizes risks and the possibility of conflicts between sugarcane suppliers and processing facilities, which are both realistic aspects of this industry. Moreover, it ensures greater transparency and reduces the problem of asymmetric information in setting the price of sugarcane, establishes a permanent and balanced forum for discussing the relationship between sugarcane suppliers and processing facilities, diminishes the bargaining power of processing facilities, and strengthens the supplier associations; it is an essential aspect because sugarcane production by

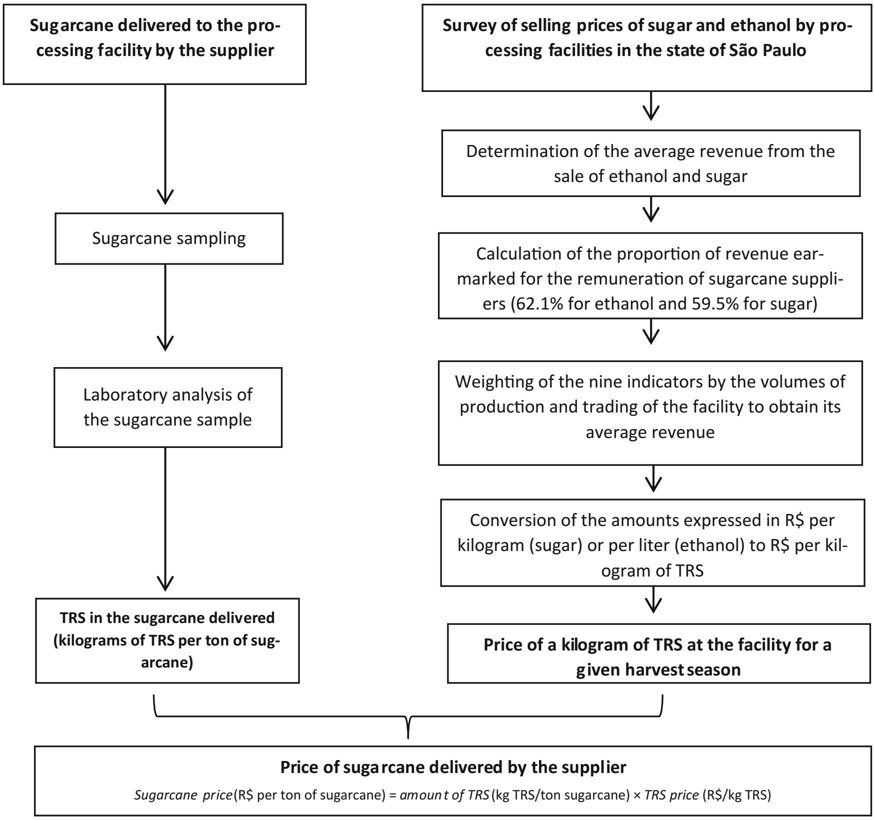

Fig. 3 The CONSECANA-SP model: a simplified scheme for determining the price of sugarcane delivered by a given sugarcane supplier to a given processing facility. *Source* Constructed by the authors

independent suppliers is highly fragmented in São Paulo State: over 85% of sugarcane growers farm on less than 50 hectares of land (ORPLANA 2013). The success of the CONSECANA-SP model is evident from the increased sugarcane production seen in the post-deregulation period: sugarcane production by independent suppliers has doubled over the last 10 years without any government intervention and sugarcane growers currently account for approximately 40% of all sugarcane processed in Brazil (MAPA 2013).

Finally, it is important to note that the model is periodically reviewed so that it may be adapted to new market conditions and requirements, as well as to changes in production technology. This represents a challenge for the system, which will need to adapt to dynamic and increasingly complex market conditions in the future without making its procedures and rules too complicated for entering players to adopt.

3.2 The Growth of the Brazilian Share in the World Sugar Market

During the regulated period, Brazilian sugar exports were exclusively under government control. However, after the beginning of the deregulation process, sugarcane mills started trading sugar in the international market and Brazil began to blossom as a major exporter. In fact, Brazilian sugar exports grew from less than 1 million tons at the beginning of the deregulation period to approximately 9 million tons by the end of the 1990s (SECEX 2013). This growth continued and actually increased after complete deregulation of the sugarcane industry, and Brazilian sugar sales on the international market reached approximately 28 million tons in 2010—three times that observed at the end of the 1990s (SECEX 2013).

According to data collected from USDA (2013), over the 20-year period beginning with the onset of deregulation in the late 1970s to the late 1990s, the global sugar market grew at an average rate of approximately 2% per year, whereas sugar exports from Brazil grew by nearly 18% per year. Consequently, Brazil's share of the global market jumped from less than 5% in the early 1990s to approximately 50% in recent years.[9] Throughout this period, countries in Asia and Africa stood out among the main destinations for Brazilian sugar exports. Sugar consumption in these regions has been stimulated by rising incomes, urbanization (which causes changes in consumption habits), and by very rapid population growth in comparison to richer countries.

Increases in sugar production since the early 1990s has been possible due to increased sugarcane crushing capacity, which grew from 222 million tons in 1990 to 307 million in 1999 (UNICA 2013), and installation of new sugar plants adjacent to the already established ethanol distilleries, which allowed a greater proportion of sugarcane to be directed to sugar production. Currently, the production of sugarcane is divided approximately equally between the production of sugar and ethanol. The strategy of producing both ethanol and sugar has allowed sugarcane-processing facilities to improve their price-risk management and to produce the highest quality sugar in order to meet different specifications required by customers. In recent harvests, for example, higher sugar prices combined with price constraints on fuel ethanol promoted new investments in sugar production facilities as add-ons to stand-alone ethanol plants. Market estimates indicate that approximately 40 new sugar production facilities were built in Brazil between 2010 and 2012 (UNICA 2013).

It is clear that the post-deregulation period was important for strengthening and consolidating Brazil's position in the world sugar market. Despite the remaining restrictions on the expansion of international trade (protectionist measures imposed by major sugar importers incentivizes domestic production via price controls and subsidies, as well as import restrictions imposed via import tariffs, quotas, and even

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[9] Brazil's share of the global market varies depending on the source cited. However, according to all sources, it has remained at approximately 50% in recent years.

non-tariff barriers), there seem to be opportunities for the country in the coming years, given that it is one of the few regions of the world with the potential to significantly expand production at a low cost.

To increase sugar sales worldwide, in addition to reducing barriers, Brazil will need to invest in infrastructure for the distribution of sugar through the expansion and decentralization of ports and, especially, the creation of low cost transport corridors interconnecting new areas of production in the states of Minas Gerais, Mato Grosso, Goiás, and Mato Grosso do Sul, where most of the plants built in recent years are located.

3.3 Changes in the Ethanol Market, the Influx of Foreign Capital and the Consolidation of the Brazilian Sugarcane Industry

Unlike the sugar market, after the price controls on fuel ethanol were lifted in the late 1990s, the demand for fuel ethanol went through a period of stagnation, as sales of ethanol-fueled vehicles became virtually nonexistent and the current ethanol-powered fleet was gradually being scrapped. The downward trend in sales of hydrous ethanol was reversed only after the introduction of flex-fuel vehicles in March 2003. By enabling a consumer to use gasoline, ethanol, or any mixture of the two, flex-fuel technology gave consumers the ability to choose which fuel to use when filling their tank rather than at the time of purchase of a vehicle.

By June 2005, flex-fuel vehicles already accounted for more than half of all light commercial Otto-cycle[10] vehicles licensed in Brazil (ANFAVEA 2013). Currently, flex-fuel vehicles represent 90% of total automobiles sales in the country and account for over 50% of the national vehicle fleet (UNICA 2013). This expansion of the flex-fuel vehicle fleet and the subsequent introduction of flex-fuel motorcycles (in March 2009) combined with the competitiveness of ethanol in much of the market from 2003 onwards led to a significant increase in the domestic consumption of ethanol and created good prospects for ethanol producers.

In addition to the consolidation of flex-fuel vehicles in the domestic market, interest in renewable fuels increased considerably across the world in the post-deregulation period. Environmental concerns linked to global warming and the ongoing search for alternative energy sources promoted the development of several public programs to stimulate the production and use of fuel ethanol in many countries. As early as the mid-2000s, projections based on existing policies indicated a significant increase in the demand for biofuels. By early 2012, public policies promoting the use of biofuels, as well as blending mandates, were in place at the national level in at least 46 countries and at the regional level in 26 states and

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[10] Otto-cycle engines include those powered by compressed natural gas, gasoline, or ethanol (excluding those powered by diesel fuel).

provinces, and fuel-tax exemptions and production subsidies had been put in place in at least 19 countries (REN 2012).

The favorable prospects on the international market and the expected growth in exports of ethanol contributed to the increased demand for fuel ethanol on the domestic market, resulting in an extraordinary increase in the production of sugarcane and ethanol. Between the harvests in 2000–01 and 2008–09, the average annual growth in sugarcane production was 10.4% per year (UNICA 2013). Similar results had only been observed at the height of Proálcool between 1975 and 1986, when sugarcane production was stimulated by the demand for hydrous ethanol to fuel ethanol-powered vehicles.

The production increase observed after 2003 was made possible by considerable expansion of existing plants and the construction of new ones (initiatives known as "greenfield" projects), with investments made by companies that were well established in the industry as well as from new companies that were both foreign and domestic. Between the harvests in 2005–06 and 2008–09, more than 100 new ethanol plants were built or were in the process of being introduced. These industrial plants were primarily built in the main sugarcane-producing state (São Paulo) as well as in new areas in the states of Goiás, Mato Grosso do Sul, and Mato Grosso e Minas Gerais. It is estimated that investments for the construction of new ethanol plants during this period exceeded US$40 billion.

However, the 2008 global financial crisis prompted a change in the flow of these investments, which were no longer directed toward the construction of new mills but were instead to be used to purchase existing companies with financial problems. The decline in sugar and ethanol prices in the 2007–08 and 2008–09 harvests, coupled with the lack of credit and rising financial costs resulting from the global financial crisis, led some companies to be bought out by more well-funded groups or merged with competitors, resulting in a broad consolidation process involving approximately a third of the companies in the industry.

Didactically, this process can be grouped into three distinct phases. The first involved only Brazilian companies—the well-funded Brazilian producers taking over companies struggling to compete in the new free market environment. The second phase was characterized by the involvement of multinational trading companies and food companies, which bought medium and large producing groups. Therefore, foreign investment largely came not only from sugar-producing companies in other countries, but also from companies with extensive experience in the production and trading of agricultural commodities, such as Bunge Limited, Cargill, Louis Dreyfus, Tereos, Abengoa, Glencore, and the Noble Group. The third and final phase involved large oil companies, including foreign companies such as Shell and British Petroleum as well as the Brazilian company Petrobras, acquiring shares of domestic producer groups.[11]

Despite the consolidation of the industry, the sugar and ethanol production sector in Brazil continues to be an unconcentrated market. Currently, there are more

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[11] More details of the consolidation process can be found in Moraes et al. (2014).

than 400 sugarcane-processing facilities that are registered by the Ministry of Agriculture and therefore capable of processing sugarcane into sugar or ethanol. According to market data, those mills are divided among 100–150 producer groups, the top 10 of which are responsible for approximately 30% of the production in the country.

After the period of rapid production growth and consolidation, the sugarcane industry found itself faced with many problems that hindered the increase of production. Climate and weather conditions combined with the postponement of investment for renovation of sugarcane plantations promoted a significant drop in the agricultural productivity of the sugarcane harvest. Additionally, the expectations for growth in the international demand for biofuels were also tempered by recognition of the fact that the export market was still quite protected and the growth of the international market for fuel ethanol had been lower than initially expected. This downturn in the growth of supply and sharp drop in investment in new ethanol plants is strongly related to the loss of competitiveness of ethanol with gasoline, which can be attributed to increased costs of ethanol production as well as the reduction in gasoline taxes for fossil fuels in Brazil.

3.4 The Competition Between Ethanol and Gasoline in the Free Market and the Presence of Flex-Fuel Cars

The introduction of flex-fuel cars brought a new dynamic to the fuel market in Brazil with excellent prospects for the ethanol industry. However, from a regulatory standpoint this change increased the complexity of the fuel market, since the consumer response to relative prices of hydrous ethanol and gasoline increased the interdependence between gasoline and ethanol markets. With the introduction of flex-fuel vehicles, consumers base their decision regarding which fuel to use on the ratio between the pump prices of gasoline and hydrous ethanol (as hydrous generates less energy than gasoline, hydrous ethanol ceases to be economically attractive when its pump price exceeds 70% of that of gasoline).

This new scenario required changes to the rules and policies in place prior to deregulation. The main changes made were intended to help avoid extreme price fluctuations and to ensure the supply of fuels (ethanol and gasoline), especially during off-season periods. Among such changes was Law No. 12,490, 16 September 2011 (Brasil 2011), which expanded the role of the *Agência Nacional do Petróleo* (ANP, National Petroleum Agency, now known as the National Regulatory Agency for Petroleum, Natural Gas, and Biofuels), which now regulates the fuel ethanol supply chain, including certain production activities.

ANP incorporated new mechanisms and distinct obligations for companies in each level of the supply chain, especially in regards to the trading of anhydrous fuel ethanol. The Agency generated incentives for distributors and producers to form contracts in order to commercialize anhydrous ethanol, and forced these agents to maintain anhydrous inventories at the end of the harvest year. Law No. 12,490 also required that the amount of ethanol in ethanol–gasoline blend ranged from 18 to 27.5%.

The adjustments made in the regulatory system appear to have reduced the seasonality of ethanol prices and improved the security of fuel supply during the sugarcane off-season. However, the system has yet to establish a guideline for the fuel market that will allow greater predictability and planning by private agents.

The passage of Law No. 9478 in 1997 (Brasil 1997) officially ended the monopoly held by the energy company *Petróleo Brasileiro* (Petrobras, Brazilian Petroleum). However, because there were no significant changes in the refining sector thereafter, the market share of Petrobras in gasoline refining has remained above 95% throughout the post-deregulation period (ANP 2013), and the company is still able to define the price of gasoline at the refinery level, enjoying a de facto monopoly. The gasoline pricing strategy adopted by Petrobras between 2002 and 2005 sought, albeit not explicitly, to link the domestic price to the international price, considering the exchange rate fluctuations. As of 2005, however, gasoline prices have ceased to vary periodically; every price increase at the refinery level was offset by a reduction in the federal taxes levied on the product so as to maintain a stable pump price.

It is interesting to note that the Contribuição de Intervenção de Domínio Econômico (CIDE, Contribution for Intervention in the Economic Domain, a variable-rate excise tax) has played an important role in the pricing of gasoline in the domestic market during this period. The CIDE was established by Law No. 10,336, passed on December 19, 2001 (Brasil 2001), and this tax can be charged, at different rates, on petroleum, petroleum-based products, natural gas, and ethanol. The standardization imposed by the legislation states that, by executive order, the CIDE rates can be reduced or increased, provided they remain within the range established. However, changes in the CIDE rates have been made in order to avoid increases in gasoline prices to consumers whenever there has been an increase in the wholesale price of gasoline at the refinery level. The CIDE rate for gasoline was R$0.28/L from 2002 through 2007, after which it was gradually reduced, reaching zero in July 2012.

This combination of changes in the price of gasoline at the refinery level and reductions in the CIDE rate for gasoline was planned in order to keep the pump price stable and to avoid having inflationary pressures in Brazil (the price of pure gasoline at the refinery level is responsible for about 70% of the pump price of gasoline sold at gas stations). This gasoline pricing policy has discouraged long-term investment in the expansion of ethanol production and in the infrastructure for its distribution and transport not only because the profitability of ethanol is unpredictable, but also because there is a lack of transparency and no clearly defined rules for all of the players operating in this market (PIRES 2013). In fact, the use of the gasoline price to control the inflation rate created a ceiling price for hydrous ethanol. This policy as well as the significant increase in the production costs of ethanol created a scenario of slim profit margins for hydrous fuel ethanol, providing no incentives for new investment in expanding production.

Decreased investment in ethanol production observed in recent years (since 2009), coupled with the aforementioned adverse weather conditions that affected agricultural production in recent harvests and the limited gasoline refining capacity in Brazil, has resulted in the need to import gasoline into the country. In 2012, about 3.8 billion liters of gasoline were imported in order to meet growing demand in the domestic market, which led to an average loss of R$0.33/L of gasoline sold by Petrobras (ANP 2013; SECEX 2013). To avoid inflationary pressure, the company sold imported gasoline in the domestic market at a lower price than the import cost.

In 2013, the company made a 6.6% adjustment in the price of gasoline at the refinery in January and another 4% increase in November (this time, the adjustment was not offset by the CIDE, which had been zeroed in July 2012). As of March 2013, the federal government also increased the level of mixture of anhydrous ethanol in gasoline from 20 to 25%, helping to reduce the need for imported fossil fuel.

At the beginning of 2013, the federal government also reduced the rate of PIS/COFINS (federal tax) levied on ethanol fuel sold in the country. In the case of anhydrous ethanol, this exemption reduced the federal tax levied on the product by R$0.48 per liter, while for hydrous ethanol the exemption allowed a reduction of R $0.12 per liter along the production chain (distribution and sale of the product). The tax reduction for fuel ethanol and the small increase in the price of gasoline observed in early 2013 improved the market competitiveness for hydrous fuel ethanol, but did not restore the conditions existent in the early 2000s. In 2002, when CIDE was created, federal taxes accounted for about 21% of the gasoline price and 9% of the hydrous ethanol price at the pump. In 2013, this differential was 7%, since the federal taxes on ethanol were eliminated and they represented 7% of the gasoline pump price.

In fact, new changes in the pricing of gasoline and in the taxation on light fuels were also verified after this period. In February 2015, the federal government promoted a new adjustment in the existent taxes on gasoline: the rate of CIDE was raised to R$ 0.10 per liter and the rate of PIS/COFINS was changed from R$ 0.26 to 0.38 per liter of pure gasoline at the refinery level. This change was made to increase tax collection, since the exemptions had made by the federal government in several sectors of the Brazilian economy increased the deficit in the public accounts.

In this context, in January 2017 it was also restored the rate of the federal tax PIS/COFINS levied on ethanol. This change ended the tax exemption carried out in 2013, and ethanol producers started paying the PIS/COFINS tax of R$ 0.12 per liter.

Furthermore, in June 2016 there was a change in the executive board and in the presidency of the oil company Petrobras. The need for the company's debt reduction motivated the announcement of a new policy in the pricing of gasoline sold domestically. The new pricing model specifies that the price of gasoline in the domestic market will be influenced by changes in international price of oil products.

These changes introduced some predictability about the price of the gasoline at the refinery, but did not create a guideline about the long-term role of ethanol in the fuel matrix of country, which is essential in promoting new investments to expand production capacity.

The Brazilian commitment presented at the Paris Climate Conference (COP-21), which requires a significant increase in ethanol production by 2030, and the need to increase domestic fuel production to reduce projected fuel imports in the next decade are additional elements that indicate the importance of a broad discussion on the future of fuel ethanol in Brazil.

It is important to recognize that the consolidation of the biofuel supply chain within the Brazilian energy matrix will also require new gains in productivity and efficiency in ethanol production. In the short term, the cost reduction can come through a return to the 2010/11 level of agricultural productivity. In the medium and long term, new technologies must be developed and those that have been developed must be disseminated in order to increase the quantity of ethanol produced per hectare of sugarcane. Such technologies include the genetic improvement of traditional sugarcane, the use of genetically modified strains to increase productivity and the concentration of sugars, and the production of second and third generations, among others.

4 Lessons from the Brazilian Experience and Future Challenges for Ethanol

Although the Brazilian case of production and use of ethanol has specific characteristics, the country's experience contributes to discussions on biofuels in Brazil and elsewhere. When Proalcool was created, Brazil was still heavily dependent on imported oil and was severely affected by the oil price shocks of 1973 and 1979. The goal of replacing petroleum was the main driver behind Proalcool. Although the program offered significant environmental and economic benefits, this was not the motivating factor at that time.

Currently, environmental and climate problems associated with the use of fossil fuels are at the forefront of the discussion on energy security in order to combat the negative effects of global warming. In addition, concerns over the price and supply of fossil fuel became important in attempts to stimulate renewable sources. Therefore, the effort by the government to develop a consumer market for fuel ethanol in Brazil is not seen in other countries.

Brazil is the only country that produces both types of fuel ethanol (anhydrous and hydrous ethanol). The use of hydrous ethanol was made possible through state intervention, removing several bottlenecks in the implementation of Proalcool. Notable obstacles that were overcome include building networks of storage tanks and fuel collection depots, development of a transportation system comprising pipelines, railways, highways, and fluvial transport to move ethanol from the distilleries to collection and mixing depots, installation of hydrous ethanol pumps at more than 25,000 filling stations around the country, and incentives for the development of ethanol-powered vehicles. For newly producing countries, adopting only anhydrous ethanol that is blended with gasoline in different proportions certainly facilitates the coordination of the entire ethanol supply chain as well as the infrastructure required.

State intervention in Brazil was also essential in defining sources for funding ethanol storage for ethanol produced during the sugarcane harvest season and for sale throughout the year, establishing the price to be paid to ethanol producers, and establishing sources of funding to finance expansion of plantations and processing capacity. In this sense, government involvement was fundamental in providing the stimuli needed for the development of ethanol production.

Although the current situation is very different from that observed when Proálcool was implemented, state involvement in the ethanol market remains important. An appropriate regulatory environment is essential for the introduction and consolidation of ethanol as a fuel, not only in Brazil but also in other countries. There are positive externalities (social, economic, and environmental) associated with the production and use of renewable fuels that are not valued independently by the market, and its production, without the necessary stimuli, may be sub-optimal.

In addition to the generation of positive externalities from ethanol production, the fact that Petrobras owns a de facto monopoly in gasoline production makes an even stronger case for supporting ethanol in Brazil and other countries with a similar type of oil production monopoly. The use of hydrous ethanol as a substitute for gasoline requires the presence of the State to establish an appropriate regulatory framework so that the coexistence of these two fuels is made possible.

Regarding social and environmental concerns, Brazil has evolved considerably in many aspects since the launch of the Proalcool, including more efficient allocation of byproducts (like the vinasse) and water use, the preservation of forests, and the regulation on burning of sugarcane as a method of straw removal. There are laws and standards regulating these issues, among them the Agroecological Zoning for sugarcane, which establishes guidelines for the expansion of the crop. The State must continue to promote the development and application of these standards. There is still room for improvement, but it is important to recognize the efforts and investments that have been made.

Another aspect from the Brazilian ethanol experience has been the positive impact on the labor market and on the agricultural sector of the country. In 2011, for example, the number of jobs directly attributable to the sugarcane, sugar, and ethanol sectors was nearly 1.2 million, including thousands of poorly educated workers in sugarcane fields. This suggests major implications for some of the less-developed countries of Latin America and Africa, which have the soil and climate suitable for producing sugarcane.

Lack of clarity about the role of ethanol in the Brazilian energy matrix and the recent discussions on biofuel programs in Europe and especially in the United States have led to significant uncertainty for investors and have hampered the efficient allocation of resources for the development of biofuels across the world. It is clear that improvements in the regulatory environment involving biofuels are not the sole determinant of the ethanol success. Efforts to develop new varieties of crops used to produce ethanol as well as new industrial process are crucial in promoting permanent gains in agricultural and industrial productivity and significant cost reductions as a result. The use of sugarcane and ethanol to produce inputs for the chemical industry and the development of a range of different products must also be pursued in order to increase the economic attractiveness of sugarcane production.

However, for these advances to become a reality, it is essential for Brazil to develop an institutional environment with stable and predictable rules that consider the positive externalities of ethanol production and allow proper long-term planning by the productive sector. Investments for the development of new technologies in this area and the expansion of production will only be achieved if there is a clear energy policy in place.

The way countries will deal with the tradeoffs involving energy security, economic development, and climate change is not entirely clear. How each nation will recognize and address the environmental components of energy security in a sustainable and cost-effective manner will determine the incentives for the development of biofuels, as well as the State's strategies in the energy, economic, and political arenas in the near future.

Finally, we must emphasize that the current time period seems to be extremely dynamic and important for the Brazilian sugarcane sector and also for the global biofuel industry. The discovery of oil reserves in Brazil and the rapidly increasing of shale gas in the United States seem to have brought new challenges to the expansion and consolidation of the ethanol as a fuel.

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Incentives and Barriers for Liquid Biofuels in Brazil

Luiz Augusto Horta Nogueira and Rafael Silva Capaz

Abstract Bioenergy has been an important share of the Brazilian energy matrix, supported by an ample basis of natural resources, an appropriate climate, large availability of land and water, and enough expertise on agriculture and forestry management. Currently, ethanol and biodiesel supply about 20% of road transport fuel in Brazil, with the major contribution of ethanol. Since the early 1900s, ethanol-blended gasoline has been used in Brazil, but a national program aimed at market development was only launched in the 1970s. Further, the production and use of biodiesel started just in 2005 with progressive blends with diesel. Gasoline has more than 20% anhydrous ethanol by volume, and hydrated ethanol is traded freely. In turn, biodiesel is blended with diesel at 7% by volume, with plans to increase to 10%. Both Brazilian biofuel programs demonstrate the relevance of adopting efficient agroindustrial strategies as well as the possibility of sound coexistence between bioenergy and other uses of agriculture. This chapter presents a summary of the evolution of ethanol and biodiesel programs in Brazil, focusing on the institutional aspects and the decisive role of public policies to foster the development of the biofuel market.

Keywords Biofuels · Ethanol · Biodiesel · Brazilian initiatives

1 Introduction

Biomass has always been an important energy resource in Brazil. It consists of sugarcane, used for ethanol and bioelectricity production; wood, used as fuel in the industrial, residential and power sectors; and vegetable oils and tallow used in biodiesel production. All of these sources provided 23.8% of the total national energy supply in 2014, or 305.6 Million tons of oil equivalent (Mtoe)[1], making it

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[1] 1.0 toe (*ton of oil equivalent*) = 39.68 million BTU.

L.A.H. Nogueira (✉) · R.S. Capaz
Institute of Natural Resources, Federal University of Itajubá, Itajubá, Brazil
e-mail: lahortanog@gmail.com

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the most important energy source after the petroleum (39.4%) (EPE 2015). Such dependence on photosynthetic energy can be attributed to suitable natural conditions, such as a favorable climate and large availability of land and water as well as a good know-how of agriculture and forestry and the associated industrial processes to convert bioenergy to fuel.

Considering only liquid biofuels, ethanol and biodiesel supplied 18.8% of road transport fuel in Brazil in 2014 (EPE 2015), suggesting that proper natural endowment and expertise are not the only reasons for biofuels to have reached such relevance; correct institutional framework and regulatory conditions are essential as well. Ethanol blending has been mandatory since 1931, pure hydrated ethanol use was introduced in 1975, and nowadays flex-fuel cars that are able to burn any blend of gasoline/ethanol (gasohol) and hydrous ethanol are widely used. In 2008/2009 Brazil harvested 570 million tons of sugarcane to produce 7.27 billion gallons (Ggal)[2] of ethanol and 30 million tons (Mton) of sugar. However, a government intervention in gasoline prices led, in part, to decreased ethanol production of 5.99 Ggal in 2011/2012.

Various factors have motivated the development of the ethanol agroindustry in Brazil since 1931. Fostering agricultural economic activity is a permanent objective for supporting biofuel production. More recently, energy security further justified biofuel production due to lack of domestic oil reserves, which has gained even more support from environmental footprint and sustainability concerns.

On the other hand, biodiesel blending has a different history, aiming to provide social benefits and help small farms. The B7 blend, i.e. 7% of biodiesel mixed with diesel (in volume), has been mandatory since 2014, and its production is becoming more competitive. The installed production capacity is about 2.0 Ggal/year, and in 2014 total production was 0.90 Ggal, coming from two primary feedstocks: soybean oil and beef tallow.

These two very different programs offer good examples of the incentives that should be implemented and the barriers to be taken into account.

2 The Ethanol Sector in Brazil

Brazilian production of ethanol employs an energy efficient route for collecting and converting energy from the sun into liquid biofuel. While sugarcane has been cultivated for nearly 500 years, the past 80 years have seen many changes in production technology, end-use, institutions, and regulations. While it has undergone important gains in productivity and resilience, it now faces more challenging times.

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[2] 1.0 m^3 is equivalent to 264.17 gallons.

2.1 Sugarcane Agroindustry Context and Evolution in Brazil

Sugarcane has been cultivated in Brazil since the sixteenth century. Even as early as the colonial period, it was extensively and successfully cultivated along the Brazilian coast. Furthermore, other areas in the country's interior were cultivated, where there were good climatic and soil conditions for sugarcane production, converting Brazil in one of main world producers of sugarcane. In 2013, worldwide sugarcane production was 1877.1 Mton, occupying 26.5 Million hectares (Mha). Brazil, India, and China were responsible for 64.2% of the world's sugarcane production, and Brazil alone was responsible for 39.4% (FAO 2015).

In Brazil, sugarcane is cultivated in many states, and it is the third most important crop in terms of area after soybeans and corn. The largest sugarcane-producing area is the Center-South region, which accounts for more than 90% of Brazilian sugarcane production, as indicated in Fig. 1, and the largest producer state is São Paulo, which accounts for close to 60% of the total. In the 2014/2015 harvest season, the national cultivated area was approximately 10.8 Mha and the total sugarcane production was 632.1 Mton (UNICAData 2015). On average, about 50% of sugar content in sugarcane is used to produce ethanol and

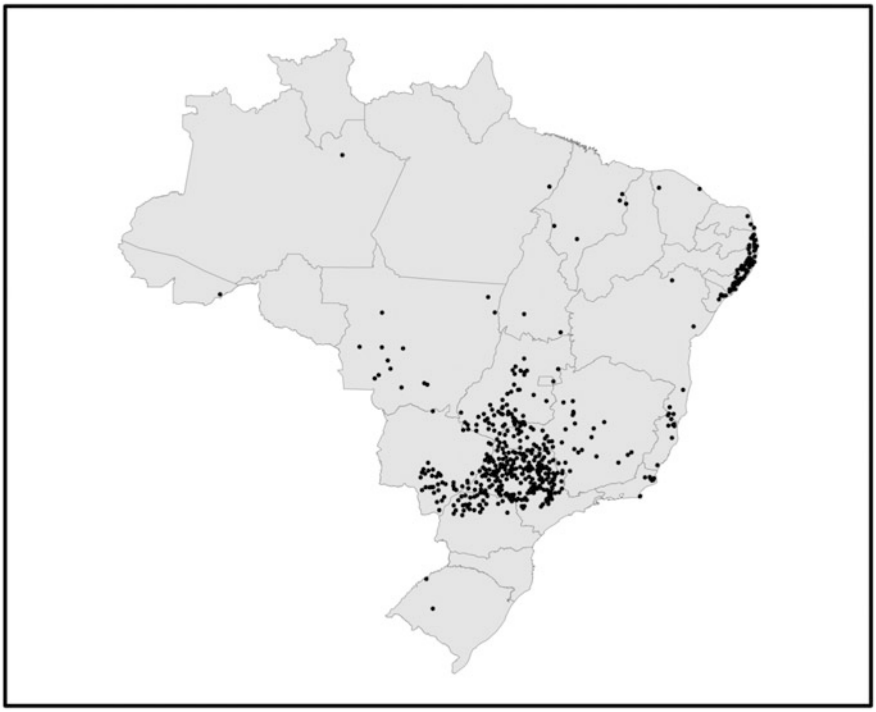

Fig. 1 Sugarcane mills in Brazil (SIGEL/ANEEL 2011)

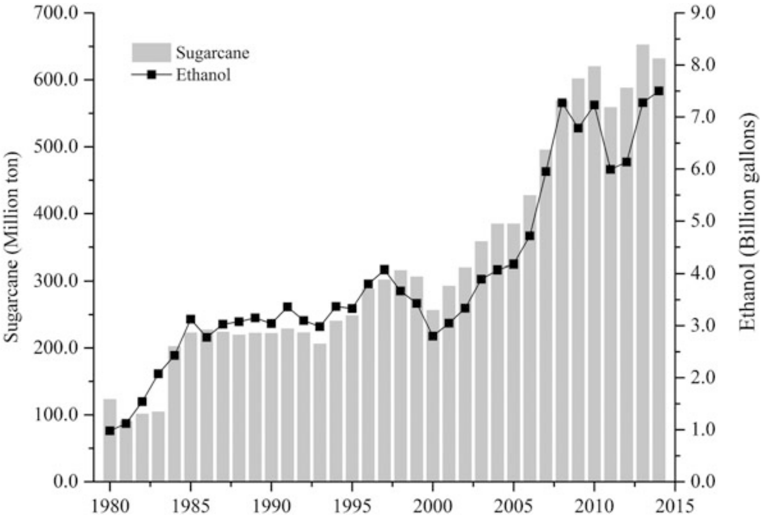

Fig. 2 Evolution of the production of sugarcane, ethanol, and sugar in Brazil (UNICAData 2015)

the remaining to produce sugar (UNICA 2016). Figure 2 shows the observed evolution of sugarcane and ethanol production in Brazil.

Ethanol production in recent decades has been led by the São Paulo State, but in recent years with the reduction of available land in São Paulo and rising land prices, new production frontiers have been opened, occupying areas previously used for pasture and, to a lesser extent, for annual crops in the Center-West region (BNDES 2008).

The expansion of ethanol production occurred alongside significant productivity gains in agricultural and industrial activities, with benefits for sugar production as well (Fig. 3). In recent decades, productivity grew at a cumulative average annual rate of 1.4% in agriculture and 1.6% in agroindustry, resulting in a cumulative average annual growth rate of 3.1% in ethanol production per hectare, as indicated in Fig. 4. As a result of these gains in productivity, the area currently dedicated to the cultivation of sugarcane for ethanol production, which is close to 4.8 Mha, is only 38% of the area that would have been required to obtain such aggregate production with the yields seen in 1975, when the national program of alcohol (Proálcool) began. This remarkable gain in productivity—2.6 times the volume of ethanol for a given area—was achieved through the steady incorporation of new technologies, mainly in the agricultural aspect of production.

However, in the last 5 years, agroindustrial productivity has declined due to the recent crises in the sector, prompted by lack of clear public policies for biofuels in the Brazilian market. A detailed review of the evolution of ethanol program in Brazil and the role of public policies is available in (Moraes and Zilberman 2014). Recent measures, as re-establishing partially the gasoline tax, have stimulated the sugarcane agroindustry and recovering sugarcane yields.

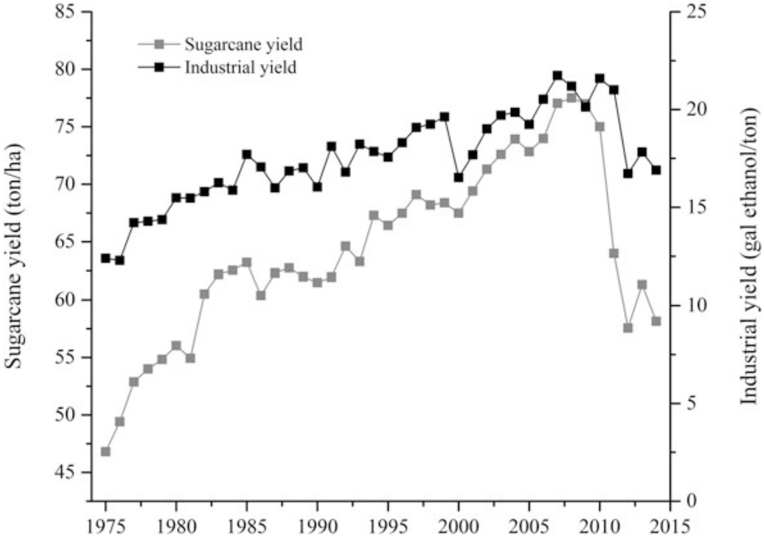

Fig. 3 Evolution of agricultural and industrial productivity in Brazilian sugarcane ethanol mills 1975–2014 [adjust from (Goldemberg 2012) and estimations]

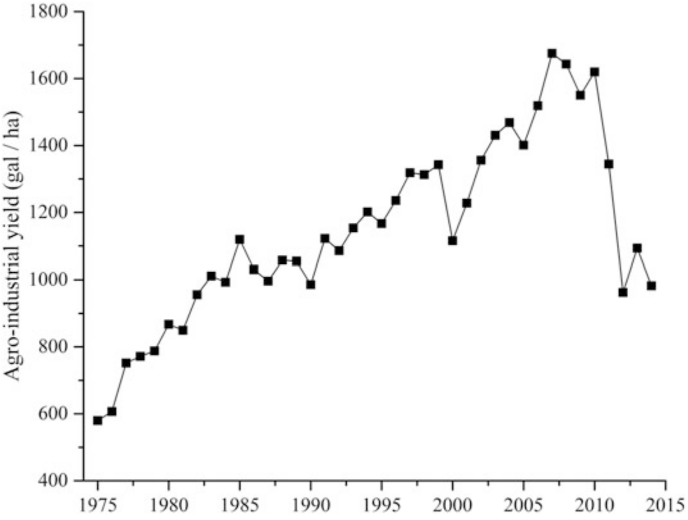

Fig. 4 Evolution of productivity in ethanol in Brazil 1975–2014

2.2 Evolution of Ethanol Policies

Based on the positive results from bench tests with different motors as well as several field and demonstration tests using regular vehicles, in 1931 the Brazilian government implemented a compulsory blend of at least 5% anhydrous ethanol in gasoline, looking to reduce the impact of total dependence on imported oil fuels and absorbing the surplus production of the sugar industry. The creation of the Sugar and Alcohol Institute (IAA, Instituto do Açúcar e do Álcool) in 1933, when the use of automotive ethanol was blossoming, provided the required institutional support for this product. In addition, from that time onwards, the sugar industry began to expand in the southeast region of Brazil, first in association with the decline of coffee plantations and later driven by the growth of the domestic sugar market (Szmrecsányi 1979).

The ethanol content in Brazilian gasoline varied over successive decades; during the period 1931–1975, an average of 7.5% of the gasoline was substituted by this biofuel. In 1975, the effects of the first oil crisis were responsible for the expansion of ethanol use in Brazilian cars (in blends with gasoline and pure hydrated ethanol), and the government launched the National Alcohol Program (Proálcool), which was a decisive step to reinforce ethanol participation in the energy matrix (MIC 1986). The combination of incentives adopted by Proálcool at that time included the following measures:

(a) Establishing higher minimum levels of anhydrous ethanol in gasoline (progressively increased up to 25%)
(b) Guaranteeing lower consumer prices for hydrated ethanol relative to gasoline (at the time, fuel prices were determined by the government)
(c) Guaranteeing competitive prices for the ethanol producer, even in the face of more attractive international prices for sugar than for ethanol
(d) Offering financing under favorable conditions for mills to increase their production capacity
(e) Reducing taxes on new cars and reducing annual registration fees for hydrated ethanol vehicles
(f) Making the sale of hydrated ethanol at gas stations compulsory
(g) Maintaining strategic reserves to ensure supply outside of the production season.

Given this favorable legal framework, the production of ethanol expanded significantly. Between 1975 and 1979, ethanol production grew from 153.2 million gallons (Mgal) to 972.2 Mgal, surpassing the established goal for 1979 by 15%. In 1979, with oil prices reaching new heights, the Proálcool program gained new force; and the use of hydrated ethanol in engines that were modified or newly built to use it, occurred. Under this encouraging scenario, ethanol production reached 3.0 Ggal in 1985, exceeding the initial target by 8%.

Around 1985, the situation began to change because of the decline in oil prices and increase in sugar prices. In 1986, the government reviewed the incentive policies for ethanol, thereby reducing the average sugarcane agroindustry returns and further stimulating the use of available sugarcane to produce sugar for export. This context made ethanol production unattractive and created difficulties for the ethanol industry that led to the end of the expansion phase of Proálcool. The mechanisms for creating safety reserves failed, and emergency measures, such as reducing the level of ethanol in gasoline, importing ethanol, and using gasoline–methanol blends as substitutes for ethanol, became necessary.

By the beginning of the 1990s, after decades of strict State control, the basic structure of the Brazilian sugarcane industry was characterized by the following elements: agricultural and industrial production under the control of the sugar mills; heterogeneous production, especially in sugarcane; underutilization of by-products; and competitiveness driven largely by low salaries and mass production (CGEE 2007). It is worthwhile to note that this situation is currently being observed in some sugarcane-producing countries.

During the early 1990s, the Brazilian government implemented administrative reforms, reviewing its role in the economy. A move toward free market pricing in the sugar–ethanol sector started in 1991, along with the progressive removal of subsidies and a reduction in the government's role in fixing ethanol prices, a process completed only in 1999. The result of those changes was the creation of a new set of rules to organize the relationships between sugarcane producers, ethanol producers, and fuel distributors. The only feature of the original framework of legal and tax measures—which provided the foundation for ethanol fuel consolidation in Brazil being maintained until recently—was the differential tax on hydrated ethanol and gasoline. This was intended to maintain approximate parity of consumer choice between hydrated ethanol and gasoline. In this context, ethanol is traded freely between producers and distributors. From the perspective of agroindustry feedstock suppliers, the sugarcane is also traded freely. But its price is mainly determined according to a contractual voluntary model coordinated jointly by the sugarcane planters and ethanol and sugar producers (Scandiffio 2005).

The institutional restructuring of the ethanol industry continued in 1997 with the creation of two important institutions: the National Energy Policy Council (CNPE), and the National Oil Agency (ANP), later renamed the National Oil, Natural Gas and Biofuels Agency. The CNPE is responsible for establishing directives for specific programs for biofuels use. The ANP oversees the regulation, contracting, and inspection of biofuel-related economic activities and implements national biofuel policy with an emphasis on ensuring supply throughout the country and protecting consumer interests with regard to product price, quality, and supply. ANP is also in charge of setting and monitoring fuel quality aspects.

In 2003, flex-fuel cars were launched and were very well accepted by consumers. Flex-fuel cars offer to owners the option of using gasoline (with 20–25% anhydrous ethanol), hydrated ethanol, or any blend of both, and thus have increased flexibility associated with price, autonomy, performance or availability conditions. Thus, the consumption of hydrated ethanol in the domestic market made a comeback, creating new opportunities for the expansion of the sugarcane industry in Brazil as well as the possibility of meeting the demand of the international market for ethanol to be used in gasoline blends.

During the period 2003–2008, the Brazilian sugarcane industry expanded rapidly. New and more efficient mills were commissioned, and a consolidation process was initiated at the same time that positive indicators for the industry's

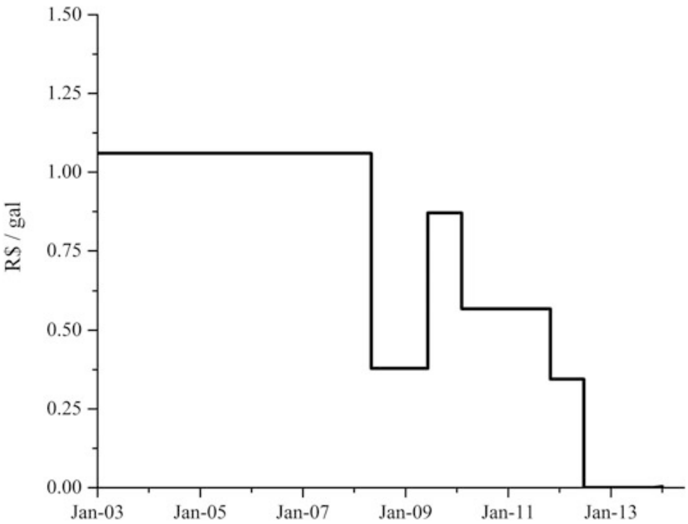

Fig. 5 Evolution of Federal tax on Brazilian gasoline (ANP 2015b)

environmental sustainability were demonstrated (Nogueira and Macedo 2005). Flex-fuel cars currently represent approximately 95% of sales of new cars, and pure ethanol (hydrated) can be used by more than 13 million Brazilian vehicles (mostly cars with flex-fuel engines), which is approximately 47% of the national fleet of light road vehicles (ANFAVEA 2012).

However, since 2008 the Brazilian ethanol agroindustry has stagnated (Angelo 2012). Some causes for this include adverse weather, cost increases, and yield reduction due to the adoption of mechanical harvesting. Nevertheless, it is clear that an important reason for this setback is the increasing lack of competitiveness due to government intervention in gasoline prices. This is crucial in a consumer market dominated by flex-fuel vehicles where consumers are able to choose the cheapest fuel, whether it be gasoline or ethanol, at a gas station.

Officially motivated by inflation control, the Brazilian government (which controls Petrobras, the main oil products supplier) intervened in the fuels market in two ways: (1) maintaining the gasoline and diesel prices at the refinery gate level (ex-taxes) below the approximated international parity prices formerly adopted, and (2) progressively reducing the Federal taxes on fossil fuels. Although taxes have historically represented more than 40% of the final price of gasoline, the Federal government gradually reduced its tax since 2008, as indicated in Fig. 5. In June 2012 the main Federal tax on gasoline dropped to zero, returning to R$100/m^3 just in 2015.

As of December 2013, the gasoline price at gas stations was approximately 20% below the value that would be expected if taxes were applied. Thus, as the Brazilian fleet is predominantly flex-fuel, ethanol demand has decreased as ethanol has been substituted by gasoline. In 2012/2013 the ethanol production was 15.6% less than in 2008/2009. More than 40 mills did not operate during the 2012/2013 harvest season and in the following two seasons a total of 60 mills closed, which generated considerable number of unemployed. The Brazilian government has taken little effective action to change this situation, which stresses the importance of public policies for the development of bioenergy. The resumption of sugar prices at the end of 2015 and the adjustment of gasoline prices has helped the sector.

2.3 Fuel Prices Evolution

The period between 2005 and 2014 was relevant to understand the role of public policies toward biofuels in Brazil and their impact on the gasoline and ethanol markets, as indicated in the next figure. The values are presented US currency using the official current exchange rate of the US dollar to the Brazilian Real for that month.

Figure 6 presents the price of regular gasoline in Brazilian refineries (ANP 2015b) and American refineries—US Gulf Cost—(EIA 2015) as well as the price of anhydrous ethanol (CEPEA 2015). The price of gasoline in the United States, which is closely related to the international oil price, was simply used as a proxy for parity, as other factors are also worthy to consider such as the exchange rate and freight and trading conditions. Three distinct periods are observed in the figure: (1) from January 2005 up to the Financial Crisis of September 2008, (2) from October 2008 until April 2011, and (3) from May 2011 to 2014.

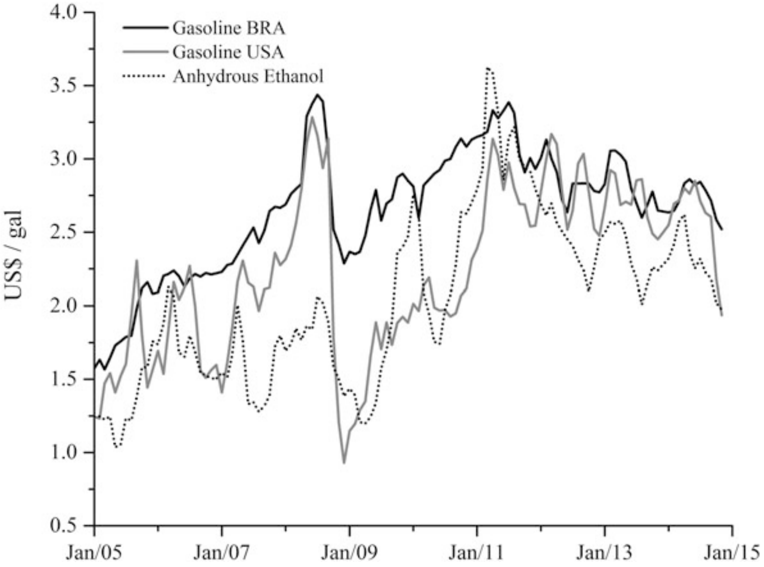

Fig. 6 Evolution of gasoline and ethanol prices at producer level, ex-taxes (ANP 2015b; CEPEA 2015; EIA 2015)

Table 1 Average producer price ratios for gasoline (US and Brazil) and anhydrous ethanol (Brazil) (ANP 2015b; CEPEA 2015; EIA 2015)

Period	Gasoline BRA/gasoline USCG	Ethanol BRA/gasoline BRA
Oct 2008–Apr 2011	1.54	0.75
May 2011–Oct 2014	1.08	0.86

In the first period, the price of gasoline for producers in Brazil was approaching the price in US refineries, thus following the behavior of the international oil price, while the price of ethanol was approximately stable. However, after September 2008 there was a strong downward movement in the gasoline market, which was followed by a recovery in the US price but not proportionately reflected in the Brazilian gasoline price, while the price of ethanol augmented essentially due to production cost increases, reducing its competitiveness. Inflation in Brazil during this period was 24%. The annual steps in ethanol prices observed in this figure mostly relate to seasonal availability of this biofuel, which is associated with the harvest period of sugarcane. In April/May 2011 there began a reduction in ethanol prices, however, not by enough to reverse the consumption retraction promoted by the gasoline subsidies.

Attending to frequent Petrobras claims about financial losses caused by the low domestic prices and the increase of gasoline imports required to complement its own production to cover a rising demand (in great part a consequence of ethanol displacement by cheap gasoline), the Brazilian Government allowed some price corrections for gasoline. However, these increase of gasoline prices at refinery gate were directly compensated by a federal taxes reduction so that consumers would not face price increases and to lessen the likelihood of inflation. So, the gasoline price at Brazilian refineries increased about 60% between 2007 and 2013 (in Brazilian currency), but its price at gas stations remained stable, shifting ethanol consumption to gasoline.

From Table 1 it can be observed that Brazilian gasoline became effectively cheaper and moved closer to the US price while the ethanol became comparatively more expensive in the last 5 years. This situation became more complicated for ethanol producers when the impact of gasoline taxes reduction was considered and is presented below.

From the consumers' point of view, Fig. 7 presents the evolution of the average prices of hydrated ethanol and gasoline (in fact, E25 or gasoline with 25% anhydrous ethanol) in Brazilian gas stations since 2005. As can be observed, there is a strong correlation between these prices, determined by the fact of most of the current Brazilian light vehicular fleet consists of flex-fuel cars. Thus, the ratio of ethanol and gasoline prices is very important because in the case of flex-fuel vehicles, after considering the differences in heating value and efficiency when using these fuels, the breakeven price of ethanol is about 70% of gasoline price. Put differently, if the price of ethanol is lower than 70% of the gasoline price, the consumers rationally prefer ethanol, but if it is higher they move to consume gasoline. Under such conditions, because ethanol faces a more restricted market, its price is essentially determined by the energy equivalent price of gasoline, which is under Government control, setting a pseudo upper threshold for the ethanol price by

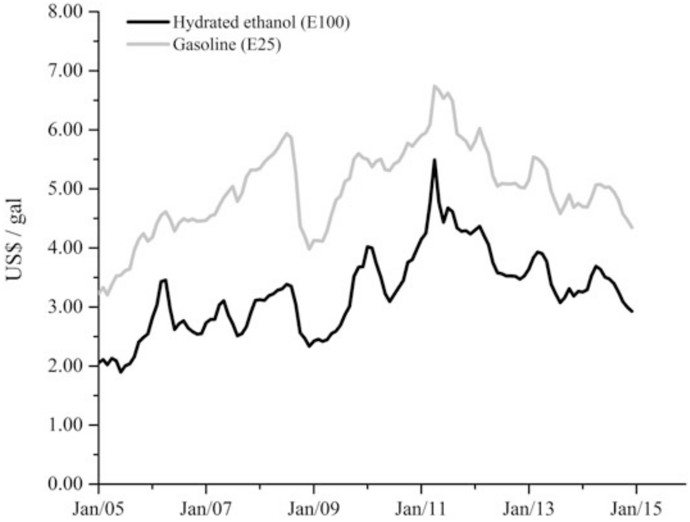

Fig. 7 Average current price of hydrated ethanol and gasoline (E25) at Brazilian gas stations (ANP 2015b)

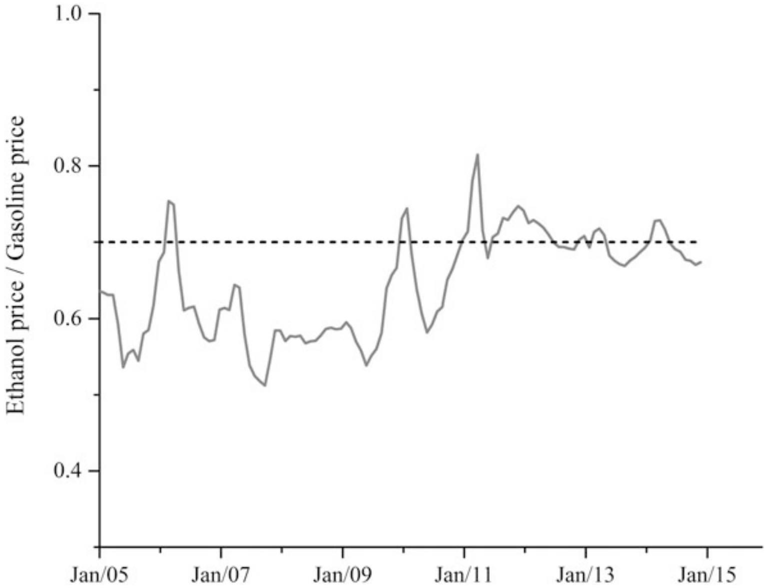

Fig. 8 Ratio of prices of hydrated ethanol and gasoline (E25) in Brazilian gas stations (ANP 2015b)

establishing the commodity value and tax on gasoline. Figure 8 depicts the price ratio for the same period as Fig. 7, ratifying the progressive loss of competitiveness of ethanol relative to the gasoline, primarily from 2011 onwards.

While brief and general, this discussion has presented how government intervention in the fuel pricing framework, which has artificially reduced the gasoline price for consumers (depressing the commodity price and reducing taxes on it), has deeply affected the feasibility and sustainability of the ethanol market in Brazil.

3 Biodiesel Production and Use in Brazil

The Brazilian biodiesel program is not comparable to its ethanol program. It has a very different history and was created under diverse conditions and objectives, but even so it is a concrete example of the crucial responsibility of government to set the playing field and create adequate rules for developing a biofuel market.

3.1 Biodiesel Industry in Brazil

In chemical terms, biodiesel is a blend of ethyl or methyl esters of fatty acids derived from natural triglycerides, such as vegetable oils, animal fats and oil residues, obtained from the transesterification process. In this catalyzed reaction, the triglycerides react with alcohol, typically methanol, generating a mixture of esters, that is called biodiesel, and glycerol.

The production of biodiesel in Brazil has increased 32.2% per year since mandatory blend B2 in 2008, reaching 0.90 Ggal in 2014 (Fig. 9), with the consumption of 0.10 Ggal of methanol and generation of 0.082 Ggal of glycerol at the same year (ANP 2015a).

The production installed capacity followed the biodiesel production with an increase of 15.3% per year, between 2008–2014, and an average of idle capacity of 62.2% in the same period. In 2014, the production capacity was 2.01 Ggal/year, approximately 2.23 times higher than production. Such overcapacity, possibly overestimated, most likely results from the strong stimulus adopted to foster biodiesel production and actually explain the claims of biodiesel producers to the government aiming to increase the current blending level.

There is good availability of fatty raw material for biodiesel production in Brazil, which is part of the limited group of countries—Argentina, Brazil, China, India, Indonesia, Malaysia, the Philippines, and the United States—responsible for almost 70% of the global production of vegetable oil in 2012, mostly derived from palm, soybean, rapeseed, and sunflower (FAO 2015). The total production of vegetable oil in Brazil corresponded to, in volume, approximately 20% of the annual consumption of national diesel oil by transport sector between 2000–2012 (EPE 2015; FAO 2015). In this context, soybean is the main oil crop cultivated in Brazil. In 2014, 2.14 Ggal of soybean oil was produced (ABIOVE 2015), which were around 90% of the total national vegetable oil production, followed by palm oil and cottonseed oil.

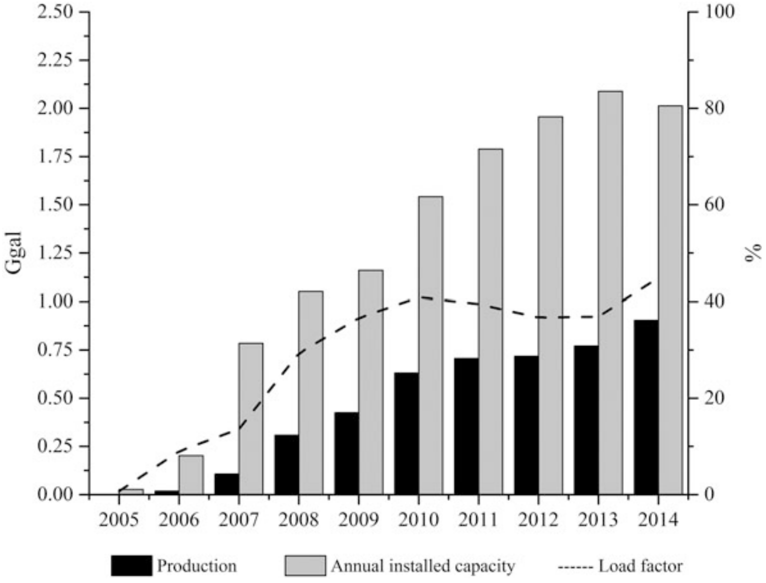

Fig. 9 Evolution of biodiesel plants capacity and production in Brazil (ANP 2015a)

Because of this large availability and the well-established agroindustry, the soybean oil has been the main feedstock for biodiesel production, being responsible by more than 75% of production (Fig. 10), except in the first year of the program when others oilseeds were used in the installed small plants. In 2014, 0.70 Ggal of soybean oil (32% of the total soybean oil produced in Brazil) were consumed in biodiesel plants (EPE 2015). On the other hand, the large cattle herd, associated to beef industry in Brazil, offers a large availability of tallow, which contributed with 19.8% of the biodiesel produced in the same year. Cottonseed oil was responsible by 2.2%. The category labeled "Others" includes palm oil, peanut oil, castor oil and used frying oil, among others in small amount.

Despite the governmental incentives, as commented below, the use of castor and palm oil has been insignificant (<1.0% of total biodiesel production) since mandatory blend B2 in 2008. It was registered as a small use of castor oil just in 2007–2009 in around of 30–90 thousand gallons, but the low productivity, technical and economic obstacles practically eliminate castor as a feasible alternative for biodiesel production. In turn, the production of palm oil in Brazil reached 135 Mgal in 2013 (FAO 2015), which would correspond around 17% of biodiesel produced in this year. Even so, just 2% of this amount was effectively used to produce biodiesel, due to high logistics cost, the production scale, the other competitive uses for this raw material, the elevated deployment cost of palm plantations and the long time to start economic production (about 5 years). However, some public policies have been launched to foster the use of more efficient routes, as palm trees (Nogueira 2011).

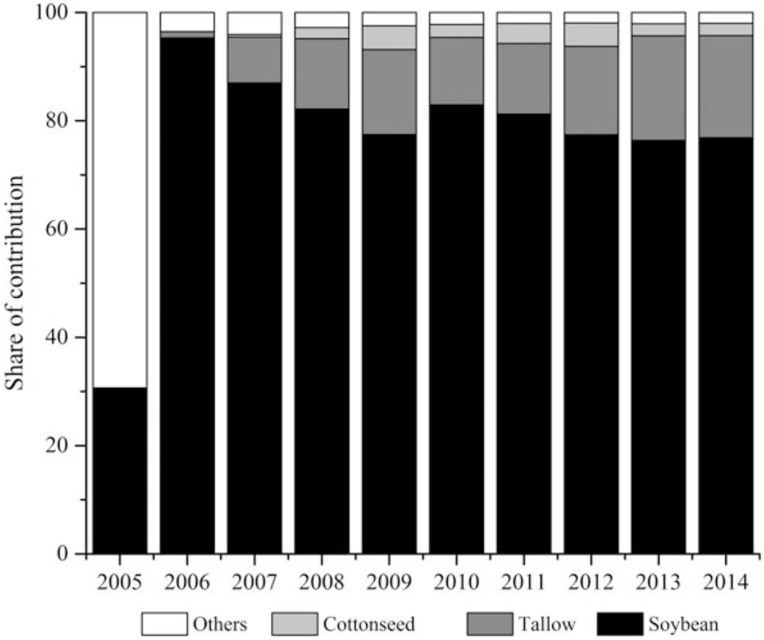

Fig. 10 Raw material used in biodiesel production in Brazil (EPE 2015)

In this context, the South and Center-West regions have driven biodiesel production in Brazil, being responsible by 80% of production in 2014, and having installed more than 75% of the production capacity. It is justified by the fact that the soybean, the major raw material used for biodiesel, is typically cultivated in these regions (Fig. 11) (ANP 2015a).

3.2 Biodiesel Policy in Brazil

In 2005, thirty years after the implementation of Proálcool, the Brazilian government launched a national program to produce biodiesel. However, the Brazilian initiatives for the use of vegetable oils as diesel substitutes started early (in 1920) with a research at the National Institute of Technology and the Institute of Industrial Technology of Minas Gerais. In 1950, studies were conducted on the use of ouricuri (*Syagrus coronata M.*), castor, and cottonseed oils in diesel engines (MIC 1985b).

In 1980, after two oil shocks in previous decade, the critical global energy scenario triggered a reduction in dependency on imported oil, and the National Energy Council established the National Program for Production of Vegetable Oils for Energy Purposes (Proóleo). Among the objectives of this program were: replacing diesel fuel consumption by vegetable oils and encouraging technological

Fig. 11 Biodiesel plants in Brazil (ANP 2015c)

research to promote the production of vegetable oils in different regions of the country (Iturra 2003). Nevertheless, the economic feasibility of producing energy from vegetable oils was questionable, and the falling of oil prices in 1985 decreased interest in this program (Nogueira and Macedo 2005). At the same time, the Department of Industrial Technology of the Ministry of Trade and Industry developed the National Renewable Energy Alternatives from Vegetable Sources Program (MIC 1979), which led to the Vegetable Oil Program (OVEG) (MIC 1985a), that specifically aimed to improve the technical development of vegetable oil use in diesel engines. Tests were developed with pure esters and blends with 30% of ester from soybean oil because of the greater availability of this feedstock (Carioca and Arora 1984). The first Brazilian patent on biodiesel was obtained in 1983 (Parente 2003).

More recently, because of increasing concerns about the sustainability of energy systems as well as the evolution of biodiesel production in Europe, interest in this source of biofuel has expanded in Brazil. Several institutions have begun to develop activities in this field, and some governmental actions have been taken. In 2002, the Ministry of Science and Technology created the Network for Research and Technological Development on Biodiesel (RBTB), with representatives from universities, the automotive industry, and potential biodiesel producers. In 2003, ANP launched the first Brazilian specification of biodiesel for use in blends with regular diesel.

The National Program of Production and Use of Biodiesel (PNPB, in portuguese), which was launched in 2005 by the Law 11.097 (Brasil 2005b), confirmed the Brazilian Government interest in this new biofuel, focusing on social and environmental benefits, basing on some specific actions: mandatory blends in diesel in progressive targets, social inclusion and tax subsidies.

The mandatory blending started with 2% of biodiesel (in volume) in diesel (B2) in January of 2008, being increased to B3 in July 2008 and to B4 in July 2009. According to the original legislation, in January 2013, the biodiesel content should be 5%, but in response to requests from biodiesel producers, the Brazilian authorities decided to anticipate the B5 to January 2010. Finally, it was established the mandatory blend of B6 in July 2014 and B7 from November 2014. Thus, all diesel sold in Brazil has currently 7% biodiesel (B7).

The social inclusion was promoted by encouraging small farmers, that are called family farmers, to supply feedstock for biodiesel production, aiming to generate job and income, mainly in low developed regions: North, Northwest and Semi-Arid (a region susceptible to severe droughts, as set by the Federal Government). In this context, the *Social Fuel Seal,* created by Decree 5.297/2004 (Brasil 2005a), sought to identify the biodiesel producer that purchases a minimum percent of its raw material from family farmers, under previous contracts, besides ensuring technical assistance and training to these contracted farmers. A family farmer is defined as holding an area of 20 ha up to 440 ha, depending on the region where the property is located. The minimum share of raw material purchased from familiar farmers in order for biodiesel producer to obtain the seal is determined by government and varies by year. In 2014, this share was 15% of Center-West and North, and 30% of Northeast/Semi-Arid.

According to Ministry of Agricultural Development (MDA 2015), in 2014, around 3.0 M ton of raw material came from family farmers, which was 20–25% of the total raw material used in biodiesel plants. In that last years, more than 90% of this volume is from soybean producers located in South or Center-West region, even the efforts of government to encourage the production in low developed regions, as North and Northwest, using regional feedstocks, as castor and palm oil.

Some aspects justify the major participation of these two regions: the large number of family farmers in PNPB, the greater capacity for organization in cooperatives, the regional predominance of soybean oilseed (raw material with technical and productive consolidation advantages in relation to others) and the size of the areas categorized as family farm, with direct effects on the volume of grain produced (MDA 2015).

The majority of the biodiesel plants in Brazil has the Social Fuel Seal (99.6% of the installed capacity in 2014), and since the mandatory blend, in 2008, up to 2014, almost US$6.0 billion were destined to obtain raw material from family farmers. The number of individual family farmers, which were accounted as suppliers of raw material under Social Fuel Seal, was from 30 thousand families in 2008, achieving more than 100 thousand families in 2011, to almost 75 thousand in 2014. The

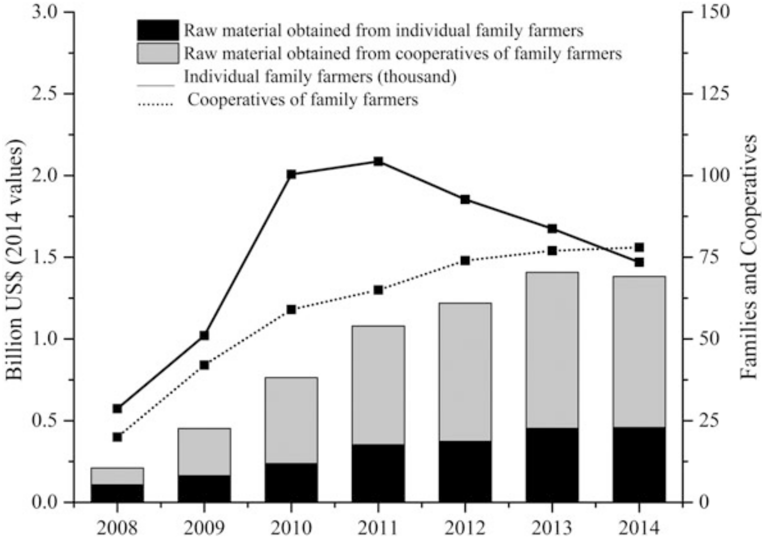

Fig. 12 Acquisitions of raw material from family farmers in 2008–2014 in constant currency-Dec/2014 (MDA 2015)

number of agricultural cooperatives, which acts as suppliers, have been growing over the years, achieving 78 in 2014, and have been responsible by 70% of the acquisitions of biodiesel producers under Social Fuel Seal (Fig. 12). At the same figure, it was observed that US$1.4 billion was destined to family farmers (individual and cooperatives) in 2014 to acquire raw material to produce biodiesel, which represented just 28% of the total acquisitions of biodiesel producers. The other share was destined to large producers.

In this context, by Fig. 13, the average income of family farmers has grown over the years. In other terms, for each gallon of the biodiesel produced in 2014, US $1.53 was destined to family farmers; or for every US$2.53 spent on the large agricultural producers, US$1.00 was spent on the familiar farmers. Finally, expenses with technical assistance, which is a criteria to receive the Social Fuel Seal, was US$92.2 million in the last four harvest seasons.

Another specific action of the PNPB was the implementation of tax subsidies. The federal taxes (PIS/PASEP/COFINS) applied along the chain production were reduced according to the region and raw material used, with higher discounts for producers which holds the *Social Fuel Seal*. In Table 2 it is observed the variations of these subsidies in comparison with federal taxes on diesel, in the beginning of PNPB and nowadays. The different exchange rates justify the near values for the diesel in the both years. Since 2012, there is a reduction on these taxes for all cases, i.e., independent of the producer region and raw material used. The biodiesel obtained of castor and palm oil from familiar farmers in North (N), Northeast (NE), and Semi-Arid (SA) regions are free of these taxes. According the presented above,

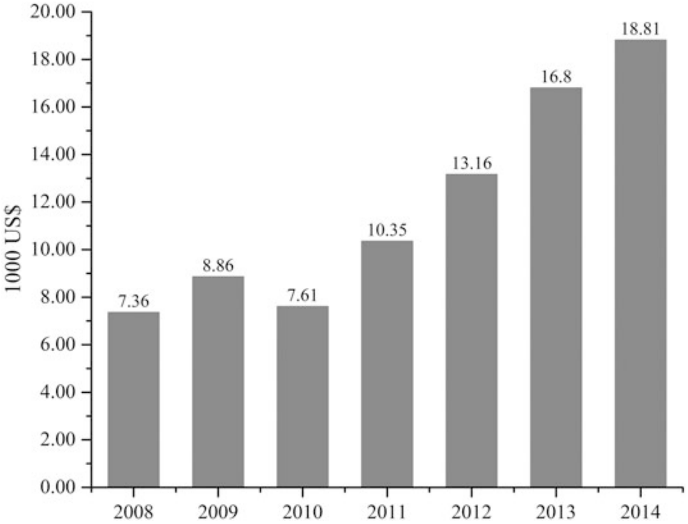

Fig. 13 Average income (constant currency-Dec/2014) of family farmers benefited by social fuel seal (MDA 2015)

Table 2 Total federal taxes on diesel and biodiesel use in Brazil (US$/gal)

Year[a]	Diesel	Biodiesel			
		General case	Castor or palm oil produced in N/NE/SA	Family farmers	Family farmers of N/NE/SA
2005	0.34	0.34	0.24	0.11	0.00
2015	0.34	0.17	0.14	0.07	0.00

[a] The exchange rates considered were: for 2005, R$/US$2.4352, and for 2015, R$/US$3.2215

the current Brazilian production profile is applied majority for the general cases and family farmers.

3.3 Fuel Prices Evolution

The price of biodiesel in Brazil is regulated by inverse auctions with a Reference Maximum Price (RMP) defined by National Agency of Oil, Natural Gas and Biofuels (ANP) likely based on industrial costs from the various raw materials used, financial costs, taxes and regional characteristics.

In 2005–2014 there were 39 auctions and one complementary auction, differing from each other due to some peculiarities, as auction format, bidding rules, regularity of the auctions and delivery schedule. Some important aspects and changes can be identified in this period.

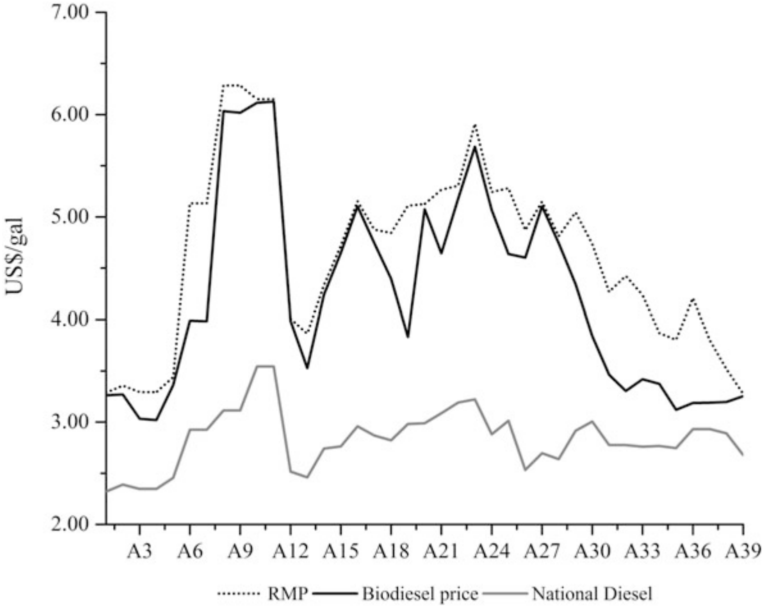

Fig. 14 Average prices from biodiesel auctions (A) in Brazil in current values (ANP 2015a; ABIOVE 2015)

Until 25th auction (June 2012), the auction was conducted with two players, which were the two main producers and importers of diesel in Brazil: Petrobras and Alberto Pasqualini Refinery (REFAP, a subsidiary of Petrobras). Subsequently, biodiesel was re-auctioned between Petrobras, Refap, and authorized distributors. In this period, 80% of the biodiesel demanded in the auction was reserved for the producers with Social Fuel Seal.

In an attempt to include transportation costs, a Logistics Adjustment Factor (LAF) was introduced in the 23rd auction in 2011. With this factor, the producers located in North and Northwest regions would receive more for biodiesel traded. This factor was used up to the 26th auction, when the actual model for biodiesel auctions, in general terms, was adopted. In this case, the authorized distributors choose the biodiesel producers directly, inputting in their costs the logistics from each producer, suggesting a more competitive market (Rico and Sauer 2015). Figure 14 shows the observed evolution of RMP and the average prices along the auctions in 2005–2014. The difference between the prices has been as high as 30%, and more frequent since the 26th auction, with the new model of auctions.

The average values of auction prices, which were pondered by quantity offered by region, varied from US$2.94/gal to US$6.90/gal, as observed in Fig. 15. The influence of LAF was small on average prices due to the few contribution of North/Northwest regions—which presented the major RMP—in volume of biodiesel produced (around 7.9%). In this context, since the beginning of PNPB,

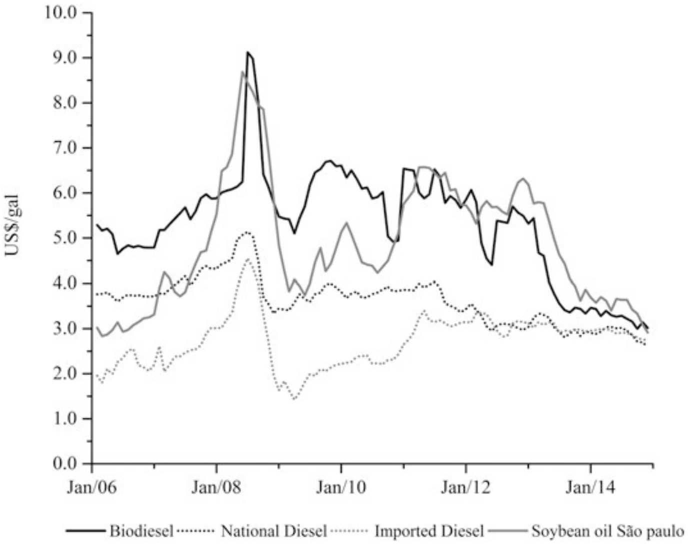

Fig. 15 Average biodiesel and diesel prices in Brazil in currency constant values of December/2014 (ANP 2015a; ABIOVE 2015; IpeaData 2015)

biodiesel prices have been higher than diesel, eventually being traded 85% more expensive than diesel, in 2012. However, since 2013 this difference has become smaller. At the end of 2014, biodiesel was sold, on average, at a price only 13% above the price of diesel, in volume base. The difference in price relative to the price of imported diesel was even higher in this period, reaching 160% at beginning in 2009, but becoming closer in the last months of 2014 (around 10%), following the soybean oil prices.

A key question that arises is whether it would have been better to export soybean oil and import diesel instead of producing biodiesel?[3] The information from Fig. 15 suggests that it would have been preferable to export soybean oil rather than produce biodiesel, especially at the last years, when the vegetable oil price is slightly higher than biodiesel and the imported diesel is still lower than biodiesel. However, the Brazilian government presents some reasons to continue producing biodiesel. Some of them fit with the objectives of the biodiesel program of decreasing dependency on fossil fuels and reducing GHG emissions and generating income for family farmers. On the other hand, biodiesel production balances the oil market, acting as an alternative destination to soybean oil surplus that would sell in unfavorable conditions otherwise.

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[3] For comparability, the soybean oil price (originally in US$/ton) was converted in US$/gal by assuming a density of 0.92 ton/m³, and 264.17 gallon/m³.

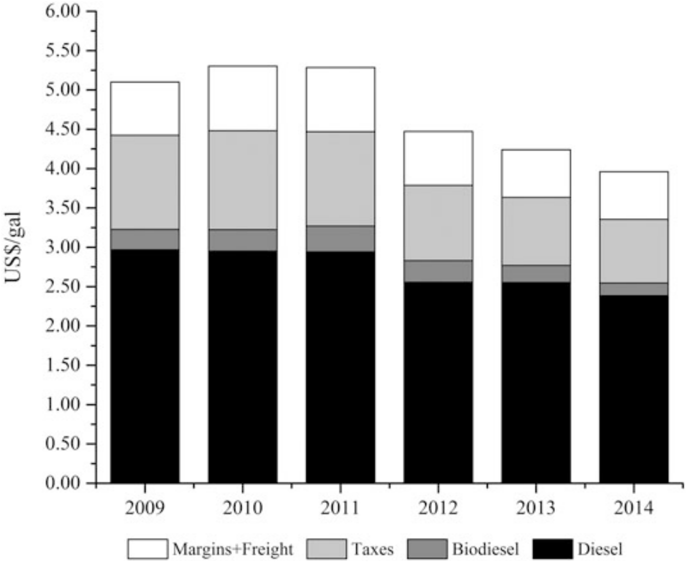

Fig. 16 Average prices to consumers (ANP 2015a; ABIOVE 2015; Fecombustíveis 2015)

Despite government subsidies, consumers pay the difference between biodiesel and diesel prices. In terms of price composition, since the mandatory blend, the cost of biodiesel has represented around 5% of the average price of diesel to consumers, as observed in Fig. 16. The taxes correspond to 20%.

From the current perspective of biodiesel in Brazil, one of the challenges is the idle installed capacity of production, which generates a constant pressure in favor of expanding the blending level. The output capacity of the biodiesel plants is about three times greater the annual consumption. In this context, at 2015, the Brazilian government began to allow the use of biodiesel blends between 20 and 30% for large volume consumers as fleets, railway companies and industrial and/or agricultural activities (CNPE 2015). The low diversity of the feedstock and the small participation of the low developed regions, as North and Northwest, have been constant challenges.

4 Final Remarks

Ethanol and biodiesel programs have been promoted for decades in Brazil for various reasons, including energy security and rural development. Both biofuels are associated with generation of relevant social and environmental benefits (BNDES 2008), and the potential to be grown without competing with food production (Nogueira and Capaz 2013).

The differences between these two programs can be observed in the items above. For the ethanol, there is a mature production chain, which has been developed along the last 40 years, with the presence of an adapted fleet that can consumed pure (hydrated) or blended ethanol. Despite the recent stagnation of the sector due to governmental intervention in gasoline prices and the increase in production costs, the production and use of the ethanol is a sustainable energy strategy for Brazil (Leal et al. 2012).

On the other hand, the biodiesel program is more recent and has a great appeal to social inclusion of familiar farmers, being strongly oriented to use of feedstocks produced in poor regions, such as castor and palm oil in Norte or Northwest. However, the production in small farms—responsible by just 25% of the raw material supplied—has been concentrated in South and Center-West regions, which are big suppliers of soybean. In this regard, biodiesel production is still improving and a shift to more efficient sources of feedstock is one of the main challenges of the program. The use of biodiesel has been mandatory and, despite the great idle production capacity and the production costs be closer to diesel in the last years, there are some technical restrictions to allow the consumption of pure biodiesel, as the no guarantee of engines manufacturers.

As made evident by the Brazilian programs of ethanol and biodiesel, the effective implementation of a sustainable biofuel market depends directly on a clear, well designed, and properly implemented strategy based on a robust technology and the availability of domestic natural resources. Essential elements of this strategy include:

(a) Creation of a guaranteed demand by requiring mandatory blending of biofuels in conventional fuels (drop-in fuel concept) that can be expanded further by promoting the use of higher blending levels and even the use of pure biofuel.
(b) Adjusting the tax regime in the fuel market in order to add value to the externalities of biofuels in relation to conventional fuels.
(c) Informing consumers, producers, and decision makers about the implications, benefits, and risks of adopting and promoting biofuels.
(d) Supporting R&D activities in the several stages of feedstock production, processing, and biofuel logistics and final use, including management and capacity building.
(e) Systematic assessment of environmental and social impacts of the biofuel production chain.
(f) Promotion of diversification and flexibility of the biofuel agroindustry, considering innovative production routes, alternative feedstocks, and new products.

With regard to the last topic, it is interesting to note the increasing role of bioelectricity in the total income of sugarcane mills with capacity for cogeneration and efficient use of the available lignocellulosic coproducts from ethanol and sugar production.

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Prospects for Biofuel Production in Brazil: Role of Market and Policy Uncertainties

Maria Paula Vieira Cicogna, Madhu Khanna and David Zilberman

Abstract Biofuel production in Brazil has been motivated by a desire to reduce dependence on fossil fuels and encourage rural economic development. Policies and technologies over the past 25 years have lowered production costs and created profitable opportunities. The industry grew through political willingness to support an infant industry, continuous technological advances in both biofuel production and complementary industries (e.g., automotive), ability to utilize agricultural byproducts, and income growth in rural areas. It was confronted by the challenges of price instability due in large part to changing oil prices, uncertainty about the prospects of biofuels as a viable source of energy, the ability to create and maintain policies conducive to its growth, and, finally limited access to credit. This paper demonstrates the importance of political economy factors in the evolution of the biofuel sector in Brazil and suggests their importance to understand the evolution of this sector in other parts of the world.

Keywords Biofuel sector · Ethanol policies · Cellulosic ethanol · Cogeneration

1 Introduction

Biofuel production in Brazil has been motivated by multiple objectives that include reducing dependence on fossil fuels and encouraging rural economic development. It has been supported by a multitude of policies and technical change over the last

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M.P.V. Cicogna
Polytechnic School, University of São Paulo, São Paulo, Brazil
e-mail: cicogna@usp.br

M. Khanna (✉)
Department of Agricultural and Consumer Economics, University of Illinois
at Urbana-Champaign, Urbana, IL, USA
e-mail: khanna1@illinois.edu

D. Zilberman
Department of Agricultural and Resource Economics, University of California at Berkeley,
Berkeley, CA, USA
e-mail: zilber11@berkeley.edu

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25 years that have lowered costs of production, made it profitable to produce ethanol and created demand by imposing blend requirements, providing tax credits for biofuel production, and adoption of flex-fuel vehicles (FFVs). These policies are implemented within the context of a broader suite of fuel policies designed to stabilize and protect domestic energy prices from international oil price volatility and make the fuel sector a source for substantial tax revenues for the government.

Sugarcane ethanol is more land efficient and energy efficient than corn ethanol with a yield of 6.2 cubic meter per hectare and energy efficiency of 9.3; corresponding figures for corn ethanol are 4.2 cubic meter per hectare and 2.3, respectively. The greenhouse gas intensity of sugarcane ethanol is 74% lower than that of energy equivalent gasoline; corresponding value for corn ethanol is 44% (Crago et al. 2010). The ethanol industry is estimated to generate nearly one million jobs and have other positive social impacts, such as higher wages for rural workers, compared to other crops in Brazil (La Rovere et al. 2011).

Biofuel production in Brazil has grown more than sixfold since 1980 and Brazil was the largest producer in the world until 2005. Brazil currently meets 50% of its domestic demand for transportation fuel and is the largest exporter of biofuel in the world. With an abundant supply of arable land, of which only 11.6% is used for sugarcane production and half of that for ethanol production from sugarcane, there is considerable potential to expand production to meet global demand for transportation fuel. The discovery of pre-salt oil reserves together with the domestic fuel policies and biofuel production have enabled Brazil to transform itself from a country importing 80% of its oil consumption in 1979 to a net exporter of oil since 2006. However, after 5 years of growth at an average rate of 13.1% per year biofuel production began to stall in 2009; since 2010 the average rate of growth of production has been only 1.48% per year with a significant reduction in exports. Production and exports recovered in 2013 and have continued to rise since. The chapter describes the trend in biofuel production in Brazil and discusses the influence of market conditions and domestic and international biofuel policies on the biofuel sector in Brazil. We discuss the mixed incentives provided by these policies and the political rationale for their implementation. The production of biofuels interacts with market conditions in the sugar sector since it competes with incentives to use sugarcane to produce sugar. Sugar and biofuel markets in Brazil differ in the demand conditions they face, the substitute products they compete against and the policy and market uncertainties they face; this influences the supply and costs of ethanol production. Uncertainty in policy and market conditions can also influence production decisions and the prospects for expanding biofuel production in the future.

This chapter is organized as follows. Section 2 discusses the trends in consumption of the mix of fuels in Brazil followed by a discussion of the factors affecting the competitiveness of sugarcane ethanol in Sect. 3 including the link between sugar and ethanol prices. Section 4 describes the mix of fuel policies implemented in Brazil, the historical trend, and uncertainty in these policies and discusses the political economic rationale for the choice of policies. Section 5 discusses the market-based factors, risks, and uncertainties that influence incentives to produce ethanol and the potential for ethanol storage and cogenerated electricity to mitigate these risks. Section 6 discusses the potential for cellulosic biofuels in Brazil and Sect. 7 concludes with a discussion of the conditions needed and the challenges to the development of the biofuel sector.

2 Trends in Fuel Consumption in Brazil

The development of the biofuel sector in Brazil has undergone three different phases. The first phase referred to as Pro-Alcohol period from 1975 to the early of 1990s involved substantial government intervention, the second one from the 1990s to 2002 was a period of deregulation of the sector when the price of ethanol was determined by market conditions. The third phase commenced in 2003 with the introduction of flex-fuel vehicles (FFVs).

The Pro-Alcohol phase was characterized by active intervention by the government to encourage adoption of ethanol-only fueled vehicles, development of infrastructure for distribution of 100% ethanol at a price lower than energy equivalent gasoline. This led mills to build the capacity to produce both sugar and ethanol with flexibility to decide on their shares annually; 58.4% of the mills now have an inbuilt capacity to produce both sugar and ethanol and did this in 45:55 ratio in the last decade, with 10% flexibility for changing that ratio in the short run. Mills produce two types of ethanol, hydrous ethanol that is consumed as E100 by FFVs and anhydrous ethanol that is sold pre-blended with gasoline in shares that have ranged from 18% to 27%. Clear gasoline, called gasoline A, is no longer sold in Brazil, instead gasoline has historically been sold pre-blended with anhydrous ethanol (called gasoline Type C or gasohol) for consumption by conventional vehicles while FFVs have the choice of consuming gasohol or E100.

While the production of ethanol increased significantly since the 1980s, the composition of ethanol has varied over this period (Fig. 1). During the Pro-Alcohol period, consumption of E100 grew rapidly due to demand from ethanol-only vehicles. By 1984 ethanol-only vehicles accounted for 80% of new passenger car sales and by 1987 ethanol consumption had reached that of gasoline.

The decline in world oil prices in the late 1980s, discovery of oil off the Brazilian coast, rising sugar prices, and growing government debt led to deregulation of the ethanol sector and an increasing price of ethanol above its energy equivalent level. Sales of ethanol fueled cars declined and by the late 1990s, ethanol consumption was less than half that of gasoline. Production of anhydrous ethanol consumption rose due to increasing consumption of gasohol and accounted for much of the increase in ethanol consumption till the early 2000s. After 2003, anhydrous consumption has increased much more slowly while consumption of hydrous ethanol grew rapidly due to the introduction of FFVs. By 2008, 90% of the new cars sold were FFVs and FFVs accounted for 30% of country's active car stock (Salvo and Huse 2011). From March 2004 to March 2007, the average growth in ethanol consumption accounted was 9.8% per year, while from April 2007 to March 2010,

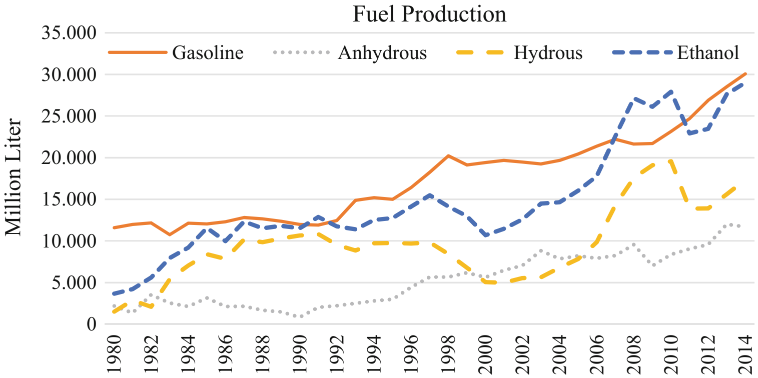

Fig. 1 Trends in Biofuel and Gasoline Consumptions since 1980 *Source* ANP (National Agency of Petroleum, Natural Gas and Biofuels). Data available at Brazilian Statistical Yearbook of Oil, Natural Gas and Biofuels http://www.anp.gov.br/?id=661

it grew by about 24% per year. It is worth noting that since then ethanol consumption decreased to an average of 3.5% per year (source: ANP[1]).

Figure 2 shows the increase in FFV sales since their inception in 2003 and the accompanying increase in consumption of ethanol till 2009 (Fig. 2). During this period, gasoline consumption remained fairly constant while the consumption of ethanol increased to achieve a 50% share in the volume of transportation fuel consumed. However, ethanol consumption stalled after 2010 and has remained below the peak level achieved since then. The share of sugarcane converted to ethanol also declined from 60.3% in 2008/2009 to 50.5% in 2012/2013, and raised to 57% in 2014/2015. Gasohol consumption on the other hand has soared and increased by 64% between 2010 and 2015.

3 Competitiveness of Sugarcane Ethanol

Since the production of sugarcane ethanol involves diverting sugarcane from sugar production to ethanol, higher sugar prices raise the opportunity cost of producing ethanol. Additionally, the cost of ethanol also depends on the costs of producing sugarcane which include the opportunity cost of diverting land from other crops to sugarcane production. Crago et al. (2010) provide a detailed assessment of the components of the cost of producing sugarcane ethanol in Brazil. The industrial costs of producing sugarcane ethanol declined by over 70% between 1975 and 2004 due to learning by doing and economies of scale and resulted in lowering the

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[1] ANP: Brazilian National Agency of Petroleum, Natural Gas and Biofuels (*Agência Nacional do Petróleo, Gás e Biocombustíveis*).

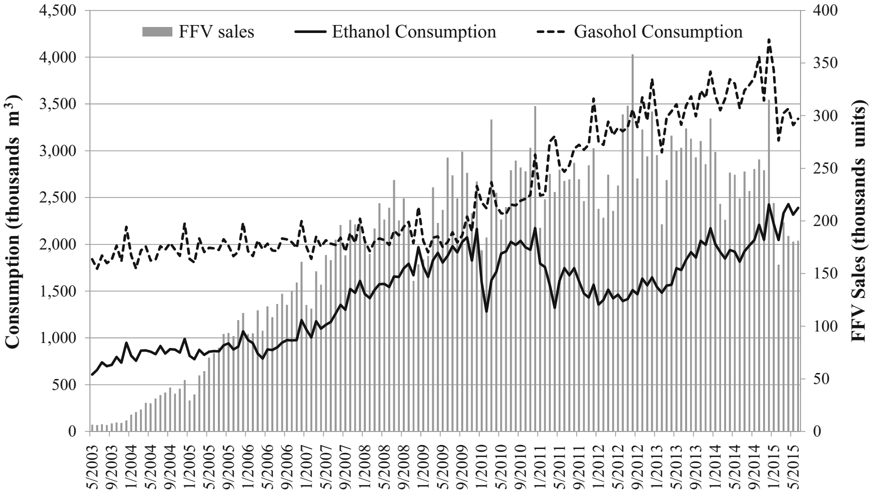

Fig. 2 Fuel Consumption and FFV Sales *Source* Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). Data available at Brazilian Statistical Yearbook of Oil, Natural Gas and Biofuels, produced by ANP. http://www.anp.gov.br/?id=661 and National Association of Automobile Manufacturers (ANFAVEA). Data available at yearbook of Brazilian automotive industry, produced by ANFAVEA http://www.anp.gov.br/?id=661

production cost of ethanol below that of gasoline in volume terms (van den Wall Bake 2009). However, the cost of ethanol has been generally higher than that of gasoline in energy equivalent terms.

Brazil has historically been the lowest cost ethanol producer internationally (Bastos 2012), but high transportation costs and an unfavorable exchange rate have limited its comparative advantage relative to corn in recent years (Crago et al. 2010). According to Valdez (2011), the average cost of producing ethanol at Brazilian distilleries was estimated to be $0.48 per liter in 2008; this was 58% lower than that for corn ethanol produced in the United States. This value includes feedstock costs, labor expenses, interest payments on operating loans, energy costs, as well as fixed costs.

From 2003 to 2009, technological innovations in the ethanol production process and in sugarcane production lowered ethanol costs and increased energy efficiency. Additionally, the increasing use of bagasse for electricity generation (cogeneration) consumed in the mill has also lowered production costs (Du and Carriquiry 2013, Hira and Oliveira 2009). Other costs such as those of labor, land, fertilizer, and energy for sugarcane production and mill costs increased (van den Wall Bake et al. 2009; Milanez et al. 2011; La Rovere et al. 2011; Valdez 2011). From 2007 to 2013, ethanol production costs increased 10.5% annually which implies a cumulative increase of 65.1% in cost (PECEGE 2013). Sugarcane production accounted for about 69% of total costs in 2013. A key determinant of these costs is the yield of sugarcane. In recent years, poor harvests and lack of investment in the field have reduced sugarcane productivity and raised mills costs. On average, sugarcane production costs increased by 84% from 2011 to 2013.

Additionally, costs of sugarcane production have increased due to the need for mechanized harvesting which is more costly and decreases productivity. Pre-harvesting burning has been progressively banned, especially in Sao Paulo State that crushes more than 54% of sugarcane in Brazil. In 2007, about 40% of the sugarcane in Sao Paulo State was mechanically harvested (Goldemberg et al. 2008). A recent law requires that pre-harvesting burning must be phased out in Sao Paulo by 2014 in areas where mechanization is possible and by 2017 in all other areas.

There is a learning curve associated with the mechanization of harvesting. It is important to not damage the roots with the use of equipment during harvest and this requires investment in appropriate equipment and employee training. Precision agriculture can help to mitigate these effects and can boost sugarcane production. All these together tend to raise harvest costs initially, but it is expected that mechanization and new technologies will improve sugarcane productivity in the medium term.

Due to upper limits on ethanol price imposed by the price of gasohol, higher costs of sugarcane production are more easily transferred to sugar consumers than to the retail ethanol prices (as can be observed in Fig. 3). The price of ethanol and sugar has risen considerably since 2008 due to supply side and demand-side factors. Balcombe and Rapsomanikis (2008) estimate the relationship between Brazilian sugar and ethanol prices and international oil prices and find that oil prices are the main driver of both sugar and ethanol prices in Brazil. Additionally, studies show that sugar

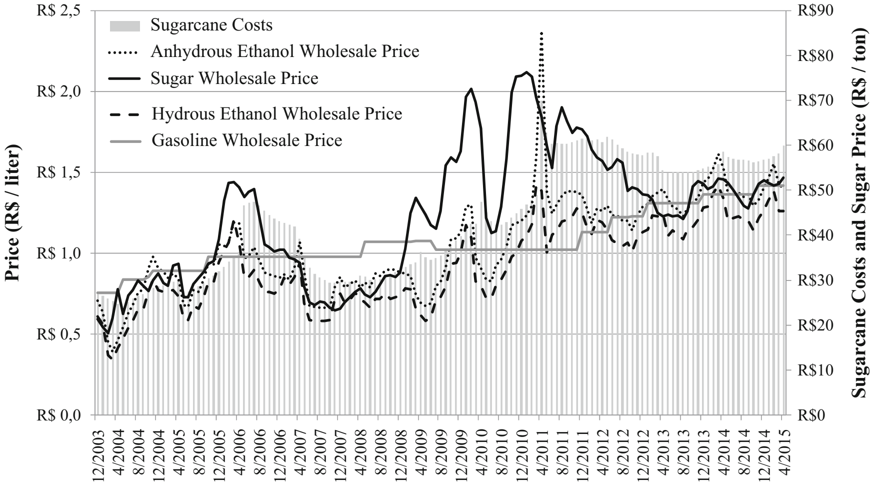

Fig. 3 Sugarcane Costs and Sugar and Ethanol Prices (in R$) *Source* Producers Council of Sugarcane, Sugar and Alcohol of São Paulo (CONSECANA). Database available at CONSECANA's website http://www.consecana.com.br/# and Center for Advanced Studies on Applied Economics (CEPEA). Database available at CEPEA's website http://www.cepea.esalq.usp.br/

prices affect ethanol price and therefore the revenue from ethanol but not the other way around (Costa 2001; Alves 2002; Serra 2011; Diehl 2001). Marjotta-Maistro (2002) showed that increases in sugar and hydrous prices tend to change the production mix in favor of these products to the detriment of anhydrous ethanol.

The price of anhydrous is a negotiated price between distributors and mills based on the domestic and international market conditions. The production of anhydrous ethanol is more expensive than hydrous. Its price depends on the cost of hydrous ethanol and the mandatory blend level; imbalances between supply and demand of anhydrous ethanol are adjusted via prices. As a result, when the US market price for ethanol became more attractive than domestic prices, exports of anhydrous ethanol increased and caused a deficit in the domestic market, leading to the observed peak in price in 2011. The spread of anhydrous price over hydrous spot prices has been about 15% during the last decade.

The production and consumption of hydrous ethanol began to stall since 2009 and price began to rise due to strong domestic demand for fuel, higher sugar demand in the international market and a decline in the sugarcane harvest caused by bad weather conditions (de Gorter et al. 2013). The ethanol sector was significantly negatively affected by the financial crisis in 2008. According to UNICA, total ethanol production per year doubled between 2003/2004 and 2008/2009 harvest; it increased from 13.6 billion liters to 26.4 billion liters, an average annual growth of almost 14.5%. To finance this growth, the mills became highly leveraged and took loans at high interest rates. The average debt over equity ratio rose to 158%. However, the return on capital was only 3% per year (Valor 2013) and much lower than the average interest rate of the Brazilian Central Bank of 8.5% per year in 2012.

In March 2014, the indebtedness of existing plants reached US $30 billion, which required 20% of revenues to cover interest payments. This debt was 38% higher than the one observed in 2009, and was equivalent to US $50 per ton of crushed sugarcane. As a result, 60 mills went bankrupt after 2009, reducing total crushing capacity by 6.2 million tons and leading to a loss of 64,000 direct job positions and 20,000 indirect job positions involved in the industrial production process alone (Neves and Trombin 2014).

The price of hydrous ethanol is limited by the energy equivalent price of gasohol and thus the domestic price of oil. To prevent energy price volatility, the government regulates the wholesale price of oil instead of letting it fluctuate with the world price. The state-owned oil producer, Petrobras, sets a reference oil price for domestic refining. This reference price is a *de facto* cap on the wholesale price of oil used domestically. In recent years, it has been lower than the price of oil in the world market and below the cost of production, resulting in an implicit wholesale price subsidy for domestic oil consumers (ANP 2015b; EIA 2013). Since 2011, the mean gasoline import price was R$ 1.5 per liter but it was sold domestically at R$ 1.2 (prior to taxes). With rising international oil prices, the gap between the regulated domestic wholesale price of gasoline and the import parity price in the Gulf of Mexico grew to about 30% in 2013. While the New York spot gasoline price increased by 93% between 2009 and 2013, the price of gasohol in Brazil increased by 14%.

The introduction of FFVs in 2003 promoted further expansion of ethanol. They led consumers to have the choice of consuming gasohol and/or E100 at the gas station; evidence suggests that the ratio of price of E100 and gasohol in energy equivalent terms and consumer preferences influence this choice (de Freitas and Kaneko 2012). The 70% energy content of E100 relative to gasohol creates an implicit cap on the price of E100 at 70% of the price of gasohol. This has led to strong mean reversion in the ratio of the price of hydrous ethanol to the price of gasohol to 70% since 2003 (Iooty et al. 2009; Du and Carriquiry 2013). Since July 2011 onward, this price ratio has been above 70% and reached 74% in November 2011 (Fig. 4).

The discount of the hydrous ethanol price over gasohol disappeared, and the price ratio since has most often been above 70%. From July 2009 to July 2013, gasohol consumption increased approximately 63%, at the same time hydrous ethanol consumption decreased 39%.

The price ratio decreased to the 70% in May 2013, the same period when the reduction of PIS/COFINS over hydrous ethanol was announced by the government. Balcombe and Rapsomanikis (2008) results suggest that increasing oil prices in the future will lead sugar price to increase by 55% and ethanol price to increase by 60% of the increase in oil price, thereby making ethanol increasingly competitive with oil.

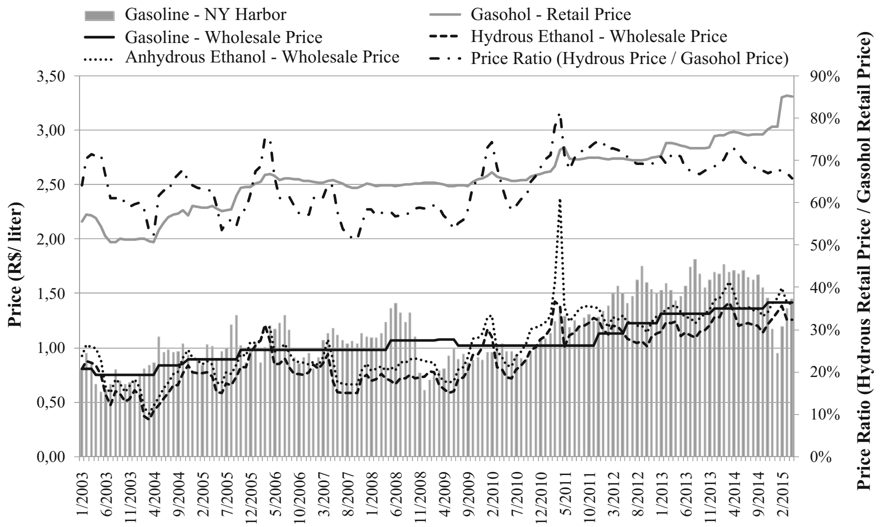

Fig. 4 Fuel Prices and Price Ratio (in R$) *Source* Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). Data available at Brazilian Statistical Yearbook of Oil, Natural Gas and Biofuels, produced by ANP. http://www.anp.gov.br/?id=661 and U.S. Energy Information Administration (EIA). Database available at EIA's website http://www.eia.gov/petroleum/

4 Policy Interventions in the Fuel Sector in Brazil

Biofuel policy in Brazil has been critical for stimulating biofuel production. It has varied considerably over time in three different phases since 1975. During the first phase, the Pro-Alcohol period was characterized by substantial government intervention with the objective of reducing dependence on imported oil. Ethanol was considered the best alternative fuel because it allowed the government and private sector to take advantage from the well-established infrastructure of sugar mills. The government provided subsides and low interest loans for infrastructure, guaranteed purchases of ethanol by the state oil company, Petrobras, at a wholesale price floor, a blend mandate, tax credits for ethanol fueled cars relative to gasoline and a ceiling on the price of ethanol relative to gasoline (Salvo and Huse 2011; Paulillo et al. 2007). The main measures implemented by the government were (i) reduction of the Tax on Industrialized Products (IPI[2]) and of the Tax on Motorized Vehicles (IPVA[3]) for ethanol fueled cars only; (ii) exemption of the Single Tax on Liquid Fuels (IUCL[4]) for ethanol sales; and (iii) establishment of a constant ratio of 65% between the price of ethanol and gasohol. Import tax on ethanol has been equal to zero for ethanol and gasoline since 2008.

With the end of oil crisis in the late 1980s and reduction in the price of oil, government incentives for ethanol were gradually reduced in the second phase initiated in 1990. This, together with relatively high sugar prices in the international market, contributed to a decline in ethanol production, leading to an imbalance between supply and demand for ethanol arising from the alcohol only vehicles (Paulillo et al. 2007; de Freitas and Kaneko 2011). Deregulation of the biofuel industry initiated in the 1990s lasted until 2002 when the Brazilian government's control over production, exports and price of ethanol was completely eliminated (MME 2007). Additionally, UNICA[5] and other organizations were created to coordinate sugarcane growers and biofuel producers and increase their bargaining power in public policy-making.

The third phase started after 2002 when the industry was deregulated and tax incentives took the form of tax differentiation. There are four fuel taxes in Brazil, namely ICMS,[6] CIDE,[7] PIS/COFINS[8], and Import Tax (II).[9] Tax benefits to ethanol are provided through the ICMS and PIS/COFINS which are much higher for gasoline. The PIS/ COFINS tax on ethanol is based on the sales prices. For the

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[2] IPI: Imposto sobre Produtos Industrializados.

[3] IPVA: Imposto sobre Veículos Automotores.

[4] IUCL: Imposto Único sobre Combustíveis Líquidos.

[5] UNICA was created in 1997 and accounts for Brazilian Sugarcane Industry Association.

[6] ICMS accounts for Tax on Circulation of Goods and Services (*Imposto sobre Circulação de Mercadorias e Serviços*). ICMS is a Local Government tax, defined by each state.

[7] CIDE is a Federal Government tax.

[8] PIS/COFINS are Federal Government taxes.

[9] Import Tax (or II, which means *Imposto sobre Importação*) is a Federal Government tax.

producer, the rate is 8.4% of sales price or the incidence of specific rate of R$ 48.00 per cubic meter of ethanol whichever is lower. Corresponding values for the distributor are 21% or R$ 120.00 per cubic meter. In the case of gasoline, the PIS/COFINS is charged only on the producer's sales price, and is set at 28.52% of the producer's sales price or R$ 261.60 per cubic meter sold.

Additionally, growth of the ethanol sector was promoted by (i) the CIDE[10] tax on fuel; (ii) subsidized interest rates to finance investments in expansion and technology improvements (for the purchase of planting, cutting, and cane harvesting machines) and the use of information technologies, such as integrated management processes, operations planning, among other initiatives (Freitas and Ribeiro 2008), and (iii) mandatory blend of anhydrous ethanol with gasoline.

The CIDE is a flat rate charged per cubic meter of fuel sold. It has been zero for ethanol since 2004. It was R$ 501.1 per cubic meter of gasohol (on the gasoline portion) in 2001 and reduced to R$ 91 in 2011, and then to zero in 2012 and then raised to R$ 100 in May 2015. The ICMS is applied to the retail price and calculated either on the marginal value added or the reference price to the consumer. The rates and the way the ICMS is calculated for gasohol and hydrous ethanol are defined by each Brazilian State. Sao Paulo State has the largest ICMS tax rate differentiation in Brazil: 25% for gasoline and 12% for hydrous ethanol. The average ICMS tax rates for the whole country are 25.7% and 24.3%, respectively. The ICMS rates for major states in Brazil are shown in Table 1.

Taxes, and in particular the ICMS tax, are an important reason for the low price ratio of hydrous ethanol to gasohol in Sao Paulo State where it is equal to 64%; the corresponding figure on average for Brazil is 80%. The difference between the tax on gasohol and hydrous ethanol has been falling gradually over the last decade. In the second quarter of 2009, when hydrous ethanol consumption reached a peak, gasohol taxes were 17% higher than hydrous ethanol taxes in Sao Paulo State. At that time, the average price ratio was around 56%. When CIDE tax over gasoline was reduced in November 2011, this difference fell to 10.3%. In July 2012, when CIDE tax on gasoline was reduced to be zero, the tax on gasoline was only 6.3% higher than on hydrous ethanol in Sao Paulo State. Cavalvanti et al. (2012) showed that the tax differential between ethanol and gasoline in 2010 was larger than the value of the GHG intensity differential between the two fuels which ranges between US$ 0.03–0.13 per liter of hydrous ethanol depending on the monetized value of the damages due to climate change in Brazil.

Figure 5 shows that while CIDE + ICMS have decreased over time, the profit margin of distributors and gas station owners (gasohol retail price) has increased since 2011. The reduction on gasohol taxes was a component of policies to control inflation. However, this was not very effective since fuel prices rose due to an increase in profit margins that are not controlled by the Brazilian government. The profit margins on gasohol, however, cannot increase indefinitely because as the

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[10] CIDE refers to Contribution for Intervention in the Economic Domain (*Contribuição de Intervenção no Domínio Econômico*).

Table 1 ICMS per Brazilian State

State	Gasohol (%)	Hydrous Ethanol (%)	Difference (gasohol—hydrous ethanol)—pp
São Paulo	25	12	+13
Paraná	28	18	+10
Bahia	25	17	+8
Minas Gerais	27	22	+5
Pará	28	26	+2
Pernambuco	27	25	+2
Acre, Alagoas, Amapá, Amazonas, Ceará, Distrito Federal, Maranhão, Mato Grosso, Mato Grosso do Sul, Paraíba, Piauí, Rio Grande do Norte, Rio Grande do Sul, Rondônia, Roraima, Santa Catarina, Sergipe, Tocantins	25	25	0
Espírito Santo	27	27	0
Rio de Janeiro	30	30	0
Goiás	27	29	−2

Source Brazilian National Treasury Department (*Secretaria do Tesouro Nacional do Brasil*). Information available at http://idg.receita.fazenda.gov.br/

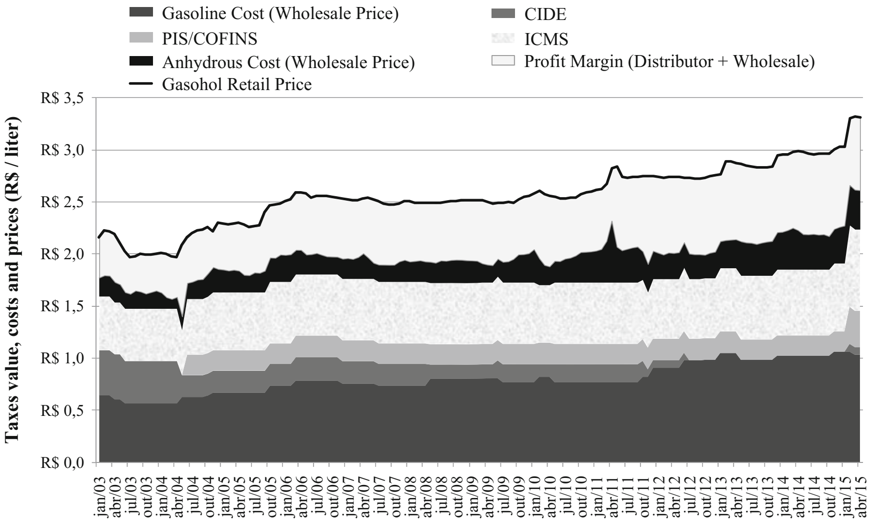

Fig. 5 Gasohol price decomposition in Sao Paulo State *Source* Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). Gasohol price available at http://www.anp.gov.br/?id=2880 and National Council for Fiscal Policy (Confaz). Tax information available at https://www.confaz.fazenda.gov.br/

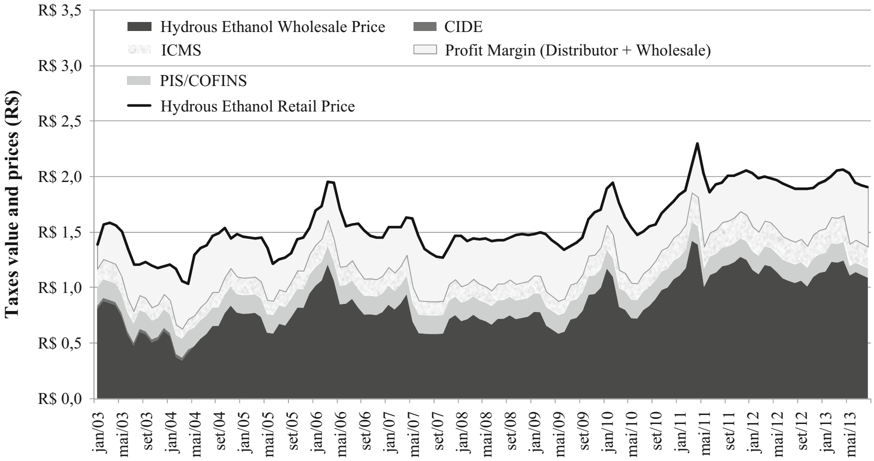

Fig. 6 Hydrous ethanol price decomposition in Sao Paulo State *Source* Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). Ethanol price available at http://www.anp.gov.br/?id=2880 and National Council for Fiscal Policy (Confaz). Tax information available at https://www.confaz.fazenda.gov.br/

retail price of gasohol increases it makes hydrous ethanol increasingly competitive. Furthermore, this policy could not be sustained in the long run since it resulted in losses for Petrobras and budget deficits for the Brazilian government. The CIDE and PIS/COFINS taxes on gasoline were raised in 2015 together with other increases in taxes to reduce the government's budget deficit.

Figure 6 shows that gasohol profit margin increased by 8.6% since 2003 while for hydrous ethanol increased by 2.7%. There was also a change in the position of the Brazilian government toward ethanol after the discovery of Pre-Salt oil reserves in 2006 (de Freitas and Kaneko 2011). These reserves have high strategic importance for the country due to their size and the potential to make Brazil among the largest oil producers in the world in the near future. In June 2012, the government approved higher fuel prices for refineries but reduced the CIDE tax on gasoline to zero to keep the price for consumers unchanged. This impaired the competitiveness of ethanol; while the gasohol retail price remained unchanged, revenues for refineries increased by 26% (UNICA 2012).

Producers and ethanol entities, especially UNICA, began to question the government's energy policy direction and the role of ethanol in the energy matrix (Marjotta-Maistro 2002). In April 2013, after considerable pressure from UNICA and ethanol producers, the government announced some policies to benefit ethanol

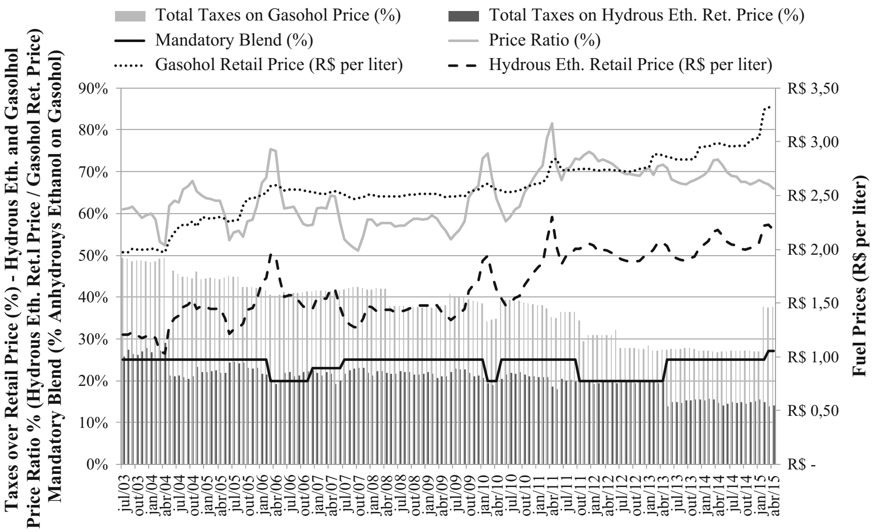

Fig. 7 Hydrous ethanol and gasohol taxes in Sao Paulo State, and comparison to the average domestic fuel prices *Source* Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). Gasohol and ethanol prices available at http://www.anp.gov.br/?id=2880 and National Council for Fiscal Policy (Confaz). Tax information available at https://www.confaz.fazenda.gov.br/

producers. Among them was the provision of credit at subsidized interest rates for the renewal of sugarcane fields and building capacity for storage of ethanol, the elimination of PIS/COFINS[11] taxes on ethanol producers, and the increase in the percentage of anhydrous ethanol from 20% to 25% in gasohol. Although these measures have improved the competitiveness of hydrous ethanol compared to gasohol, the benefit to the final consumers depends on the State-level ICMS tax.

Ethanol production costs have been increasing in recent years while taxes on gasohol are presently declining. This has negatively affected the competitiveness of ethanol compared to gasohol. Given the dependence of the ethanol sector on public policies, the lack of long term planning and a holistic vision for the energy sector as a whole has had adverse consequences for development of the ethanol sector in Brazil. Figure 7 summarizes the changes in taxes and prices over time as a result of policy interventions in the sector.

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[11] PIS accounts for Contribution to the Social Integration Program (*Contribuição ao Programa de Integração Social*), and COFINS means Contribution to Social Security Financing (*Contribuição para Financiamento da Seguridade Social*).

4.1 Recent Policy Changes and Effect on Domestic Demand for Biofuels

Brazilian government has relied on three instruments to alter fuel prices. These include the mandatory blend, which represents a subsidy to ethanol and an implicit tax on gasoline, fuel taxes, and control over the wholesale price paid to Petrobras for oil sold domestically, which in practice has operated as a public subsidy on international oil prices. However, the stringency of these policies has varied considerably over time.

Gasoline prices have been modified 29 times since 2000 by ordinances and decrees; of these 25 changes occurred between 2000 to June 2009. Until 2009, gasoline prices were modified in sync with international oil prices, although these changes did not occur at the same speed or in the same amount as international oil prices.

Between June 2009 and August 2013, gasoline prices increased by 15% while international gasoline price increased by 84%. Since 2010, the gap between domestic gasoline price and international gasoline prices grew faster than before and this has affected the price of hydrous ethanol. Government interference in the gasohol market acted as an inflation control policy. The mandatory blend has also been varied ten times since February 2000 and averaged 23% over this period although it was generally 25%. In March 2015, the mandatory blend rate was set at 27%.

Fuel taxes on gasohol and ethanol have fluctuated over time. The difference in the tax rate on these fuels was around 20% in January 2003 and was about 12% in December 2013 and 23.5% in April 2015. A lower tax differential hampers the competitiveness of hydrous ethanol compared to gasohol. In Sao Paulo State, the tax on gasohol was 40.9% of the retail price from January 2003 to July 2012 and decreased to 26.4% when the CIDE tax was reduced to zero until January 2015; the tax presently is 38%. The corresponding tax on hydrous ethanol was 22% till 2012, decreased to 16.4% in 2014 and then to 14.6% in 2015.

The mandatory blend policy benefits ethanol producers by providing assurance of demand and raising the price that can be charged for hydrous ethanol. Uncertainty about the blend rate hinders production planning and ethanol industry profitability. The decreasing gap between the after tax price of gasohol and ethanol also has a negative impact on demand for hydrous ethanol.

4.2 Political Economy of Biofuel Production

The decision about promoting biofuels is the product of a political system and political economic factors that include both aggregate macro-economic considerations (such as the impact of policies on balance of trade, inflation, government deficit) and micro-level distributional effects on various groups, including farmers, oil producers, and consumers (Rausser et al. 2011). The literature also argues that policy decisions depend on the governance structure as well as the distribution of political power among different groups (Zilberman et al. 2014).

In Brazil, the governance structure has changed numerous times. The country was ruled by military dictatorship between 1964 and 1985, the moderate right parties ruled between 1985 and 2002, followed by a big shift to the left with the election of Lula in 2002 (Skidmore 1999). Taxation of transportation fuels has been a major source of revenue for both the federal and state governments in Brazil for much of the twentieth century. The military dictatorship introduced biofuels in the 1970s, mostly because of balance of trade considerations, through a combination of direct controls and subsidies, as noted earlier in this chapter. The policy also contributed to an increase in the price of sugar, and thus benefited the agricultural sector. The transition to a democratically elected government with free market tendencies led to reduction of support towards biofuel in the 1980s and 90s. That, along with the decline in the price of oil, led to drastic declines in the size of the biofuel sector in the late 1980s. But, the rise in the scarcity of oil after the first Iraq war in 1991 led to the extension of some support for biofuel (de Moraes and Zilberman 2014).

The rise of energy prices and technological progress in sugarcane and biofuel as well as continued support for it led to expansion of the biofuel industry after the new millennium. However, several other political and economic forces shaped the biofuel industry during this time period. The discovery of new oil reserves in Brazil made it much less dependent on fuel imports. The rising price of agricultural commodities, like corn and soybean, and the expansion of their production in Brazil improved the Brazilian balance of trade. The election of Lula in 2002 led to a change in the policy mentioned previously and increased the weight placed on supporting the well-being of lower income groups and reducing inflation. Thus, the domestic prices of fuels in Brazil were capped, even though they were still taxed. The cap on the price of fuels and fuel taxes served to reduce the profitability of ethanol.[12]

Furthermore, the value of biofuel as a mechanism to directly improve balance of trade declined, which limited the incentive to support its growth. It also appeared more profitable for Petrobras to invest in the development of the newly discovered oil reserves rather than biofuel.[13] Yet Petrobras, with its significant political clout, did not oppose the development of biofuel for domestic use because they benefited from its utilization in Brazil, as it could increase their exports and allow them to avoid the domestic fuel price cap. One possible source of support for the biofuel industry could have come from the environmental community, but that might have been muted because of concerns about deforestation associated with the expansion of biofuel. Agricultural sugar producers are natural supporters of a viable biofuel sector because it expands the demand for sugar and is likely to raise its price.

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[12] Especially when it is not exported and export opportunities are limited.

[13] Petrobras earns more from oil than biofuel because it does not have to pay rents to farmers.

Khanna et al. (2015) analyzed the welfare economics of current biofuel policies in Brazil, and found that existing policies are significantly inferior to a policy that maximizes the welfare of consumers and producers in Brazil, taking into account net gains from trade in fuel and sugar minus the value of greenhouse gas emissions. The current policies actually hurt fuel and sugar consumers because they raise the price of fuel and sugar, benefit farmers by increasing the price of sugar, and reduce the loss to Petrobras from selling subsidized fuel in the domestic market. The large efficiency loss from existing biofuel policies is a drag on the economy, and Khanna et al. (2015) simulated that there is a 13% welfare loss of the status quo situation compared to no policy and a 15% loss compared to the first best policy.

As the Brazilian economy stagnates, there may be large pressure to change biofuel policies. Our analysis suggests that the expansion of the biofuel sector in Brazil has suffered for several reasons. First is low profitability, which was partially caused by capped fuel prices with rising costs of producing ethanol. Second, the expansion of biofuel has not been a priority of Petrobras. Third, the macroeconomic situation resulted in a high cost of capital, which is a constraint on increasing the productivity by replanting sugarcane and expanding the industry. Fourth, limitations on ownership of land and other resources by foreign companies restrict the extent to which foreign direct investment in the sector will be possible (de Moraes and Zilberman 2014). Changes in global economic and domestic political situations (for example, increased global demand for clean energy and increased credit availability) as well as technological innovations that increase the profitability of biofuel, are likely to affect the evolution of the industry.

5 Incentives, Risks and Uncertainties in Ethanol Markets

Ethanol production competes with sugar and it is therefore important to examine the influence of demand and market conditions in the sugar market on incentives to produce ethanol. Brazil is the biggest sugar producer in the world with a 22% share of the global sugar market since 2009/2010. Brazil's exports about 69% of its total production, with an average standard deviation of 1.7% and an average growth rate of 0.6% per year (USDA 2014). Sugar exports from Brazil expanded significantly in the 1990s. The main driving factors were (i) the liberalization of exports in July 1994, which ended the regime of quota taxes (before that, exported volumes higher than the pre-defined quota were taxed at 40%); (ii) the increase in the global demand; and (iii) the expiration of special trade agreements between some countries, which allowed Brazil to enter into previously closed markets. The large supply side potential for growth in sugarcane production also enabled expansion of exports faster than any other sugar producing country (Alves and Bacchi 2004).

The well consolidated international sugar market has enabled a steady increase in Brazilian sugar production and exports. Since the 2008/2009, sugar production has been increasing 0.3% per year with a standard deviation of 3% of the average production (USDA, 2014). Over the same period, the average growth rate in ethanol production was 1.4%, but the standard deviation was more than 9% of average production.

The limit on ethanol prices imposed by the price of gasohol together with rising production costs and low sugarcane productivity have led to low financial margins for producing ethanol compared to sugar. White and VHP sugar had a mean financial margin of 26.4% and 15.7% in 2012, respectively, while the financial margin for anhydrous and hydrous ethanol were −0.8% and −4.2%, respectively (PECEGE 2012). Even with the recent decrease in commodity prices, White and VHP sugar showed higher financial margins than ethanol. In 2013, financial margin for White sugar was equal 4.93%, and for VHP was 6.73%, while it was −7.63% for anhydrous ethanol and −13.87% for hydrous ethanol (PECEGE 2013).

Additionally, sugar production is governed by international commodity markets and a well-developed derivative market that allows producers to hedge sugar revenues. Future sugar contracts are traded on the New York Mercantile Exchange (NYMEX—CME Group), and at the London International Financial Futures and Options Exchange (LIFFE—NYSE Euronext). In contrast, the price of hydrous and anhydrous ethanol is determined entirely on the spot market and is more volatile than that of sugar. The average annual volatility of monthly returns for sugar was 3.6% from March 2014 to April 2015, while for anhydrous and hydrous ethanol was 5.9% and 5.2%, respectively. Data on price volatilities are shown in Fig. 8.

The amount of production of sugar and anhydrous ethanol is specified by contracts which are defined at the beginning of the harvest and determine the share of ethanol to be converted to sugar and anhydrous ethanol. However, these contracts do not set the price and thus the producer remains exposed to market risk.

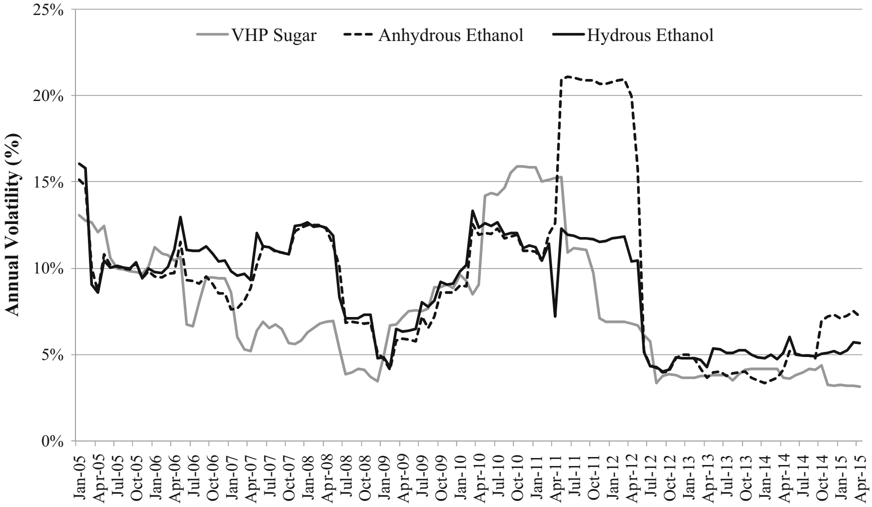

Fig. 8 Price Volatilities of VHP Sugar, Anhydrous Ethanol and Hydrous Ethanol *Source* Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP). Gasohol and ethanol prices available at http://www.anp.gov.br/?id=2880

While the quantities of sugar and anhydrous ethanol are decided in advance based on contracts, the mill has the ability to choose the mix of products to produce with the remaining sugarcane which could be sugar, anhydrous or hydrous ethanol all of which would be sold on the spot market. Currently, 58.4% of the mills in Brazil have an inbuilt capacity to produce both sugar and ethanol, which is typically produced in a 60:40 ratio with 10% flexibility in the short run. The production mix decision is first taken at the beginning of each harvest season which runs from April to November. Factors that are likely to influence these expectations include gasoline prices, existing stocks of ethanol, forecasts about sugarcane prices and harvest, and the expected supply and demand of ethanol and sugar. This decision is then modified over the course of the year as new information about market price, supply and demand for various products becomes available.

With much of the production decision about quantities of different final products from sugarcane determined by contracts, revenue management is difficult. Only sugar prices can be hedged through futures markets for sugar. The 5–10% flexibility to change the share of sugar and ethanol produced plays a small role in managing revenues and is mainly used to manage revenues from anhydrous and hydrous ethanol.

The price volatility of ethanol suggests that financial mechanisms to manage price risk can benefit the development of ethanol market in Brazil. Among the commodities with future contracts negotiated at the Brazilian Mercantile Exchange (BM&FBovespa), on average, the price volatility of ethanol spot prices between May 2010 and April 2012 was equal to 16.7% and lower only than that of coffee, whose price volatility was 24.8%. The soybean price volatility was around 16.3%, corn price volatility was 14.7% and live cattle price volatility was 12.9% (Quintino and David 2013).

Volatile prices and uncertainty about future produce prices, costs, taxes and regulatory policy increase risks and uncertainty about profitability of ethanol production which can depress investment and lead to investment deferral with substantial dampening effects on the aggregate industrial output level (Dalal and Alghalith 2009; Lee et al. 2011; Ahmed et al. 2012; Aye et al. 2014; Bernanke 1980; Pindyck 1990). The existence of forward and future markets allows firms to hedge their uncertainties and make production decisions independent of the producers' degree of risk aversion and price expectations. When forward markets exist for all outputs and inputs whose prices are random, the firm uses forward prices to make its production decisions in exactly the same way as a firm faced with certain prices uses those prices in its production decisions (Danthine 1978; Holthausen Jr. 1980; Honda 1983; Ishii 1984).

Since May 2010, future contracts on hydrous ethanol are being traded on the BM&FBovespa market exchange in Brazil. The volume of ethanol future contracts traded is relatively small; about 13.6% of that of live cattle and 21.4% of that for coffee. However, the volume of ethanol futures trading grew 9.25 times between June 2010 and June 2014; corresponding figures for live cattle and coffee were 0.21 and −0.38, respectively. This indicates that the market is growing. Even with the potential to cross-hedge with future contracts traded on NYMEX—CME Group, Quintino and David (2013) argue that the high market concentration among the few distributors of ethanol harms the development of the ethanol future contract market. Moreover, distributors do not have incentives to trade future contracts because they can transfer price risk to the retail market.

Sugar production is governed by international commodity markets and a well-developed derivative market that allows producers to hedge sugar revenues. Sugar has yielded not only a higher mean return but returns that are less volatile than those of ethanol which is sold entirely on the spot market. In spite of a more stable sugar market and the well-developed derivative market to manage revenues, sugar demand has been stalling. Domestic consumption was equal to 154.4 million tons in 2008/2009, 167.5 million tons in 2013/2014 and is projected to be 170.5 million tons in 2014/2015 (USDA 2014). The average growth rate of global sugar consumption was equal to 2% per year during this period, but has been decreasing: It was 3.3% in 2012/2013 and is projected to be 1.8% per year in 2014/2015.

In contrast, the demand for sugarcane ethanol is expected to grow considerably in the near future. The expansion of FFVs in the Brazilian vehicle fleet and the expected increase in the external demand for ethanol—even though exports currently represent a small share of total sales—could lead ethanol to play a dominant role in meeting energy demands for transportation fuel in Brazil (Milanez et al. 2011). The ethanol market is more volatile and currently has poorer financial margins but prospects for long run growth in domestic demand are more promising than for sugar.

Incentives for production of biofuels in Brazil have to also be examined in an international context. In 2007, Brazil was the world's largest producer and exporter of biofuels. In 2010 its exports were close to zero and since 2011 it has been periodically importing ethanol from the US. The competitiveness of sugarcane ethanol relative to corn ethanol in the world market has been declining as the efficiency of corn ethanol production has improved, cost of corn has declined and the US dollar has remained depreciated. Constraints on biofuel consumption in the US due to the blend wall have also limited the market for sugarcane ethanol in the US.

5.1 Ethanol Storage as a Mechanism for Mitigating Market Uncertainties in Brazil

Since sugarcane cannot be stored, all harvested sugarcane must be processed into one of its by-products (mainly hydrous ethanol, anhydrous ethanol, and sugar), regardless of the level of demand and prices. As a result, the product mix decision and inventory management over time is very important. Additionally, sugarcane production is seasonal while demand is continuous throughout the year; during the harvest months, production is higher than demand. Inventories accumulated during the harvest months are used to meet demand in off-season periods. A mill's decision about the mix of products to produce and the sell versus store decision for ethanol is based on its expectations about future prices. The capacity to store ethanol provides a mechanism to reduce the mill's exposure to price risk by allowing it to holding out for a more favorable price. Storage is however costly and mills differ in their capacity to store sugar and ethanol, depending on their financial condition. Storage requires the availability of working capital that is tied in the stored product and it involves foregoing current returns with certainty for uncertain future returns. Most mills are extremely leveraged, with a debt equity ratio of 158% and an average profit margin of R$ 40 million in 2012 (3% return on capital), according to Valor Economico (2013).

Sao Paulo State is responsible for approximately 54% of total ethanol storage, followed by Minas Gerais, which accounts for almost 25% of total storage in the last three harvests (from 2011 to 2015). Both states are in the Southeast (with harvest between April and November) demonstrating the importance of this region to ethanol supply, especially in off-season periods (Bressan Filho 2010). Average harvest data from 2011/2012 to 2014/2015 shows that storage occurs primarily in the months of October and November and thus the percentage of production stored is high. In the months of April and May (which are at the beginning of the harvest season), the average inventory is low and more uncertain (Table 2).

According to MAPA data, in 2011/2012, total ethanol storage capacity was 71% of the total ethanol production in Brazil. However, use of storage capacity for anhydrous versus hydrous ethanol varies seasonally and over time. Anhydrous storage increases over time following harvest while hydrous ethanol storage decreases. Initial hydrous ethanol storage is high because its demand is mainly a spot market and extremely uncertain. Anhydrous ethanol demand is more dependent on gasohol production and it is a more contract-based. Total ethanol storage

Table 2 Average Percentage of Storage to Production Between Harvests 2011/2012-2014/2015 (standard deviation in parenthesis)

Month	Ethanol (total)	Hydrous	Anhydrous
April	49.2 (6.4)	36.6 (11.9)	67.4 (32.7)
May	58.2 (18.5)	54.8 (12.7)	49.0 (7.9)
June	59.6 (4.4)	60.7 (8.1)	57.6 (6.5)
July	59.4 (7.1)	61.2 (5.2)	56.8 (15.0)
August	62.8 (7.5)	64.0 (5.0)	61.4 (15.9)
September	68.8 (9.7)	68.4 (8.2)	69.8 (16.2)
October	70.0 (8.3)	68.2 (6.6)	73.0 (13.8)
November	70.1 (9.6)	66.6 (9.6)	75.8 (12.8)
December	65.6 (6.0)	60.7 (7.3)	73.1 (6.5)
January	55.0 (2.9)	48.9 (5.0)	64.0 (3.4)
February	40.6 (3.4)	34.1 (4.5)	50.1 (4.7)
March	27.5 (4.3)	21.4 (5.0)	36.5 (5.5)

Source Ministry of Agriculture, Livestock and Food Supply (MAPA). Database available at http://www.agricultura.gov.br/acessoainformacao/estatistica capacity has decreased since 2010/2011 and the share of storage capacity used for hydrous ethanol has decreased while that for anhydrous ethanol has increased. This increase in anhydrous ethanol storage can be, in part, be explained by the ANP Resolution No. 67 published in December 2011 after the scarcity of anhydrous ethanol in the domestic market due to the large exports to the US which caused a price spike in April 2011. The main purpose of this resolution was to increase the predictability of anhydrous ethanol supply throughout the year by greater reliance on contracts between distributors and ethanol producers. At the same time, this observed tendency in anhydrous ethanol storage is a result from the constant increase on gasohol consumption observed in the last harvests.

However, storage maintenance is costly and requires that the mills have available working capital (Marques and Paulillo 2013). It involves exchanging current and known prices for uncertain future returns. However, storage capacity is the only way to manage ethanol prices ethanol producers with access to capital. The need for capital to finance storage maintenance has grown from R$ 2.77 billion in the 2004/2005 to almost R$ 5.29 billion in 2008/2009; as a result 91.1% more working capital was needed in 2008/09 than in 2004/05 (Bressan Filho 2010). This increased investment in storage capacity has led to an increase in the mills' leverage levels.

The Brazilian government has offered subsidized storage loans to ethanol producers, through BNDES (National Bank of Economic and Social Development) and other public banks, such as Banco do Brasil. In 2009/2010, BNDES allocated R$ 2.3 billion to finance the storage of up to 5 billion liters (Valdez 2011). In March 2012, the government announced a new subsidized credit line of R$ 2 billion to finance storage and prevent the supply shortage observed in 2011. However, many mills cannot access this new credit line due to their currently high leverage levels.

5.2 *Cogeneration of Electricity*

Sugarcane mills can also increase revenues by selling surplus electricity generated as a co-product of ethanol production to the national grid. While all mills generate energy from sugarcane bagasse to meet internal needs for electricity and steam, only 40% of the total 336 existing mills exported surplus bioelectricity to the National Interconnected System (SIN) in 2012. The percentage of mills that adopt high-pressure boilers for cogeneration in their production processes has been increasing over time but many mills continue to use boilers that are not very efficient in converting bagasse to energy. Markets for bagasse and for co-product electricity are limited and there is little incentive to retrofit boilers to make them more efficient. This has the potential to change with technological opportunities for high value uses for bagasse that create incentives for investment in utilizing it more efficiently (La Rovere et al. 2011; Furlan et al. 2013).

In 2011/2012, there were 100 ethanol-only mills of which 50% are in the Midwest region of Brazil where the most recent expansion in sugarcane production is taking place (CONAB 2013). These new units have opted for no flexibility between the production of sugar and ethanol, in order to increase productivity and reduce costs of cogeneration and ethanol production. Energy is produced from the steam generated during the production of ethanol. Hydrous ethanol production leads to higher energy production, since it releases more steam during its production process. Cogeneration reduces operating costs by reducing the expenditures on purchasing electricity.

In 2013, 90% of the electricity generated using biomass that was delivered to SIN was cogenerated using sugarcane bagasse. This electricity accounts for 3.3% of Brazilian consumption and meets the equivalent of 12% of the annual residential demand in the country. Production of cogenerated electricity is growing rapidly and besides being environmentally friendly also has a strategic role to play in meeting electricity needs of Brazil. Demand for electricity in Brazil is growing by 2.9% annually and at various points in time consumption has been constrained by supply availability (for example during the energy crisis in 2001 when low water levels in reservoirs restricted hydroelectricity generation and led to nationwide rationing) (IEA 2012). Increased cogeneration reduces dependence on hydroelectricity and can complement hydroelectricity production during the year. Cogeneration is more intensive during the rainless months when sugarcane crushing reaches its highest level and the reservoirs have their lowest levels. Growth in cogeneration would benefit the Southeast and the Midwest regions in Brazil which are the largest producers of ethanol and responsible for the consumption of 60% of electricity produced in the country. The South-Eastern region was also the worst affected by the lack of power in 2001.

Unlike many countries, Brazil does not have quotas or feed-in tariffs to encourage renewable electricity generation. While the government envisions a growing role for renewable electricity, this is expected to be primarily in the form of hydroelectricity (IEA 2012). Electricity prices remain quasi-regulated by the government, with large, subsidized industrial customers providing a demand boost (IEA 2012). The auctions regulated by the National Electric Energy Agency (ANEEL) discourage new investments and increase in bioelectricity supply. Based on Law No. 10,848/2004, contracts for power supply are offered to companies that offer the lowest price per megawatt. Costs of production of electricity from sugarcane bagasse are higher than those for wind energy or thermal energy generated from coal. The cost of power from bagasse is approximately 40% higher than the cost of wind power.

Current policies do not reward renewable electricity generation or the reduction in losses related to transmission of electricity. Additionally, they require the mill to bear the cost of connecting the power generator to the SIN grid. Increasing cogeneration requires mills to modernize their production processes and invest in better boilers to reduce steam consumption and generate more energy with the same amount of bagasse. The ethanol sector crises in recent years and low electricity prices have led mills to postpone investments in cogeneration.

Currently the industry could sell 3400 MWm (mean megawatts) to the SIN, but the mills are able to sell only 1700 thousand MW. With the investments already made, the total power generation capacity of the mills is 9339 MW, which is

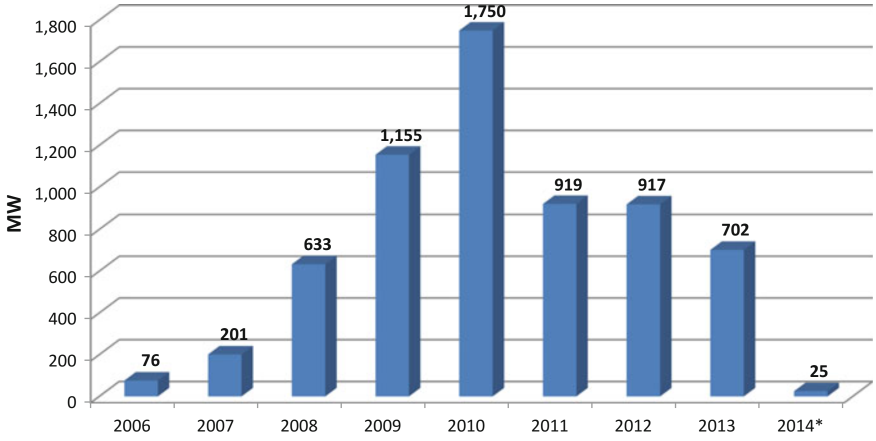

Fig. 9 Increase in installed cogeneration capacity of the mills *Source* UNICA and CCEE (Brazilian Marketing Chamber Electricity). Database available at http://www.ccee.org.br/portal/faces/pages_publico/o-que-fazemos/infomercado?_adf.ctrl-state=wcbtzviz_4&_afrLoop=988029538070542

equivalent to 70% of energy produced by Itaipu Plant, the largest domestic hydroelectric plant. However, since 2010 the annual additions to the installed power generation capacity of the mills have been decreasing considerably (Fig. 9).

Electricity prices are extremely volatile when traded on the spot market (free energy market or energy not hired). The Difference Settlement Price (PLD—*Preço de Liquidação das Diferenças*), or the trading price of energy is extremely sensitive to the water levels in the reservoirs and its high variation makes it difficult to forecast the return on investment for medium and long term. Figure 10 shows the monthly price traded on PLD system, as well as its volatility. The variability in the price of electricity makes the returns from investments in cogeneration uncertain and together with existing regulations limit incentives for new investment in cogeneration by the mills.

6 Prospects for Cellulosic Biofuel Production

Despite the adverse market conditions for first generation (1G) biofuels there has been increasing interest in second generation (2G) biofuels made from sugarcane bagasse which can substantially increase the yield of ethanol per hectare. As discussed above, Brazil has considerable potential to use bagasse to not only generate electricity but also to produce 2G biofuels. Brazil also has considerable advantage in producing 2G ethanol relative to the US due its lower feedstock costs. Bagasse is expected to cost US$9.85 per ton in 2020 while these costs are US$ 30.00 per ton in the US (MME 2007). The potential to produce 2G ethanol will compete for the use of

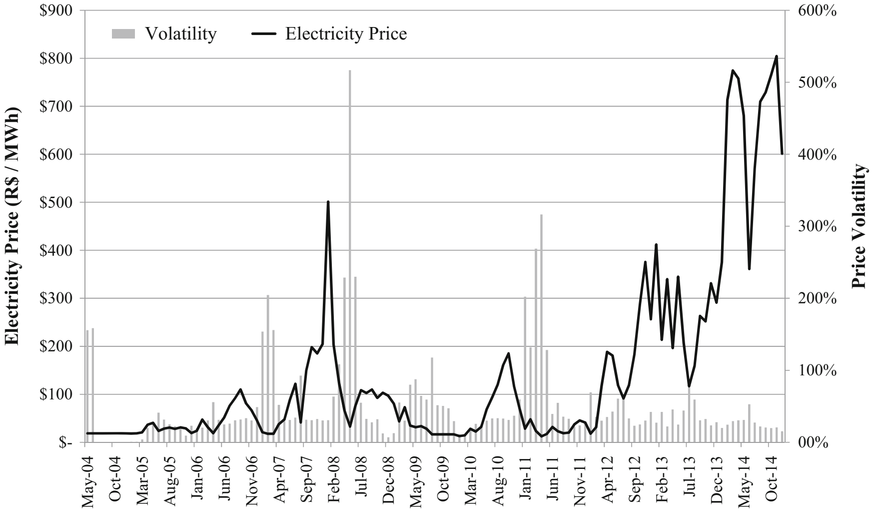

Fig. 10 Average Electricity Price per Month and its Volatility *Source* CCEE (Brazilian Marketing Chamber Electricity)

bagasse and raise the opportunity cost of cogeneration (Palomino 2009). However, the new technology can also optimize energy use in the mill, since it allows for a better utilization of the surplus bagasse after meeting the heat and electricity needs. Moreover, a flexible mill that can produce 1G ethanol, 2G ethanol, and cogeneration will be more able to absorb fluctuations in relative prices than a less flexible mill (La Rovere et al. 2011, Ferreira 2012, Furlan et al. 2013, Dias et al. 2013). Dias et al. (2013) argue that 2G ethanol may compete favorably with cogeneration, once integrated 1G and 2G production decreases ethanol production costs.

It is estimated that 2G ethanol can increase biofuel productivity by about 50% in terms of liters per hectare. Currently, one hectare can produce around 7000 liters of ethanol 1G, but with the use of bagasse and straw, the output can reach 10,000 liters of ethanol per hectare. When the production of 2G ethanol reaches commercial scale, it is expected that Brazilian ethanol production can grow by 10 billion liters per year, which represents an increase of R$ 12 billion in revenues to the ethanol sector (Nyko et al. 2013). It is expected that a part of this production will be exported to countries such as the US where biofuel policies incentivize the consumption of cellulosic ethanol and could lead to higher price for 2G ethanol compared to first generation ethanol because of its environmental benefits.

However, 2G ethanol production is still in a development stage with on-going research and development to reduce costs of production. The Brazilian Ministry of Mine and Energy Report from 2007 projects production of 1.7 million m^3 of cellulosic ethanol in 2015 and 7.1 million m^3 in 2030 with the corresponding use of 3.6% of bagasse for cellulosic biofuels in 2015 and 8.3% in 2030 as shown in Fig. 11.

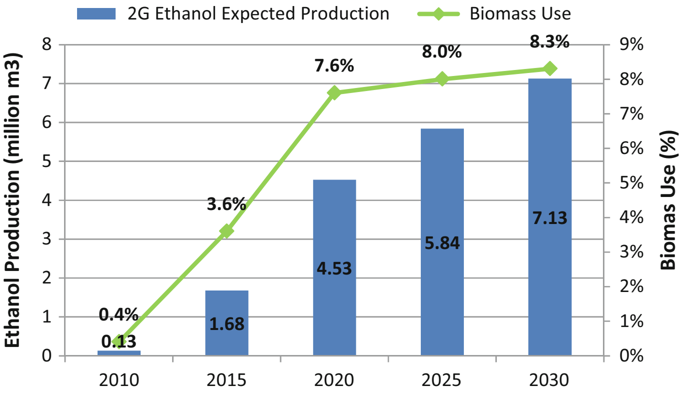

Fig. 11 Second generation ethanol expected production and biomass use *Source* Ministry of Mines and Energy Report (2007). Data available at National Energy Matrix 2030, report produced by Brazilian Ministry of Mines and Energy Report (2007), available at http://www.mme.gov.br/web/guest/publicacoes-e-indicadores/matriz-energetica-nacional-2030

7 Conclusions

Brazil has been a pioneer in the production of biofuels, and its sugarcane ethanol has been economically viable and environmentally beneficial for much of this time. Thus, Brazil provides an excellent case study about the development of renewable transport energy and renewable energy in general. The analysis in this chapter identifies several key factors that contribute to the evolution and success of the biofuel sector.

First, it takes political willingness to build an industry and support it in its early stages. Biofuel in Brazil, in many ways, is an example of an infant industry that is slowly reaching maturity. Second, the viability of alternative energy depends heavily on continuous technological innovation and progress. The productivity of sugarcane in Brazil has increased and the cost of processing has declined. This also suggests the importance of supporting research and development as well as an educational system that leads to innovations and their adoption. Additionally, the notion of technological change is broad, and includes complementary technologies. For example, the biofuel sector in Brazil benefited from the development of ethanol-only vehicles in the 1980s and flex-fuel vehicles since 2000. These innovations allowed the biofuel industry to expand through increased demand for its product. Third, the economic viability of the biofuel sector depends on utilizing residue material. In the case of biofuel in Brazil, bagasse, considered a waste product, was converted to produce energy, and its projected conversion to second generation biofuel will be a source of future growth of the industry. The importance of utilizing residue materials highlights the need to design creative biorefineries that use a mixture of materials and enhance the profitability of the industry. Fourth, the biofuel sector in Brazil has played an important role in rural development and generated important sources of income in remote areas. The development of advanced biorefineries that increase the use of feedstock will enhance these benefits. Finally, the economics of the biofuel industry tend to be unstable. The biofuel industry flourishes when the price of energy was high and the price of feedstock was low.

The story of biofuel in Brazil also includes many challenges. First, the industry had to build resilience during periods of low prices of oil, and when that happened, many producers and users of biofuels incurred significant losses. The long run success of the industry depends on adjusting to price variations and reducing its cost. Second, uncertainty in the energy market as well as the biological nature of the production makes the biofuel industry volatile. The economic volatility of the industry can be addressed by using insurance, futures markets, and different types of storage, which are topics for future research. Another key challenge for the industry is transportation costs. Currently, shipping of biofuel depends on trucks, and the economic and environmental costs of the industry may decline significantly by introducing pipelines (Bell et al. 2014). Third, the health of the biofuel industry and its contribution to the economy depends on effective policies, and political economic considerations may sometimes lead to policies that are not economically sound. The recent upper-bound placed on the price of energy without compensation for the reduction in greenhouse gas emissions from biofuel recently hurt the economic viability of the industry and limited its capacity to grow. Fourth, the inability to provide access to credit and barriers to entry in the industry plays a big role in its expansion and prevents it from reaching its potential. This chapter has demonstrated the importance of political economy factors in the evolution of the biofuel sector in Brazil. It also suggests that future studies of the biofuel sector in Brazil and other countries should consider the role of political economic factors in influencing the choice of biofuel policies and their economic viability.

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Part II
Land Use and Greenhouse Gas Effects of Biofuel Production in the US and Brazil

Biofuel Life-Cycle Analysis

Jennifer B. Dunn, Jeongwoo Han, Joaquim Seabra and Michael Wang

Abstract Life-cycle analysis (LCA) is an important tool used to assess the energy and environmental impacts of biofuels. Here, we review biofuel LCA methodology and its application in transportation fuel regulations in the United States, the European Union, and the United Kingdom. We examine the application of LCA to the production of ethanol from corn, sugarcane, corn stover, switchgrass, and miscanthus. A discussion of methodological choices such as co-product handling techniques in biofuel LCA is also provided. Further, we discuss the estimation of greenhouse gas (GHG) emissions of land use changes (LUC) potentially caused by biofuels, which can significantly influence LCA results. Finally, we provide results from LCAs of ethanol from various sources. Regardless of feedstock, bioethanol offers reduced GHG emissions over fossil-derived gasoline, even when LUC GHG emissions are included. This is mainly caused by displacement of fossil carbon in gasoline with biogenic carbon in ethanol. Of the ethanol pathways examined, corn ethanol has the greatest life-cycle GHG emissions and offers 30% reduction in life-cycle GHG emissions as compared to gasoline when LUC GHG emissions are included. Miscanthus ethanol demonstrates the highest life-cycle GHG emissions reductions compared to gasoline, 109%, when LUC GHG emissions are included.

Keywords Life cycle analysis · Land use change · Greenhouse gas emissions

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J.B. Dunn (✉) · J. Han · M. Wang
Energy Systems Division, Argonne National Laboratory, Argonne, IL 60439, USA
e-mail: jdunn@anl.gov

J. Seabra
UNICAMP, Campinas, São Paulo, Brazil

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Acronyms

Acronym	Definition
AEZ	Agro-ecological zone
BNDES	Brazilian Development Bank
BLUM	Brazilian land use model
CARB	California Air Resources Board
CCLUB	Carbon calculator for land use change from biofuels production
CGE	Computable general equilibrium
CGEE	Center for Global Environmental Education
CHP	Combined heat and power
COLE	Carbon online estimator
DOE	Department of Energy
EC	European Commission
EIO	Economic input-output
EISA	Energy Independence and Security Act
EPA	Environmental Protection Agency
EU	European Union
FAPRI-CARD	Food and Agricultural Policy Research Institute—Center for Agricultural and Rural Development
FASOM	Forestry and agricultural sector optimization model
FQD	Fuel quality directive
GHG	Greenhouse gas
GREET	Greenhouse gases, regulated emissions, and energy use in tranpsortation
GTAP	Global trade analysis project
HWP	Harvested wood product
ICONE	Institute for international trade negotiations
IEA	International energy agency
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
iLUC	Indirect land use change
IPCC	Intergovernmental panel on climate change
LCA	Life-cycle analysis
LCFS	Low-carbon fuel standard
iLUC	Land use change
NCASI	National Council for Air and Stream Improvement
PE	Partial equilibrium
PTW	Pump-to-wheels
RED	Renewable energy directive
RFS2	Renewable fuel standard
RTFO	Renewable transport fuels obligation
SOC	Soil organic carbon
SOM	Soil organic matter
SRWC	Short rotation woody crops

UK	United Kingdom
UNICA	Brazilian Sugarcane Industry Association
USDA	United States Department of Agriculture
WTP	Well-to-pump
WTW	Well-to-wheels

1 Introduction

Biofuels are among possible technology advancements that will reduce the environmental impacts of transportation fuels, including greenhouse gas (GHG) emissions. Their development would also foster rural economic development (U.S. DOE 2011b; IEA 2012). On the other hand, some posit that biofuels could cause GHG emission increases because of indirect land use changes (LUC) caused by biofuel production (Fargione et al. 2008; Searchinger et al. 2008). Investigations that seek to better understand whether biofuels increase or decrease environmental footprints relative to fossil fuels often use LCA. LCA is a methodological approach to quantifying the environmental burdens of a product, such as bioethanol, over the course of each stage of its life cycle, as diagrammed in Fig. 1.

One important benefit of LCA is that it identifies where burden shifting, or the transfer of an environmental impact from one life-cycle stage or environmental medium (air, water) to another, might occur. This burden shifting could then be mitigated or avoided. Additionally, analyzing a product over its full life cycle can uncover impacts such as the consumption of a limited resource in the production stage that would go unaddressed if only the later life-cycle stages were considered. In the context of biofuels, one example is N_2O emissions from fields where biofuel feedstocks are grown. In cases that require a significant amount of nitrogen fertilizer for feedstock growth, N_2O emissions can be a significant GHG emission source for biofuels. Another potentially “hidden” example is LUC. Two types of LUC can be

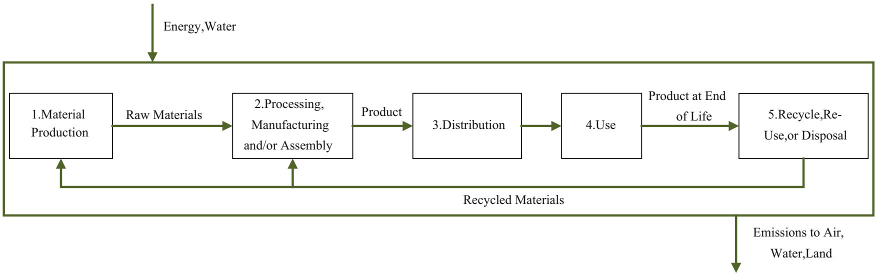

Fig. 1 Stages considered in LCA

considered in biofuel LCA. Direct LUC is the conversion of land to the production of biofuel feedstocks. The converted land could have originally been in agriculture, but producing other crops including those used for food, feed, or fiber. Alternatively, the converted land could have been a forest, pastureland, or marginal land. Indirect LUC occurs when land is converted to food, feed, or fiber production from other uses or states (e.g., forest, grasslands) to make up for the production of these commodities that was displaced by biofuel production. If belowground and aboveground carbon decreases as a result of LUC, GHG emissions can occur. LUC can increase GHG emissions through other mechanisms besides above and belowground carbon changes (Georgescu et al. 2011; Pielke et al. 2011).

In this chapter, we discuss LCA as applied to biofuels, with a focus on ethanol. First, we review the methodology of LCA as applied to biofuels including the system boundary and biofuel LCA models. In Sect. 3, we discuss how LCA has been applied in developing regulations to promote biofuel adoption. Next in Sect. 4, we discuss three bioethanol pathways in detail: corn ethanol, sugarcane ethanol, and cellulosic ethanol. A discussion of technical issues, such as how to allocate life-cycle energy consumption and emissions among co-products, follows in Sect. 5. LUC implications of biofuels are covered in-depth in Sect. 6. The chapter concludes with a discussion of LCA results for the ethanol pathways considered with an emphasis on LUC impacts and uncertainty in LUC GHG emissions.

2 Biofuel LCA Methodologies, Models, System Boundaries, and Co-products

The first step in conducting a biofuel LCA is to establish the system boundary. A generic system boundary for a biofuel is sketched in Fig. 2.

The life cycle of a biofuel begins with feedstock production. Growing feedstocks consumes fertilizers, herbicides, and pesticides in addition to fuels. Varying by location and feedstock type, feedstock nutrient requirements can significantly affect biofuel life-cycle impacts. Common nitrogen fertilizers include ammonia, urea, and ammonium nitrate (Table 1). Nitrogen fertilizer contributes N to the soil, a portion of which is converted to N_2O, a potent GHG, through nitrification and denitrification processes. N_2O emissions from these processes are called direct emissions. Indirect N_2O emissions stem from transport of N from farming areas to ground and surface waters in nitrate, and subsequent volatilization. Typically in LCA, the total amount of N in applied fertilizer is multiplied by a conversion rate to calculate the amount that is directly and indirectly emitted as N_2O. The Intergovernmental Panel on Climate Change (IPCC) recommends a rate of 1.325% for Tier 1 emission rates. A recent review of the literature suggests a slightly higher rate (1.525%) may be appropriate for cornfields (Wang et al. 2012). These emissions can contribute significantly to biofuel life-cycle GHG emissions. The degradation of urea to CO_2 is typically a less significant contribution to these emissions.

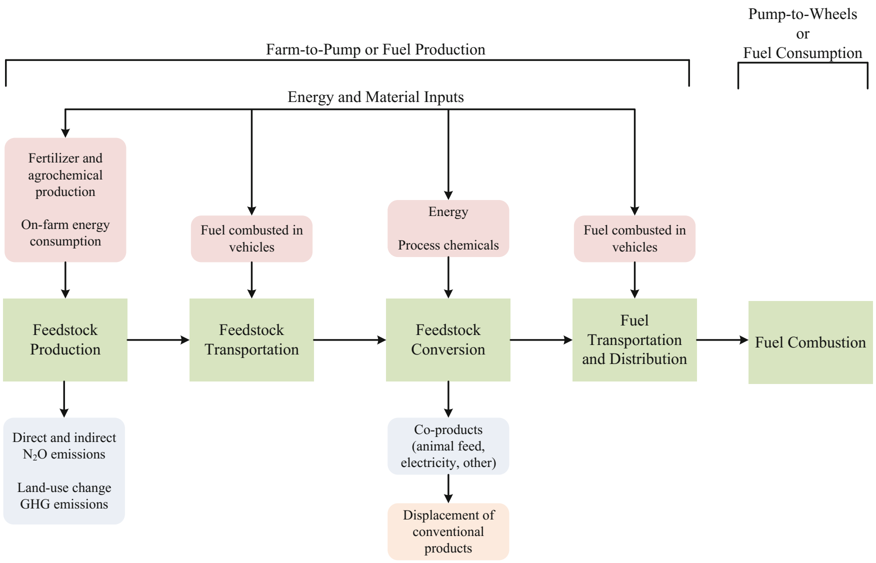

Fig. 2 General stages considered in biofuel LCA. *Red boxes* contain direct inputs to the biofuel's life cycle. The indirect (or upstream) energy and materials consumed to produce these inputs are rolled into the LCA. *Blue boxes* contain impacts and co-products of the biofuel life cycle. The displacement of conventional co-products (*orange box*) is incorporated when the displacement methodology is used

Table 1 Energy and GHG impacts of common fertilizers (Argonne National Laboratory 2012)

Fertilizer	Total energy consumption (MJ/ton nutrient)	GHG emissions (kg CO_2eq/ton nutrient)	
		During production	From field
Ammonia (NH_3)	45,800	3160	7140[a]
Urea (CH_4N_2O)	54,200	2190	8710[b]
Ammonium nitrate (NH_4NO_3)	66,000	10,550	7140[a]
Phosphorous pentoxide (P_2O_5)	8550	674	–
Potassium oxide (K_2O)	8570	651	–
Calcium carbonate ($CaCO_3$)	187	15	440[c]

[a] N_2O emissions
[b] 18% from CO_2 emissions, 82% from N_2O emissions
[c] CO_2 emissions

Phosphorous- and potassium-containing fertilizers are also commonly used in feedstock agriculture. Less energy intensive to produce than the nitrogen-containing fertilizers, their consumption, and that of calcium carbonate fertilizer, are generally a minor contributor to biofuel life-cycle impacts.

Feedstock agriculture can cause other effects that influence life-cycle GHG emissions. For example, the production of the feedstock may change soil organic carbon (SOC) content at the site, an example of an effect of direct LUC. In the case of corn, feedstock production likely decreases soil carbon (Kwon et al. 2013). In the case of switchgrass and miscanthus, however, SOC can rise as a result of feedstock production. Changes in soil carbon result in CO_2 emissions or sequestration. While emissions will occur over a short time during the land's conversion to biofuel feedstock production, carbon sequestration will continue for a certain length of time until SOC equilibrium is reached. In the case of switchgrass, equilibrium may be reached after a long time (Andress 2002). A shorter time period is generally predicted for miscanthus (Hill et al. 2009; Scown et al. 2012). Treatment of temporal aspects of biofuel GHG emissions associated with LUC are an open research question, with researchers examining the most appropriate time horizon for SOC changes and the treatment of future emissions as compared to near-term emissions (Kløverpris and Mueller 2013; O'Hare et al. 2009). On one hand, a near-term approach that limits the time horizon to two or three decades could be used. This approach benefits from weighting near-term events that are more certain more heavily. On the other hand, some LCA standards, such as PAS 2050 (BSI 2011) advocate a 100-year time horizon for the LCA of any product. With this long-term approach, however, future emissions should be discounted, although the methodology for this discounting is unresolved. In addition, the uncertainty associated with land use for over a century is large. Biofuel life-cycle analysts continue to examine these issues that can certainly influence GHG emissions results significantly.

Techniques to estimate indirect LUC typically incorporate models that attempt to capture the economic linkages that drive LUC on an international scale. These models are described briefly in this chapter (Sect. 6.1) and in detail in other chapters. Indirect LUC will cause belowground and aboveground changes that can be incorporated into biofuel life-cycle GHG emissions. It is important to note that impacts of LUC likely extend beyond carbon content changes and may include altering the land's albedo and stored soil water (Pielke et al. 2011; Georgescu et al. 2011). Although potentially significant, these impacts are largely excluded from biofuel LCA because they are not yet well understood.

Once the feedstock is harvested, some amount of processing, such as baling and chipping, may occur at the feedstock production site. During these processes, dry matter loss may occur, reducing the effective feedstock yield. As a result, to collect a given amount of feedstock at the production facility gate, the energy, fertilizers, and agrochemicals consumed rise. Another source of dry matter loss can be the storage of the feedstock once harvested. Feedstocks can be ensiled or stored in bales that may be covered or uncovered. The amount of dry matter loss stemming from storage is a function of this storage format.

This format can also influence the impacts of transporting the feedstock between the production site and the conversion facility or biorefinery. For example, a cellulosic feedstock could be transported as square or round bales. The most common means of feedstock transport to the biorefinery is heavy-duty trucks, with a payload dependent on feedstock density. The distance that the feedstock must travel is a function of the conversion facility capacity, the yield of the feedstock in the field, and the amount of land surrounding the conversion facility that is available for feedstock production (Gold and Seuring 2011).

Once at the conversion facility, the feedstock may undergo further processing before conversion via biochemical or thermochemical processes. An example of a biochemical process is a pretreatment step such as enzymatic hydrolysis followed by fermentation (Humbird et al. 2011). An example of a thermochemical process is indirect gasification (Dutta et al. 2011). Examples of process inputs are enzymes, sulfuric acid, diammonium phosphate, and others. Thermochemical processes often use catalysts. To be complete, the upstream impacts of producing process inputs should be included in biofuel to the extent possible. For example, including enzyme and yeast impacts the life-cycle GHG emissions of bioethanol produced through enzymatic hydrolysis and fermentation significantly (Dunn et al. 2012).

The co-products of biorefineries differ depending on the conversion technology. Examples of co-products are animal feeds, bio-char, other fuels, electricity, and steam. In LCA, co-products can be handled with different methodologies, essentially accounting techniques. The choice of methodology can significantly influence biofuel LCA results (Wang et al. 2011a). More discussion of co-product allocation techniques is in Sect. 5.

Once produced, the biofuel must be transported to a refueling station. In the case of bioethanol, rail and trucks are the key modes of transportation. As the fuel is combusted in a vehicle in the final stage of the supply chain, it releases biogenic CO_2 that the feedstock incorporated during its growth. Many biofuel LCAs consider the carbon uptake in the feedstock growth phase and carbon emissions in the use phase to net to zero.

Several models are available with which to conduct biofuel LCA. Two US-focused models are the University of California at Davis' Life Cycle Emissions Model (Delucchi 2003), and the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET 2011) model, developed at Argonne National Laboratory (Argonne National Laboratory 2012). National Resources Canada develops the GHGenius model while the E3 database and the BIOGRACE model can be applied to EU-based analyses (LBSM 2012; BioGrace 2013). While these models focus on transportation fuels and technologies, commercial LCA software packages are also available that can be used for biofuel LCA. It should be noted that the approach to biofuel LCA that we describe in this section is called "attributional LCA." It examines, at a process level, each step in the biofuel life cycle and develops energy and material inventories for each. Another LCA technique that has been applied to biofuel and other systems LCA is called "consequential LCA" (Creutzig et al. 2012). The emphasis in consequential LCA is on interactions among economic sectors. One example of a consequential LCA model is Carnegie Mellon's Economic Input-Output Life Cycle Assessment (EIO-LCA) Model (Carnegie Mellon 2008). In addressing LUC issues in biofuel LCA, GREET partially incorporates consequential LCA. A review of this alternative approach to LCA is provided elsewhere (Earles and Halog 2011).

3 LCA Applications in Biofuel Regulations[1]

Of the basic principles of biofuels' sustainability, the requirement for GHG emissions reduction (compared to the equivalent fossil option) has been seen as one of the most relevant aspects. With such a goal, many governments have set biofuels targets in terms of volumetric mandates and/or GHG emission intensity as part of their energy and climate policies toward renewables and emissions mitigation (Timilsina and Shrestha 2011; Scarlat and Dallemand 2011).

In the US, there are two major low-carbon fuel policies in place: the federal Renewable Fuel Standard (RFS2) and the California Air Resource Board's (CARB) Low Carbon Fuel Standard (LCFS). In Europe, the European Commission's Renewable Energy Directive (EU-RED) and the UK's Renewable Transport Fuels Obligation (UK-RTFO) were established. A comparison of the biofuels goals and the GHG emissions targets of these four schemes is given in Table 2.

To estimate the GHG balances in biofuels production, these regulatory schemes have used different approaches based on the LCA technique. The UK-RTFO approach has been recently aligned with the EU-RED (DfT 2012), but the U.S. Environmental Protection Agency's (EPA) Renewable Fuel Standard (RFS2) and CARB's LCFS vary greatly not only among themselves, but also in relation to the European regulation. An overview of these accounting methodologies is provided below and summarized in Table 4.

CARB To estimate the direct emissions of producing and using transport fuels, CARB used an adapted version of the GREET model, called CA-GREET. It is based on version 1.8b of GREET, which was modified to better represent California-specific conditions, parameters, and data (CARB 2009a, b). CARB provides default values for the GHG emissions per unit of fuel energy delivered (g CO_2eq/MJ) for a number of biofuel pathways. Emissions from both direct and indirect land use changes (LUC & iLUC) are assessed using the Global Trade Analysis Project (GTAP) model developed by Purdue University and an emission factor model called AEZ-EF that was developed for CARB (Plevin et al. 2014). AEZ-EF provides GHG emission factors per unit of land area converted to produce biofuel feedstocks. GTAP and AEZ-EF estimate GHG emissions associated with the worldwide land conversion as a result of production and/or expansion of energy crops by land type (see Sect. 6.1).

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[1] Mostly based on Khatiwada et al. (2012).

Table 2 Biofuels goals and GHG emissions targets in European and American regulatory schemes[a]

Targets	EU-RED	UK-RTFO	RFS2	LCFS
Biofuel use	Target of 10% renewable energy in transport; the Fuel Quality Directive (FQD) requires a reduction of 6–10% life-cycle GHG emissions by 2020	At least 3.25% of biofuels supplied to transport by 2009/10 and 5% in 2013/14	36 billion gallons of biofuels by 2022, of which 21 billion gallons from advanced biofuels	10% reduction of average life-cycle carbon intensity of ground transportation fuel pool (in terms of GHG) by 2020
Life cycle GHG emissions reduction	Biofuels produced in installations that commence operating after July 1, 2014 should achieve 60% GHG emissions savings compared to reference fossil fuels. The savings for installations operating before July 1, 2014 must be 35% until December 31, 2017 and 50% after January 1, 2018	Targets for GHG savings to be achieved by biofuels during the obligation period[b] are: 40% (for 2008/09), 45% (for 2009/10), and 50% (for 2010/11)	The target depends on the biofuel category, i.e., at least 20, 50, and 60% GHG reductions for corn ethanol, biodiesel or sugarcane ethanol, and lignocellulosic ethanol, respectively	There is no minimum carbon intensity limit for individual renewable fuels, e.g. biofuels. The fuel mix should achieve 10% reduction target by 2020, compared to the baseline fuels

[a] *Source* Khatiwada et al. (2012)

[b] An obligation period runs from April 15 in one year and April 14 in the next. RTFO year 1 spans April 15, 2008 to April 14, 2009

US EPA The U.S. EPA used models that consider emissions from fuel and feedstock production, transportation, distribution, and use, including economic models that foresee transformations in agricultural sectors. This also considers the indirect or secondary impacts of extended biofuels use on GHG emissions with results from economic global market models. EPA used the Forestry and Agricultural Sector Optimization Model (FASOM) for estimating U.S. domestic changes in agricultural land and associated GHG emissions resulting from secondary impacts of increased demand for biofuel feedstock. This includes changes in livestock and/or crop-shifting due to higher prices for energy crops (EPA 2010). FASOM estimates changes in GHG emissions (CO_2, CH_4, N_2O) from agricultural activities and tracks carbon sequestration and carbon losses over time.

In FASOM, the GHG emissions factors (for fuel and fertilizer) are adapted from the GREET model dataset; emission factors for livestock follow the IPCC guidance. To estimate domestic N_2O emissions from agricultural soils (i.e., from nitrogen fertilizer, crop residues, volatilization, leaching, etc.), CENTURY and DAYCENT models were used, while for N_2O emissions outside the US, emission factors were adopted from the IPCC approach. Looking at the impacts of biofuels feedstock production on international agricultural and livestock production, EPA used the integrated Food and Agricultural Policy Research Institute/Center for Agricultural and Rural Development (FAPRI-CARD) model from Iowa State University (FAPRI 2011). FAPRI-CARD simulates changes in crop areas and livestock production globally as a result of increased demand for biofuels. However, the model does not include changes in fertilizer or energy use and associated land type (e.g., pasture or forest) interactions. Therefore, these parameters were estimated separately and combined with the FAPRI-CARD results to estimate the total GHG impacts. Emission factors from transportation (fuel type, distance and modes) were taken from the GREET model. Energy use in biofuel processing facilities was calculated based upon data from industry sources, reports, and process modeling.

The scope of LCA for estimation of the total GHG emissions was based on two scenarios: (a) business as usual, which estimates the volumes of a particular renewable fuel on the likely fuel pool in 2022 without Energy Independence and Security Act (EISA), and (b) the control EISA volume scenario of renewable fuels as mandated by EISA for 2022. The system boundary not only covers domestic biomass production, fuel production and fuel use but also considers indirect impacts in the economy, indirect land use change, food/feed demand, and other agricultural impacts at the global level. LUC & iLUC were taken into account for estimating carbon intensity, including discounting methods.

EU-Renewable Energy Directive (EU-RED) The Renewable Energy Directive defines rules and methodologies for calculating the total GHG emissions of biofuels. These emissions include: (1) the GHG emissions from the extraction/cultivation of raw materials (e_{ec}), annualized carbon stock changes caused by LUC (e_{l}), processing (e_p), transport and distribution (e_{td}), the fuel in use (e_u), and (2) emissions savings from soil carbon accumulation via improved agricultural management (e_{sca}), carbon capture and replacement/geological storage (e_{ccs} and e_{ccr}), and excess electricity from cogeneration (e_{ee}). The balance is then estimated as follows (EC 2009):

$$E\,[g\ \mathrm{CO_2eq/MJ}] = e_{\mathrm{ec}} + e_l + e_p + e_{\mathrm{td}} + e_u - e_{\mathrm{sca}} - e_{\mathrm{ccs}} - e_{\mathrm{ccr}} - e_{\mathrm{ee}}$$

Typical and default values of GHG emissions, along with the GHG emissions reductions (%) compared to reference fossil fuels for a range of common biofuel pathways are provided in the regulation, disaggregated into cultivation (e_{ec}), processing (including excess electricity, i.e., $e_p - e_{\mathrm{ee}}$), and transport and distribution

(e_{td}). The default values provided simplify the administrative burden of compliance, but are to be updated as improved reliable data become available. One tool that may also aid biofuel producers in compliance with the RED is the BIOGRACE model (www.biograce.net). BIOGRACE was developed to create a harmonized methodology for the calculation of biofuel life-cycle GHG emissions in the EU that complies with that directive and the fuel quality directive (FQD). Allocation of GHG emissions to co-products is by energy content, except waste and excess electricity, which are separately dealt with by system expansion (or displacement). See Sect. 5 for a discussion of co-product handling techniques. GHG emissions from LUC, which were not included in the RED, were recently proposed (EC 2012). The proposed values are provided in Tables 3 and 4.

Table 3 European Commission proposed indirect LUC GHG emissions

Feedstock group	Estimated indirect LUC GHG Emissions (g CO_2eq/MJ)
Cereals and other starch rich crops	12
Sugars	13
Oil crops	55

Table 4 Comparison of methodological approaches for calculating GHG emissions from biofuels[a]

Parameters	EU-RED	U.S. EPA RFS2	CARB LCFS
Type of LCA	Attributional and consequential (esp. for treatment of excess electricity)	Consequential	Attributional and consequential (for treatment of co-products and impact of iLUC)
Scope/system boundaries[b]	Well-to-wheel	Well-to-wheel	Well-to-wheel
Functional unit	MJ of fuel	MJ of fuel[c]	MJ of fuel
GHG emissions for the reference fuel	83.8 g CO_2eq/MJ (gasoline)	93.1 g CO_2eq/MJ gasoline in 2005	95.85 g CO_2eq/MJ (gasoline with 10% corn-derived ethanol blend)
Co-product method	Allocation by energy content; Export of electricity from system expansion approach[d]	System expansion (displacement)	Mostly based on system expansion; By energy content when system expansion is not applicable
Constituents of emissions and Global Warming Potential (GWP)	CO_2, CH_4 and N_2O; GWP as per 3rd IPCC report with 100-year time horizon	CO_2, CH_4 and N_2O; GWP as per 2nd IPCC report with 100-year time horizon	CO_2, CH_4 and N_2O; GWP as per 4th IPCC report with 100-year time horizon; VOC and CO are also considered using molecular weight ratios for conversion to CO_2eq

(continued)

Table 4 (continued)

Parameters	EU-RED	U.S. EPA RFS2	CARB LCFS
Direct land use change (LUC)[e]	Annualized emissions (by dividing equally over 20 years) from C-stock changes; Not discounted; Default values do not consider direct LUC; Reference land use on Jan. 2008; Based on EU guidelines: 2010/335/EU (EC, 2010)	Included in the rules; Modeling approach is used; Annualized GHG results using 30-year with 0% discount rate: divided into domestic and international LUC	Included in the regulation with 30-year annualized method; Economic modeling approach is used; Direct and indirect LUC are treated jointly
Indirect land use change (iLUC)	No iLUC value added to the LCA. The European Commission recently proposed iLUC values (see Table 3) but these have not yet been approved or adopted	Included in the rules; Annualized period as in LUC; Economic modeling approach is used for estimating the market-mediated effects; Divided into domestic and international LUC; direct and indirect LUC are treated jointly	Included in the regulation with 30-year annualized method; Economic modeling approach is used for estimating the iLUC effects
Impact assessment (emission savings)	Life-cycle GHG emissions saving (%) compared to the baseline fuel	Life-cycle GHG emissions (annualized net present value) saving (%) compared to the baseline fuel	Calculation of carbon intensity (in g CO_2eq/MJ) is performed, rather than emission savings
Tools for assessing/modeling	BIOGRACE[f]	GREET, CENTURY, DAYCENT, FASOM, and FAPRI-CARD	CA-GREET and GTAP

[a] Adapted from Khatiwada et al. (2012)

[b] Direct emissions from the construction of plants/infrastructure/machinery/equipment are not considered

[c] RFS2 units of energy are mmBtu, but we convert to MJ here for ease of comparison with other regulations. The reference fuel GHG emissions are given as 98,204 g CO_2e/mmBtu in the RFS2

[d] Co-product electricity shall not be accounted for when it is from agricultural crop residues, including straw and bagasse. Also, these agricultural crop residues shall have zero life-cycle GHG emissions until the process of collection (EC 2009)

[e] In the EU-RED, a bonus of 29 g CO_2eq/MJ is given if severely degraded land and heavily contaminated land are converted (EC 2009)

[f] A specific model was not used in the EU-RED. For the purpose of harmonizing a computational procedure to estimate GHG emissions across Europe, an EU funded BioGrace project (www.biograce.net) has developed an Excel model, considering similar inputs and emissions factors taken from the EU's JRC consortium (IEE 2010). Note that the BioGrace's Excel model is not mandatory when making biofuels GHG calculations in the RED and RTFO

A comparison of these GHG accounting approaches shows that agricultural practices (especially soil carbon and nitrogen dynamics), co-product credits from animal feeds and surplus electricity and uncertainties around economic modeling approaches for iLUC are the major areas where methodological divergences exist (Khatiwada et al. 2012). Furthermore, temporal and geographical coverage and the database used also vary among the analyses. The combination of these aspects has led to very different default carbon intensities, especially because of the LUC impacts. Figure 3 illustrates such divergences for three important biofuels, although the list of default values is substantially longer.

For some biofuels several scenarios have been evaluated, and a wide range of values is presented. CARB, for instance, found values between 77 and 105 g CO_2eq/MJ for different corn ethanol pathways, while EPA presents corn ethanol life-cycle emissions ranging from approximately 49–111 g CO_2eq/MJ, depending on the plant technology. Additionally, a distribution of results is also given by EPA for each scenario based on the uncertainty in the LUC assumptions. For sugarcane ethanol, CARB initially estimated LUC GHG emissions (LUC + iLUC) for ethanol as 46 g CO_2eq/MJ but revised this estimate to a proposed 26.5 g CO_2eq/MJ in 2014. Much smaller contributions from land use change (~5 g CO_2eq/MJ) were estimated by the US EPA. Despite all the divergences in terms of methodology, databases and results, these initiatives are promoting a great effort to improve knowledge of biofuels, which may lead to sounder regulations in the future.

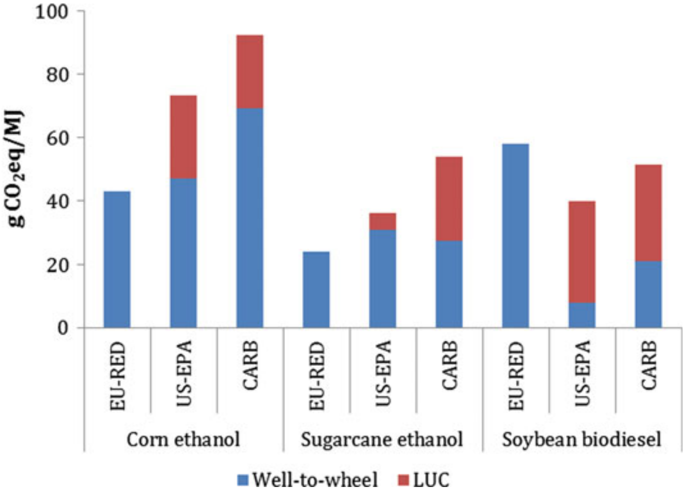

Fig. 3 Default carbon intensities of biofuels, including LUC emissions, in different regulatory schemes. *EU-RED* Values refer to default GHG emissions (indirect LUC impacts are not covered, though recently proposed). *EPA* Values for dry mill natural gas corn ethanol scenario, sugarcane ethanol with no residue collection, and soybean biodiesel. *CARB* Values for average Midwest corn ethanol, baseline sugarcane ethanol pathway and Midwest soybean biodiesel. *Note* CARB values are those proposed in March 2014 (CARB 2014)

4 Bioethanol Production Pathways Subject to LCA

Ethanol is the major biofuel currently in production. Figure 4 shows the growth in ethanol production in both the U.S. (corn) and Brazil (sugarcane). Accessing cellulosic feedstocks for conversion to ethanol could increase the production of this biofuel further. The U.S. Department of Energy (DOE) estimates that approximately one billion tons of cellulosic feedstocks could be tapped to yield over 340 billion liters of ethanol per year (U.S. DOE 2011a). In this section, we describe in detail the steps involved in producing ethanol from a number of feedstocks: corn, sugarcane, and cellulosic biomass. For cellulosic ethanol, we will focus on feedstocks of switchgrass, miscanthus, and corn stover.

4.1 Corn Ethanol

Corn is the traditional feedstock for ethanol production in the U.S. Its agriculture is well established although advances in crop biology continue to shape corn production. For example, the use of nitrogen, phosphorous, and potassium fertilizers in corn agriculture has exhibited a marked decline since the 1970s (USDA 2010) as Fig. 5 illustrates. Furthermore, energy use in corn farming, dominated by diesel fuel consumption in farming equipment, has also dropped as show in Fig. 6.

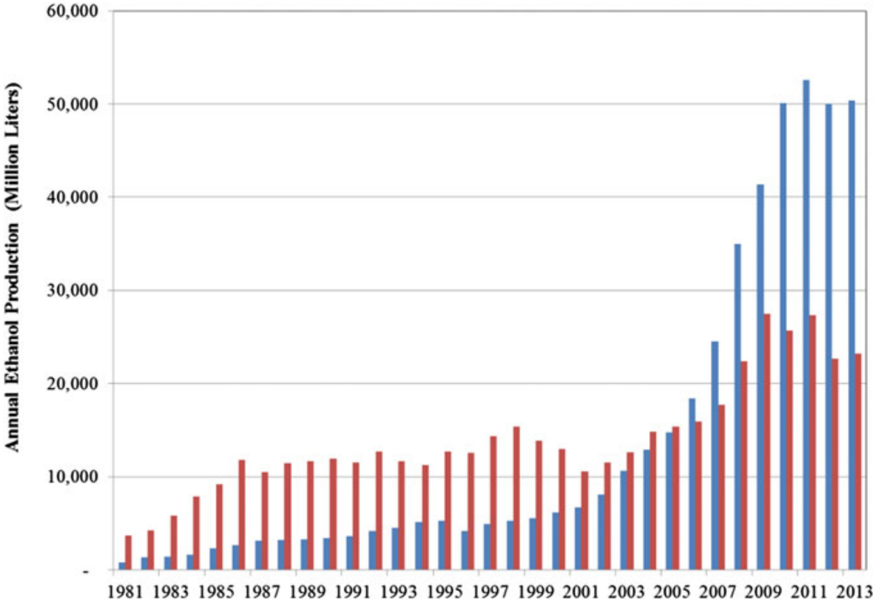

Fig. 4 Annual ethanol production in the U.S. and Brazil (RFA 2013; UNICA 2013)

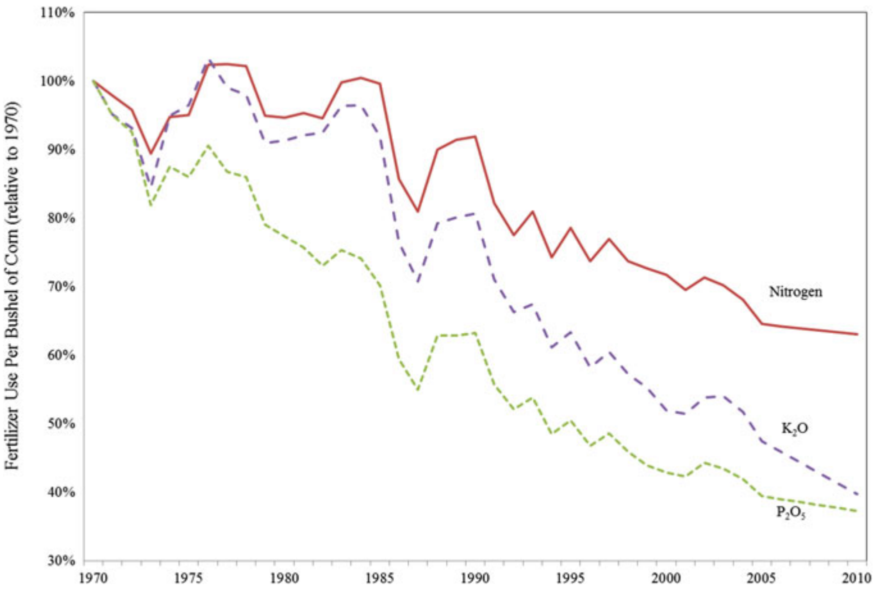

Fig. 5 Relative intensity of U.S. corn farming fertilizer use from 1970 to 2010 (USDA 2010)

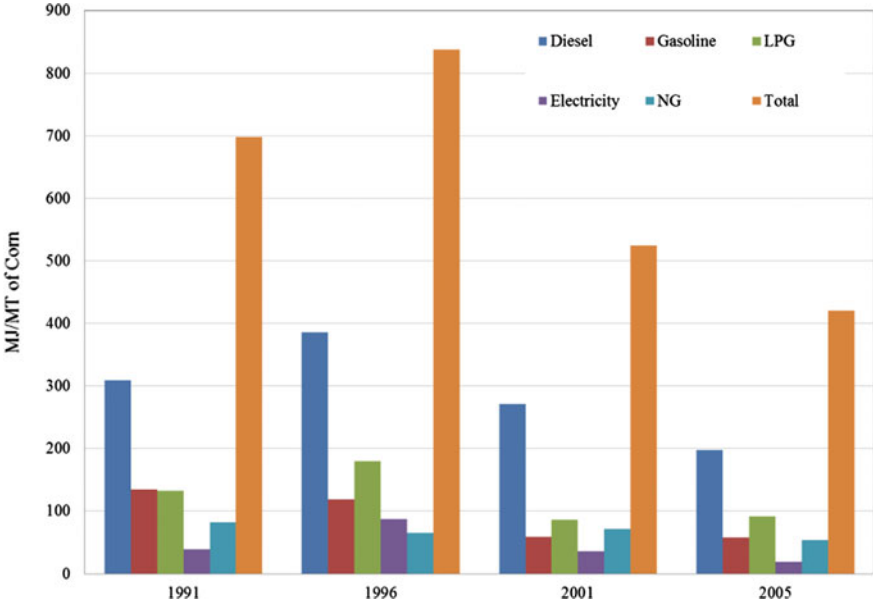

Fig. 6 Energy consumption in U.S. corn farming, 1991–2005 (Wang et al. 2011b)

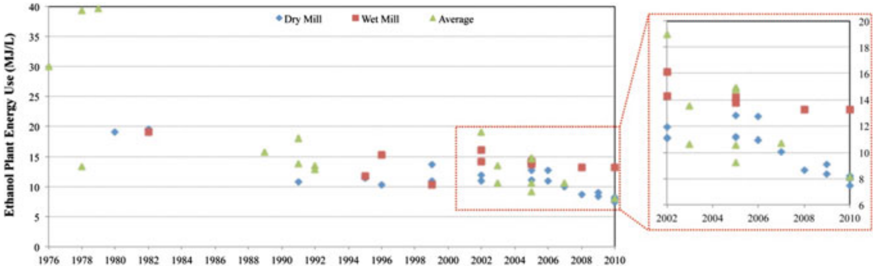

Fig. 7 Ethanol plant energy use from 1976 to 2010 (Wang et al. 2011b)

Once harvested, corn is stored and transported to conversion facilities largely by truck. These facilities can either employ dry- or wet-milling technologies. In plants using wet milling, corn kernels are first soaked in SO_2-containing water. Next, the germ and oil are removed from the kernels, which are then ground to yield starch and gluten. Ethanol is produced when the corn starch is fermented. Dry-milling plants ferment the starch in milled corn kernels to ethanol. At present, about 90% of U.S corn ethanol plants use dry-milling technology. As the corn ethanol industry has matured, corn ethanol plants have made great strides in reducing their energy intensity (Fig. 7). Especially notable is that dry-milling plants are significantly less energy intensive and it is the industry's shift to this technology that has helped to drive down the average ethanol plant energy intensity.

Corn ethanol production uses enzymes and yeast. Enzymes prepare the feedstock for fermentation through processes such as liquefaction and saccharification. The two enzymes used in corn ethanol production are alpha-amylase and glucoamylase. The level of consumption of these enzymes has been optimized as the industry has matured and roughly 0.3 and 0.7 kg/dry metric ton of substrate of alpha-amylase and glucoamylase, respectively, are consumed during ethanol production (Dunn et al. 2012). Of these two enzymes, glucoamylase is the more energy intensive to produce as seen in Fig. 8. Nutrients contribute minimally to total fossil energy consumption in the production chain of these two enzymes.

Corn ethanol plant residue, called distillers grains solubles (DGS), are an animal feed that displaces conventional animal feed. DGS can be sold in wet (WDGS) or dry (DDGS) form. Producing DDGS incurs the cost of drying the DGS, whereas WDGS has a shorter shelf life and is more expensive to transport because it is heavier. DGS can displace corn, soybean meal, and urea at the ratios provided in Table 5. Technology advancements (corn fractionation and oil extraction) at corn ethanol plants has led to the production of higher value co-products, such as high-protein dried distillers grain, corn gluten feed, corn germ, de-oiled DGS, and corn oil. With this last co-product there is an interesting linkage with biodiesel production, for which corn oil is increasingly used as an input. As these co-products enter the market and displace conventional animal feed, LCA practitioners must

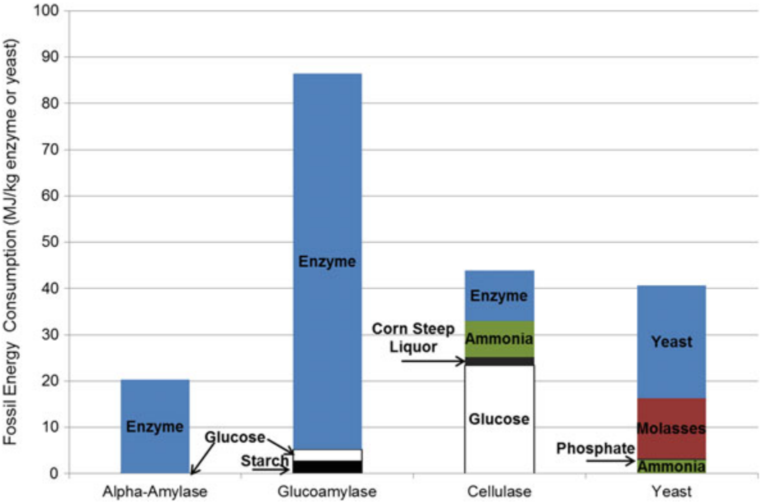

Fig. 8 Contribution of ingredients and manufacturing to the fossil energy consumption (MJ/kg) during enzymes and yeast production (Dunn et al. 2012)

Table 5 DGS displacement ratios in animal feedlots

	Displacement ratio between DGS and conventional feed (kg/kg of DGS on a DM basis)					
	Dry DGS			Wet DGS		
Livestock	Maize	Soybean meal	Urea	Maize	Soybean meal	Urea
Beef cattle	1.203	0.000	0.068	1.276	0.000	0.037
Dairy cattle	0.445	0.545	0.000	0.445	0.545	0.000
Swine	0.577	0.419	0.000			
Poultry	0.552	0.483	0.000			
Average	0.751	0.320	0.024			
				Dry and Wet DGS combined		
				0.788	0.304	0.022

Source Arora et al. (2011)

examine and incorporate their impact into corn ethanol LCA. Considering the displacement ratios in Table 5 it is clear that as DGS displaces conventional feed from corn and soybeans, reducing the demand for these two crops, computable general equilibrium (CGE) models used to estimate LUC impacts associated with corn ethanol production could take the impact of DGS into account throughout the entire agricultural supply chain. This inclusion could reduce the total amount of land estimated to be converted for the production of corn as an ethanol feedstock, thus reducing LUC-related GHG emissions.

4.2 Sugarcane Ethanol

The environmental advantages of sugarcane ethanol, regarding gasoline substitution and GHG emissions mitigation, have been known since the first comprehensive life-cycle studies were available (Silva et al. 1978; Nogueira 1987; Macedo 1992). Update studies have been published ever since (Macedo 1998; Macedo et al. 2004), following the evolution of agricultural practices in the sugarcane sector and the scientific advances concerning environmental aspects.

In the last decade, a number of studies have estimated the energy use and GHG emissions from sugarcane ethanol in Brazil using the LCA technique (Pimentel and Patzek 2007; Wang et al. 2008; Macedo et al. 2008; Soares et al. 2009; Oliveira et al. 2005). In general they indicate that ethanol leads to net energy savings and emissions reductions compared to gasoline, but the magnitude of the benefits varies considerably among the analyses due to divergences in the methodology and database.

The complete sugarcane crop cycle is variable, depending on local climate, varieties and cultural practices. In Brazil, it is usually a 6-year cycle, which comprises five cuts, four ratoon cultivation treatments, and one field reforming. The traditional harvest system involves the previous burning of the sugarcane crop and manual cut of the whole stalk. This system, however, is being gradually replaced by the mechanized harvest of green chopped sugarcane (without burning), due to environmental restrictions on burning practices. After harvesting, sugarcane is promptly transported to the mill by trucks (BNDES and CGEE 2008).

With respect to the N inputs, it is worth mentioning the lower levels of fertilizers required by sugarcane in Brazil compared to other countries. Intrinsic aspects, such as the lack of response of the plant cycle and costs, are in part responsible for the lower application rates. Moreover, an important aspect in Brazilian sugarcane cultivation is the recycling of nutrients by the application of industrial residues: vinasse and filtercake from sugarcane mills (Walter et al. 2013). Vinasse, for instance, is managed as nutrient source (rather than a residue) because of its high potassium content, and its application has been optimized within the topographic, soil, and environmental control limits (Macedo et al. 2008). The potential of nutrients recycling associated with sugarcane residues is summarized in Table 6.

Besides the mineralization of the crop residues and soil organic matter, additional nitrogen inputs through biological fixation have been investigated. Using natural abundance techniques, Boddey et al. (2001) concluded that 60% of the N

Table 6 Potential of nutrients recycling associated with sugarcane residues[a]

Nutrient (kg/t)	Filtercake[b]	Vinasse[c]	Straw
N	12.5	0.36	3.71
P_2O_5	21.8	0.14	0.7
K_2O	3.2	2.45	6.18

[a] *Source* Macedo (2005)
[b] *Total yield* 12 kg/t sugarcane
[c] *Total yield* 10–15 L/L ethanol

absorbed by a crop without mineral N fertilizer application was provided by biological fixation, mainly from endophytic and soil associative diazotrophic bacteria. But more research is needed to understand the role of biological fixation in sugarcane, and the role of N cycling in soil organic matter (Walter et al. 2013). In terms of N_2O emissions, however, experiments comparing burned and unburned harvesting systems indicate that the maintenance of sugarcane straw on the field increases soil N_2O emissions, with an even more marked increase when vinasse is applied (Carmo et al. 2012).

The production of ethanol in Brazil is based on the fermentation of either sugarcane juice, molasses, or a mixture of both. Most of the mills in Brazil are sugar mills with adjacent distilleries, but the number of standalone distilleries has been increasing with new greenfield projects. The entire energy consumed by the process (electricity, mechanical, and thermal energy) is provided by combined heat and power systems that use only bagasse as energy source. The mills in Brazil are, therefore, self-sufficient in energy, and many units in fact sell electricity to the grid and small amounts of bagasse surplus to other industries. On average, the electricity currently produced by sugarcane mills is twofold higher than the consumption. For the future, the electricity exports tend to expand as mills adopt modern, commercial high pressure-temperature cogeneration systems (BNDES and CGEE 2008).

Today all new mill units (and most of retrofitting projects) are equipped with modern cogeneration systems and many are adopting better process designs to reduce energy consumption. Such configuration enables the generation of more than 60 kWh/t cane of electricity surplus using only bagasse as fuel. But the implementation and evolution in cane trash recovering will eventually enable the generation of much greater amounts of electricity surplus (Walter et al. 2013).

4.3 Cellulosic Ethanol

Cellulosic ethanol can be made from a number of feedstocks including crop residues, such as corn stover, forest residue, short rotation woody crops (SRWC), and dedicated energy crops (switchgrass, miscanthus, energy cane). In the United States, there is a strong interest in using feedstocks that fit into the definition of “renewable feedstock” as defined in RFS2. This definition specifies that renewable feedstocks must be planted crops and crop residue harvested from existing agricultural land that was cleared or cultivated prior to December 19, 2007 and was actively managed after that date. Forest residue or SRWC can also qualify if they are from non-federal lands that were cleared before December 19, 2007 and actively managed after that date. Animal waste material and animal by-products are also eligible in addition to algae.

In the United States, different regions of the country are better suited to produce certain cellulosic feedstocks. For example, the key corn growing states such as Illinois and Iowa are potentially large producers of corn stover. The southeastern U.S. is better suited for energy crops (U.S. DOE 2011a, b). The life-cycle impacts of producing cellulosic feedstocks are largely dependent upon the fertilizer application rate and the energy consumed during feedstock harvesting. For many energy crops, for example, switchgrass, the optimal fertilization rate is still subject to research (Parrish and Fike 2005; Guretzky et al. 2010). Ideally, cellulosic crops would be grown in a climate and in soils where they require minimal fertilizer. In addition, harvesting techniques for cellulosic crops are still under development.

The transportation of cellulosic feedstocks to biorefineries also incurs an energy and environmental burden. At present, the most common means of feedstock transport is heavy-duty trucks, with a payload dependent on feedstock density. The distance that the feedstock must travel is a function of the conversion facility capacity, the yield of the feedstock in the field, and the amount of land surrounding the conversion facility that is available for feedstock production.

Cellulosic feedstocks can be converted to ethanol via biochemical or thermochemical means. In the biochemical case, the feedstock likely needs to undergo pretreatment such as dilute acid or wet oxidation steps. Next, the feedstock undergoes enzymatic hydrolysis, which, in the case of switchgrass ethanol, can contribute 24% of the life-cycle GHG impacts of bioethanol from this feedstock (Dunn et al. 2012). This contribution is large in the production of cellulosic ethanol because the dosage of this enzyme is quite high (about 10 kg/dry ton substrate) compared to the enzyme dosage in the corn ethanol process. As enzyme technology advances, however, dosages may decline, limiting enzymes' effects on bioethanol life-cycle GHG emissions. Following hydrolysis, fermentation of the sugars in the feedstock produces ethanol. Typical analyses (Humbird et al. 2011) consider that biochemical ethanol plants will combust residual lignin in a combined heat and power (CHP) system to produce steam for plant consumption and electricity that will be sold to the grid, displacing conventional electricity. In the context of LCA, this set of assumptions generates large benefits, especially if the conventional electricity to be displaced is carbon intensive (e.g., produced largely from coal-fired plants). As cellulosic ethanol plants are developed, it is possible they will not opt to include CHP because it is capital-intensive. LCAs of this bioethanol pathway will then need to be re-evaluated. Another possible advancement is that ethanol plants could integrate the production of ethanol from corn and corn stover. This type of integration would facilitate a transition from first generation biofuels to second generation biofuels. As several companies move to commercialize biochemical conversion technologies (e.g., DuPont, POET) LCA practitioners will need to update analyses to reflect the state of the technology.

Thermochemical technologies to produce ethanol from cellulosic feedstocks include indirect gasification (IG) (Dutta et al. 2011). Rather than producing electricity, the IG pathway can produce mixed alcohols as co-products. Another difference between thermochemical and biochemical routes is that inorganic catalysts, which may contain metals such as platinum, molybdenum, and aluminum, are often used in the latter technologies. The impact of these catalysts should be included in LCA. The proprietary nature of catalyst development, however, can complicate the gathering of composition and consumption rate data.

5 Analytical Issues in Biofuel LCA

When conducting an LCA, an analyst faces several choices that can strongly influence the results. These include choosing a co-product allocation technique and selection of a time horizon for the analysis. These issues are covered in the Sects. 5.1 and 5.2, respectively. Sect. 5.3 reviews key sources of uncertainty in biofuel LCA.

5.1 Co-product Allocation Method

The selection of a co-product handling method, either displacement (sometimes called system expansion) or an allocation technique, can significantly affect results (Wang et al. 2011b). If displacement is applied to the corn ethanol pathway, for example, DGS is treated as displacing conventional animal feed. The energy and emissions burdens of producing conventional feed are subtracted from the overall energy consumption and emissions associated with corn ethanol production. In the case of cellulosic ethanol, the co-produced electricity can be treated as displacing conventional electricity. One disadvantage to this approach is that the energy and emissions profile of the conventional product being displaced must be well-characterized. To properly account for the displacement of conventional animal feed, for example, the supply chains of corn, soybean meal, and urea must be well understood. However, the energy and emissions profile of a displaced entity often changes over time and varies by region. Also, if the co-product floods the market, defining the conventional product could become complex. Another disadvantage is, when the co-products are produced in amounts larger than the main product (fuel), the ensuing overwhelming displacement credits may cast doubt on the results' reliability.

An alternative approach is to allocate the burdens of the biofuel pathway among the co-products based on their share of mass, energy content, or market value. While these approaches require less information about conventional products the co-products might displace, challenges can arise in their application. For example, electricity is a massless co-product and cannot be incorporated into LCA results with mass-based allocation techniques. Mass and energy allocation techniques can be problematic when co-products have wide-ranging end uses. Energy allocation, however, is a good fit when the majority of products are energy carriers (e.g., fuels and electricity). The market value approach normalizes all products to a common basis regardless of their end use. Its application, however, depends heavily upon the prices of the co-products, which shift with time.

5.2 Time Horizon Selection

An additional choice LCA practitioners face is the time period of analysis, which affects the technology that is in place. For example, if the year chosen for an analysis of corn ethanol is 2000, life-cycle energy consumption and GHG emissions will be higher than for an analysis year of 2010 because of higher fertilizer consumption and greater energy intensity of farming and conversion. Technology advancements must be tracked and incorporated into biofuel LCA.

5.3 Key Sources of Uncertainty in Biofuel LCA

The LCA of bioethanol has several factors that drive uncertainty in results. One is the N_2O conversion rate of nitrogen fertilizers, which might substantially impact the environmental benefits of ethanol (Crutzen et al. 2007; Searchinger et al. 2008; Fargione et al. 2008). The magnitude of fluxes between soil and atmosphere depends largely on soil temperature, soil water content, oxygen availability, N substrate availability (nitrate and ammonium), and organic carbon. In addition, these regulators are strongly influenced by weather, vegetation, soil properties (bulk density, organic matter, pH, and clay content), and land management (Walter et al. 2013). Strikingly little data is available for N_2O flux rates from lands growing lignocellulosic crops like miscanthus. One study (Drewer et al. 2012) found that an unfertilized miscanthus production site emitted less N_2O than a neighboring site producing willow. No strong dependence of N_2O emission rate on season, soil moisture, or soil respiration was observed. It was therefore difficult to draw general conclusions about climate and soil type impacts on N_2O emissions. The study authors reiterate that a good deal more data is needed on N_2O emission rates before LCAs can capture this impact of biofuel production with more accuracy.

Another source of uncertainty in cellulosic bioethanol LCA is the yield of co-produced electricity. Although techno-economic analyses (Humbird et al. 2011) and LCAs often consider electricity as a co-product from cellulosic ethanol production, it may be that as cellulosic ethanol plants come on line they may not adopt CHP technology. If co-produced electricity is included in LCA of corn stover ethanol, the fuel achieves a nearly 100% reduction compared to baseline gasoline with the displacement method. If the electricity is not included, this reduction drops to 34%. Additionally, electricity yields may be different for different feedstocks depending on their heat content.

Biomass yield is an additional significant source of uncertainty in biofuel LCA. If yield is increased while holding fertilizer and energy inputs constant, life cycle impacts of feedstock production will significantly decline as will LUC effects. Many dedicated energy crops are just at the beginning of agronomics research and development modifications that so benefitted yields of grain crops like corn. Additionally, yield is highly dependent upon location.

Other sources of uncertainty include feedstock loss during harvesting, storage, and transport in addition to the yield of cellulosic ethanol as a function of feedstock identity. Clearly, staying abreast of technology changes is critical to reducing uncertainty in bioethanol LCA, especially for cellulosic ethanol.

6 Biofuel Land Use Modeling in the Context of LCA

Incorporation of land use impacts from biofuel production is generally performed separately from the calculations of effects of other life-cycle stages. Generally, LCA models such as GREET do not contain the modeling tools described in the next sections that estimate amounts and types of LUC or the modeling tools that calculate above and belowground carbon stock changes and other impacts of LUC. LUC and agroecosystem model output, however, is readily incorporated into LCA tools as the following sections describe.

6.1 Land Use Change Modeling

The first step in calculating the LUC GHG emissions associated with a biofuel pathway is to determine the amounts and types of land that will be converted. In some analyses, a simplifying assumption is made that biofuel production will occur on a certain type of land, at times in one particular region. For example, Scown et al. (2012) assumed miscanthus production would occur only on active cropland or CRP land. Many other analyses consider how land will be affected the world over for biofuel production and rely on economic models to predict LUC. The chapters in Section II of this book provide detailed descriptions of several of these models including the Food and Agricultural Policy Research Institute Center for Agricultural and Rural Development (FAPRI-CARD) model (Chapter "Global Land Use Impacts of U.S. Ethanol: Revised Analysis Using GDyn-BIO Framework"), Forest and Agricultural Sector Optimization model (FASOM, Chapter "Modeling Bioenergy, Land Use, and GHG Mitigation with FASOMGHG: Implications of Storage Costs and Carbon Policy"), the Mirage-BioF model (Chapter "Empirical Findings from Agricultural Expansion and Land Use Change in Brazil"), and the Global Trade Analysis Project (GTAP) model (Chapter "Land Use Change, Ethanol Production Expansion and Food Security in Brazil"). This section contains a brief overview of commonly used models and their advantages and drawbacks with a high-level summary of select models in Table 7.

Two general types of economic models are used to simulate biofuel-induced LUC (Djomo and Ceulemans 2012). The first is a computable general equilibrium (CGE) model. These models consider all markets to be in equilibrium at each time step. The second general model type is a partial equilibrium (PE) model. PE models consider the agricultural sector in detail while other sectors, including perhaps the

Table 7 High-level overview of select LUC models[a]

Model	Institution	Type	Second generation biofuels	Co-products	Advantages	Drawbacks
GTAP[b]	Purdue University	CGE	Y[c]	Y	• Economy-wide coverage	• No detailed sectoral analysis
MIRAGE-Biof[d]	IFPRI[e]	CGE	N	Y	• Dynamic, multi-sector and multi-region	• Does not include marginal or fallow lands
GLOBIOM	IIASA[f]	PE	Y[g]	N	• Models carbon stocks and flows	• Feedstock production restricted to managed forests, croplands, and tree plantations
FAPRI-CARD[h]	Iowa State University	PE	N	Y	• Interconnected network of several PE models • Covers all major temperate crops	• Limited to agriculture and land use sectors; does not link agriculture and energy sectors
FASOM[i]	Texas A&M University	PE	Y[j]	Y	• Allows for analysis of crop-shifting and other impacts of crop production	• Covers U.S. domestic only
BLUM[k]	ICONE[l]	PE	N	Y	• Detailed analysis of Brazilian biofuels sector	• No coverage of regions outside Brazil

[a] Based in part on Djomo and Ceulemans (2012) and Edwards et al. (2010)
[b] Global trade analysis project
[c] Corn stover, switchgrass, miscanthus
[d] Uses the GTAP database
[e] International Food Policy Research Institute
[f] International Institute for Applied Systems Analysis
[g] Woody feedstocks only
[h] Food and Agricultural Policy Research Institute; Center for Agricultural and Rural Development
[i] Forest and Agricultural Sector Optimization Model
[j] Miscanthus
[k] Brazilian land use model
[l] Institute for international trade negotiations

energy sector, are treated at a much higher level without linkage to the agricultural sector. In this chapter, we estimate LUC GHG emissions associated with corn and cellulosic ethanol with LUC results from the GTAP model (Taheripour et al. 2011).

A number of modeling advancements will improve estimates of LUC associated with biofuels. For example, incorporating dynamic crop yields into LUC models would benefit LUC GHG emissions estimates. Additionally, these models could be developed at a finer resolution to allow pairing LUC results with high-resolution carbon content data. Further, the yield elasticity, a time-dependent parameter on price (Djomo and Ceulemans 2012) could also be refined. This improvement is dependent in turn on the availability of limited real-world data that could be used to calibrate this parameter. Despite their limitations, economic models are the main tool available to predict LUC associated with biofuels.

6.2 Above and Below Ground Soil Carbon Content Modeling

With LUC data in hand, the next step is to estimate the impacts of converting land from the base case scenario to a scenario in which biofuel production has occurred. Although there are several possible environmental effects of biofuel-induced LUC including altered air quality (e.g., tropospheric ozone changes), a disturbed surface water balance, shifts in albedo, and changes in the soil microbial community that can effect soil organic matter and CO_2 emissions, most biofuel LCAs currently consider only above and belowground carbon impacts of LUC (Djomo and Ceulemans 2012; Pielke et al. 2011; Georgescu et al. 2011).

Belowground carbon resides in root biomass and soil organic carbon (SOC). Changes in SOC can be estimated with agroecosystem models such as CENTURY (Kwon et al. 2013). CENTURY simulates the dynamics of three SOC pools (i.e., active, slow, and passive) and interrelated nitrogen pools. Users can investigate the impacts of different land management practices such as no-till and reduced-till farming in addition to fire, grazing, and fertilizer addition. In general, no-till land management practices reduce GHG emissions from soils because the soil structure and SOC is disturbed less frequently. Climate factors such as temperature and precipitation are taken into account in CENTURY. Importantly, the CENTURY model permits the construction of a detailed land use history that is critical to capturing the impact of land conversion. Some coefficients of the CENTURY model, such as those that influence modeling of the site-specific decay rate of soil organic matter (SOM) pools as influenced by cultivation practices, benefit from calibration with real-world data (Kwon and Hudson 2010). These data, however, are generally in short supply for lignocellulosic crops, which introduces some uncertainty and reemphasizes the need for field data (Kwon et al. 2013). In addition to calculating below ground carbon, CENTURY also produces aboveground carbon estimates for crops.

The conversion of forests to biofuel feedstock production is of particular concern because forests are an inherently carbon-rich land cover (Gibbs et al. 2010; Popp et al. 2011) that in some cases may be a carbon sink. Their conversion to biofuel feedstock production land could incur a significant carbon penalty (Fargione et al. 2008). While estimation of belowground SOC content can be accomplished with CENTURY, other data sources may be needed to estimate the amount of aboveground carbon in forests. In the United States, the U.S. Department of Agriculture (USDA) Forest Service and the National Council for Air and Stream Improvement, Inc. (NCASI) developed the Carbon Online Estimator (COLE) (Van Deusen and Heath 2010). COLE reports five non-soil carbon components of forests: aboveground live tree carbon density, aboveground dead tree carbon density, understory carbon density, forest floor carbon density, and coarse woody debris carbon density. These data are valuable in constructing an aboveground carbon profile of U.S. forests.

It is also important to consider the fate of carbon in harvested wood products (HWP). This carbon may end up being burned, emitted through a decay process, or stored in a HWP such as furniture. Some biofuel LCAs have considered that no carbon is stored in HWP (Searchinger et al. 2008) and obtain very high LUC GHG emissions in part because of this assumption. An analysis by Heath et al. (1998), however, indicates that if 60% of combined aboveground live and dead tree carbon density is removed from a forest, 21% of that removed wood will be used in carbon sequestering HWP and another 21% will be used to produce useful energy, which offsets the production of fossil-based energy. The exact percentage of HWP that sequester carbon undoubtedly varies, is a source of uncertainty, and would benefit from further research. If scenarios are investigated that do not involve the conversion of forests, however, it is unimportant.

6.3 Land Use Change GHG Emissions Modeling for Biofuels Production in the U.S

In this section, we discuss how the GREET model incorporates SOC modeling results from CENTURY, aboveground carbon data from COLE, and LUC modeling results from GTAP to estimate LUC GHG emissions associated with bioethanol pathways. First, GTAP modeling runs were conducted to assess the LUC that would occur if the biofuel production scenarios in Table 8 were carried out. The data and assumptions underpinning the GTAP modeling are described in Taheripour et al. (2011). It is important to note that in these modeling runs, bioethanol was produced from only one feedstock at a time. The amounts of U.S. domestic and international lands converted for each feedstock are displayed in Figs. 9 and 10, respectively. In the U.S., the most affected land type is cropland-pasture although some forest is converted, most notably for switchgrass production. Internationally, GTAP predicts an increase of forest area for corn grain

Table 8 GTAP modeling scenarios

Scenario	Scenario description	Increase in ethanol (BL)
1	An increase in corn ethanol production from its 2004 level of 13 billion liters (BL) to 57 BL	45
2	An increase of ethanol from corn stover by 35 BL, in addition to 57 BL corn ethanol	35
3	An increase of ethanol from miscanthus by 27 BL, in addition to 57 BL corn ethanol	27
4	An increase of ethanol from switchgrass by 27 BL, in addition to 57 BL corn ethanol	27

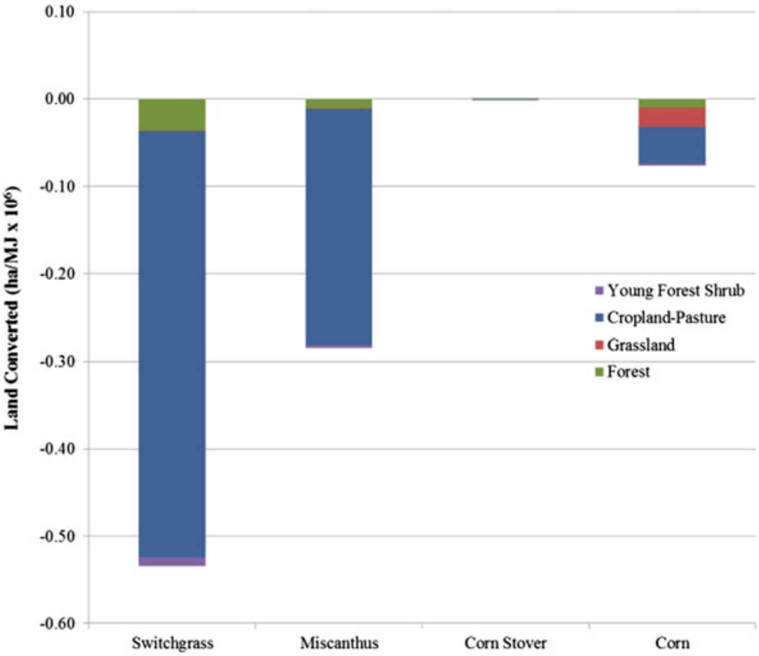

Fig. 9 Domestic LUC for switchgrass, miscanthus, corn stover, and corn ethanol. *Legend* Negative values indicate a decrease in land area

production, but a decrease in forest area when switchgrass is the feedstock being produced. Note that GTAP does not permit uncertainty analysis, only point estimates have been obtained for each scenario modeled.

Next, CENTURY runs were conducted to develop SOC emission factors for each domestic LUC scenario as Fig. 11 diagrams (Kwon et al. 2013). The resulting emission factors (EFs) were at a state-level and subsequently rolled up to the AEZ level (at which GTAP generates LUC results) to match the resolution of the GTAP results. Root mass values for forests corresponded with aboveground carbon stock

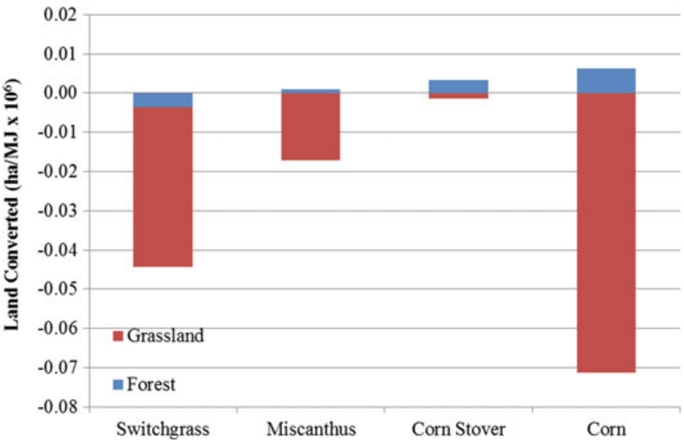

Fig. 10 International LUC for switchgrass, miscanthus, corn stover, and corn ethanol. *Legend* Negative and positive values indicate a decrease and increase, respectively, in land area

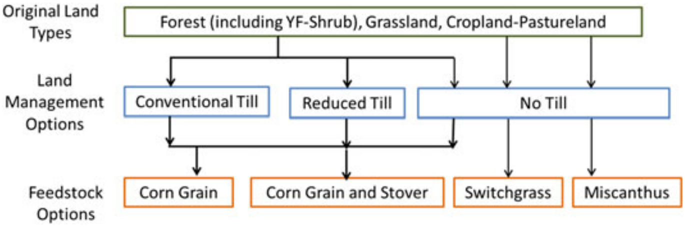

Fig. 11 LUC scenarios considered in CENTURY

values as reported in COLE (Mueller et al. 2012). CENTURY was run with a number of modeling parameter variations. For example, one set of CENTURY results does not include the impact of erosion, which is minimal (Dunn et al. 2013). For each feedstock, modeling runs were conducted with calibrated parameters specific to that feedstock or with default CENTURY parameters. Another modeling variable was the feedstock yield, which was assumed to be either constant over the time period considered, or increasing as a result of technology improvements. From the CENTURY modeling runs, we observed that emissions associated with forest conversion were the greatest for any individual feedstock. Additionally, emission factors were higher for transitions to corn and corn stover production, regardless of the initial land use. Figure 12 displays these trends for two key AEZs, 7 and 10, which were where the greatest amount of land was converted for energy crops and corn, respectively. AEZ 7 includes a large portion of the Western U.S. and AEZ 10 is the U.S. corn belt.

EFs for each scenario and set of modeling parameters along with the GTAP data were combined in a GREET module called the carbon calculator for land use

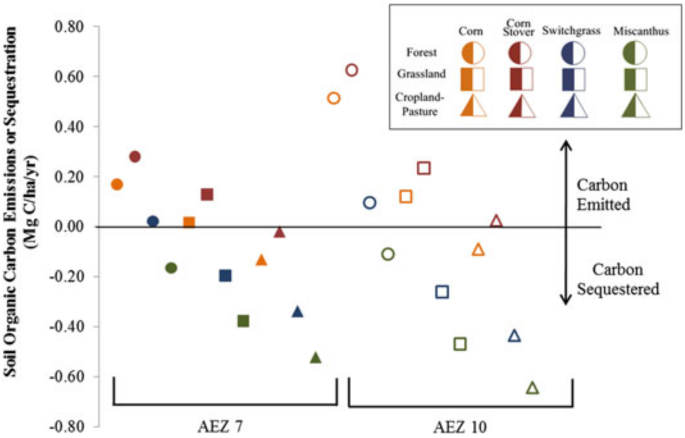

Fig. 12 Soil organic carbon content changes from domestic land use transitions. *Legend* Solid and hollow markers denote transitions in AEZs 7 and 10, respectively. Forest, grassland, and cropland-pasture transitions are denoted by *circles*, *squares*, and *triangles*, respectively. *Orange*, *red*, *green*, and *blue* markers reflect transitions to corn, corn stover, miscanthus, and switchgrass production, respectively. These results were generated from CENTURY modeling runs with calibrated parameters, feedstock yields that increase with time, and with erosion effects

change from biofuels production (CCLUB). The ability for users to investigate the impact of the HWP factor is also included in CCLUB; it permits the user to choose between 0% carbon sequestration in wood or a factor based on Heath et al. (1996).

For the analysis of LUC GHG emissions from US-based biofuel production in this chapter, we developed probability distribution functions for each feedstock. The building of these functions took as input the CCLUB results for each combination of modeling possibilities available. The resulting data were then fit to a number of distributions to assess which was the best fit. For each feedstock, the normal distribution function was the most appropriate. The results of this analysis that incorporated these probability distribution functions into GREET analysis of bioethanol pathways is in the following section.

6.4 LUC GHG Emissions for Sugarcane Ethanol Produced in Brazil

Regarding sugarcane ethanol LUC emissions, data for the specific LUC for sugarcane expansion in the last decade indicates that less than 1% occurred over native vegetation areas (with higher C stocks) and the overall effect may actually be of increasing the C stocks in soil. For the expansion from 2002 to 2008, Macedo and Seabra (2008) estimated LUC emissions as –118 kg CO_2eq/m^3 ethanol (−5.5 g CO_2eq/MJ ethanol), although large uncertainties exist because of the lack of information on carbon stocks. For the future, this carbon removal trend could be sustained as the sugarcane growth scenarios for 2020 indicate a progressive use of pasture lands (many with relatively low levels of carbon stocks) in the expansion.

Relevant impacts may also be expected due to alterations in sugarcane cultivation management. Studies have indicated the trend for carbon sequestration under green cane management (De Figueiredo and La Scala Jr. 2011), though it is conditioned by factors, such as climate, soil texture, nitrogen fertilizer management, time since the adoption of the unburned harvest, initial carbon stocks, and the level of soil disturbance during the re-planting operation. Estimates from 12 sites indicated a mean annual C accumulation rate of 1.5 t/ha year (Cerri et al. 2011).

As for the indirect effects, there is no scientific consensus on a methodology to evaluate these emissions. But the large area availability in Brazil and the intensification of the cattle raising systems, along with the current legislation, indicate that the iLUC effects may be small. As discussed in Sect. 3, CARB's initial estimate of sugarcane ethanol LUC GHG emissions, 46 g CO_2eq/MJ, is now under revision. EPA's estimate of these emissions was much lower ($\sim$5 g CO_2eq/MJ) (EPA 2010).

Lapola et al. (2010), on the other hand, indicate that the indirect effects of biofuels expansion in Brazil could offset the carbon savings from ethanol and biodiesel. However, the authors stress that an increase of 0.13 head per hectare throughout the country could avoid the indirect LUC caused by biofuels (even with soybean as the biodiesel feedstock), while still fulfilling all food and bioenergy demands.

The impact of the EU mandate on biofuels was assessed by Laborde (2011), using an updated version of the MIRAGE-Biof model. The study estimated that the LUC emissions induced by the additional EU biofuels mandate would be 38 g CO_2eq/MJ of biofuels in the scenario without trade liberalization, and 40 g CO_2eq/MJ with trade liberalization. Specifically for sugarcane ethanol, Laborde (2011) estimated LUC emission coefficients as 13.4 and 17.2 g CO_2eq/MJ, for status quo and free trade policy scenario, respectively.

Based on an alternative approach, Nassar et al. (2010) evaluated LUC emissions of ethanol using an allocation methodology, where the substitution of productive activities (and natural vegetation by productive activities) was calculated from absolute variations observed 2005 and 2008. Considering the ethanol expansion in this period, the authors estimated a direct and indirect emission factor (LUC + iLUC factor) of 7.63 g CO_2eq/MJ of sugarcane ethanol.

As pointed out by Khatiwada et al. (2012), regardless of the model or method adopted to estimate LUC, the progressive improvement of pasture yields in Brazil cannot be ignored. As presented by UNICA (2009), the increasing stocking rates and beef production verified in the last decade suggests that pasture yields tend to grow when more pasture land is released for crops and other uses, which means that pasture yields respond strongly to cattle price changes. The low level of pasture intensification reinforces the argument that there is still considerable room for even greater improvements on pasture intensification in Brazil, which can potentially liberate substantial amounts of land for the expansion of other crops without effects on native vegetation. This indicates that the indirect LUC GHG emissions derived from the expansion of bioenergy in Brazil is likely to be small in the future (Khatiwada et al. 2012).

7 Key Biofuel LCA Results and Conclusions

In this section, we provide full life-cycle results for ethanol produced in the U.S. from corn and cellulosic crops and in Brazil from sugarcane. In the case of the US-based crops, we assess the effect of co-product handling methodology on results.

7.1 Results for U.S. Produced Biofuels

Well-to-wheels (WTW) (or in the case of biofuels, farm-to-wheels) results for ethanol produced from corn, corn stover, switchgrass, and miscanthus are in Fig. 13 and Table 9. In Figs. 13 and 14, the bottom and top ends of the error bars indicates the 10th and 90th percentiles (or p10 and p90) out of sample results from 1000 Monte Carlo simulation runs, respectively. These results were produced with the GREET model (version GREET1_2012) using parameters and probability distribution functions for feedstock production and conversion as reported in Wang et al. (2012). LUC GHG emissions are amortized over an assumed 30 year time period of the RFS2 policy. Regardless of feedstock, bioethanol offers reduced GHG emissions over fossil-derived gasoline, even when LUC GHG emissions are included. Of the ethanol pathways in Fig. 13, corn ethanol has the greatest GHG emissions. It offers a 30% reduction in life-cycle GHG emissions as compared to gasoline when LUC GHG emissions are included.

WTW results for each of the three cellulosic pathways are statistically equivalent and are lower than life-cycle GHG emissions for corn ethanol. When LUC GHG emissions are included for miscanthus ethanol, the fuel transitions from net GHG emissions to net GHG sequestration over its life cycle. The high yield of miscanthus translates into less land converted for its production than for lower yielding crops such as switchgrass. Additionally, land producing miscanthus could be expected to exhibit an increase in SOC (Fig. 12). Switchgrass ethanol WTW results have the greatest associated uncertainty for two reasons. First, the switchgrass fertilizer nitrogen consumption rate is twice that of the nitrogen consumption rate for miscanthus.[2] As a result, uncertainty in the N_2O conversion rate has a strong impact on this pathway (Wang et al. 2012). Second, more LUC is associated with the switchgrass ethanol pathway than the other cellulosic ethanol pathways (Figs. 9 and 10). Uncertainty in LUC GHG emissions therefore has a slightly stronger influence on results for this pathway. Incorporating the uncertainty associated with

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[2] N_2O emissions for corn stover ethanol from supplemental fertilizer application are treated as net zero. N_2O emissions from supplemental fertilizer applied to the field are assumed to be equal to N_2O emissions that would have been emitted if the stover had been left on the field in a scenario without biofuel production because the N content of the removed stover and the supplemental fertilizer are equal.

Table 9 Results summary for bioethanol produced in the U.S. (g CO_2eq/MJ)

Pathway	Corn ethanol	Corn stover ethanol	Switchgrass ethanol	Miscanthus ethanol
Nominal WTW result without LUC	57	2.2	6.8	1.9
Uncertainty without LUC[a] (range)	43–71 (28)	−2.3 to 26 (28.3)	1.8–38 (36)	−2.5 to 29 (32)
Nominal result with LUC	65	1.0	9.6	−8.5
Uncertainty with LUC[a] (range)	52–79 (27)	−3.5 to 25 (28.5)	11–49 (38)	−8.0 to 23 (31)
WTW GHG emission reduction compared to baseline gasoline with/without LUC[b]	30%/38%	99%/98%	90%/92%	109%/98%
Default co-product handling method	Displacement of conventional U.S. animal feed	Displacement of the U.S. average mix	Displacement of the U.S. average mix	Displacement of the U.S. average mix

[a] 10th and 90th percentiles
[b] Based on nominal values

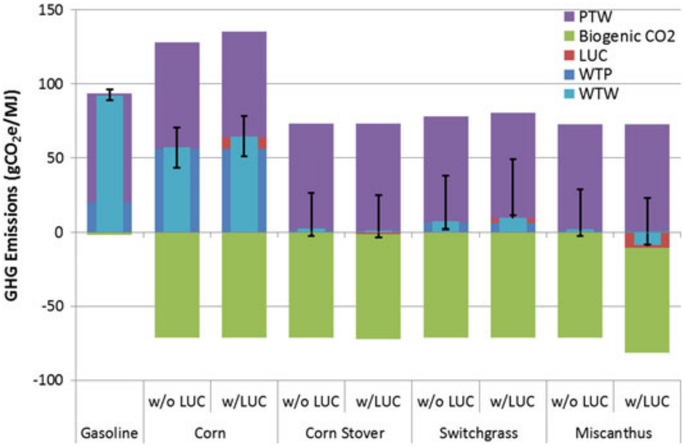

Fig. 13 Well-to-wheels (WTW) results for U.S.-produced ethanol. PTW denotes pump-to-wheels; WTP denotes well (or farm) to pump

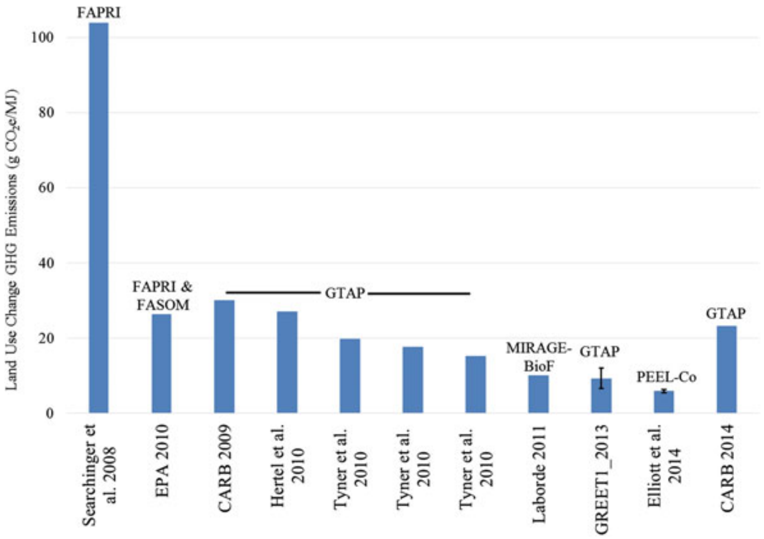

Fig. 14 LUC GHG emissions of corn ethanol from recent studies

LUC GHG emissions increases the difference between the 10th and 90th percentiles for each pathway by less than 2 g CO_2eq/MJ.

Results for corn ethanol LUC GHG emissions from this study are compared to those from recent studies in Fig. 14. Clearly, estimates of these emissions have decreased substantially as modeling techniques have improved. Updated GTAP modeling and the replacement of coarse SOC EFs with finer scale EFs, in addition to specific assumptions about HWP, contribute to the lower nominal value for corn ethanol LUC GHG emissions in the present work. Results are in reasonable agreement, however, with those of Laborde (2011) who used the Mirage-BioF model. Fewer results are in the literature for cellulosic ethanol LUC GHG emissions. Scown et al. (2012) reported slightly higher GHG sequestration than we do (between –3 and –16 g CO_2eq/MJ) from miscanthus ethanol production, but limited their study to feedstock production on active cropland or CRP land. An important conclusion is that the modeling approach and assumptions integrated into calculating LUC GHG emissions strongly influences results.

The results in Fig. 13 use the GREET default co-product treatment for that pathway as summarized in Table 9. As discussed in Sect. 5, the treatment of co-products in biofuel LCA can significantly alter life-cycle GHG emissions results. Figure 15 explores the effect of co-product treatment. For corn ethanol, nominal results are lowest when the energy allocation technique is used to allocate life-cycle burdens among the fuel and animal feed co-products of the ethanol plant. The production of conventional animal feed is not GHG intensive and does not provide a substantial GHG credit to the corn ethanol pathway when the displacement technique is used. In the case of cellulosic ethanol pathways, however, fewer GHGs are emitted when the co-produced electricity is treated as displacing the U.S.

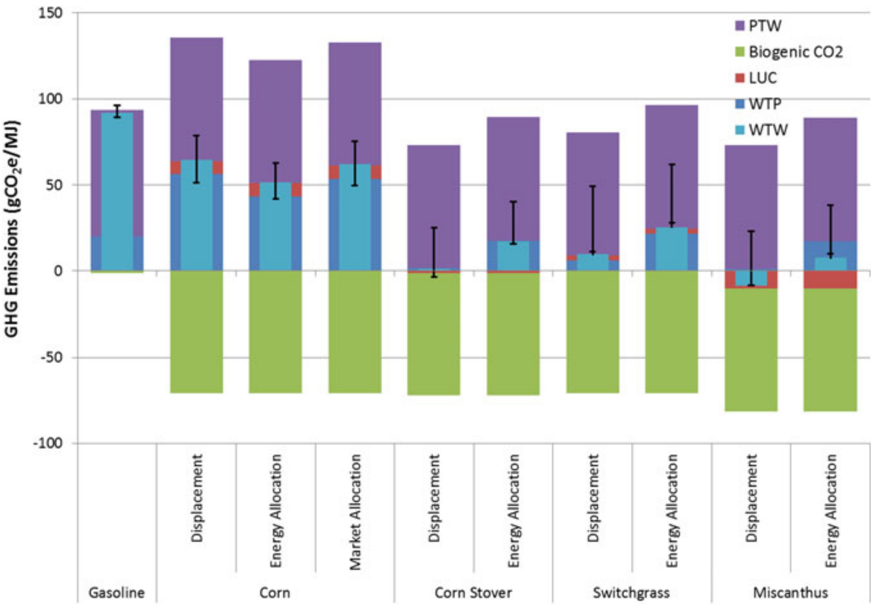

Fig. 15 WTW results with different co-product energy allocation methods

average mix. This treatment yields large displacement credits because the U.S. electricity mix is fossil fuel-intensive.

7.2 *Results for Ethanol Produced in Brazil*[3]

In a recent study, Seabra et al. (2011) evaluated the life-cycle energy use and GHG emissions related to cane sugar and ethanol, considering bagasse and electricity surpluses as co-products. The study performed an overall balance for the Brazilian Center-South region, based on parameters from the database of the sugarcane technology center (CTC) for the 2008 season (for some parameters, the sample consisted of 168 mills). The GREET 1.8c.0 model was used for the "well-to-wheels" calculations. Ethanol life-cycle emissions were evaluated at 21.3 g CO_2eq/MJ, with relevant contributions from field emissions and diesel consumption for sugarcane farming (Table 10). The study paid special attention to the variation of some parameters among producing units, and the consequent uncertainties in ethanol life-cycle emissions were assessed through a Monte Carlo analysis. The results showed that the p10–p90 interval for anhydrous ethanol emissions in the current conditions is 15–33 g CO_2eq/MJ (Fig. 16). Note this analysis did not include an assessment of LUC GHG emissions.

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[3] Mostly based on Walter et al. (2013).

Table 10 Sugarcane ethanol life-cycle GHG emissions (g CO_2eq/MJ)[a]

Sugarcane farming	6.8
Straw burning[b]	3.8
Field emissions[c]	6.7
Agr. inputs production	3.8
Sugarcane transportation	1.4
Sugarcane processing	2.6
Ethanol T&D[d]	1.8
Tailpipe emissions	0.8
Credits from co-products[e]	
Electricity[f]	−3.7
Bagasse[g]	−2.7
Total	*21.3*
LUC GHG emissions[h]	5.0–17.2
Total range with LUC GHG emissions	26–39

[a] *Source* Seabra et al. (2011)

[b] For 35% of unburned cane harvesting

[c] Includes emissions from the soil due to fertilizers, residues and limestone application

[d] Considering road transportation using heavy-duty trucks and a total transportation distance (including distribution) of approximately 340 km

[e] Co-product credits were assessed through the displacement method

[f] 10.7 kWh/t cane displacing natural gas thermoelectricity generation

[g] 3.3% of surplus bagasse displacing fuel oil fired boilers. It was assumed 10% bagasse losses in handling and storage

[h] *Sources* EPA (2010), Laborde (2011). The value CARB originally proposed, 46 g CO_2eq/MJ, is not included in this range because it is under revision

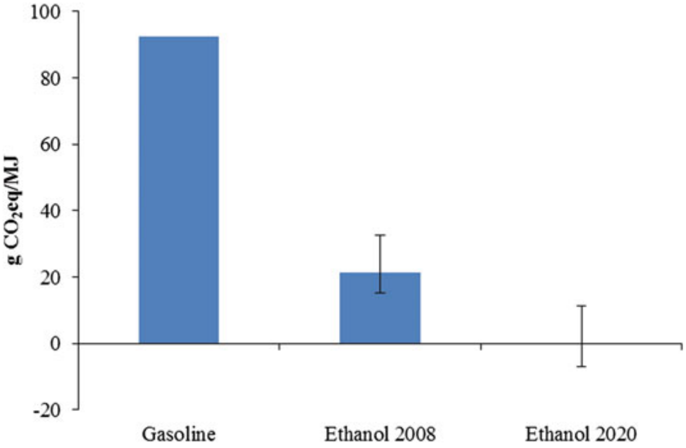

Fig. 16 Monte Carlo uncertainty analysis for sugarcane ethanol life-cycle emissions. Error bars indicate p10 and p90 values (based on Seabra et al. 2011)

Despite the relatively high uncertainty, Seabra et al. (2011) point out that there is a clear trend for the next decade, with a significant GHG emissions reduction. Due to the complete elimination of sugarcane trash burning, rational use of sugar mill residues in agriculture and, mainly, high level of electricity exports (approximately 70 kWh/ton cane), authors evaluate that ethanol net emissions could be close to zero on average in 2020. But the overall benefit of ethanol concerning emissions mitigation could even increase with the employment of advanced technologies for biomass utilization (e.g., biochemical conversion to ethanol) (Seabra and Macedo 2011).

7.3 Conclusions

LCA is a tool that is widely used to analyze biofuel life-cycle GHG emissions, among other environmental impacts, with the aim of understanding the potential benefits of these fuels compared to conventional gasoline in a holistic way. Another motivation of biofuel LCA is to identify the life-cycle inputs that most influence GHG emissions and could possibly be targeted for reductions. The United States, California, the UK, and the EU have all adopted some form of LCA in legislation related to biofuels.

LUC GHG emissions are one of the most uncertain and controversial aspects of biofuels' environmental impacts. Several modeling tools can be used to estimate the magnitude and type of LUC. Each tool has drawbacks and advantages. Similarly, modeling is also used to estimate the above and belowground carbon impacts of LUC, which are often incorporated into LCA. Other aspects of LUC (e.g., disturbed surface water balance, shifts in albedo, and changes in the soil microbial community) that could influence life-cycle GHG emissions are typically not included in LCA at this point. Further, additional indirect effects such as the influence of biofuel production on fossil fuel prices are generally not incorporated although the system boundary could be expanded to include this and other indirect effects (Zilberman et al. 2013). Differences in modeling approaches can significantly affect estimates of LUC GHG emissions. When reporting biofuel LCA results, analysts should clearly document assumptions and methodologies pertaining to LUC GHG emissions calculations.

All bioethanol pathways analyzed in this chapter offer life-cycle GHG emissions reductions benefits as compared to baseline gasoline, even when LUC GHG emissions of the fuel pathways are considered. Miscanthus ethanol is estimated to offer the greatest reductions in contrast to gasoline followed by (in order of decreasing GHG reductions) corn stover, switchgrass, sugarcane, and corn ethanol.

It is likely that improvements to the economic models that predict LUC and estimates of aboveground carbon, belowground carbon, and other physical changes to impacted lands will continue to improve, as LCA methodologies and critical data are improving LCA practitioners should continue to incorporate these improvements into estimates of life-cycle GHG emissions of biofuels.

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Effect of Biofuel on Agricultural Supply and Land Use

David Zilberman, Deepak Rajagopal and Scott Kaplan

> *History doesn't repeat itself, but it rhymes*
>
> —Mark Twain

Abstract While biofuels were introduced, in part, to reduce greenhouse gas emissions through replacing fossil fuels, comparing their impact to conventional sources has been difficult. This is largely due to the challenges of quantifying indirect land use change due to biofuels, which has proved controversial. This paper introduces a stylized, dynamic framework to analyze the evolution of land use expansion as well as deforestation over time. Our analysis suggests that land use change is a dynamic process and that relationships between variables are not regular over time and space. Technological change and effective environmental policy, of both agriculture and forests, can curtail deforestation. Outcomes of the model are illustrated with empirical data from the U.S. and Brazil. In the United States, deforestation does not lead directly to cropland expansion, as there is a transition period during which land is used as pasture or left idle. In Brazil, with four times more land in pasture or underutilized land than in cropland, there is significant potential for cropland expansion from this underutilized land.

Keywords Biofuels · Indirect land use change · Biofuel impact on agricultural supply

1 Introduction

The introduction of biofuels like corn and sugarcane ethanol was partially motivated by the desire to reduce greenhouse gas (GHG) emissions through replacing fossil fuels. However, the assessment of the GHG impacts of biofuel using lifecycle analysis (LCA) has proved to be quite challenging. The direct effects of carbon fuel

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D. Zilberman (✉) · S. Kaplan
Department of Agricultural and Resource Economics,
University of California at Berkeley, Berkeley, CA, USA
e-mail: zilber11@berkeley.edu

D. Rajagopal
Institute of the Environment and Sustainability, University of California at Los Angeles,
Los Angeles, CA, USA

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on GHG emissions vary depending on the types of fuels used in production, processes used in producing each fuel, and the type and amount of fertilizer used in producing feedstocks (Farrell et al. 2006). Furthermore, Searchinger et al. (2008) suggested that in addition to the direct effects of biofuel production, there are indirect effects associated with the impacts of biofuel on commodity prices and the environment. He singled out indirect land use change (iLUC), which results from the introduction of biofuels, leading to higher prices of feedstocks that will likely lead to expansion of cropland acreage with a resulting decline in acreage for more environmentally friendly purposes (e.g., forestland).

Yet, the computation of iLUC has become controversial. In most cases, it was done using numerical simulation, either through computable general equilibrium (CGE) models, dynamic programming models, or partial equilibrium models (Khanna and Zilberman 2012). These studies vary significantly in their modeling approaches and estimation of parameters, and thus exhibit different results. The literature has realized that CGE has significant limitations, including arbitrary selection of model specifications and the selection of estimated parameters. In this paper, we assess the results of these models using a different approach. First, we develop a model to assess the inherent dynamics of the evolution of agricultural land use and its relationship to economic and technological factors. Second, we use empirical data from various sources to assess basic relationships between changes in agricultural commodity prices and agricultural land use. We find that the relationship between agricultural prices and land use at the extensive margin is *not regular* (namely that it cannot be reflected by a stable coefficient) while policy-makers and scientists are looking to obtain relationships that are *regular*.[1] For example, the gravitational coefficient g is regular and equal to 9.81 m/s^2 on Earth. On the other hand, indirect land use coefficients vary substantially between studies, and our conceptual analysis suggests that they are likely to change during periods of cropland expansion, but remain close to zero once total cropland has stabilized. They are affected by resource availability, regulation, inventory, technology, and demand. More fundamentally, the elasticities that are the life-blood of CGE modeling, which is used heavily in impact assessment, are not regular and reflect the changes over space and time, as mentioned above.

This paper presents a conceptual analysis and its outcomes are illustrated using empirical findings. The conceptual analysis consists of two sections: the first presents an optimal control model of optimal land allocation between agricultural land and the environment. This is followed by an analysis of the model, institutional and policy implications, and a discussion of other factors not included in the model that are likely to affect land allocation between agriculture and the environment. The model emphasizes the evolution and changes in land use in response to changes in demand and other parameters over time, reflecting the impacts of changing

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[1] They are regular in the sense that they produce outcomes that occur frequently under the same conditions (allowing some random errors that do not affect the average). For example, a constant elasticity reflects a regular relationship.

technology and the finiteness of land. The discussion demonstrates the importance of policy intervention in controlling processes like deforestation and effective management of land resources. The conceptual analysis as a whole suggests that elasticities of supply and demand for land and crops are likely to vary over time, and identifies considerations that are essential for realistic policy analysis. The empirical section of the paper will use data and observations from the U. S. and Brazil to illustrate how agricultural land use in these countries has evolved over time and how elasticities of aggregate land use with respect to crop prices vary in these countries based on cropland expansion and stabilization.

2 Conceptual Analysis

2.1 The Basic Model

Agricultural economists have long realized that locational heterogeneity in agro-climatic conditions impacts agricultural productivity. Studies on the history of agricultural production and the foundation of agricultural policy (Cochrane 1979; Schultz 1964; Olmstead and Rhode 2008) emphasize that trade-offs between the intensive and extensive margin and the increase in agricultural productivity has been a gradual process that involves expansion of land as well as changes in composition of inputs and their productivity.

Land is a unique resource whose quantity is finite, and its productivity varies across locations. There has been a large body of literature to understand the evolution of land use, land prices, and the impact each has on productivity (Lambin and Meyfroidt 2011). This analysis will rely on the literature on nonrenewable resources to assess the dynamics of land use. The total amount of land in a region is viewed as a finite resource, and economic development may entail conversion of wild land to agricultural production. We use the methods and techniques developed in Xabadia, Goetz, and Zilberman (2006) that models variation and land use patterns over space and time. Similarly, we initially solve for the socially optimal resource allocation over time and determine the policies that will lead to optimal outcomes for a competitive agricultural industry. Using this result, an allocation rule can be developed to determine when policies are suboptimal and should be modified. The derivation of the resource allocation rule under different conditions will help clarify how land use changes in response to changes in demand for output or to changes in other parameters.

2.2 The Social Optimization Problem

We assume that the objective of the social optimization problem is to maximize net discounted social welfare. The welfare measure at each period is the sum of benefits from consumption of biofuel and environmental amenities (associated with open space), minus the cost of production, R&D, and land conversion. The choices are constrained by the available technology, denoted by the production function, the evolution of technology as a result of investment in innovation, the dynamics of demand for agricultural output, and the finiteness of land resources.

Let output produced in period t be denoted by Y_t, so the aggregate production function at time t can be written as $Y_t = F(X_t, A_t, S_t)$ where X_t is the aggregate level of variable inputs used, A_t the amount of land available at time t, and S_t the stock of agricultural capital available at time t, measured in monetary terms. Agricultural land and agro-climatic conditions are heterogeneous, so the aggregate production of biofuel presented here may be interpreted as the aggregation of outcomes of micro-level optimization by multiple units subject to regional and behavioral constraints.[2] The capital stock variable reflects both human and physical capital, which is assumed to be given in the short run and accumulating over the long run. The increase in agricultural yields over time reflects that accumulation of capital is due to both private and public investment (Mundlak 2001), which will not be explicitly modeled in detail but discussed subsequently.

The investment in agricultural capital at period t is denoted by I_t and is measured in monetary units. The agricultural capital is growing according to $\dot{S}_t = \frac{\mathrm{d}s_t}{\mathrm{d}t} = I_t - \gamma S_t$, where γ is the depreciation of the capital stock. Agriculture is subject to increased vulnerability from evolving diseases, and some of the investment is used to maintain agricultural production.[3]

The agricultural land available for production must go through a process of conversion. The total land available in the region is $\bar{A}$, and the stock of land available for agricultural activity at time t is denoted by $A_t < \bar{A}$. The cost of land use is increasing at an increasing rate, and includes both land preparation and transportation. We denote this cost as $C(A_t)$, where $C_{A_t} > 0$ and $C_{A_t A_t} > 0$ where the subscript denotes the order and variable with which the derivative is taken.

We conduct a partial equilibrium analysis where social welfare at each period is the result of benefits from consumption of agricultural output and environmental amenities minus the cost of production and investment. The framework is very similar to Hochman and Zilberman (1986), but allows a more flexible functional form. The benefit from consumption at time t is denoted by B_t and is measured in monetary units. The total benefit is the area under the inverse demand curve, $B_t = \int_0^{Y_t} D^{-1}(\varepsilon, \propto_t)\mathrm{d}\varepsilon$, where $D^{-1}(\varepsilon, \propto_t)$ is the inverse demand function with quantity ε, and $\propto_t$ is the benefit shifting parameter at time t. The benefit function represents the area under the demand curve, and a higher $\propto_t$ can represent increases in demand for output, say grain, because of biofuel or population growth. It is assumed that the marginal benefit of $\propto_t$ is positive. Consumers also benefit from

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[2] This distinction results from the Cambridge controversies (Cohen and Harcourt 2003). Xabadia, Goetz, and Zilberman (2006) derived such relationship with a dynamic framework—expanding on the original aggregation of Houthakker (1955).

[3] Zilberman (2014) presents a framework for modeling agricultural systems that recognizes heterogeneity among producers, dynamic elements, and evolving pest damage.

environmental amenities provided by wilderness not converted to agriculture. The amount of wildland at time t is $E_t = \bar{A} - A_t$, and the value of the environmental benefits from wildland, in monetary terms, at time t is denoted by $V(E_t, \beta)$, where β is an indicator of environmental awareness (higher levels of β reflect higher awareness), so $V_\beta(E_t) \geq 0$. It is assumed the environmental benefits of wildlands are increasing at a decreasing rate, thus $V_E\left(E_{t,\beta}\right) \geq 0$ and $V_{EE}\left(E_{tt,\beta}\right) \leq 0$.

Using this notation, the objective function of the dynamic optimization is

$$\underset{Y_t, X_t, A_t, E_t, I_t, C_t,}{\max} \int_{t=0}^{\infty} e^{-rt}[B(Y_t, \propto_t) - w_t X_t + V(E_t, \beta) - C(A_t) - I_t]\mathrm{d}t \tag{1}$$

Subject to:

$$\text{The production function constraint:} \quad Y_t = F(X_t, A_t, S_t) \tag{2}$$

$$\text{The full land use constraint:} \quad E_t = \bar{A} - A_t \tag{3}$$

$$\text{The equation of motion of agricultural capital:} \quad \dot{S}_t = \frac{\mathrm{d}S_t}{\mathrm{d}t} = h(I_t) - \gamma S_t \tag{4}$$

As a starting point, we assume that the concavity of the benefit and production functions and the convexity of the cost functions hold, so that the necessary conditions of optimal control apply (Caputo 2005).

The temporal Hamiltonian to this optimization problem is

$$\begin{aligned} H_t =&\{B(Y_t, \propto_t) - w_t X_t + V(E_t) - I_t - C(A_t) + p_t[F(X_t, A_t, S_t) - Y_t] \\ &+ e_t[\bar{A} - A_t - E_t] + u_t[I_t - \gamma S_t]\} \end{aligned} \tag{5}$$

where p_t is the shadow price of output, e_t the shadow value of environmental amenities produced on an acre of wildland, u_t the shadow value of expanding agricultural stocks by one unit at period t, and l_t the shadow value of expansion of land at period t.

The first-order conditions to this optimization problem are solved below where * defines the optimality outcome:

$$\frac{\partial H_t}{\partial Y_t} = 0 \Leftrightarrow B_{Y_t}\left(Y_t^*, \propto_t\right) = D^{-1}\left(Y_t^*, \propto_t\right) = p_t^* \tag{6}$$

$$\frac{\partial H_t}{\partial X_t} = 0 \Leftrightarrow p_t^* F_{X_t}\left(X_t^*, A_t^*, S_t^*\right) = w_t^* \tag{7}$$

$$\frac{\partial H_t}{\partial E_t} = 0 \Leftrightarrow V_{E_t}\left(E_t^*, \beta\right) = e_t^* \tag{8}$$

$$\frac{\partial H_t}{\partial A_t} = 0 \Leftrightarrow p_t^* F_{A_t}\left(X_t^*, A_t^*, S_t^*\right) = e_t^* + C_{A_t}\left(A_t^*\right) = V_{E_t}\left(E_t^*\right) + C_{A_t}\left(A_t^*\right) \tag{9}$$

$$\frac{\partial H_t}{\partial I_t} = 0 \Leftrightarrow u_t^* = 1 \tag{10}$$

$$-\frac{\dot{\partial} H_t}{\partial S_t} = \dot{u}_t^* - r u_t^* \Leftrightarrow \dot{u}_t^* = (r+\gamma) u_t^* - p_t^* F_{S_t}\left(X_t^*, A_t^*, S_t^*\right) \tag{11}$$

Equation (6) shows that at the social optimum, output is selected to meet the level required by demand. According to Eq. (7), variable input used in each period is at the level where the value of its marginal product is equal to its price. Equation (8) states that when land is allocated optimally to environmental activities, the shadow price of land is equal to the marginal value of environmental amenities provided by the land. Equation (9) states that the optimal allocation of land to agriculture occurs when the value of the marginal product of production minus marginal cost of land is equal to the shadow price of land, or put differently, when the value of output from the land is equal to the marginal cost of the land plus the marginal benefits of the environmental amenities provided by the land when not farmed agriculture. Equation (10) states that optimal investment in capital at time *t* should be where the social marginal value of the output it generates is equal to the marginal cost of investment (which is \$1 since investment is in monetary terms). Finally, condition (11) states that the temporal shadow price of the stock of agricultural capital changes over time so that growth in the shadow price of capital over time is equal to its shadow price multiplied by the sum of the discount and depreciation rates minus the value of the marginal product of agricultural capital. The reason for this condition is that delay in employing a unit of capital in production will enable gains from interest in alternative uses and will delay depreciation, but will lead to a loss of the output the capital would have produced during the period of the delay. Equations (6)–(11) and the early Eqs. (2)–(4) form the optimality conditions. The optimal path also includes the initial stock of agricultural capital S_0 and that the discounted shadow price of increasing agricultural capital reaches 0, as shown by the $\underset{t \to \infty}{\text{limit}} e^{-rt} u_t = 0$.

2.3 *The Implications of the Model*

Due to space limitations, we will not analyze the outcome formally through rigorous tools of comparative dynamics (Caputo 2005), but rather analyze the changes implied by the individual first-order conditions to approximate the direction of changes in key variables in response to changes of key parameters. In particular, we are interested in impact of changes in demand (larger $\propto_t$) and changes in environmental preferences (larger β) on the socially optimal outcomes.

1. **The impacts of a larger $\propto_t$**: Eq. (6) suggests that increase in demand for output will increase $D^{-1}(Y_t, \propto_t)$, and thus output price p_t, at least in the short run. Higher output price in the short run will lead to increased input use intensity [based on Eq. (7)], increased land use [as long as the land constraint is not binding, based on Eq. (9)], and increased investment (since the gain from future agricultural capital use increases).[4] Increased investment may increase capital accumulation over time (higher levels of S_t for $t > t_\alpha$ where t_α is the moment at which the demand increases). The larger agricultural stocks in the longer run (at some time $t > t_\alpha$) may lead to a partial reversal of the short-run effect—lower output prices, less variable input use, decline in overall land use, and slower investment.
2. **The impacts of a larger appreciation of environmental amenities (β) (from a certain $t \geq t_\beta$)**: According to Eq. (8), the immediate effect of this change may be to reduce land in agriculture.[5] The reduction of agricultural land because of higher β will increase output prices, increase variable input use, and may lead to further investment. In the longer run, higher investment increases agricultural capital and reduces output prices, which may counter some of the increase in variable input use but actually expand the reduction in land use if capital and land are substitutes.
3. **The impact of demand shifts on the dynamics of output**: Both $\propto$ and β affect the dynamic path of the optimal solution. If they are constant over time, the production and utility functions are concave in all inputs and the cost function is convex, the standard optimality conditions hold, and the model is likely to have a stable steady state (Caputo 2005). However, we assumed that $\propto_t$ is growing over time to represent population growth as well as the introduction of biofuels. β may increase as well due to heightened awareness of the benefit of environmental amenities. The increase in $\propto_t$ will raise prices, so output will increase over time. The increase in demand will also lead to an increase in investments, which will increase the capital stock, tending to reduce prices. One major issue in our analysis is the effect of agricultural capital on productivity. Historically, the increase in agricultural capital because of both public and private sector investments led to very large increases in output, which actually resulted in prices declining over time (Schultz 1964). There may be an element of increasing returns to scale in capital, and a more rigorous analysis may apply in some of the tools and thinking that was developed to address the economics of

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[4] Higher output price leads to lower gains from delaying the introduction of capital, since $\dot{u}_t = (r+\gamma)u_t - p_t F_{S_t}(X_t, A_t, S_t)$ declines over time and investment become more valuable. The increase in output price has the same qualitative effect as a reduction in interest rate, namely increased investment.

[5] Unless we are at a corner solution where all the land is in farming, as the increase in β is not sufficient to lead to conversion of land back from farming to wilderness.

increasing returns to scale (Arthur 1996). Thus, the relationship between output, land use, and variable input use is evolving over time, even under our optimal scenario. Given the difficulty in measuring capital, it is very unlikely that this relationship can be captured by a few stable or regular elasticities.

The analysis thus far has assessed the changes in optimal behavior with respect to biofuel production. The first-order conditions provide a benchmark to obtain many useful insights and analyze plausible scenarios. But outcomes in reality may deviate significantly from the optimal outcome. The economy may exhibit competitive behavior without any interventions to protect the environment or ensure the provision of public goods. Yet, comparison of such an economy with optimal outcomes can provide some key lessons. In particular:

1. **The importance and value of governance**—The optimal outcome may be obtained with a government that imposes: (i) an environmental policy (taxes, zoning, subsidies) where the de facto price of the land providing environmental amenities at each period is equal to e_t, and (ii) the appropriate support for R&D. The private sector will invest in private agricultural capital, but government intervention to finance public R&D is needed to complement it in order to provide the optimal $I_t = I_t^*$ in each period. An important exercise is to assess the social welfare under the optimal outcome versus a *laissez faire* regime.
2. **Likely underinvestment in agricultural capital**—There is a large literature documenting and analyzing the underinvestment in public research in agriculture. This underinvestment can be mostly explained by political economic reasons (Rausser, Swinnen, and Zusman 2011). In developed countries, total R&D expenditure has not declined over time because private sector investment increased during periods of decline in public sector spending. However, the literature suggests that public and private sector spending are not substitutes, rather they are complements, and thus the decline in public sector investment suggests overall underinvestment in research (Alston, Beddow, and Pardey 2009). In developing countries, the degree of underinvestment is more pronounced (Bell and Pavitt 1997). Underinvestment in agricultural research $(I_t < I_t^*)$ may lead to suboptimal levels of agricultural capital, slow increases in output, and a decline in prices over time.
3. **Likely overuse of land**—Assuming that during an initial period there is no enforcement of environmental policies ($e_{t_0} = 0$), and that there is low initial agricultural capital and underinvestment in agricultural capital such that $S_t < S_t^*$, the allocation choice of land in that period is determined according to:

$$p_t F_{A_t}(X_t, A_t, S_t) = C_{A_t}(A_t) \tag{12}$$

Comparison of Eq. (12) to Eq. (9) suggests that the likely lower marginal cost of land without government intervention will result in overuse of land for agricultural purposes, namely $A_t^* < A_t$. In some cases, it will result in agricultural settling of all the arable land so that after some point in time t_1, $\bar{A} = A_t$. The large amount of deforestation that occurred historically in older and population-intensive civilizations like Europe, China, and India may reflect centuries of growing demand, minimal environmental protection of wildland, and low technological progress. The settlement of the United States from coast to coast in the nineteenth century also reflects similar tendencies (Cochrane 1979), and much of the intensification of U.S. agriculture occurred after most of the continent was settled.[6]

Our discussions thus far suggest that introduction of environmental policies and expanded investment in agricultural R&D may actually lead to decline in total agricultural land. The idea that investment in research may lead to actual reduction in agricultural land is well known, and was previously suggested by Cochrane (1979). Cochrane (1979) also suggested that agricultural land in the United States reached a peak in 1920, and innovations and conservation programs led to smaller agricultural acreage levels throughout most of the twentieth century. Without concern about the environmental side effects of agriculture and technology that lead to intensification, population growth is likely to lead to expansion in agricultural land use and possibly deforestation (Binswanger and Mcentire 1987).

2.4 Going Beyond the Original Model

The formal model presented above simplifies primary features of the system to explain some key elements of the dynamics of land use. To develop a more complete understanding of reality, we discuss complexities and variations and their implications less formally.

1. **The difference between clearing of land and establishment of a farming system**. In our analysis, it is assumed that the transition from wildland to agricultural land is instantaneous. But, the reality is more complex—deforestation activities in many cases can occur instantaneously, but the conversion of forestland into productive agricultural land may take a long period of time. Geist and Lambin (2002) found that the purpose of deforestation might eventually be for agricultural settlement, wood use, and expansion of infrastructure, among other reasons. Wood has been a major source of energy for millennia and was a major cause of deforestation. The first wave of land use change involves clearing forests and using the wood for fuel or other purposes. Next, individuals begin deforesting land in order to start farming it extensively and establish property rights, which will enable them to benefit from more intensive use in the future (Southgate 1990). In those cases, land may be used as pasture before it is converted for intensive crop production. The original model can be developed along the lines of Southgate (1990) to account for these time delays. A major

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[6] In this case, there were political reasons for fast settlement.

point emphasized in our model that resonates with both Southgate and Geist is that intensive deforestation occurred mostly because of a lack of enforcement, as deforesters often did not pay the social cost of cutting the trees, but received the immediate benefits from its use. In cases where there is a time gap between significant agricultural utilization of land and deforestation, one may expect to see large amounts of land that are denoted as pastures or undeveloped land.

2. **Transportation costs**. We assume that marginal costs of production are increasing with acreage, and that may correspond to a situation where as acreage increases, transportation costs to an urban center or port is increasing. But, we did not explicitly consider the cost of transportation over space and how the costs of transportation may change over time as a result of investment and infrastructure development. For example, the building of railroads and waterways in the United States were crucial in the development of farming in the Midwest (Nichols 1969). Without sufficient infrastructure, roads, processing facilities, etc., development of intensive agriculture in frontier regions may be limited. Thus, more complete analysis of the relationship between agricultural output prices and land use may require taking into account the investment and time required to expand transportation systems as well as consider the constraints on land use expansion because of transportation costs.
3. **Variability**. Our analysis assumes homogenous, identical inputs as well as full certainty. However, Lichtenberg and Zilberman (1988) suggested that economic choices are affected by variability, which may include random events such as inclement weather, heterogeneity, and lack of knowledge. Timing of land use is affected by variability over time, both in terms of climate and economic conditions. Dixit and Pindyck (1995) suggested that the randomness of prices and other variables are considered in investment decisions, and that new investments are not made based on profitability under average conditions, rather when the profitability level is sufficient to overcome a hurdle that represents the cost of the uncertainty involved. Thus, their analysis suggests that uncertainty about economic conditions and other factors may serve to delay land use choices. Heterogeneity also affects land use patterns. Specific topographic and climatic conditions may affect where, how, and to what extent land use change occurs, and topographic barriers may set limits to such changes. Finally, knowledge and technology are also crucial in affecting the dynamics of land use changes. For example, the discovery of a new technology that utilizes wood may accelerate deforestation processes.
4. **Inventory considerations**. Our analysis assumes that output prices clear instantaneously, but major agricultural commodities are storable and random forces of weather and disease affect their supply. Thus, consumption and production choices as well as prices are affected by these inventory levels. When there is an increase in demand and inventories are low, prices will increase drastically, which may trigger increases in supply, including expansion of land use, which is much more significant than when inventories are sufficient (Wright 2011). Hochman et al. (2014) argue that the expansion of biofuel regulation in 2008 resulted in a large price effect because of the low level of inventory, and

Wright (2014) emphasized that the price increase was compounded by the effect of low inventory and expectation of higher prices in the future because of the biofuel mandate. These implications suggest that the dynamics of production and prices are affected by inventory availability and policy.

5. **Reforestation**. We assume that β is an indicator of environmental preference and that it may change over time. For example, as countries get richer, there is higher willingness to pay for environmental amenities. If this occurs, the optimal acreage allocated to agriculture may decline after it reaches a peak, and we may witness a phenomenon where land will be reallocated to wildland. This corresponds to observed situations in reality where there is reforestation. Our conceptual framework suggests that these situations are more likely to occur when the increase in β is combined with large increases in productivity and relatively low increases in demand.
6. **Political Considerations**. The analysis thus far reflects optimal choices by economic agents. But, land use decisions reflect policy choices by governments. Governments may elect to design institutions, build incentives, and encourage projects to expand the land they control. Design and construction of the railroads in the U.S. as well as the Homestead Act that provided people the right to land they settled were part of a large scale settlement in the U.S., among other projects (Cochrane 1979). The Brazilian government took initiatives to develop land in the Amazon, including developing a homesteading system and building the trans-Amazon freeway (Moran 1981). The Brazilian government also invested a significant amount in agricultural research infrastructure that resulted in soybean varieties that can grow under the agro-ecological conditions in Brazil. These development activities were conducted with the intention of developing millions of hectares of land. The expansion of soybean in Brazil combined R&D investment a significant amount of subsidies with a vision to expand close to one hundred million hectares of land, most of it outside the Amazon (World Development Report 1986; Goldsmith and Hirsch 2006; Warnknen 1999). Freire de Sousa and Busch (1998) emphasize the role of investment in R&D in establishing the Brazilian soybean industry, and argue that as a technology develops and settlement expands, networks of support for the nascent industry are established, which propel its growth even further.
7. **Distinguishing between short and long-term land expansion decisions**. Our discussion of possible expansions of the model has one common theme: there is a distinction between activities that result in long-term commitments and short-term choices. For example, the construction of a railroad, investment in research that results in new varieties, or investment in processing centers and land improvement are the major land use choices that establish long-term supply that allows short-term decisions to be made by comparing immediate revenues to costs. Much of the long-term expansion of agricultural capacity that drives the settlement process is determined as the result of long-term vision that takes into account long-term predictions as well as political considerations, and may not necessarily be affected by short-run fluctuations. Thus, settlement processes were motivated by both individual long-term profitability as well as desire for

> political expansion and economic development, but were constrained by either technical or financial feasibility, and in particular land availability and awareness of the value of alternative uses of the land in conservation or environmental amenities. Short-term considerations might affect the timing of execution of expansion activities as well as specific selection of crops and intensities.

Analysis of the model and its limitations has significant implications for analyzing land use changes associated with increases in demand. Because the amount of land available is finite, even under the simple formulation of the model, the rate of change of conversion of land to farming may vary over time depending on how much land has been developed and how much is left for possible development. It will also be affected by long-term investments in infrastructure and technology as well as regulation and market conditions. When agricultural expansion is profitable, land availability may be the driving constraint on expansion unless environmental regulations are introduced and enforced.

The numerical exercises that aim to calculate indirect land use through general partial equilibrium models or other simulations (Khanna and Zilberman 2012) assume that the integrated economic and agro-biophysical systems have regularity that can be captured relatively well through statistical means. The parameters of the systems are assumed to be regular, stable over time, and able to be estimated statistically to provide reliable predictions. For example, many of these models assert a constant elasticity or a consistent relationship between two variables of interest. However, our analysis thus far suggests that the process of land use change is dynamic and the parameters that reflect land use change may not be regular. It is a process with a beginning and an end that may evolve at a different pace over time and be represented by coefficients that also change over time. These changes in parameters may reflect omitted factors that introduce biases. Therefore, our conceptual model and discussion suggest that estimating stable and regular coefficients to capture the basic parameters of indirect land use may be challenging, and in many cases, not feasible. It suggests that coefficients of land use vary significantly with the method of estimation, location, and period of time.

3 Empirical Analysis

There are several bodies of evidence that support some of the major conclusions of our conceptual model. In particular, we will present evidence that shows that the agricultural acreage in developed countries will start to plateau over time, and only in regions where development is rising. Figure 1 shows the agricultural acreage in the United States. It shows that land in farms, including both pastures and cropland, reached a peak in the 1950s (Alston et al. 2009). Furthermore, cropland in the United States peaked in the 1920s, and during the post war period it increased and declined with the ebb and flow of agricultural business cycles (Cochrane 1979).

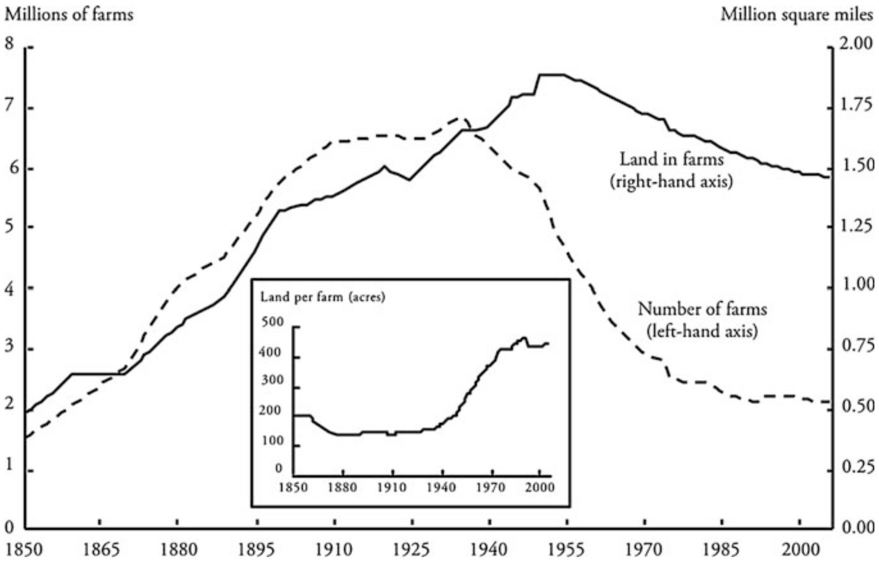

Fig. 1 United States Farmland Trend from 1850 to 2000; *Sources* Number of farms (1910–1999) and Land in farms (1911–1999) are from Olmstead and Rhode (2008, series Da 4 and Da 5, respectively). For both variables, values for 2000–2006 are from USDA ERS (2007); 1900 and 1890 values for farm numbers are from the U.S. Bureau of the Census (1975, series K-4 and K-5); 1910, 1900, and 1890 values for land in farms are from series K-5 of the same resource. *Notes* For farm numbers, intercensus values were estimated using a linear interpolation wherever no value was provided

Cochrane as well as Schultz also argue that in response to food shortages and increased demand in agriculture over the past century, in the short-term prices increase and crop acreage increases on the margin, but higher prices lead to investments in capital goods and increases in productivity, which leads to overshooting of demand and results in lower prices that reduce agricultural acreage on average (as shown in Fig. 2).

Furthermore, Goldewijk et al. (2004) analyzed land use change over the last 300 years and found that acreage of global agricultural cropland has expanded since the 1700s. As our model predicts, there are changes in regime once an implicit land availability constraint is binding. However, in the old world (Europe), acreage reached a peak in the 1920s and in new developed countries (United States, Canada, Australia) it reached a peak in the 1950s, but in the developing world, agricultural acreage continues to grow, as seen in Fig. 3 (Goldewijk et al. 2004). The land availability constraint is a result of both physical constraints and regulatory limits. We are aware that production in the Old World continues to grow significantly beyond the peak of acreage, and the same is true in the new developed countries like the United States and Australia (the countries that produce much of the world's food). In these countries, intensification was the main course of action to increase food supply, and sometimes, as Schultz and Cochrane argue, increases in

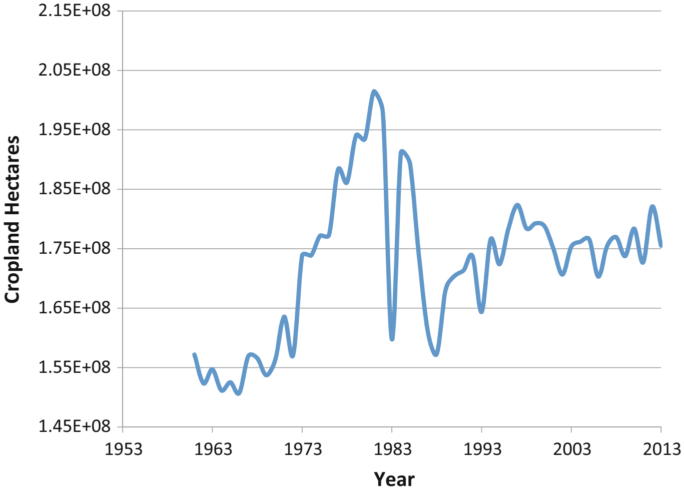

Fig. 2 Agricultural Acreage Trends in the United States from 1961 to 2013 *Source* Authors own aggregation from the Food and Agricultural Organization of the United Nations (FAO)

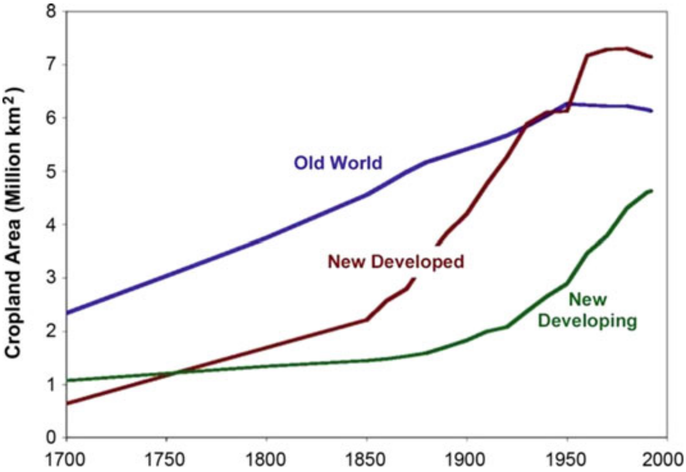

Fig. 3 Cropland trends in the developed and developing worlds *Source* Goldewijk et al., (2004)

productivity will outpace increased demand, causing agricultural acreage in these countries to decline. In the developing world, agricultural acreage continues to grow because of lack of environmental regulation and lack of investments in and capacity to increase intensification.

More refined analysis of land use change since the industrial revolution is shown in Table 1 (Goldewijk et al. 2004).

Table 1 Land use change by different types of land between 1700 and 1990

Reference year	Forest/woodland	Steppe/ savanna/ grassland	Shrubland	Tundra/hot desert/ice desert	Cropland	Pasture	Total
Klein Goldewijk (2004)							
Undisturbed	58.6	34.3	9.8	31.4	0.0	0.0	134.1
1700	54.4	32.1	8.7	31.1	2.7	5.2	134.1
1850	50.0	28.7	6.8	30.4	5.4	12.8	134.1
1990	41.5	17.5	2.5	26.9	14.7	31.0	134.1

Source Goldewijk et al. (2004)

As the table suggests, between 1700 and 1990, agricultural land increased by 37.8 million km^2 (from 8.1 to 45.7 million km^2). This change includes deforestation (12.9 million km^2), conversion of grassland (14.6 million km^2), shrubland (6.2million km^2), and tundra (4.2 million km^2). However, more than 2/3 of agricultural land is pasture (31 million km^2) while less than 1/3 is cropland (14.7 million km^2). More than twice as much of the converted land from its natural land uses was used as pasture, and much of the pasture is used extensively (i.e., much of the conversion of natural land uses was not to increase cropland, but to take advantage of the wood and other resources). The conversion to pasture was either because of the low productivity of the land as cropland or as a transitional state that would enable assumption of ownership of the land (Southgate 1990).

As Table 2 suggests, Brazil is an example of a country where most of the arable land is either in pasture or is available for agricultural production. Less than 20% is used for crop production and there is a large acreage in grazing, which is mostly done extensively. If there is a need to increase agricultural production when environmental regulations are enforced, it can come from conversion of rangeland to cropland, rather than deforestation.[7]

Obviously, increases in food prices make conversion of land to cropland more attractive. But in many parts of the world, most agricultural land reaches its peak and much of the conversion of land for agriculture was by nonagricultural uses. In particular, the major cause for the conversion to cropland was not the profitability of agriculture, but the fact that the economic and regulatory barriers to conversion were minimal.

Further evidence supporting our model was found in Swinton et al. (2011) and Barr et al. (2011). Swinton et al. (2011) estimated that between 2006 and2009, a 64% increase in profitability of agriculture increased acreage in the Midwest by only 2%. Their analysis implies a land elasticity with respect to profitability of 0.03,

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[7] There may be some GHG emissions from conversion of rangeland to cropland, but it depends on cultural practices (Lal 2002). For example, use of low or no tillage can minimize it, and in some cases can even help to rebuild the carbon stock in the soil.

Table 2 Land use in Brazil

Millions of hectares			% of Brazil	% of arable land
Brazil		**851.4**		
Total arable land		**329.9**		
1	Crop land—total	**59.8**	***7.0***	***18.1***
	Soybean	21.6	*2.5*	*6.4*
	Corn	14.4	*1.7*	*4.4*
	Sugarcane	8.1	*0.9*	*2.5*
	Sugarcane for ethanol	**4.8**	***0.6***	***1.5***
2.	Pasture land	**158.7**	***18.6***	***48.1***
3.	Protected areas and native vegetation	**495.6**	***58.2***	–
4.	Available area	**137.2**	***16.1***	–

Source IBGE (2011). Produção Agrícola Municipal. Instituto Brasileiro de Geografia e Estatística

which reflects farmers' reluctance to increase the land base because of implicit high marginal costs. They view it as a constraint in the introduction of second generation biofuel through expansion of the agricultural land base. Barr et al. (2011) estimated the elasticities of land use with respect to expected returns and implied agricultural commodity prices in the U.S. and Brazil. Like most of the literature that studies the elasticity of acreage of specific crops (e.g., soybean and corn) with respect to changes in returns or price, they study the elasticity of total acreage following the insight of Galbraith and Black (1938), namely that the elasticity of demand for land with respect to output price or profit is high, but that change in *total acreage* is much less elastic. It is surprising that despite the importance of these observations, no one until Barr et al. (2011) has attempted to verify it using recent data. Table 3 is based on their paper, and derives the elasticities of total agricultural acreage in the U.S. with respect to (w.r.t.) expected returns and agricultural commodity prices. As one can see, this elasticity is very low, reflecting what both our theory as well as Fig. 1 suggests.

The data from Brazil is more interesting. As Table 4 suggests, the elasticity of total crop acreage with respect to both returns and agricultural commodity prices is quite high, even though it has declined over the last 10 years. These elasticities are much higher compared to those in the United States, suggesting that crop acreage in Brazil is continuing to expand. As our theoretical model suggests, during a period of agricultural expansion, the elasticity is positive but not necessarily constant. The

Table 3 Elasticity of Land Use in the United States

		2003–05 to 2007–09	2004–06 to 2007–09	2007–09 trend to 2007–09 actual
United States	Acreage elasticity w.r.t. expected returns	0.005	0.014	0.028
	Implied acreage elasticity w.r.t. implied price	0.007	0.020	0.029

Table 4 Elasticity of Land Use in Brazil

		1997–99 to 2001–03	1997–99 to 2001–03 (2-year lag for land)	2004–06	2006–09
Brazil	Acreage elasticity w.r.t. expected returns	0.330	0.444	0.162	0.192
	Implied acreage elasticity w.r.t. implied price	0.664	0.895	0.382	0.477
Brazil (including pasture)	Acreage elasticity w.r.t. expected returns	0.100	0.122	0.003	0.033
	Implied acreage elasticity w.r.t. implied price	0.201	0.245	0.007	0.082

elasticity is close to zero when agricultural cropland has more or less stabilized, as is the case in the United States.

But, to gain a better understanding of the process of deforestation in Brazil, one must consider the elasticity of total agricultural land, including pasture, with respect to expected returns and crop prices. These elasticities of total agricultural land, including both cropland and pastures, are smaller than the elasticities of cropland with respect to expected returns and prices. Moreover, these elasticities decline significantly in the new millennium compared to the 1990s, despite the rise in the price of agricultural commodities. This result suggests that the expansion of agricultural land is mostly occurring into pasture, supporting our previous analysis that the deforestation process does not necessarily consist of immediate conversion of wildland to cropland, rather there is a transition period such that this land is converted to pasture. Furthermore, the decline in the elasticity of total agricultural land with respect to commodity prices since the new millennium suggests that the decline in conversion of wildland, including forests, into agricultural land (mostly pasture) occurred during a period when Brazil enforced stricter environmental laws to curb deforestation and commodity prices were rising. This suggests that an effective way to curtail the process of deforestation is to make it costly by instituting and enforcing strong forest and wildland protection laws.

Thus, if one is interested in assessing the impact of biofuel or similar activities that extend use of agricultural land, they should use the elasticities obtained by Barr et al. (2011) or similar studies that estimate elasticities of overall land conversion with respect to changes in commodity prices. Their low magnitudes as well as the aggregate data presented previously suggest that the effect of increasing commodity prices because of biofuel and other activities is minimal in mature countries as well as in growing countries that introduce effective environmental regulation.

One may argue that without the introduction of biofuel, the processes of reforestation would have advanced further, and thus biofuel may slow or reverse these processes, which may be the case. However, the process of reforestation is occurring because of the increase in the profitability of agriculture that leads to further innovation and enhancement of productivity per acre, and thus the increase in productivity induced by biofuel may eventually lead to contraction of the land base to the most productive land. The net effect is not clear, and we do not have a quantitative estimate for regulating the indirect land use effect of biofuel. But, it is clear that policies restricting the introduction of technologies that enhance agricultural productivity per acre do not help reforestation processes.[8]

4 Conclusion

This paper introduces a stylized, dynamic framework to analyze the evolution of land use expansion as well as deforestation over time, and suggests that given a finite amount of land and some social benefit from wilderness, the process of land expansion is of finite length, and as an economy matures, it will reach its peak and stabilize. This peak level will be determined by growth in demand, rate of technological change, and preference for environmental amenities. As technological change and environmental preferences begin to increase faster than increases in demand, the acreage in crops in the long run will decline, and in some cases may be associated with reforestation.

Empirical data appears to support the major implications of the conceptual model. Total crop acreage in the U.S. and Europe has already peaked, and has actually declined in recent years, while agricultural acreage in developing countries continues to increase. But, further analysis suggests that deforestation is not likely to lead directly to cropland expansion, but that there is a period of transition between deforested land and conversion to cropland where the land is either idle or used for pasture. In countries like Brazil, there is four times more land in pasture or that is underutilized than in cropland, suggesting significant potential for cropland expansion from pastures or underutilized land. Since the turn of the century, stricter environmental regulation was introduced in Brazil, and the total agricultural acreage, including cropland, has become much less responsive to changes in agricultural crop prices, suggesting that a major tool to slow deforestation is for the government to change deforestation policies. Deforestation declines if expansion of the land base is not an explicit objective of government policies as well as if there are forceful mechanisms to curb deforestation activities. The analysis suggests that it is unlikely to have a regular land use coefficient that can be utilized for a long period of time in policy analysis, and that effective environmental policy can curtail deforestation while increased agricultural prices will instead lead to intensification.

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[8] For example, the banning of GMOs. Barrows et al. (2014) demonstrate how the introduction of GMOs actually reduce the carbon footprint of agriculture.

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Global Land Use Impacts of U.S. Ethanol: Revised Analysis Using GDyn-BIO Framework

Alla A. Golub, Thomas W. Hertel and Steven K. Rose

Abstract This paper describes dynamic extension of the comparative static computable general equilibrium (CGE) GTAP-BIO model—framework employed in assessments of biofuel policies. In the dynamic extension, called GDyn-BIO, several structural components of the static model, including food demand responses to higher incomes and intensification options in land-based sectors and food processing, were revised to better capture changes in derived demand for land under pressure of growing population and per capita incomes. The impact of 15-billion gallon biofuel mandate on land use, analyzed with the GDyn-BIO model, evolves significantly over time. In particular, net global cropland brought into production due to the mandate declines over time, which is in sharp contrast to the results of static analysis where policy impacts are pictured as fixed for the next 30 years. Despite the fact that land use change impacts of this policy are transitory, environmental impacts and the global warming implications of such policies should not be underestimated. The policy causes earlier conversion of forest and pasture lands to cropland, resulting in earlier GHG emissions and lost carbon sequestration that contribute to global warming.

Keywords Biofuels · Dynamic general equilibrium model · Land use change

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A.A. Golub (✉) · T.W. Hertel
Department of Agricultural Economics, Center for Global Trade Analysis,
Purdue University, 403 W. State St., West Lafayette, IN 47907-2056, USA
e-mail: golub@purdue.edu

S.K. Rose
Electric Power Research Institute, 1325 G Street NW Suit 1080,
Washington, DC 20005, USA

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1 Introduction

Assessing global impacts of biofuels is a very complex task. Most of today's biofuels are produced from feedstocks traditionally used for food or animal feed, thus increased production of biofuels has a direct effect on food prices. As more agricultural land is diverted to biofuel production, demand for food, feed and fiber will likely lead to intensification on current cropland and pastures, as well as conversion of forests and other ecosystems to agricultural lands—the so-called indirect land use change effect. As production of first-generation biofuels expands, more coproducts become available to substitute for other feed in livestock feed rations. Further, the biofuel mandates affect the price of liquid fuels, which in turn affects the overall demand for liquid fuels, as well as agricultural and nonfarm production costs.

In recent years, many economic models, including partial and general equilibrium, static and dynamic, have been used to quantify the impacts of bioenergy on land use, food and fuel prices, and greenhouse gas emissions. One of them is a modified version of the GTAP computable general equilibrium (CGE) model nicknamed GTAP-BIO (Birur et al. 2008)—the modeling framework mandated for use in California's Low Carbon Fuel Standard assessments of biofuels. GTAP-BIO is static, yet most biofuel policies refer to some future period in time, and without an explicit baseline, it is difficult to evaluate the relative stringency of such policies. In addition, presenting biofuels-induced land use change analysis in the context of a dynamic baseline is more appealing to policy makers.

This chapter discusses the development and application of a recursive dynamic version of the GTAP-BIO model—GDyn-BIO—to the analysis of expanded production of U.S. corn ethanol over 2004–2030 period. While other analyses of biofuels have been done with dynamic models (Gitiaux et al. 2009; Laborde 2011; Wise et al. 2014), this work builds on a broad foundation of previous research and offers potentially valuable insights for policy makers. This includes effects of diminishing stringency of the policy, expected improvements in crop yields, and impact of factor accumulation overtime on path of land use change resulted from the expanded production of biofuel. Many structural elements of the static version of the model have to be modified to better represent land use change in the context of the dynamic analysis–responsiveness of consumer demand for food and intensification options in land using sectors and food processing. Further, in an attempt to improve GTAP-BIO framework, static or dynamic, in this chapter the structure of land supply is modified to reflect the greater sensitivity of land supply to relative returns among crops and livestock than between production forests and agriculture —where the land allocation decision can be irreversible in the near term.

2 Modeling Framework

2.1 Dynamic General Equilibrium Model

The model is based on two existing CGE platforms—the dynamic GTAP model nicknamed GDyn (Ianchovichina and McDougall 2001) and static GTAP-BIO (Birur et al. 2008). GDyn is a multisector, multiregion, recursive dynamic applied general equilibrium model that extends the standard GTAP model to include international capital mobility, endogenous capital accumulation, and an adaptive expectations theory of investment. This model was used to analyze the role of global economic integration, population and income growth in determining land use change with special attention paid to consumer demands and technological progress in agriculture as drivers for supply and demand for land (Golub and Hertel 2008). The previous analysis with this dynamic model, however, had not incorporated land use impacts of biofuels programs.

The GTAP-BIO (Birur et al. 2008) model is a modification of GTAP-E [GTAP-energy and environment model, Burniaux and Truong (2002) and McDougall and Golub (2007)] with standard GTAP sectors disaggregated to handle first-generation biofuels and their by-products (Taheripour et al. 2011a). Production and consumption structures of GTAP-E are modified to incorporate these new products. Grain-based ethanol, sugarcane ethanol, and oilseeds-based biodiesel substitute for petroleum products in liquid fuel consumption. Biofuels coproducts (Dried Distillers Grains with Solubles (DDGS) and oilseed-meals) compete with other feedstock in livestock feed use (Taheripour et al. 2011b). Several studies employed the static GTAP-BIO framework to analyze land use change impacts of expanded production of biofuels (Birur et al. 2008; Tyner et al. 2010; Hertel et al. 2010a; Taheripour et al. 2011b). However, due to static nature of the model, in these analyses the land use change impacts are pictured as permanent or at least fixed for some period of time. In contrast, analysis presented in this chapter demonstrates that land use changes from biofuel policies may be transitory.

2.2 Consumer Demand

The most important driver of the demand for land is the consumer demand for food. Changes in demands for staple crops, livestock products, and processed foods will determine changes in the derived demand for land in each of these activities. In GTAP-BIO, as well as in the standard GTAP model (Hertel 1997), the consumer preferences are represented by constant difference elasticity (CDE) consumer demand system.[1] The calibration of this demand system involves choosing the values of the substitution parameters to replicate the desired compensated, own-price elasticities of demand, then choosing the expansion parameters, to replicate the target income elasticities.

In the projections from 2004 to 2030, per capita incomes are rising significantly in developing countries, and food consumption response to changes in income is an important determinant of the derived demand for land. The income elasticities provided with GTAP Data Base package are obtained from estimating an implicit, directly additive demand system (AIDADS) on GTAP Data Base (Hertel et al. 2008). Comparison of the model income elasticities of demand for food with econometric estimates reported in Muhhamad et al. (2011) is shown in Table 1 for a subset of model regions. The comparison reveals that GTAP Data Base income elasticities for meat and dairy in developed countries are twice as large as the elasticities suggested by Muhhamad et al. (2011). For developing countries, GTAP income elasticities for both crops and meat and dairy are larger than estimated in Muhhamad et al. (2011) (Table 1). Thus, in simulations with the model, the impact of income growth on food consumption and derived demand for land may be too large. Further, one would expect that low-income countries are more responsive to changes in income and, therefore, make larger adjustments to their food consumption pattern when incomes change. For meat and dairy and processed food, this pattern is observed in Muhammad et al. (2011), but not in the GTAP Data Base income elasticities. Based on this comparison, it is desirable to recalibrate the income elasticities to move them closer to the estimates reported in Muhammad et al. (2011). It is also important to take into account that over the time horizon of this analysis, per capita incomes will grow, and goods that are luxuries in 2004 at low-income levels will become much less sensitive to changes in income in 2030 at higher incomes. With CDE demand system, however, consumption goods that are luxuries at the beginning of the projection period will remain luxuries as incomes grow over the time horizon of the analysis. For example, if meat consumption in a developing country is very sensitive to changes in income in 2004, it will remain very sensitive in 2030, even when per capita income improves relative to 2004. Thus, over time, as incomes grow in developing countries, initially large income elasticities for food may result in implausibly large growth in per capita food consumption in the model. To address these problems, first, the demand system is recalibrated using elasticities reported in Muhhamad et al. (2011). Second, the income elasticities for food in rapidly growing low-income developing economies are further modified so they more closely match the income elasticities for food in currently middle-income countries (a similar method is also used in Anderson and Strutt 2012).

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[1] CDE functional form was first proposed by Hanoch (1975). It is called “constant difference” because for consumption goods i, j and k the difference between Allen partial elasticity of substitution between commodities i and k and Allen partial elasticity of substitution between commodities i and j is constant. CDE lies midway between the nonhomothetic constant elasticity of substitution and the fully flexible functional forms (Hertel 1997).

Table 1 Comparison of income elasticities for food in GTAP v.7 data base and econometric study by Muhammad et al. (2011)

	USA	EU27	JAPAN	CANADA	Mala_Indo	CHIHKG	INDIA	S_S_AFR
GTAP v.7 Data Base								
Coarse Grains and crops	0.04	0.11	0.03	0.06	0.43	0.62	0.60	0.58
Meat and dairy	0.91	0.85	0.88	0.86	0.94	0.88	1.00	0.98
Processed food	0.95	0.93	0.93	0.92	0.72	0.78	0.68	0.79
Muhammad et al. (2011)								
Coarse Grains and crops	−0.09	0.02	0.08	0.08	0.25	0.25	0.54	0.51
Meat and dairy	0.34	0.49	0.49	0.47	0.64	0.64	0.78	0.77
Processed food	0.44	0.63	0.64	0.62	0.87	0.87	1.33	1.42

2.3 Production Structure

In the standard GTAP model, the production sectors are represented by constant returns to scale, nested constant elasticity of substitution (CES) functions, which first combine primary factors into composite value added, and imported and domestic intermediate inputs into composite intermediates, before aggregating these composites into an aggregate output. With income and population rising over the projection period, it is important to incorporate various intensification possibilities to respect historical observation and reduce pressure on scarce resources, such as land. For this purpose, standard production structure is modified in land using and food processing sectors.

In the livestock sectors, we implement a multilevel nested structure similar to one reported in Taheripour at el. (2011a). In the new structure, feed products are combined into a feed composite following multi-nested structure presented in Fig. 1. An important departure from Taheripour et al. (2011a) is that feed composite does not enter in fixed proportion with non-feed input and value added into aggregate output. Instead, feed is combined with land to allow direct substitution between feed and grazing. Therefore, if land rents rise faster than prices of feed composite over the projection period, dairy and ruminant meat producers will shift toward feedlots and intensify their production practices.

In crop production, we allow substitution between land and other inputs to reflect the fact that producers will use more fertilizers and other factors of production to increase yields per hectare as land rents rise under the pressure of increasing demand for land. To simplify calibration of the endogenous crop yield response, we follow Keeney and Hertel (2009) and represent crop sectors with a single (non-nested) CES production function. With this structure, land competes directly with all other inputs and the CES parameter and cost share of land in total crop sector costs determine the potential for substitution away from land and hence the yield response to crop price. Hertel and Keeney (2009) conduct a literature review and choose elasticity of corn yield with respect to corn price equal to 0.25.

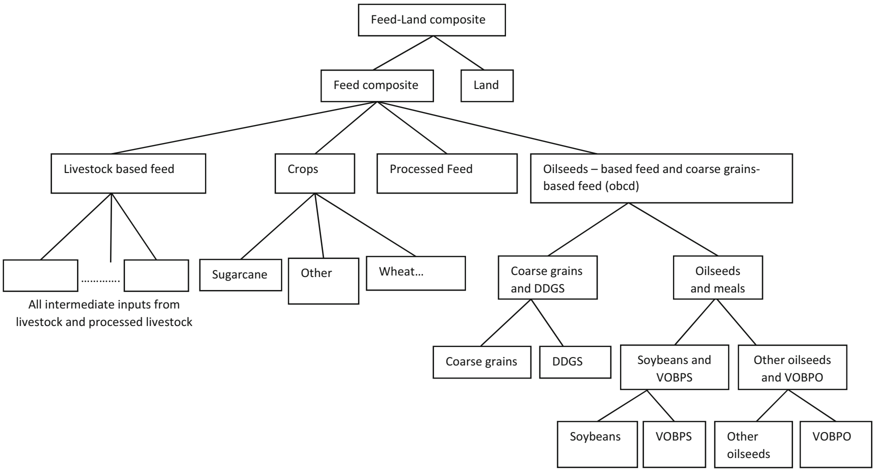

Fig. 1 Nested structure of feed-land composite in livestock sectors. *Note* Non-ruminant livestock sector does not use land. Its feed-land composite is just feed composite

This value was used in calibration of static GTAP-BIO. In this modeling, baseline land rents raise strongly from 2004 to 2030. When combined with relatively high elasticity of yields to prices, these factors contribute to large increase in crop yields over time. For this reason we choose smaller target for yield-to-price elasticity and calibrate crop production functions to 0.1 elasticity of crop yield to price. Our choice is motivated by Berry and Schlenker (2011) and econometric estimates for US corn yields reported in Huang and Khanna (2010) (Appendix 1 provides details of calibration of the CES parameter).

The fraction of the average consumer's food dollar devoted to the raw farm product has been continually declining over the past century (Wohlgenant 1989; Economic Research Service (ERS), US Department of Agriculture (USDA) 2006). For this reason, we introduce the possibility of substitution between farm and marketing inputs in processed ruminants, processed dairy, processed non-ruminants and other processed food. When farm prices rise, or technology changes, there is potential to reduce the cost share of processed sector outputs devoted to the farm product.

We now discuss intensification in forestry sector. In a model with many intensification options introduced in the agricultural sectors and sectors that process agricultural output, leaving forestry without an option to intensify leads to unrealistically large increases in land rents in forestry, relative to agricultural sectors, over the projection period. Representation of the forestry sector in the model follows standard GTAP production structure described above. When land rents rise, the only intensification option available to forestry producers in the model is substitution from land toward capital and labor within value added of the forestry sector. Using Global Timber Model (Sohngen and Mendelsohn 2007), Hertel et al. (2009) observe that changes in management intensity permit substantial changes in forestry output per unit of land. Based on this observation, we increase the elasticity of substitution between land and other value-added inputs in forestry sector.[2]

2.4 Supply of Land

Each model region's land endowment is disaggregated in an effort to reduce the heterogeneity of land. Following the pioneering work of Darwin et al. (1995), this is accomplished via the introduction of Agro-Ecological Zones (AEZs) (Lee et al. 2005). In each region of the model, there may be as many as 18 AEZs which differ along two dimensions: growing period (six categories of 60-day growing period intervals), and climatic zones (three categories: tropical, temperate, and boreal).[3] Even after introduction of AEZs, there is still considerable heterogeneity within these units, and this, in turn, is likely to limit the mobility of land across uses within an AEZ. In addition, there are many other factors—beyond those reflected in the diverse AEZs—that limit land mobility. These include costs of conversion, managerial inertia, unmeasured benefits from crop rotation, etc. (Golub et al. 2009). Therefore, land mobility across uses within an AEZ is constrained by a Constant Elasticity of Transformation (CET) frontier.

In the static GTAP-BIO model, land mobility is constrained by a two-level nested CET frontier. The land owner first decides on land allocation among three land cover types. Then, based on relative returns to various cropping activities, the land owner distributes land across crops. With cropland, pasture and forests in the same nest, this structure is likely to overstate land mobility between forests and agricultural land categories (cropland and pasture). In this dynamic model, the nesting structure is revised following the approach developed in Ahammad and Mi (2005) and later incorporated in the modified GDyn model (Golub and Hertel 2008). In the new structure (see Fig. 2), owners of the particular type of land (AEZ) first decide on the allocation of land between agriculture and forestry to maximize the total returns from land. Then, based on the return to land in crop production relative to the return on land used in ruminant livestock production, the land owner decides on the allocation of land between these two broad types of agricultural activities. Finally, based on relative returns in cropping activities, cropland is allocated to different crops. As the landowners' allocation decisions move down the supply tree (Fig. 2), the CET parameter increases by absolute magnitude, reflecting the greater sensitivity to relative returns among crops and livestock than between forestry and agriculture—where the allocation decision can

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[2] We increase elasticity of substitution in value added from 0.2, magnitude usually used in applications with the standard GTAP model, to 1.

[3] In each region of the model, there is a single national production function for each commodity. AEZs enter as inputs into this production function. Thus, in the model land use change results are AEZ and region specific, while changes in land using sector output are obtained at regional level. See Hertel et al. (2009) for further discussion of this modeling approach.

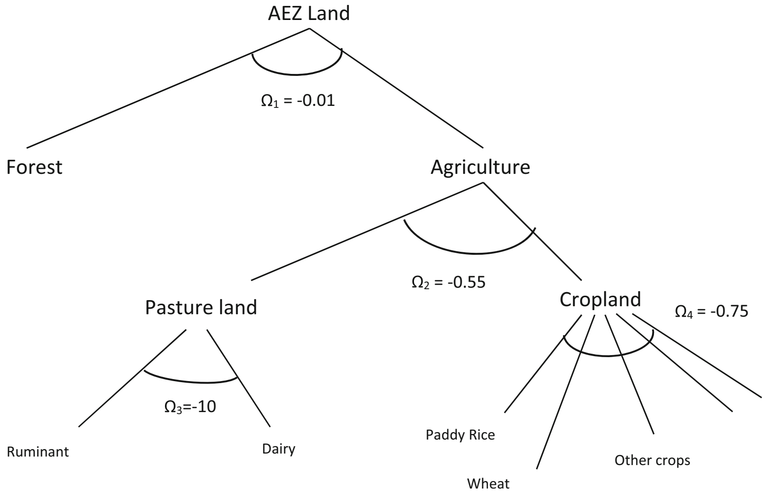

Fig. 2 Land supply structure

be irreversible in the near term (calibration of the nested CET is described in the Appendix 2).

One important limitation of the CET function is that the endowment constraint in the CET production possibility frontier for land in a given AEZ is not expressed in terms of physical hectares, but rather in terms of effective hectares—that is productivity-weighted hectares. To estimate land use changes measured in physical hectares, the static GTAP-BIO incorporates (1) an additional constraint that requires that physical hectares add up and (2) an endogenous adjustment variable which permits satisfaction of this additional constraint. These two elements are introduced at each level of the CET tree. That is, there is an adjustment and adding-up constraint for the crops nest, and separate adjustment and adding-up constraint for the land cover nest. The adjustment variable within the cropland nest reflects changes in average productivity of cropland in a given AEZ due to changing mix of cropping activities. Similarly, the adjustment variable within the land cover nest reflects changes in AEZ-wide productivity of land in a given AEZ due to changes in the mix of cropping, grazing, and forestry activities.[4]

The magnitude of these productivity adjustments are driven by differences in per hectare land rents. In the GTAP Data Base, cropland rents are much larger than land rents in forest and ruminant sectors. As a result, the productivity adjustments in the land cover nest may be large and can have a significant impact on the results. Yet, with some investments, the converted pasture or forest land might be nearly as productive as current crop land (Golub and Hertel 2012). For this reason, a model parameter that can be specified exogenously determines how many additional

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[4] See Golub and Hertel (2012) for detailed discussion of the endogenous productivity adjustments.

hectares of marginal lands are required to make up for one hectare of average crop land. Tyner et al. (2010) have calculated regional land conversion factors at the AEZ level using the Terrestrial Ecosystem Model (TEM) of plant growth and suggested the use of these factors to determine how many additional hectares of marginal lands are required to make up for one hectare of average crop land.

With the new land supply structure (Fig. 2), the adding up and the productivity adjustments should be introduced at each of the three levels of the CET tree. However, land rents per hectare in forestry are much smaller than land rents in agriculture, leading to very large areas of forests converted to agriculture, contrary to what we expected when we introduce additional nests. Instead of letting the model determine number of forest hectares to be converted for a given expansion of agricultural land, we assume that forests converted to agricultural land, on average, are equally productive as land currently employed in agricultural activities.[5] Given that cropland usually is much more productive than pasture, this also implies that forest land is more productive than current pasture land, but less productive than current cropland.

Moving to the next nest in Fig. 2 (cropland vs. pasture), we find that cropland rents per hectare are much larger than pasture land rents in the GTAP Data Base. Large differences between cropland and pasture rents per hectare results in large productivity adjustment within agricultural land nest. Following the approach employed with the two-nest land supply structure of GTAP-BIO, we use TEM-based factors (Tyner et al. 2010) to specify ratios of marginal land productivity to current cropland productivity across AEZs and regions. Cropland expands directly through conversion of pasture, but also indirectly through expansion of agricultural land (upper nest in Fig. 2). Thus, TEM-based factors used to quantify ratio of productivity of natural land (forest, grasslands, and other ecosystem types) to productivity of current cropland are also applied here.

All the model features listed above help to determine the extent of land use change in the model. Below we identify some key factors that operate at a sectoral level in order to determine changes in output of the corn ethanol sector.

2.5 *Ethanol and Energy Markets*

There are two types of demand for ethanol. Until recently, the main role of ethanol was a fuel additive—aimed at allowing the fuel to burn cleaner, thereby meeting stricter air quality standards. This demand became particularly important after the primary additive (MTBE) was banned due to its role in polluting groundwater.

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[5] We emphasize that this is an assumption. Using TEM, Tyner et al. (2010) estimated productivity of marginal land relative to productivity of current cropland. In principal, the productivity of forest hectares relative to productivity of current agricultural land can be estimated using TEM model and approach similar to one described in Tyner et al. (2010). However, such estimation is beyond the scope of this study.

The additive accounts for a relatively small share of total fuel use. Since it is demanded in fixed proportion to the total amount of fuel consumed, this source of ethanol demand is relatively price insensitive. The second source of ethanol demand is much more sensitive to price, as this demand is based on its energy content. This is where ethanol can potentially compete directly with petroleum products. The effectiveness of this competition depends first and foremost on the so-called ‘blend wall’ (Taheripour and Tyner 2008). While it is currently legal to sell gasoline which contains a 15% ethanol blend, this is only approved for use in more recently produced automobiles. As a consequence, there are few gas stations selling the E-15 blend. This means that the effective constraint on aggregate ethanol use in US liquid fuels for transportation is 10% of the total—since the E-10 blend is approved for use in all automobiles. However, with time, with the turnover in the auto stock, we expect the blend wall to become less prominent. As a result, we abstract from this in the subsequent discussion.

In the absence of a blend wall, the factors determining demand for ethanol as a fuel substitute in the model include the price of petroleum products and the elasticity of substitution between ethanol and petroleum products in liquid fuel mix in private consumption. The corn price, on the other hand, is the main determinant of the cost of ethanol production, and therefore it affects the equilibrium volume of ethanol produced. Here we focus on the elasticity of substitution between ethanol and petroleum products, and discuss factors influencing the cost of ethanol and the price of petroleum products in the baseline section below.

In the model, private consumption of ethanol, petroleum products, and other liquid fuels are combined into liquid fuels composite using CES function. The substitutability within the composite depends on the magnitude of the CES parameter which can be calibrated to an econometric estimate of ethanol–gasoline cross-price elasticity. Until recently, econometric estimates of the substitutability of biofuels for conventional fuels were unavailable due to the absence of historical data on biofuels in most parts of the world. For this reason, Birur et al. (2008) calibrate the CES parameter using general equilibrium simulation of the GTAP-BIO model over historical 2001–2006 period, taking into account drivers of demand for biofuels over this historical period. In a recent study, using 1997–2006 monthly data for ethanol (E85) and gasoline (E10) prices and sales volumes at 200 fueling stations in Minnesota, Anderson (2012) estimated elasticity of ethanol with respect to gasoline price. Anderson (2012) finds this elasticity ranges between 2.3 and 3.2. We use middle range estimate (2.75) to calibrate the substitution parameter between petroleum products and ethanol in private consumption in the model. This calibration results in smaller substitution parameter (2.9) than in earlier analysis with GTAP-BIO (3.95) suggesting that demand for ethanol is less sensitive to changes in gasoline price. The importance of the substitutability between biofuels and gasoline should not be underestimated. In our model, this parameter together with other factors (petroleum and corn prices) will determine equilibrium quantity of ethanol in the baseline simulation.

3 Baseline Assumptions

Together with the structure of the model outlined above, baseline assumptions determine crop yields, the level of biofuels produced over the time horizon of the analysis, and the overall demand for land.

Our analysis is based on the GTAP version 7.0 Data Base, representing global economy in 2004, aggregated up to 36 sectors and 19 regions (regional and sectoral aggregations are presented in Tables 5 and 6 in Appendix 3). Projections are undertaken from 2004 to 2030.[6] Over this period, labor force, population, and productivity growth are all exogenous to the model and therefore serve to determine its dynamic path. Historical and projected population and labor force (skilled and unskilled labor) growth rates for 2004–2030 are taken from Chappuis and Walmsley (2011). The population growth rates are highest in Sub-Saharan Africa region, and lowest (negative) in Japan and Russia (Table 2, column 3). Historical real GDP growth rates are taken from Chappuis and Walmsley (2011). The real GDP path for 2012–2030 is driven by assumptions about productivity growth in various sectors of the economy. Productivity growth rates in non-land using sectors are based on our assumptions about economy-wide labor productivity growth in each region (Table 2, column 2). These rates are adjusted for productivity differences across sectors using estimates reported in Kets and Lejour (2003). The resulting baseline annual average real GDP growth rates are shown in Table 2, column 6.

Land using sectors in the model include agricultural sectors and forestry. Agricultural sectors, in turn, include seven crops, ruminants, dairy, and non-ruminants. In our model, the non-ruminant livestock sector does not use land directly. However, it is a heavy consumer of feed which requires land for production. For the crops and livestock sectors, the projected total factor productivity (TFP) growth rates are taken from Fulgie (2010) and Ludena et al. (2006), respectively, and reported in Table 3. TFP growth rates in forestry are assumed to be equal to the average of productivity growth rates in crops, dairy and ruminants sectors, weighted by their output shares in total agricultural sector output. This assumption ensures that TFP is not a major source of forest land conversion in the model.

Processed food sectors' demand for farm-produced inputs (grains, fruits and vegetables, and meat) is another important determinant of the derived demand for land. This sectoral demand depends on technological improvements in food processing: sectors equipped with better technology will require fewer inputs to produce a given amount of output. We introduce technological progress in processed food sectors according to TFP growth estimates reported in Emvalomatis et al. (2009). These authors estimated TFP growth rates for ISIC 2 digit level category of manufacturing of food products, beverages, and tobacco. These correspond to the following sectors in the model: processed dairy, processed ruminants, processed

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[6] The step of projection is one year.

Table 2 Annual average labor productivity, population, skilled and unskilled labor, and real GDP growth rates, %

Region	Labor productivity	Population	Skilled labor	Unskilled labor	Real GDP
1	2	3	4	5	6
USA	1.1	0.99	1.61	0.15	1.61
EU27	0.9	0.39	1.50	−1.11	1.60
Brazil	1.5	0.93	2.99	0.58	3.05
CAN	1.1	1.04	1.34	0.45	1.83
Japan	1	−0.02	0.98	−1.45	0.71
CHIHKG	6 (2011–2015), 5 (2016–2030)	0.47	2.85	0.02	5.22
India	5 (2011–2015), 4 (2016–2030)	1.40	4.03	1.37	4.13
C_C_Amer	1.3	1.27	3.79	1.00	2.88
S_o_Amer	1.5	1.38	3.44	0.89	3.38
E_Asia	1.5	0.49	2.38	−0.35	2.81
Mala_Indo	3	1.14	3.98	0.92	3.92
R_SE_Asia	3	0.96	3.66	0.75	3.88
R_S_Asia	3	1.66	4.75	1.88	4.19
Russia	2	−0.02	0.85	−1.04	2.16
Oth_CEE_CIS	2	0.74	1.90	−0.32	2.49
Oth_Europe	0.8	0.72	1.48	−0.58	1.89
MEAS_NAfr	3	1.86	4.07	0.70	3.65
S_S_AFR	2	2.25	5.38	2.56	4.48
Oceania	0.8	1.57	1.88	1.02	2.40

non-ruminants, beverages, processed rice, and processed food. Emvalomatis et al. estimate TFP in food processing in EU to be around 0.8%/year from 2000 to 2005. This is similar to available estimates for US. In the absence of regionally differentiated estimates, we adopt the 0.8% annual rate of growth in TFP in food processing sectors in all regions.

In dynamic settings, a policy impact is evaluated relative to baseline path over time. With respect to biofuels, there are two approaches to construction of the baseline and policy scenarios. Under the first approach, the baseline depicts impacts of biofuel mandates over historical period, plus scenarios involving possible future developments in these policies over the time horizon of the analysis. To evaluate land use impacts of biofuel mandate under this approach, one needs to create counterfactual representing the world without the policy. Land use in the counterfactual scenario may then be compared to baseline, and any differences are attributed to expanded production of the biofuel.

Under the second approach to analyzing the impact of biofuel mandates in a dynamic model, the baseline is the world without biofuel targets, and thus, unobservable. In the baseline simulation, quantities of biofuels produced and consumed

Table 3 Annual average total factor productivity growth in agriculture and forestry, %/year

Region	Crops	Dairy farms	Ruminant	Non ruminant	Forestry
USA	1	0.30	0.30	0.67	0.85
EU27	1	0.30	0.30	0.67	0.86
Brazil	1	1.52	1.52	4.73	1.07
CAN	1	0.30	0.30	0.67	0.86
Japan	1	0.30	0.30	0.67	0.93
CHIHKG	1	3.27	3.27	6.90	1.14
India	1	1.52	1.52	3.52	1.03
C_C_Amer	1	1.52	1.52	4.73	1.09
S_o_Amer	1	1.52	1.52	4.73	1.10
E_Asia	1	1.52	1.52	3.52	1.04
Mala_Indo	1	1.52	1.52	3.52	1.02
R_SE_Asia	1	1.52	1.52	3.52	1.02
R_S_Asia	1	1.52	1.52	3.52	1.15
Russia	1	0.54	0.54	2.13	0.84
Oth_CEE_CIS	1	0.54	0.54	2.13	0.89
Oth_Europe	1	0.30	0.30	0.67	0.70
MEAS_NAfr	1	−0.28	−0.28	−0.24	0.78
S_S_AFR	1	0.57	0.57	−0.04	0.96
Oceania	1	0.30	0.30	0.67	0.75

Note Source for TFP growth rates in livestock is Ludena et al. (2006). 1% growth in TFP in crops is based on Fulgie (2010). TFP growth rate in forestry is weighted average of the TFP growth rates in crops and livestock

will change endogenously due to changes in supply and demand conditions (e.g., petroleum and corn prices in the case of US corn ethanol). Biofuel targets are imposed in the policy scenario. In this analysis, we adopt the second approach where in the baseline simulation we do not impose any of biofuel targets and quantities of U.S. ethanol (and other biofuels produced in US and other regions) are determined endogenously in the model, while in policy simulation the quantities of corn ethanol produced in U.S. are imposed exogenously.

We now turn to the elements of a baseline that determine the quantity of ethanol demanded and produced in the baseline. As noted previously, gasoline and ethanol are substitutes, and the price of gasoline is an important determinant of the demand for ethanol. Accordingly, we impose an exogenous path for the crude oil price from 2004 to 2030 using historical prices and the forecast from the International Energy Agency. The price of corn is the main determinant of ethanol production costs. While historical US corn price data are readily available, the use of these prices in the model baseline is problematic because historically observed prices are those that were themselves influenced by the mandate. In fact, recent estimates suggest that corn prices were about 30% greater, on average, between 2006 and 2010 than they would have been if ethanol production had remained at 2005 levels (Carter et al. 2012). Instead of corn price, we impose historically observed U.S. corn yields.

Yield outcomes in a given year are mostly driven by weather and past R&D, and are thus largely independent of the policy (ignoring the modest intensification effect which will be discussed below in the Results section). With corn yields exogenously imposed in the model between 2004 and 2011, we observe higher corn prices and higher cost of ethanol production in years when yields were low, and vice versa. Post 2011, U.S. corn yields are endogenously determined and heavily influenced by the crop TFP assumptions reported in Table 3.

The final element of the baseline relates to biofuel policies reflected in the database employed in the analysis. Until 2011, the U.S. government paid a tax credit to the blenders for each gallon of ethanol incorporated into liquid fuels, and a tariff was levied on imported ethanol. Both the tax credit (modeled here as a production subsidy) and the import tariff are present in the GTAP-BIO data base. These two instruments were eliminated in the end of 2011. To reflect these recent policy changes, we eliminate them in baseline and policy model simulations from 2012 onwards.

4 Results

4.1 Baseline

Assumptions about productivity improvements in crop and livestock sectors, the elasticity of demand for food with respect to changes in prices and income, as well as other structural and parameters assumptions, together determine the time path of global production of crops in the model. Overly income elastic demand and/or too high TFP growth may lead to unrealistically large increases in crops production. We conduct a simple validation exercise wherein global cereals output produced in the model over historical 2004–2010 period is compared to FAO data. In baseline simulation from 2004 to 2010, global cereal production increases by 8.3% which closely follows historical changes in global cereals production (8.8%) (FAOSTAT).

Driven by the demand for food, and other non-food demands, global cropland expands by 4.7% between 2004 and 2030 in the baseline. The main source of the new cropland (95%) is conversion of pasture land that is reduced by 2.5% between 2004 and 2030. Over this time horizon, 0.2% of accessible forests are converted to new cropland, contributing about 5% of the total cropland expansion. Figure 3 shows regional changes in cropland, pasture, and forest area in thousands of hectares. In all regions, almost all additional cropland comes from pasture—a factor driven by our land supply structure discussed above. By 2030, forest area declines in all regions except Russia. USA, Rest of South Asia (R_S_Asia), Russia and East Europe and Rest of Former Soviet Union are large contributors to global cropland expansion (Fig. 3). Within crop land uses, wheat and paddy rice areas experience reductions, while coarse grains and other agriculture areas (fruits and vegetables and plant-based fiber) expand. Crop yields in the baseline are driven by TFP

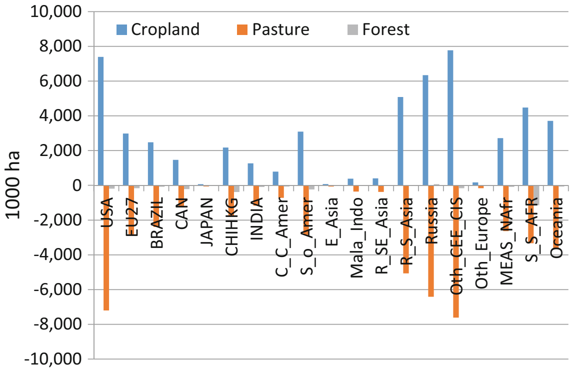


Fig. 3 Regional baseline changes in land cover between 2004 and 2030, 1000 ha

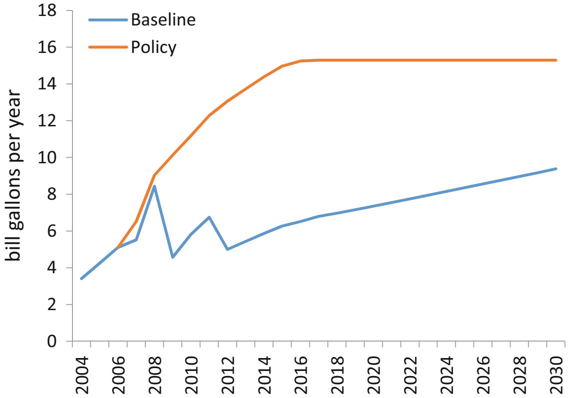
Table 4 Coarse grains yield decomposition, 2004–2030 cumulative % change

Component of yield change	USA	EU27	CHIHKG	INDIA
Driven by TFP assumption	27.2	29.5	29.5	29.5
Intensification effect	2.6	1.8	3.2	5.4
Extensification effect	−7.2	−5.8	−5.7	−0.2
Total change in yield	21.1	24.2	26.0	36.2

growth, endogenous yield intensification, and changes in yields as marginal lands and/or land under other crops are converted. By way of example, changes in coarse grains yields are decomposed into these three components in four regions of the model (Table 4). TFP is the main source of yield changes, followed by the yield drag caused by area expansion into less productive lands, which is offset to some degree by the endogenous intensification of production in response to land scarcity.

In the baseline, volumes of corn ethanol and other biofuels produced reflect those quantities demanded in the absence of biofuel targets. They are determined endogenously in the model and driven by petroleum prices, the ease of substitution between petroleum products and biofuels, and the cost of biofuel production. The baseline quantity of US ethanol fluctuates between 2007 and 2013 and then gradually rises to about 9 billion gallons per year in 2030 (Fig. 4, blue line). The increase in 2008 and subsequent reduction in 2009 are driven by fluctuations in fossil oil prices. The reduction in 2012 is due to elimination of the tax credit to the blenders and tariff on imported ethanol. This baseline indicates that, without the mandate, US corn ethanol production would not reach 15 billion gallons per year neither by 2015, nor anytime over the next 15 years. Therefore, in this analysis the biofuel mandate is always binding over the baseline.

Fig. 4 Mandated and baseline volumes of US ethanol, billion gallons per year



4.2 *Impacts of Expanded Production of US Ethanol*

In the policy scenario, the ethanol mandate comes into play in 2007 with the volumes of ethanol produced following the historical volumes in 2007 and 2008, and then those volumes reported in the FAPRI Agricultural Outlook.[7] After 2015, the volume of U.S. corn ethanol is fixed at the 15 billion gallons per year (Fig. 4, orange line).

Globally, prices for all food categories rise, relative to baseline, due to the biofuel mandate. The largest impact is observed in coarse grains, followed by soybeans and then other cereals and food products. The cumulative deviation from baseline in the US coarse grains price index reaches 10% in 2016 and then declines to 7% in 2030 (Fig. 5). Consumption of all food categories falls in all regions with largest reduction observed in consumption of livestock products (0.32% reduction of non-ruminant meat consumption in US), but the impact on quantities consumed is much smaller than on prices.

Policy-induced changes in global cropland, pasture, and forests are shown in Fig. 6. These changes represent deviations from baseline and are measured in 1000 ha. Pasture land is the main source of the new cropland with only a small fraction of forests lost due to expanded production of US ethanol. The largest changes in land use due to the expanded production of US ethanol are observed in 2009—about 800,000 hectares of additional cropland are brought into production. After 2013, the land use change impact gradually diminishes to about 100,000 hectares of additional cropland brought into production. Regional impacts of the expanded production of US ethanol on land use are shown in Fig. 7a–c in terms of

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[7] We use FAPRI-CARD control case production levels available at http://www.noticeandcomment.com/3-Fapri-Card-Control-Case-Results-fn-53809.aspx. Historical volumes of US corn ethanol production were higher during 2009–2011 and lower in 2012 and 2013 than in FAPRI-CARD control case. Historical volumes are reported by Renewable Fuels Association http://www.ethanolrfa.org/pages/statistics#B.

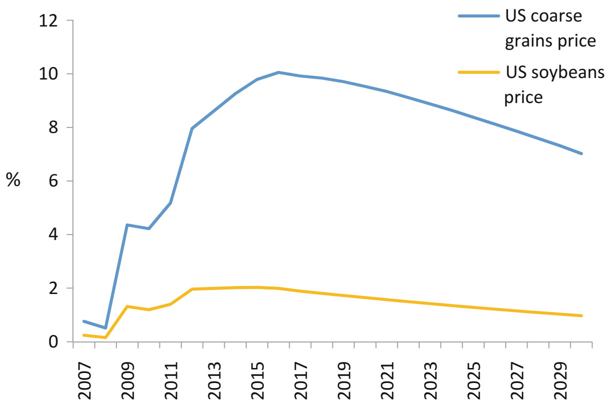

Fig. 5 US coarse grains and soybeans price effects of expanded production of US ethanol, cumulative % deviation from baseline

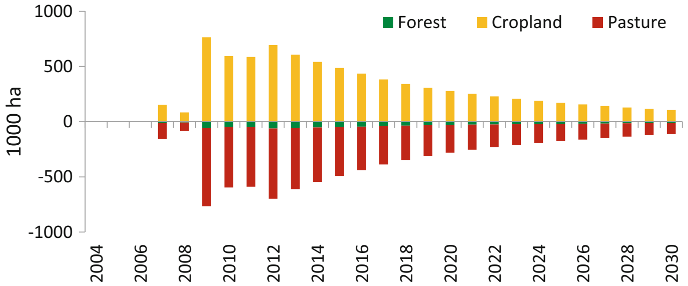

Fig. 6 Global land conversion due to expanded production of US corn ethanol, 1000 ha difference between policy and baseline

absolute deviations (1000 ha) from baseline. The largest cropland expansion and reduction in pasture land are observed in US, followed by Europe (Fig. 7a, b). Regional reductions in forest area are much smaller than reduction in pasture land, and most noticeable in Africa, Asia, and Europe (note change in scale in Fig. 7c).

The impact of the policy on land use pictured in this analysis is transitory, with land conversion due to the mandate diminishing over time (Fig. 6). There are two reasons for this outcome. First, given our assumptions about crop TFP growth as well as oil prices, baseline quantities of ethanol are rising over time while the mandated quantity is fixed after 2015. This results in a reduction in the additional quantity of ethanol that the mandate is forcing onto the market (the difference between orange and blue lines in Fig. 4 is getting smaller). In addition to this, the net additional cropland requirement per unit of additional ethanol produced falls over time.

The net additional cropland requirement metric is often used as a summary measure of the impact of biofuel policies on land use. It is calculated as ratio of a net increase in global cropland, induced by expanded production of biofuel, to that additional amount of biofuel. This summary metric is plotted in Fig. 8. In this analysis, we started from static a version of GTAP-BIO model. In the static version, increase in US corn ethanol production from 2004 level (which is 3.41 billion gallons per year) to 15 billion gallons per year results in 0.18 ha of net additional cropland per each 1000 gallons of additional ethanol forced into the market.[8] This result is shown by purple line in Fig. 8. The blue line in the same figure shows the ha/1000 gallons metric calculated with GDyn-BIO. For each year within the analytical time horizon of the dynamic analysis, the metric is calculated in similar fashion: it is a ratio of net increase in global cropland (yellow bar in Fig. 6) to additional ethanol forced into the market due to the mandate (the difference between orange and blue lines in Fig. 5). For example, in 2015 the difference between policy and baseline volume is 8.7 bill gallons, and the difference between policy cropland and baseline cropland is 486,784 ha. The metric is 486,784/(8.7*10^6) = 0.06 ha/1000 gallons in Fig. 8. In the dynamic analysis, the net additional cropland requirement metric shows a gradual decline from 0.15 in 2007 (the first year when policy is implemented) to 0.02 ha/1000 gallons in 2030. The implication of the gradual decline is that the average net cropland requirement depends on time horizon of the analysis. For example, over 2007–2030 period weighted average net cropland requirement per 1000 of gallons of additional ethanol produced is 0.05 ha/1000 gallons, while weighted average over 2007–2015 period is 0.08 ha/1000 gall.[9]

Why is the impact of the policy pictured in the dynamic analysis so different from the static results? There are several important differences between dynamic framework developed in this study and the static framework from which we started. First, some of the structural elements of the model were modified. These include: introduction of intensification possibilities in food processing, livestock, and forestry sectors, and reduced response of yields to crop prices. Other things being equal, intensification options in livestock and forestry should increase availability of cropland: as land rents increase due to expanded production of ethanol, livestock, and forestry producers will substitute away more easily from relatively more expensive land input. The assumption of less sensitive crop yields to prices should also result in larger ratio of additional cropland requirement per 1000 of gallons of ethanol produced. Intensification in food processing, on the other hand, has opposite effect making non-biofuel demand more elastic and reducing amount of

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[8] Khanna and Crago (2012) compare this metric across studies devoted to estimation of land use change impacts of expanded production of biofuels. For earlier studies employing GTAP-BIO, Khanna and Crago (2012) report ILUC in 30-90 hectares/million liters range for expanded production of US corn ethanol. In this chapter, we start from static version of GTAP-BIO and find that ILUC impact of expanded production of US corn ethanol is 0.18 ha/1000 gallons. 0.18 ha/1000 gallons equivalent to 48 hectares/million litters. This is within the range reported in Khanna and Crago (2012) and close to the results in Tyner et al. (2010) included in Khanna and Crago (2012) survey.

[9] The weighted average is calculated as sum over time of additional (to baseline) cropland divided by sum over time of additional ethanol forced into market.

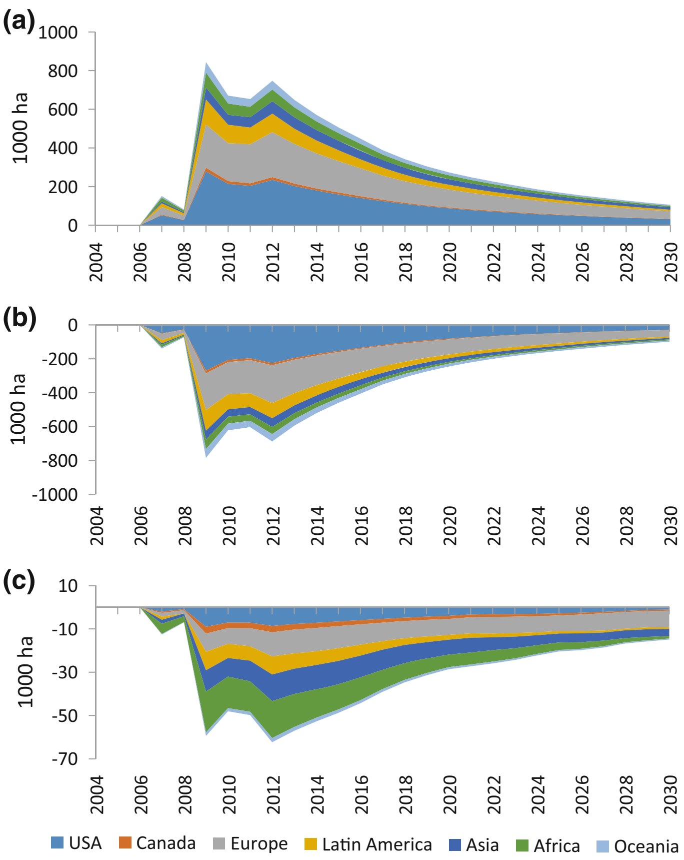
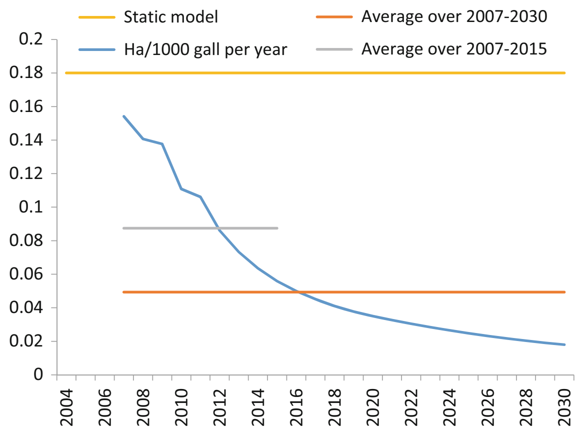


Fig. 7 **a** Regional changes in cropland due to increased production of US ethanol, 1000 ha deviation from baseline. **b** Regional changes in pasture due to increased production of US ethanol, 1000 ha deviation from baseline. **c** Regional changes in accessible forest area due to increased production of US ethanol, 1000 ha deviation from baseline

Fig. 8 Global additional cropland requirement per 1000 gallons of extra US ethanol produced, ha/1000 gallons



land conversion as a consequence of the mandate. Another modification of the model structure relates to the land supply. Though the direction of impact of this change to the model is difficult to assess a priori, we expect this modification will result in small changes in the net cropland requirement for a given biofuel shock,[10] but change the composition of land converted to cropland with more pasture and less forest converted. The overall impact of these structural changes can be assessed by implementing these changes in the static GTAP-BIO framework, estimating the net cropland requirement due to the mandated 15 billion gallons of corn ethanol, and comparing the results with those from the static model before the changes in structure. The comparison reveals that the structural changes alone do not result in reduction in the net global cropland requirement per 1000 gallons. In fact, they lead to an increase in the net global cropland requirement from 0.18 to 0.27 ha/1000 gallons, suggesting that increasing impacts of lower crop yield elasticity and added intensification in livestock and forest sectors dominate decreasing impact of intensification in food processing on net cropland requirement.

A second important difference between the dynamic and static analyses is that the dynamic analysis captures future changes in technology. Crop yields are rising from 2004 to 2030 driven by TFP growth and intensification induced by higher crop prices. These factors result in smaller gross cropland expansion for a given quantity of ethanol. For example, doubling corn ethanol production in 2004 (increase from 3.41 bill gallons to 6.82 bill gallons) at corn yield observed in 2004 (9.08 tonnes/ha) results in 3.84 mill hectares of gross cropland expansion. To increase corn ethanol production by the same amount in 2030 at projected 11 tonnes/ha yield (see Table 4 for cumulative 2007–2030 yield increase), one would need just 3.17 mill hectares of gross cropland expansion.[11]

Finally, as primary factors of production (capital and labor) are accumulated over time, agents' responses to any lingering changes in market signals becomes more price elastic. To isolate these adjustments from impacts of changes in productivity and population growth, we construct hypothetical world where only capital can grow over time.[12] In this experiment, we eliminate all changes in productivity, as well as any labor or population growth. We also eliminate the potential for intensification in the crops sectors. In the absence of total factor

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[10] Small changes in the net cropland requirement may be due to general equilibrium effects. For example, compare to two levels CET, with three levels CET changes in the composition will leave more land in forests and less land in pasture. This, in turn, will affect relative prices of crops, livestock and timber, which in turn, may affect demand for crops, cropland area employed in production, and finally, net cropland requirement.

[11] The calculation assumes that ethanol yield (gallons per tonne of corn) does not change over time.

[12] Depreciation (fixed rate in this analysis) and investment determine capital stock in each period in each region. Investments are driven by disparities in rates of return to capital across regions. Over time, investors gradually reallocate capital across regions to equalize rates of return in the long run. When the hypothetical economy achieves steady state, capital does not change and investment is only sufficient to cover depreciation. See Ianchovichina and McDougall (2001) for details.

productivity growth and intensification, yields on current cropland are fixed.[13] We conduct two sets of illustrative experiments. The first set compares general equilibrium (GE) demand elasticities in the beginning (2004) and end of analytical time horizon (2030) to demonstrate that demands become more elastic over time. The GE elasticity reflects adjustments in all markets and can be constructed for a commodity in a given region by shocking market price of the commodity in that region by 1% and recording the effect of the increase on the commodity output.[14] Taking coarse grains in the US as an example, the demand elasticities for this commodity in 2004 and 2030 are −0.7 and −0.9, respectively. Another example is energy intensive sector in US with elasticities −1.6 and −2.1 in the beginning and end of the analytical time horizon, respectively. These examples show that *demands become more elastic over time as capital accumulates in the economy.*

The second set of experiments with this hypothetical economy demonstrates that even in the absence of endogenous and exogenous (TFP) improvements in yields, the net cropland requirement falls over time. In the baseline of this experiment, the quantity of ethanol is fixed at 3.41 billion gallons per year over the entire 2004–2030 period. In the policy scenario, the quantity of corn ethanol is increased from 3.41 to 15 billion gallons in 2005 and is fixed at this level until 2030. Thus, in this experiment, the difference between policy and baseline quantities of ethanol is the same over the analytical time horizon and equal to $15 - 3.41 = 11.59$ billion gallons. Figures 9 and 10 show that the net global cropland expansion and net additional cropland requirement per 1000 gallons of ethanol falls nonetheless. In the final experiment, we eliminate intensification options in livestock and forestry and compare net cropland expansion and ha/1000 gallons ratio (gray lines in Figs. 9 and 10) with the results obtained when these sectors can intensify their production (blue lines). When no intensification in livestock and forests is allowed, initial cropland expansion is smaller than in the case with intensification. This makes sense. When option to intensify forest and livestock sectors is not available, land required for corn for ethanol production will come mostly from other crops, resulting in smaller total cropland expansion. In contrast, if intensification options in forest and livestock are available, when land rents go up due to the expanded production of ethanol, producers of livestock and forests will intensify their production. Land that is freed up in this process will be converted to cropland and result in larger net global cropland expansion.

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[13] Average yield, however, is not fixed due to changes in yields on extensive margin (land conversion from one crop to another and conversion of marginal lands to cropland); these cumulative 2004–2030 changes in yields are small in this experiment.

[14] In the model, under the standard closure, the market price is an endogenous variable and output tax/subsidy is exogenous. To measure GE elasticity, market price is “swapped” with output tax such that the tax variable become endogenous and price become exogenous and available for shock.

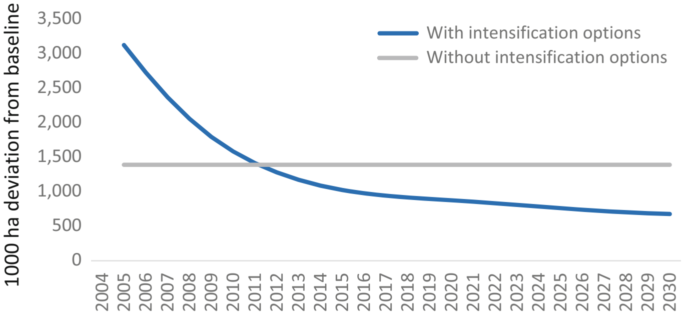

Fig. 9 Net global cropland expansion due to increased production of US ethanol in the absence of total factor productivity growth, labor and population growth, and intensification in crop sectors, 1000 ha deviation from baseline. *Blue* and *gray lines* shows the deviation with and without intensification options in livestock and forestry

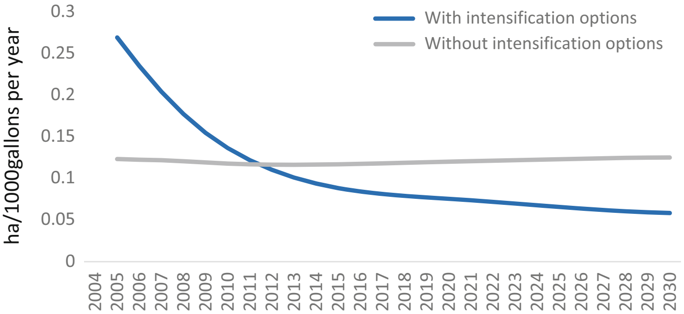

Fig. 10 Global additional cropland requirement per 1000 gallons of extra US ethanol produced in the absence of total factor productivity, labor and population growth, and intensification in crop sectors, ha/1000 gallons per year. *Blue* and *gray lines* shows the ratio with and without intensification options in livestock and forestry

A second observation is that, when no intensification options are allowed, net global cropland expansion and ha/1000 gallons do not change over time horizon of the analysis. In contrast, with intensification options, ha/1000 gallon and net global cropland expansion are higher initially but then they fall over time. Gradual fall in net cropland expansion indicates that land initially drown into crop production returns back to livestock and forests. Given that there is no intensification in crops allowed, this indicates gradual reduction in crops output deviations from baseline. Over time, relatively cheap capital becomes available to substitute for resources in limited supply. Goods and services that do not use land or can substitute away from land (forest and livestock in this experiment) become relatively cheaper, and consumption bundle shifts away from crops and crops-based goods.

5 Summary

This chapter documents a dynamic version of the GTAP-BIO model and conducts illustrative analysis of the impact of expanded production of US corn ethanol on land use. Several structural elements of the model were revised to better capture changes in derived demand for land in the medium to long run. Per capita food demand responses to changes in income in the model were modified to match econometric estimates more closely. Various intensification options in land using sectors and food processing were incorporated to reduce pressure on land resources from growing population and per capita incomes.

The impact of the ethanol mandate on land use pictured in this analysis evolves significantly over time. In particular, net global cropland brought into production due to the biofuel mandate declines over the time horizon studied here. This stands in sharp contrast to the results of static analysis where policy impacts are pictured as fixed for the next 30 years—an assumption often made to allocate the GHG emissions from land use change to the volume of biofuels produced (Searchinger et al. 2008; Hertel et al. 2010a).[15] There are several forces behind the result. First, driven by increasing price of fossil fuels and crop yields, use of ethanol is expanding in baseline path of the global economy. Thus, baseline volumes of ethanol are rising while the mandated quantity is fixed after 2015. These factors result in falling stringency of the mandate and in diminishing over time additional quantity of ethanol the policy forces into the market. Second, net additional cropland requirement per unit of additional ethanol produced is falling. This is partly due to growing crop yields over the time horizon of the analysis in all crop sectors and regions, but also market adjustments in the long run.

Despite the fact that land use change impacts of this policy are transitory, environmental impacts and the global warming implications of such policies should not be underestimated. Let us assume an extreme case when stringency of the mandate falls to zero by the end of analytical time horizon (baseline and policy ethanol volumes are the same in the end of the analytical time horizon). This would also suggest that additional global cropland brought into production by the policy is gradually falling and cumulative deviation in global cropland in policy scenario from baseline is zero. Though cumulative impact of the policy on cropland is zero, the policy, however, causes earlier conversion of forest and pasture lands to cropland than it would happen in the absence of the policy (Fig. 6). The earlier land use changes result in earlier GHG emissions and lost carbon sequestration that contribute to global warming (O'Hare et al. 2009; Kloverpris et al. 2013).

A natural next step in this analysis is to translate estimated changes in land use to GHG emissions. Ideally, one would like to measure cumulative land use change emissions due to biofuel policy as a difference between policy and baseline emissions from land use changes. Gibbs et al. (2014) developed new geographically explicit

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[15] Hertel et al. (2010a) attempts to overcome this “fixed” impact by conducting post simulation adjustment to reflect corn yield growth in US between 2001 and 2007.

estimates of soil and biomass carbon stocks consistent with GTAP model region and AEZ definitions. Using this data base, Plevin et al. (2014) constructed detailed region and AEZ specific carbon fluxes by combining carbon stock estimates by Gibbs et al. (2014) with assumptions about carbon loss from soils and biomass, mode of conversion, forgone sequestration, and other assumptions. Extending this work to changes in land use modeled in dynamic settings will enable quantification of land use change GHG emissions from biofuel policies modeled with GDyn-BIO.

Appendix 1: Calibration of the Crop Production Functions

Following GTAP-BIO, in this modeling the functional form of a crop sector (coarse grains, wheat…) is represented by a nested CES. All non-energy inputs (including land) and capital-energy composite are in the same nest. For the CES production structure, the own Allen-Uzawa elasticity of substitution (AUES) of input *i* entering the top of the production structure can be calculated using this formula

$$\sigma_{ii} = \left(1 - \frac{1}{S_i}\right) * \alpha \tag{1}$$

where σ_{ii} is own-AUES elasticity of input i, S_i is cost share of input i in total cost of the sector, and α is substitution parameter in the CES production function. Using (1), parameter α can be expressed as a function of the cost share and own-AUES

$$\alpha = \sigma_{ii} S_i / (S_i - 1) \tag{2}$$

For a given estimate of own-AUES, parameter α can be calibrated using (2). Keeney and Hertel (2009) develop a simple theoretical model of supply and producer demand for production factors. Assuming factor market equilibrium, they solve the model for own-price elasticity of sector output. The elasticity depends on the AUES, factor supply elasticities and cost shares of production factors. Next, those authors define a long run as a period over which prices of non-land factors are determined outside of the agriculture, and these factors are available to crop sectors at infinitely elastic supply. Then, land remains the only quasi-fixed factor of crop production. Given these assumptions

$$\varepsilon_i = -\sigma_{\text{land,land}} \tag{3}$$

where ε_i is supply elasticity of crop output (e.g., coarse grains), and $\sigma_{\text{land, land}}$ is land own-AUES.

If land is fixed, then the only way producers can increase the coarse grains output is through the increase in yield. Thus, using Eqs. (2) and (3) and land cost shares, crop production function can be calibrated to a given own-price yield elasticity.

Appendix 2

In this model, land supply is represented with three-level nested CET frontier (Fig. 2). The values of the CET parameters are calibrated to estimates of own-return land supply elasticities (Lubowski 2002; Ahmed et al. 2008). The relationship between CET parameter in the top of the nested structure and own-return land supply elasticity to forest use is

$$\sigma_1 = \frac{\varepsilon_{\mathrm{f}}}{\theta_{\mathrm{f}} - 1} \tag{4}$$

where σ_1 is the CET parameter in the top nest of the nested structure, ε_{f} is own-return land supply elasticity to forest use, and θ_{f} is forest land rents share in total land rents. In U.S., for 10 year time span, Ahmed et al. (2008) report $\varepsilon_{\mathrm{f}} = 0.01$ (Fig. 2). Share of forest land rents in total U.S. land rents is 0.13 (GTAP 7 Data Base). Using (1), the calibrated elasticity of transformation in the upper nest of the land supply tree in U.S. is −0.01.

Moving down the tree structure to the agricultural land nest, the relationship between CET parameter and own-return elasticity of land supply to cropping activity is

$$\sigma_2 = \frac{\varepsilon_{\mathrm{c}} - \sigma_1(\theta_a - 1)\theta_{\mathrm{c}}}{\theta_{\mathrm{c}} - 1} \tag{5}$$

where σ_2 is the CET parameter within agricultural land nest, ε_{c} is own-return land supply elasticity to cropping activity, and θ_{c} is crop land rents share in total land rents. In U.S., ε_{c} is about 0.1 (Fig. 2 in Ahmed et al. 2008). Share of crop land rents in total U.S. land rents is 0.82 (GTAP 7 Data Base). Using (2), the calibrated elasticity of transformation in the agricultural land nest of the land supply tree in U. S. is −0.55. The elasticity of transformation among crops and the elasticity of transformation in ruminant livestock nest are left the same as in the earlier analysis with GTAP-BIO, at −0.75 and −10, respectively (Tyner et al. 2010).

To calibrate the elasticities of land transformation in other regions, region specific estimates of own-return elasticities of land supply are needed. For many regions, however, such estimates do not exist. In this analysis we assume that elasticity of transformation in a given level of the CET structure is uniform across AEZs and regions.

Appendix 3

Table 5 Aggregation of GTAP regions

Code	Region in the model	GTAP regions
USA	United states	United states
EU27	European Union 27	Austria, Belgium, Denmark, Finland, France, Germany, United Kingdom, Greece, Ireland, Italy, Luxemburg, Netherlands, Portugal, Spain, Sweden, Cyprus, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Bulgaria
BRAZIL	Brazil	Brazil
CAN	Canada	Canada
JAPAN	Japan	Japan
CHIHKG	China, Hong Kong	China, Hong Kong
INDIA	India	India
C_C_Amer	Central and Caribbean Americas	Mexico, Rest of North America, Costa Rica, Guatemala, Nicaragua, Panama, rest of North America, Rest of Central America, Caribbean
S_O_Amer	South and Other Americas	Colombia, Peru, Venezuela, Rest of Andean Pact, Argentina, Chile, Uruguay, Rest of South America
E_Asia	East Asia	Korea, Taiwan, Rest of East Asia
Mala_Indo	Malaysia and Indonesia	Indonesia, Malaysia
R_SE_Asia	Rest of South East Asia	Cambodia, Lao People's Democratic Republic, Myanmar, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia
R_S_Asia	Rest of South Asia	Bangladesh, Pakistan, Sri Lanka, Rest of South Asia
RUSSIA	Russia	Russian Federation
Oth_CEE_CIS	Other East Europe and Rest of Former Soviet Union	Albania, Belarus, Croatia, Ukraine, Rest of Eastern Europe, Rest of Europe, Kazakhstan, Kyrgyzstan, Turkey, Armenia, Azerbaijan, Georgia, Rest of Former Soviet Union, Rest of Europe, Rest of Eastern Europe
Oth_Europe	Rest of European Countries	Switzerland, Norway, Rest of EFTA
MEAS_NAfr	Middle East and North Africa	Iran, Egypt, Morocco, Tunisia, Rest of North Africa, Rest of Western Africa
S_S_AFR	Sub Saharan Africa	Nigeria, Senegal, Rest of Western Africa, Central Africa, South Central Africa, Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, South Africa, Rest of South African Customs
Oceania	Oceania	Australia, New Zealand, Rest of Oceania

Table 6 Aggregation of standard GTAP sectors and new biofuel-specific sectors

Code	Sector in the model	GTAP commodities
Paddy_Rice	Paddy Rice	pdr
Wheat	Wheat	wht
CrGrains	Coarse grains	gro
Soybeans	Soybeans	New commodity disaggregated from osd
Soybeans		New commodity disaggregated from osd
Sugar_Crop	Sugar cane, sugar beet	c_b
OthAgri	Other agriculture goods	v_f, pfb, ocr
Forestry	Forestry	frs
Dairy	Raw milk	rmk
Ruminant meat	Cattel, sheep, goat, horses	ctl, wol
Non Ruminant meat	Non-ruminant livestock	oap
Proc_Dairy	Processed dairy products	mil
Proc_Rum	Processed ruminant meat products	cmt
Proc_NonRum	Processed non-ruminant meat products	omt
vol	Vegetable oils and fats	vol
Bev_Sug	Beverages, tobaco, sugar	sgr, b_t
Proc_Rice	Processed Rice	pcr
Ofd	Food products n.e.c.	ofd
OthPrimSect	OtherPrimary: Fishery & Mining	fsh, omn
Coal	Coal	coa
Oil	Crude Oil	oil
Gas	Natural gas	gas, gdt
Oil_Pcts	Petroleum	p_c
Electricity	Electricity	ely
En_Int_Ind	Energy intensive Industries	i_s, nfm, fmp, crp
Other_transp	Other transport	otp
Water_transp	Water transport	wtp
Air_transp	Air transport	atp
Oth_Ind_Se	Other industries and services	tex, wap, lea, lum, ppp, nmm, mvh, otn, ele, ome, omf, cns, trd, cmn, ofi, isr, obs, ros
NTrdServices	Other services (Government), dwellings, water	osg, dwe, wtr

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Land Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy

Xiaoguang Chen and Madhu Khanna

Abstract This paper examines the changes in land use in the U.S. likely to be induced by biofuel and climate policies and the implications of these policies for GHG emissions over the 2007–2030 period. The policies considered here include a modified Renewable Fuel Standard (RFS) by itself as well as combined with a cellulosic biofuel tax credit, a carbon price policy, or a low carbon fuel standard (LCFS). We use a dynamic, spatial, multi-market equilibrium model, biofuel and environmental policy analysis model (BEPAM), to trace the impacts of alternative biofuel policies on the mix of biofuel feedstocks, crop prices, land use pattern, and GHG emissions. We endogenously determine the effects of these policies on cropland allocation, food and fuel prices, and the mix of first- and second-generation biofuels. We find that the RFS could be met by diverting 5% of cropland for biofuel production and would result in corn prices increasing by 31% in 2030 relative to the business-as-usual baseline. The reduction in GHG emissions in the U.S. due to the RFS is about 4%; these domestic GHG savings can be severely eroded by emissions due to indirect land use changes and the increase in gasoline consumption in the rest of the world. Supplementing the RFS with a carbon price policy, a cellulosic biofuel tax credit, or a LCFS induces a switch away from corn ethanol to cellulosic biofuels and achieves the mandated level of biofuel production with a smaller adverse impact on crop prices. These supplementary policies enhance the GHG savings achieved by the RFS alone, although through different mechanisms; greater production of cellulosic biofuels with the tax credit and the LCFS but larger reduction in fossil fuel consumption with a carbon tax.

X. Chen
Research Institute of Economics and Management, Southwestern University of Economics and Finance, 610074 Chengdu, China
e-mail: cxg@swufe.edu.cn

M. Khanna (✉)
Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Urbana, IL, USA
e-mail: khanna1@illinois.edu

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1 Introduction

Concerns about energy security, climate change, and air quality have led to considerable policy support for biofuels in the U.S. The Renewable Fuels Standard (RFS) requires the blending of 136 billion liters of biofuels with petroleum fossil fuels by 2022. This includes up to 57 billion liters of corn ethanol, at least 61 billion liters of cellulosic biofuels, and 19 billion liters of undifferentiated advanced biofuels based on their lifecycle greenhouse gas (GHG) emissions relative to conventional gasoline. The U.S. also provides a cellulosic biofuel producers tax credit (CBPTC) to fuel blenders to reduce their costs of meeting the RFS mandates. The CBPTC was authorized by the Farm Conservation and Energy Act of 2008 and re-authorized by the Farm Bill in 2012. The tax credit is uniform across all cellulosic biofuels produced from various cellulosic feedstocks. Moreover, a performance-based standard implemented in California and being considered by several states and at the national level is a LCFS that requires blenders to meet an increasingly stringent target to reduce GHG intensity of transportation fuel.[1]

These policies can have significant direct and indirect implications for land use in the U.S. and elsewhere by diverting land from existing uses to biofuel feedstock production and by affecting crop prices and the profitability of alternative land uses. These biofuel policies can also affect GHG by promoting the production of biofuels and reducing the consumption of fossil fuels. The land use and GHG effects of biofuel policies will depend on the nature of the policy support, the type of biofuels that are induced, and technology development in the biofuel industry.

The first-generation biofuels currently consumed as a transportation fuel in the U.S. are mainly derived from food-based crops, such as corn and soybeans, and sugarcane ethanol imported from Brazil. Concerns about their negative impacts on food prices have led to increased emphasis on the development of second-generation biofuels produced from nonfood-based cellulosic biomass feedstocks, such as crop and forest residues, dedicated energy crops (switchgrass and miscanthus), and short-rotation woody crops. These feedstocks differ considerably in their yields, land use requirements, and GHG intensity relative to each other and relative to first-generation feedstocks (Khanna et al. 2011a). Currently, cellulosic biofuels are not produced on a commercial scale due to high industrial

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[1] A state-wide LCFS has been established in California, which requires a 10% reduction in the GHG intensity of transportation fuels sold in the state by 2020 CARB. "Proposed Regulation to Implement the Low Carbon Fuel Standard Volume I." California Environmental Protection Agency Air Resouces Board: http://www.arb.ca.gov/fuels/lcfs/030409lcfs_isor_vol1.pdf. Many other states have also proposed regional or state-level LCFS and a proposal for a national LCFS was also included initially in the proposed American Clean Energy Security Act in 2009.

processing costs and high production costs of cellulosic biomass. Several possible biomass feedstocks and conversion technologies are currently under research and development and expected to be available over the next two decades (EIA 2010; Hamelinck and Faaij 2006).

Biofuel policies differ in the mechanisms through which they affect the competitiveness of different types of biofuels. The RFS is likely to induce the least-cost cellulosic biofuels that meet the GHG saving threshold. The addition of volumetric subsidies is expected to shift the mix of biofuels toward low-cost and high-yielding feedstocks but not necessarily towards the ones with lower GHG intensity. Because the LCFS provides implicit subsidies for biofuels based on their GHG intensity relative to the standard, the levels of subsidies provided to biofuels will not be uniform. Therefore, compared with the RFS and the volumetric subsidies, the LCFS is more likely to encourage the production of biofuels with lower carbon intensity. Alternatively, a carbon tax can provide incentives to produce cellulosic biofuels due to their lower carbon emissions than first-generation biofuels. However, the carbon tax would induce the least-cost strategy for reducing GHG emissions, and may not be large enough to induce any cellulosic biofuels.

The purpose of this paper is to examine the impacts of alternative biofuel and climate policies on the mix of feedstocks induced, spatial and temporal changes in land use, and implications for GHG emissions. The policies considered here include the biofuel mandate by itself as well as combined with the CBPTC, a carbon tax and a LCFS, respectively. We analyze the effect of these policies on land use change and specific geographical locations and types of land likely to undergo changes in cropping patterns. Moreover, we examine these effects to variations in various demand-side and supply side conditions that can influence the mix of biofuels produced and their competitiveness with fossil fuels, including fuel demand elasticity, land availability and crop production costs.

When assessing the impact of biofuel and climate policies on GHG emissions, it is important to consider two market-mediated effects of biofuels on GHG emissions in the agricultural and fuel sectors, namely the indirect land use change (ILUC) effect and the rebound effect. The ILUC effect is expected to arise because the increase in crop prices in the world markets induces crop acreage expansion on native vegetation and forested land in other regions of the world which releases the carbon stored in these ecosystems. Estimates of the ILUC effect of biofuels differ across studies, across feedstocks, and across modeling assumptions within a study (Khanna and Crago 2012; Khanna et al. 2011b). Here, we do not determine the magnitude of the ILUC effect of biofuel production. Instead, using estimates of the ILUC effect obtained by other studies, we examine the extent to which it offsets the GHG savings achieved in the U.S. under various policy, technology, and market scenarios.

As a large consumer of world oil production, policy-induced biofuel production in the U.S. that displaces oil consumption in the world market is expected to lower the world price of oil. This will cause gasoline consumption to decrease by less than it would have in the absence of this price effect, and lead to a rebound effect in the domestic and rest of the world (ROW) gasoline markets. Estimates of this global rebound effect of biofuels differ across studies and within a study depending on the scenario (see Chen et al. 2012). The global rebound effect can offset some of the reduction in demand for gasoline that would otherwise have been displaced by biofuels and reduce the GHG savings achieved by biofuels. We examine how the rebound effects differ as biofuel policies and market and technology parameters (such as the elasticities of demand and supply of gasoline) change.

We conduct this analysis using a dynamic, multi-market equilibrium, nonlinear mathematical programming model, BEPAM (Chen et al. 2012). The model simulates the transportation and agricultural sectors in the U.S. and considers trade in gasoline, biofuels, and agricultural commodities with the ROW. It endogenously determines the effects of various policies on land allocation, fuel mix, and prices in markets for fuel, biofuel, food/feed crops and livestock and on GHG emissions in the U.S. at annual time scales over the period 2007–2030. Among the alternative fuels we consider first-generation biofuels produced domestically from corn and soybeans and imported sugarcane ethanol. We also consider various second-generation biofuels from cellulosic feedstocks.

2 Previous Literature

Several partial equilibrium and computable general equilibrium models have been used to examine the implications of the RFS-induced first-generation biofuel production in the U.S. for food/feed prices and land use (see review in Chen et al. 2011; Khanna et al. 2011a). These models have focused on analyzing the ILUC effect of biofuels but have not analyzed the direct and indirect effects of the biofuel mandate on land use change and aggregate GHG emissions. Using the global trade analysis project (GTAP) model, Hertel et al. (2010) examine the direct and indirect land use changes of the mandate for corn ethanol in the U.S. They find that the corn ethanol mandate only leads to a very modest increase in cropland (by about 1%) in the U.S. with much of the increase in land under biofuel feedstocks coming from a reduction in land under other agricultural crops and some from reductions in land under pastureland and accessible forest land. They also find that biofuel production is expected to reduce the world price of oil. However, they do not examine the magnitude of the rebound effect and its implications for aggregate GHG emissions from fuel consumption. The Forest and Agricultural Sector Optimization Model (FASOM) includes both first- and second- generation biofuels and examines the implications of the RFS (Beach and McCarl 2010). It suggests a modest impact of the RFS on land use with some increases in cropland and pasture land accompanied by a reduction in land under forests.

These studies discussed above examine the effect of biofuels on GHG emissions from the agricultural sector but do not examine the overall implications of biofuels for GHG emissions from the fuel sector. These studies differ in the manner in which they model the demand for biofuels and incorporate the feedback effect of biofuels on oil prices. While GTAP assumes that biofuels and oil are imperfectly substitutable with a constant elasticity of substitution, the FASOM model assumes that the two are perfect substitutes. The FAPRI-CARD model includes demand curves for each of the ethanol blends (E10, E85) that differ in their price responsiveness (Elobeid et al. 2007). The newer version of the FAPRI-CARD also includes a reduced form relationship between the production of biofuels and the price of oil.

Several studies have examined the effects of biofuel policies on GHG emissions by focusing only on the fuel sector. Thompson et al. (2011) find that the biofuel mandate, tax credits and tariff in the U.S. can increase or decrease GHG emissions depending on the mix of corn and sugarcane ethanol consumption they induce in the U.S. and the extent to which they cause a reduction in biofuel consumption abroad and its replacement by oil. Drabhik and de Gorter (2011) analyze the effects of a blend mandate with and without a tax credit on GHG emissions and find that while the mandate reduces domestic GHG emissions it increases global GHG emissions by 0.6–0.7%. The provision of a tax credit with the mandate could result in higher or lower emissions because it lowers fuel price for consumers domestically (which increases domestic demand for gasoline) but can lead to an increase in world gasoline price and a smaller international leakage effect relative to a mandate alone. Using a stylized model, Hochman et al. (2010) examine the effect of the structure of the oil market on the GHG emissions reduction due to a biofuel mandate in the U.S. They show that GHG emissions reduction is higher if OPEC behaves as a monopolist and reduces oil production in response to the emergence of biofuels. Chakravorty and Hubert (2013) use a regionally aggregated global model to show that a blend mandate reduces fuel consumption and direct emissions in the U.S. (by 1%) and the world but increases global emissions due to a large ILUC effect.

BEPAM differs from the other partial equilibrium models in several aspects. First, it integrates the agricultural and fuel sectors and endogenously determines the mix of feedstocks used to produce biofuels and the share of first-generation and second-generation biofuels. Second, it derives the demand for alternative fuels from projected demands for alternative types of gasoline and diesel vehicles with consideration of their technological limits to fuel substitution. These technological limits to substitution change over time as the vehicle fleet structure changes to allow higher substitutability among fuels in the future. Third, it considers separate supply functions for domestically produced gasoline and imported gasoline, and determines the imports and the price of gasoline in the U.S. endogenously. Fourth, the regional land use and crop production decisions in BEPAM are made at Crop Reporting District (CRD) level (each CRD consists of 9–10 countries), which takes into account regional heterogeneity in crop yields, costs of production, and resource availability. Finally, given the uncertainties about market and technological conditions, we examine the sensitivity of the land use and GHG outcomes of biofuel policies to various parameter assumptions and provide an assessment of key factors likely to determine the effect of these outcomes.

BEPAM has been used previously to analyze the impacts of various biofuel and climate policies, such as the RFS, a LCFS and a carbon tax, on agricultural and transportation fuel markets (see Chen et al. 2011, 2012, 2014; Huang et al. 2013). Chen et al. (2011) examined the impact of the RFS on agricultural commodity prices, while Chen et al. (2014) compared the welfare effects of the RFS, a LCFS, and a carbon tax that are normalized to achieve the same level of domestic GHG emissions. Chen et al. (2012) discussed the impacts of different biofuel policies and production technologies (both demand and supply sides) on aggregate GHG emissions and regional land use changes.

3 Model Description

BEPAM is a multi-market, multi-period, price-endogenous, nonlinear mathematical programming model that simulates the U.S. agricultural and fuel sectors and the formation of market equilibrium in the commodity and fuel markets including international trade with the ROW. Market equilibrium is achieved by maximizing consumers' and producers' surpluses in the fuel and agricultural sectors subject to various material balances, resource availability constraints, and technological constraints underlying commodity production. This model determines several endogenous variables simultaneously, including vehicle kilometers traveled (VKT), fuel and biofuel consumption, domestic production and imports of liquid fossil fuels, imports of sugarcane ethanol, mix of biofuels and the allocation of land among different food and fuel crops, and livestock over a given time horizon.

3.1 Transportation Fuel Sector

The transportation sector considers demand curves for VKT with conventional vehicles, flex-fuel vehicles, gasoline hybrid vehicles, and diesel vehicles, which set limits on the potential to blend fossil fuels and biofuels. The demand for VKT with these alternative types of vehicles generates demands for liquid fossil fuels and biofuels given the energy content of alternative fuels, the fuel economy of each vehicle type, biofuel blend limits for each type of vehicle and a minimum ethanol blend for all gasoline to meet the oxygenate additive requirement. More details can be found in Chen et al. (2012).

The biofuel sector includes several first- and second-generation biofuels; the former consists of domestically produced corn ethanol and biodiesel as well as imported sugarcane ethanol while the latter consists of biofuels produced from cellulosic biomass (such as crop and forest residues, miscanthus, and switchgrass). Cellulosic biomass can also be converted to either lignocellulosic ethanol to be blended with gasoline or to biomass to liquids (BTL), a Fischer–Tropsch process derived diesel fuel to be blended with petroleum diesel. Biodiesel pathways include soybean oil biodiesel, DDGS corn oil biodiesel, and renewable diesel from waste grease, and various cellulosic biomass feedstocks. We assume that industrial processing costs of biofuels decline with learning-by-doing (Witt et al. 2010).

3.2 Agricultural Sector

The agricultural sector in BEPAM includes conventional crops, livestock and bioenergy crops, as well as co-products from the production of corn ethanol and soymeal. The model incorporates spatial heterogeneity in crop and livestock production activities, where production practices (rotation, tillage, and irrigation), crop production costs, yields, and resource endowments are specified differently for each region and each crop. The livestock sector considers the supply of various types of livestock and livestock products and is linked to the crop sector, which provides feed for the production of livestock animals.

We consider each CRD to be a supply unit with its own resource endowments, crop yields, and costs of production. A rational representative producer allocates available production resources in a CRD among a specified set of production activities to maximize the total net returns from producing various crop and livestock products using Leontief production functions. There are 295 CRDs in 41 of the contiguous U.S. states in five major regions. Crop yields are assumed to grow over time at an exogenously given trend rate and to be responsive to crop prices, based on econometrically estimated trend rates of growth and price responsiveness of crop yields in the U.S. (see Chen et al. 2011). Following Hertel et al. (2010) and for lack of other data, we assume that marginal lands have a crop productivity that is 66% of that of the average cropland.

The model includes several types of land for each CRD, including cropland, idle cropland, cropland pasture, pasture land, and forestland pasture. We obtained CRD-specific planted acres for 15 row crops from USDA/NASS (2010), estimated at 123 M ha for the 295 CRDs considered here.[2] In 2007, the availability of pastureland and forestland pasture was estimated to be 155 M ha and 10.5 M ha, respectively while that of idle cropland was about 17 M ha and of cropland pasture is 11 M ha. Most of the idle cropland in 2007 (15 M ha) was enrolled in the conservation reserve program (CRP). About 11 M ha of CRP, 1.5 M ha of idle land and 9 M ha of cropland pasture were in the rainfed states of the U.S. and potentially suitable for energy crop production without irrigation. Cropland availability in each CRD is assumed to change in response to crop prices. Idle land and cropland pasture can be converted for the production of energy crops with conversion costs. Pasture land and forestland pasture are fixed at 2007 levels while land enrolled in the CRP is fixed at levels authorized by the Farm Bill of 2008. We impose a limit of 25% on the amount of land in a CRD that can be converted to perennial grasses due to concerns about the impact of monocultures of perennial grasses on biodiversity or subsurface water flows.

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[2] Total cropland in 2007 under all crops in these CRDs was estimated to be about 150 M ha.

4 Data and Assumptions

We obtain demands for VKT for each of the four vehicle types from 2007 to 2030 from EIA (2010). Demand curves for VKT are calibrated using information about fuel consumption in 2007 from Davis et al. (2010), retail fuel prices, markups, taxes and subsidies from EIA (2010) and assuming a demand elasticity for VKT of −0.2 (Parry and Small 2005). We calibrate these VKT demand curves for year 2007 using a linear functional form and then shift the demand curves outwards annually based on the EIA projections. Fuel economy in terms of kilometers per liter of fuel for each vehicle type is derived from EIA (2010).

The short-run supply curve of gasoline in the U.S. and demand and supply curves for gasoline for the ROW are assumed to be linear and upward-sloping and are calibrated for 2007. The short-run price elasticity of domestic gasoline supply in the U.S. is assumed to be 0.049 (Greene and Tishchishyna 2000). We assume the same price responsiveness for the domestic supply curve of diesel. The exports of gasoline from the ROW to the U.S. and its price responsiveness are determined by specifying demand and supply functions for gasoline for the ROW. We assume a value of −0.26 for the elasticity of demand for gasoline in the ROW (based on a review of the literature by Hamilton (2009), and a short-run price elasticity of supply of gasoline of 0.2 (following the review of literature in Leiby 2008).

The feedstock costs of biofuels consist of two components: a cost of producing the feedstock, which includes costs of inputs and field operations, and a cost of land. The former are calculated at a county level for each crop using data and methods described in Chen et al. (2011) while the latter is endogenously determined in the model. The costs of converting feedstock to biofuel are estimated using an experience curve approach by specifying conversion efficiencies, initial conversion costs and learning rates (Khanna et al. 2011a). We use U.S. ethanol retail prices and imports from Brazil and Caribbean countries in 2007 as well as an assumed elasticity of the excess supply of ethanol import of 2.7 to calibrate the sugarcane ethanol import supply curve for the U.S (Lee and Sumner 2009).

The sources of data used to represent the agricultural sector are described in Chen et al. (2014). The conversion costs from primary to secondary commodities as well as nutrition requirements and costs of production for each livestock category are also obtained from various sources (see Chen et al. 2012). In the absence of long-term observed yields for miscanthus and limited data for switchgrass, we use a crop productivity model MISCANMOD to simulate their potential yields. These estimated yields are used to obtain the costs of producing these energy crops, as described in Chen et al. (2011), Khanna et al. (2011a) and Jain et al. (2010). The yields of crop residues, corn stover, and wheat straw, are estimated based on grain-to-residue ratios and residue collection rates under different tillage in the literature. The cost of collecting stover and straw includes the additional fertilizer cost needed to replace the loss of nutrients and soil organic matter due to residue removal and the costs of harvesting, staging, and storage of crop residues based on the state-specific hay harvesting budgets.

We use lifecycle analysis to estimate GHG intensity of each type of biofuel, which includes emissions generated during the process of crop production, transportation, and conversion to liquid fuel as well as the soil carbon sequestered during the process of crop production. The emissions during the agricultural phase include emissions from agricultural input use, such as fertilizer, chemicals, fuels, and machinery. We obtain GHG emissions for biofuel conversion, distribution, and use from GREET 1.8c. We assume an average rate of soil carbon sequestration per dry metric ton of biomass produced for switchgrass and miscanthus from Anderson-Teixeira et al. (2009) and for conservation tillage from Adler et al. (2007).

We use BEPAM to estimate the GHG emissions from the fuel and agricultural sectors in the U.S., including those due to direct and indirect land use change. For estimating the impact of international ILUC related emissions due to biofuels we take the central estimates for the ILUC related GHG intensity of biofuel from each of the feedstocks considered here obtained from EPA (2010) and add these to the direct GHG intensity of these biofuels. Since the analysis by EPA (2010) does not consider miscanthus as a feedstock and therefore does not provide an ILUC related GHG intensity for miscanthus, we assume it is the same as for switchgrass. Additionally, the ILUC effect of a particular biofuel type is expected to be dependent on the mix of policies as these will influence the mix of biofuels and its impact on land use and commodity prices. In the absence of policy-specific ILUC effects, we use the EPA (2010) estimates to provide an order of magnitude for the ILUC effect on the GHG mitigation potential of biofuels. The ILUC estimates used here are 30.33 g CO_2/MJ for corn ethanol, 40.76 g CO_2/MJ for soybean oil diesel, 14.22 g CO_2/MJ for cellulosic biofuels, and 3.79 g CO_2/MJ for sugarcane ethanol. Since there is a wide range for the ILUC related GHG intensity of biofuels, we also consider the case, where these estimates are 100% larger (see Huang et al. 2013).

5 Results

We examine the effects of four policy scenarios on the agricultural and fuel sectors, which include various mixes of policies accompanying the RFS. The volume of second-generation biofuels as mandated by the RFS in the Energy Independence and Security Act (EISA) of 2007 is considered unlikely to be achieved according to the Annual Energy Outlook (AEO) (EIA 2010). Instead, we use the AEO projections for the annual volumes of first-generation biofuels (corn ethanol, sugarcane ethanol imports, biodiesel produced from vegetable oils) and second-generation biofuels (cellulosic ethanol and BTL) to set the achievable biofuel mandate for the period 2007–2030. Following AEO projections, we assume that cellulosic biofuel production commences in 2015. We impose a target of 149.1 billion ethanol equivalent liters of biofuel in 2030 with an upper limit of 57 billion liters on corn ethanol. The USEPA implements the quantity mandate by determining a blend rate for biofuels with expected fossil fuel use such that the desired quantity of biofuel consumption will be achieved. The blend rate determines the obligations of fuel refiners and blenders, who are the responsible parties for meeting the mandate. We iteratively solve the model to find the annual blend rates that achieve the annual volumetric targets projected by the AEO. These blend rates are found to range from 6% in 2007 to 24.5% in 2030.[3] We endogenously solve for the mix of first- and second-generation biofuels and the mix of feedstocks used.

Scenario (a) considers the RFS following AEO projections. Scenario (b) considers the RFS in (a) with the volumetric tax credits for cellulosic biofuels. Scenario (c) includes the RFS accompanied by a domestic carbon tax of $30 per metric ton of CO_2e on U.S. transportation fuel and agricultural sectors. Scenario (d) considers the RFS with a national LCFS that requires a reduction in GHG intensity of transportation fuels by 15% relative to the GHG intensity of conventional gasoline of 93.05 g CO_2/MJ in 2005 (Huang et al. 2013). We compare results under these biofuel policies to those under a business-as-usual (BAU) scenario in 2030. The BAU scenario is defined as one without any biofuel or carbon policy. In all scenarios considered here, we include a fuel tax on liquid fossil fuels and biofuels, which is set at $0.10 per liter for gasoline and ethanol and $0.12 per liter for diesel, BTL, and biodiesel. No tariff is imposed on imported sugarcane ethanol in any scenario. Results on the impact of these policies on the allocation of cropland and food prices are presented in Table 1, while Table 2 shows the composition of cellulosic feedstocks produced under these biofuel policy scenarios. Table 3 presents the results for fuel prices and consumption in 2030 and cumulative GHG emissions over the 2007–2030 period.

5.1 Business-as-Usual (BAU) Scenario

In the absence of any government intervention in biofuel markets, we find that the demand for total cropland would be 119.5 million hectares (ha) in 2030. Of this, about 28.9 million ha and 29.6 million ha would be allocated to corn and soybeans, respectively. Due to the demand for ethanol as an oxygenator, 3.1 million ha would be used for corn ethanol production. In the absence of any biofuel policies, about 19.3 billion liters of first-generation biofuels would be blended with gasoline in 2030, consisting of 14.7 billion liters of corn ethanol and 4.6 billion liters of imported sugarcane ethanol.

5.2 The RFS

The amount of corn ethanol that can be used to comply with the RFS is capped at 57 billion liters from 2015 and beyond with the remaining portion of the 92 billion

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[3] Blend rates after 2030 are assumed to be the same as that in 2030.

Table 1 Effects of biofuel policies on the agricultural sector in 2030

	BAU	RFS only	RFS with volumetric subsidies	RFS with carbon tax	RFS with LCFS
Total cropland (million ha)	119.5	125.9	126.5	126.2	128.8
Corn (million ha)	28.9	36.0	27.7	35.7	29.2
Corn for ethanol	3.1	11.8	2.3	11.7	5.2
Corn for food/feed	25.8	24.3	25.4	24.0	24.0
Soybeans (million ha)	29.6	25.1	27.4	25.0	23.8
Crop residue collection (million ha)		33.6	43.5	25.2	36.0
Energy crops (million ha)		7.0	15.0	8.0	22.4
Regular cropland		1.7	6.4	2.4	13.7
Marginal land		5.3	8.6	5.6	8.7
Land for biofuels (million ha)	3.1	18.7	17.3	19.7	27.6
Corn price ($/MT)	124.5	163.4	123.2	166.8	155.7
Soybean price ($/MT)	324.7	403.7	356.4	400.5	411.1

Table 2 Mix of cellulosic biomass in 2030 (Million Metric Tons)

	RFS only	RFS with volumetric subsidies	RFS with carbon tax	RFS with LCFS
Corn stover	118.2	122.6	99.2	124.4
Wheat straw	24.0	36.7	15.0	25.8
Miscanthus	111.2	252.1	134.5	394.5
Switchgrass	17.6	17.2	18.2	17.2
Forest residues	16.0	16.7	15.9	16.4
Pulpwood	–	21.3	–	8.9

liter achievable mandate in 2030 to be met by sugarcane ethanol, cellulosic biofuels, and biodiesel. Due to the high processing costs of cellulosic biofuels, we find that second-generation biofuels would not become economically competitive with the first-generation biofuels by 2030. In 2030, about 66.3 billion liters of first-generation biofuels would be produced to meet the RFS; of this, 57 billion liters are produced from cornstarch, 5.2 billion liters from sugarcane ethanol, and the rest is biodiesel produced from vegetable oils. The production of cellulosic ethanol would be 81.4 billion liters in 2030. High processing costs of BTL biodiesel preclude its production over the time horizon considered here.

The RFS-induced demand for biofuel requires an additional 15.6 million ha for biofuel production (including land under energy crops and land for increased corn

Table 3 Effects of biofuel policies on the fuel sector and GHG emissions

	BAU	RFS only	RFS with volumetric subsidies	RFS with carbon tax	RFS with LCFS
Effects on Fuel Prices and Mix in 2030					
Producer price of gasoline ($/liter)	0.95	0.90	0.89	0.98	0.96
Producer price of diesel ($/liter)	0.97	1.01	1.01	1.09	0.92
Consumer price of blended fuel ($/liter)[1]	0.95	0.90	0.89	0.98	0.96
First-generation biofuels (billion liters)	19.3	66.3	15.8	66.1	32.6
Second-generation biofuels (billion liters)	0.0	81.4	132.9	80.2	162.2
Gasoline consumption (billion liters)	505.5	425.8	428.0	422.2	424.7
Gasoline import (billion liters)	313.5	248.2	250.5	244.6	247.2
ROW gasoline consumption (billion liters)	735.6	776.2	769.2	769.9	768.5
Domestic rebound effect (%)		4.4	9.9	−1.1	4.2
Global rebound effect (%)		53.0	49.0	40.5	43.1
Reduction in Cumulative GHG emissions relative to Baseline, 2007–2030 (billion tons)[2]					
U.S. GHG emissions		−2.3	−3.4	−3.5	−3.9
		(−4.4)	(−6.5)	(−6.6)	(−7.4)
U.S. GHG emissions with average ILUC		−1.6	−3.1	−2.8	−3.3
		(−3.1)	(−5.9)	(−5.3)	(−6.2)
U.S. GHG emissions with high ILUC		−0.9	−2.8	−2.1	−2.7
		(−1.8)	(−5.3)	(−4.0)	(−5.1)
U.S. GHG emissions with average ILUC and ROW gasoline emissions		−0.3 (−0.6)	−1.8 (−3.4)	−1.2 (−2.3)	−1.9 (−3.5)

1. Producer prices of ethanol after tax credits or carbon taxes
2. Numbers in the parentheses represent the percentage changes in GHG emissions under each policy relative to the no-policy baseline scenario. The change in global GHG emissions is estimated after including the ILUC effect in the BAU and in the policy scenarios and net of the global rebound effect. US GHG emissions over the period 2007–2030 are 52.3 billion tons under the BAU scenario

ethanol production) compared to the BAU scenario in 2030. This represents 12.4% of the total cropland of 125.9 million ha used for biofuel production under the RFS in 2030. Of this 15.6 million ha, changes at the extensive margin lead to 6.4 million ha of net conversion of idle/crop-pasture land to crop production (most of this is for energy crop production) and the remaining 9.2 million ha are released from other food/feed crops. Energy crops will be planted on 7.0 million ha, of which only 1.7 million ha are diverted from cropland and the rest is converted from land currently idle/cropland pasture. Crop residues (corn stover and wheat straw) will be harvested from 33.6 million ha of corn and wheat land in 2030. Corn ethanol production requires an additional 8.6 million ha relative to the BAU scenario but land under corn increases only by 25% (7.1 million ha) because higher corn prices lead to reduced domestic consumption and exports. As a result of these changes, corn and soybeans prices will increase by 31 and 24% in 2030, respectively, relative to the BAU.

About 287 million MT of cellulosic biomass will be produced in 2030 for cellulosic ethanol production. Of this, corn stover and miscanthus will be the primary feedstock types, accounting for 41 and 39% of the total biomass production, respectively (see Table 2). Wheat straw and switchgrass together will account for 14% of the total biomass produced, while the role of forest residues and pulpwood in meeting the RFS is negligible. A biomass price of $58 per MT in 2030 would be needed to induce the large-scale cellulosic biomass (Fig. 1). Figure 2 shows the spatial distribution of crop residues and bioenergy crops in 2030 under alternative policy scenarios. As displayed in Fig. 2a, crop residues are harvested mainly in the Plain, Midwestern, and Western States in 2030, where the costs of corn stover and wheat straw collection are relatively low. Of the land under energy crops, about 72% is allocated to miscanthus while the rest to switchgrass; 76% of the land under energy crops was formerly idle land or cropland pasture. The production of energy crops is fairly concentrated in the Great Plains, the Midwest, and along lower reaches of the Mississippi River.

The increase in ethanol consumption reduces gasoline consumption by 15.8% and imports by 20.8%, resulting in a reduction in the producer price of gasoline in the world market by 5.3% in 2030. Consumer price of the blended fuels will decreases by 6.7% relative to the BAU scenario. This offsets some of the reduction in liquid fossil fuels consumption that would otherwise have been achieved by biofuels, both domestically and globally. As a result, the domestic rebound effect on the gasoline market is 4.4%, while the global rebound effect is as large as 53.0%. This implies that gasoline displaced by a unit of biofuel is discounted by 4.4% domestically and 53.0% in the ROW.

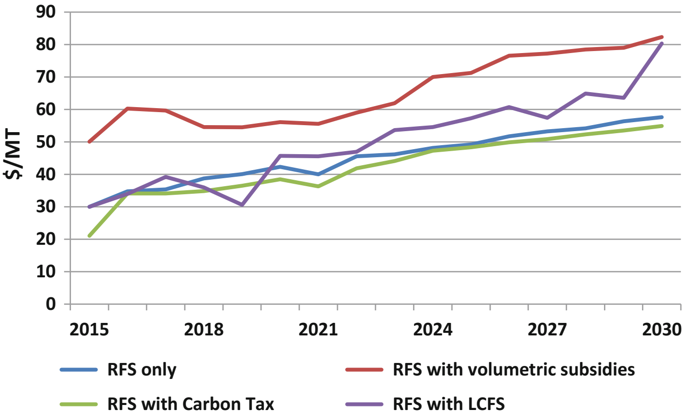
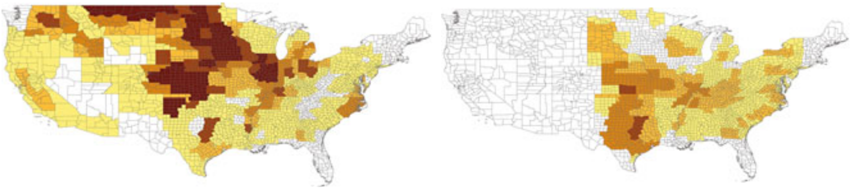


Fig. 1 Biomass prices under alternative biofuel policies ($/MT)

(a) Mandate alone

(b) Mandate with volumetric subsidies for cellulosic biofuels



(c) Mandate with a carbon tax

(d) Mandate with a low carbon fuel standard

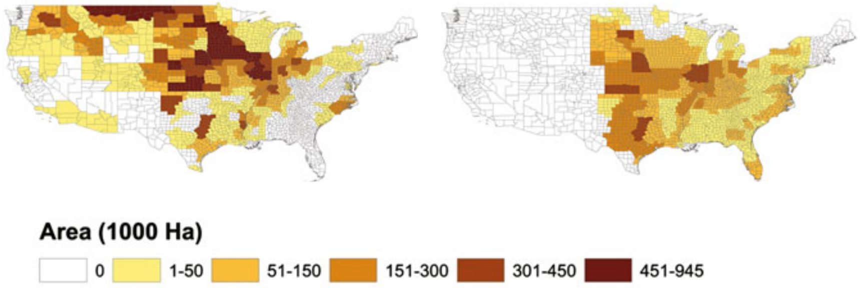


Fig. 2 Spatial distribution of crop residues and bioenergy crops

Despite the domestic rebound effect, cumulative GHG emissions from the fuel and agricultural sectors in the U.S. over the 2007–2030 period (including those due to domestic land use changes but not including the ILUC effect) under the RFS are 4.4% lower than under the BAU. Inclusion of the ILUC effect at the average levels projected by the EPA (2010) decreases this reduction to 3.1%. If ILUC effects are assumed to be 100% higher than the averages estimates, the reduction in GHG emissions attributed to the RFS drops to 1.8%. When considering GHG emissions due to gasoline consumption in the ROW, the reduction in global GHG emissions under the RFS is even smaller by 0.6% compared to the BAU scenario.

5.3 Biofuel Mandate with Cellulosic Biofuel Production Tax Credit

In the presence of the biofuel mandates, the provision of CBPTC increases the production of second-generation biofuels to 132.9 billion liters, while reducing the production of first-generation biofuels to 15.8 billion liters in 2030. This is because the provision of CBPTC significantly improves the competitiveness of cellulosic biofuels relative to first-generation biofuels, such as corn and sugarcane ethanol.

The tax credits increase the acreage under bioenergy crops to 15.0 million ha, 8.0 million ha higher than that under the mandate alone. The tax credits also increase the acreage from which crop residues are harvested from 33.6 million ha under the RFS alone to 43.5 million ha. Of the additional 8.0 million ha under bioenergy crops, 3.3 million ha are obtained at the extensive margin by converting idle land or cropland pasture, and the rest is from the reductions in land under other food or feed crops. The provision of these tax credits also mitigates the competition for cropland relative to the mandate alone. Corn and soybean prices in 2030 would be 25 and 12%, respectively, lower than the prices under the RFS scenario.

With the provision of the tax credits, 467 million MT of cellulosic biomass will be produced in 2030, which is 63% higher than under the RFS alone. Corn stover and miscanthus will still be the major feedstocks for cellulosic ethanol production, together accounting for 80% of the total biomass production in 2030, while wheat straw, switchgrass, and forest residues account for another 20% of the total biomass production. To induce this large amount of biomass production, a biomass price of $82 per MT in 2030 would be needed.

As compared to the RFS alone, the provision of tax credits leads to a significant expansion of acreage under bioenergy crops. As shown in the right panel of Fig. 2b, the production of bioenergy crops is now profitable in upper parts of Wisconsin, Michigan, and North Dakota, as well as in lower parts of Texas, Mississippi, Alabama, and Georgia. Moreover, the tax credits result in a significant increase in land under which crop residues are harvested, primarily in the Midwestern, Plain, and Western states.

The provision of the CBPTC leads to a significant increase in the share of second-generation biofuels, but does not increase the production of total renewable fuels. As a result, we find the reduction in domestic gasoline consumption and imports are similar to those under the RFS alone. The rebound effect in domestic gasoline market is slightly higher than under the RFS alone, up to 10%, while global rebound effect is 49%. Due to the large volume of second-generation biofuel production, we find that the reduction in cumulative GHG emissions under this scenario is larger by 6.5% relative to the BAU without including ILUC related emissions and by 5.9% after including ILUC related emissions. Including the ROW gasoline emissions reduces the effect of this combined policy on GHG emissions to 3.4%. This is unlike Drabhik and de Gorter (2011) who found that a blend mandate with a tax credit results in higher emissions than the mandate alone because it induces more gasoline consumption to maintain a fixed share of biofuels and does not consider low carbon second-generation biofuels.

5.4 The RFS with a Carbon Price

Compared to the RFS alone, the addition of a carbon tax does not lead to a significant change in the mix of biofuels. Although the tax creates incentives to blend more second-generation biofuels, the carbon tax assumed here does not improve the competitiveness of second-generation biofuels relative to first-generation biofuels to the same extent as the CBPTC.

The total land required for crop and biofuel production needs is 5.6% (6.7 million ha) higher than that under the BAU and marginally (0.3 million ha) higher than that under the RFS alone, mainly due to the increase in demand for bioenergy crops (8.0 million ha) to produce second-generation biofuels. Of the 8.0 million ha, about 2.4 million ha are converted from idle land or cropland pasture while 5.6 million ha are obtained from land previously under conventional crops, such as corn, soybeans, and wheat. The acreage under which crop residues are harvested shrinks to 25.2 million ha, which is 25% smaller than under the RFS alone. Corn price would be marginally higher than under the RFS alone scenario, due to the large carbon content of corn production. In comparison to the BAU, corn and soybean prices are 34.0% higher and 23.3% higher, respectively.

The addition of the carbon tax slightly increases the share of miscanthus in the total biomass production due to its low carbon content. Of the 283 million MT of cellulosic biomass production in 2030, about 50% will be miscanthus, while the rest will be consisted of switchgrass and crop and forest residues. A biomass price of $55 per MT would be needed to induce farmers to produce this large amount of cellulosic biomass in 2030.

Figure 2c shows the regions in the U.S. where crop residues and perennial energy grasses will be produced under the RFS with the carbon price. The carbon price policy makes more areas suitable for the production of bioenergy crops as compared to the RFS alone, because the carbon tax encourages the use of energy crops for the production of biofuels given their low carbon intensities. Similar to the RFS with subsidies, energy crops would be produced in the upper Midwest, northern Plains, and southern Atlantic states, while crop residues are collected in areas similar to those under the RFS alone in general.

The carbon tax will increase producer prices of gasoline and diesel by 2.8% and 11.8%, respectively, leading to reduced gasoline and diesel consumption and reduced VKT, as compared to the BAU scenario. Under the carbon tax, gasoline consumption is reduced more than the increase in biofuel production because the carbon tax not only induces the substitution of biofuels for fossil fuels but also penalizes fossil fuel consumption. As a result, the domestic rebound effect is negative since the reduction in fossil fuel consumption is larger than the increase in energy equivalent biofuel use. The carbon tax also reduces the global rebound effect to 40.5%, compared to that with the RFS alone. Consequently, total U.S. GHG emissions decrease by 6.6% and by 5.3% after including the average ILUC related emissions as compared to the BAU. The increased gasoline consumption by the ROW further offsets a part of the GHG savings by the U.S. and global emissions decline by a little over 2.3%.

5.5 *Biofuel Mandate with Low Carbon Fuel Standard*

In the presence of the biofuel mandates, the addition of a LCFS not only leads to a significant increase in the volume of total biofuel produced, but also the share of second-generation biofuels in total biofuel. Specifically, total biofuel production will increase to 194.8 billion liters in 2030, which is 32% higher than that under the RFS alone. Of this, about 83% (162.2 billion liters) are second-generation biofuels, the largest amount produced across all policy scenarios considered here. Since the LCFS provides implicit subsidies to biofuels, BTL will be economically viable in 2030 (28.0 billion liters). The production of first-generation biofuels declines to 32.6 billion liters in 2030 (instead of 66.3 billion liters under the RFS alone).

The addition of the LCFS increases the acreage under bioenergy crops to 22.4 million ha, which is 15.4 million ha higher than that under the mandate alone. The LCFS also increases the acreage from which crop residues are harvested from 33.6 million ha under the RFS alone to 36.0 million ha. Of the additional 15.4 million ha under bioenergy crops, 9.3 million ha are obtained at the extensive margin by converting idle land or cropland pasture, and the rest is from the reduction in land under other food or feed crops, including corn, soybeans, wheat and sorghum. Reduced corn ethanol production leads to a reduction in land used for corn ethanol production to 5.2 million ha, which is 56% smaller compared to the RFS alone. Although most of the increase in land under energy crops is met by converting marginal lands, it does require converting a small amount of the land under conventional crops. As a result, corn and soybean prices in 2030 under this policy scenario will be 25 and 27%, respectively, higher than the prices under the BAU scenario.

To produce 162.2 billion liters of second-generation biofuels, about 587 million MT of cellulosic biomass will be produced in 2030, highest among scenarios considered here. Due to its low carbon content, the addition of the LCFS significantly increases the share of miscanthus in total biomass production to 67%. The rest of biomass production includes 150 million MT (25%) of crop residues, 25 million MT (5%) of forest residues, and 17 million MT (3%) of switchgrass. Biomass price needed in 2030 will be $80 per MT.

Figure 2d shows the regions in the U.S. where crop residues and perennial grasses will be produced under the RFS with the LCFS. The provision of the LCFS leads to a significant expansion of acreage under bioenergy crops. Land under energy crop production in 2030 will increase more than 220% relative to the RFS alone. The production of bioenergy crops will be primarily concentrated in Plain and Midwestern states with cost and yield comparative advantage. The LCFS also results in a modest increase in land under which crop residues are harvested, primarily in the Midwestern, Plain, and Western states.

Similar to the carbon tax, the LCFS also imposes (implicit) taxes on gasoline and diesel. Producer price of gasoline will increase by 0.5% in 2030 relative to the BAU scenario, while the producer price of diesel will decline by 5.7% due to the large displacement by BTL (14% smaller relative to the BAU scenario). The effects of this combined policy scenario on US gasoline consumption, gasoline imports, and ROW gasoline consumption are similar to those under the RFS alone. The rebound effects in domestic and global gasoline markets now are 4.2 and 43.1%, respectively, which are smaller than under the RFS alone. Due to the large volume of second-generation biofuel production (particularly BTL), the reduction in cumulative GHG emissions under this scenario is the largest across all scenarios considered here, by 7.4% relative to the BAU without including ILUC related emissions and by 6.2% after including ILUC related emissions. With the inclusion of emissions from ROW gasoline consumption, the net effect on GHG emissions will be reduced to 3.5% relative to the BAU scenario.

5.6 Comparison of Different Biofuel Policies

These biofuel policies differ in the total amount of domestic land required for biofuel production in the US, mix of biofuels induced, and emissions reductions achieved. To compare these polices, we construct two indicators, namely US cropland requirement per unit of emissions reduction and emissions reduction achieved per liter of biofuels. As shown in Table 4, because of the heavy reliance on cellulosic biomass for ethanol production, the RFS accompanied with the volumetric subsidies requires the smallest amount of cropland to reduce one unit of U.S. GHG emissions (2.3 ha/thousand MT) across the policy scenarios considered here, followed by the RFS with the carbon tax and the RFS alone (3.0 ha/thousand MT and 3.9 ha/thousand MT). Although the RFS with the LCFS also induces a large amount of cellulosic biofuels, it does require converting a considerable amount of the land previously under food crops for energy crop production. As a result, it needs relatively larger amount of cropland to reduce one unit of U.S. GHG emissions (4.4 ha/thousand MT). As compared to other biofuel policies considered here, the RFS relies most heavily on land-intensive first-generation biofuels to meet

Table 4 Comparison of different biofuel policies

Scenarios	RFS only	RFS with volumetric subsidies	RFS with carbon tax	RFS with LCFS
Cropland requirement per US GHG reduction (ha/thousand MT)	3.9	2.3	3.0	4.4
US emissions reduction per liter of biofuels (kg/liter)	1.06	1.65	1.73	1.76
Cropland requirement per global GHG reduction (ha/thousand MT)	40.1	4.4	8.4	9.2
Global emissions reduction per liter of biofuels (kg/liter)	0.10	0.87	0.61	0.85

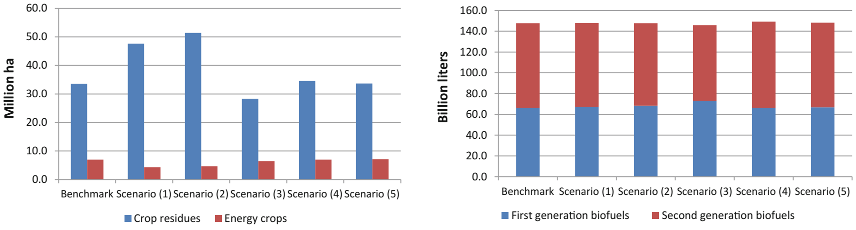
the mandates. As a result, we find that each liter of biofuel can only reduce 1.1 kg of CO_2 under the RFS alone, which is 36–40% smaller relative to the other three policies.

When considering GHG emissions in the ROW, the RFS alone will be the most inferior policy instrument across policy scenarios considered. It requires 40.1 ha of cropland to reduce one unit of global GHG emissions, which is primarily because of the large global rebound effect on the fuel market under the RFS alone that erodes emissions reductions achieved by biofuels. The RFS with volumetric subsidies will still be the preferred policy in this regard. With the consideration of GHG emissions in the ROW, emissions reduction achieved per liter of biofuels will be considerably smaller across nearly all policy scenarios compared to the corresponding result when we only consider U.S. GHG emissions. Under the RFS scenario, each liter of biofuel reduces about 0.1 kg of CO_2, which is 83–88% smaller relative to the other biofuel policies that promote cellulosic biofuels and generate smaller rebound effects on fuel markets.

5.7 Sensitivity Analysis

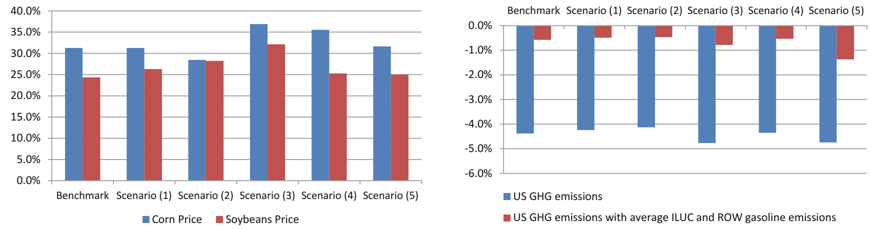
We examine the sensitivity of land allocation, food and fuel prices, the mix and quantity of biofuels, and GHG emissions to the key assumptions about technology and cost parameters in the model. We compute the percentage changes in the outcome variables under the RFS relative to their corresponding BAU scenarios with each of the parameter changes considered here. In Scenario (1), we change the upper limit of 25% on the amount of cropland that can be converted for perennial grass production at a CRD to 10%. In Scenarios (2)–(3), we consider scenarios that would result in high costs of production of cellulosic biofuels. Specifically, in Scenario (2), we consider a case with relatively high costs of production of perennial grasses than assumed in the benchmark scenario. In Scenario (3), we consider a pessimistic case, where initial processing costs of cellulosic biofuels are assumed to be 100% higher than that in the benchmark scenario. In Scenario (4) the demand elasticity of VKT is changed from −0.2 to −0.4, while in Scenario (5) the ROW supply elasticity of gasoline is increased from 0.2 to 0.4. Results are presented in Fig. 3.

A change in the upper limit on the land that can be planted under energy crops in a CRD to 10% in Scenario (1) leads to a reduction in land under bioenergy crops to 4.3 million ha and an increase in land on which crop residues are harvested to 47.6 million ha in 2030 (see Fig. 3a). Despite these changes in land under energy crops and crop residues, we find the production levels of corn ethanol and cellulosic



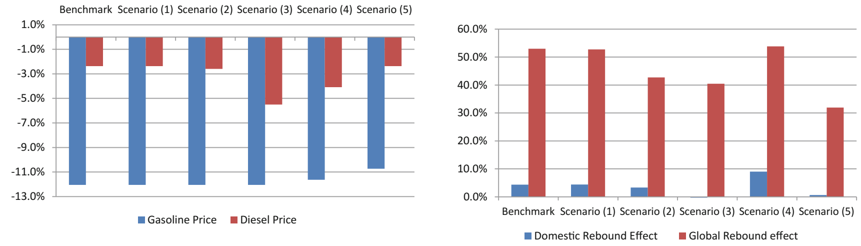
(a) **Land for cellulosic biomass production (million ha)**

(b) **Mix of biofuels (billion liters)**



(c) **Food crop prices (%)**

(d) **GHG emissions (%)**



(e) **Fuel prices (%)**

(f) **Rebound effects (%)**

Fig. 3 Sensitivity analysis. *Notes* Percentage change in **c**–**e** is calculated under the RFS relative to the corresponding BAU scenario with the changed parameters. Scenarios: *1* upper limit of 10% on energy crop acres in a CRD; *2* high costs of production of miscanthus and switchgrass; *3* high processing costs of cellulosic biofuels; *4* high demand elasticity of VKT; and *5* high supply elasticity of gasoline. Because there is no cellulosic biofuels production under baselines, we report absolute numbers under crop residue collection and perennial energy crops in **b**. Rebound effects in **f** on gasoline markets are computed under the mandate scenario relative to the corresponding BAU scenario with the same set of parameters ethanol remains stable as compared to the benchmark scenario. Thus, there are no significant changes in crop and fuel prices and overall GHG emissions as compared to the benchmark scenario.

Scenarios (2) and (3) show that high costs of production of energy crops or high processing costs of cellulosic biofuels make cellulosic biofuels more costly, leading to a reduction in cellulosic biofuels and greater reliance on first-generation biofuels (particularly corn ethanol) to comply with the RFS mandates compared to the benchmark scenario (Fig. 3b). Reduced reliance on cellulosic biofuels in these two Scenarios increases the demand for corn for ethanol production. As a result, corn and soybean prices increase significantly (by 29–37% for corn and 28–32% for soybeans) relative to the corresponding BAU scenarios (Fig. 3c). Despite these large effects on land use and crop prices, the impact of high costs of cellulosic biofuels on U.S. GHG emissions reduction is fairly modest, ranging from −4.1% in Scenario (2) to −4.8% in Scenario (3), very close to the reduction levels in the benchmark scenario (Fig. 3d). The increased reliance on first-generation biofuels in Scenario (2) leads to a smaller reduction on global GHG emissions as compared to the RFS alone. High processing costs of cellulosic biofuels in Scenario (3) results in a negative domestic rebound effect, which implies that the reduction in fossil fuel consumption is greater than the energy equivalent increase in biofuel consumption, and reduced total fuel consumption. Thus, we find the reduction in global GHG emissions is larger compared to the benchmark results.

The effects on the fuel sector and on emissions of increasing the demand elasticity of VKT from −0.2 to −0.4 (Scenario 4) and changing the ROW supply elasticity of gasoline from 0.2 to 0.4 (Scenario 5) are in the same direction as expected. We find that increased consumption of biofuels with a higher demand elasticity of VKT has a smaller negative impact on producer price of gasoline (−11.6% vs. −12.1% in the benchmark) (Fig. 3e) but it does not lead to much increase in VKT or gasoline consumption; as a result the domestic and global rebound effects on the gasoline market are marginally larger (9.0 and 53.8% vs. 4.4 and 53.0% in the benchmark) (see Fig. 3f), and the reduction in U.S. and global GHG emissions is also slightly smaller. On the other hand, a flatter supply curve for gasoline in Scenario (5) leads to a small reduction in producer price of gasoline (by 10.7%) and leads to smaller domestic and global rebound effects and a larger reduction in domestic and global GHG emissions.

In general, we find that changes in technology and cost parameters as well as land availability for bioenergy crops that limit the potential to expand production of high-yielding energy crops in the agricultural sector affect the mix of biofuels, land uses, and crop prices. The effect of these parameter changes on total land requirements of the RFS is modest at less than 1% across scenarios considered here. However, since biofuel production is binding under the RFS alone, changes in cost and technology parameters in the agricultural sector have small effects on liquid fossil fuel consumption or prices; as a result the domestic and global rebound effects are not significantly different from the benchmark scenario. Changes in parameters in the fuel sector do affect biofuel mix and fuel prices but do not have a significant impact on land use and crop prices. Across the scenarios considered here we find that the impact of the RFS on domestic GHG emissions ranges from −4.1% in Scenario (2) to −4.8% in Scenario (3). With the inclusion of the average ILUC effect and the effect on global gasoline consumption, the impact of the RFS on global GHG emissions is rather modest, and ranges from −0.5% to −1.4%. If the ILUC effect is larger, it would further erode the reduction in GHG emissions achieved by the RFS.

6 Conclusions and Discussion

This paper examines the changes in land use in the U.S. likely to be induced by biofuel policies and the implications of these policies on food and fuel prices and GHG emissions under various technological assumptions. We also explore the implications of market-mediated effects of biofuels on GHG emissions because these policies affect food and fuel prices and can lead to indirect land use changes and increased gasoline consumption in the ROW. We do not estimate the magnitude of the indirect land use change-related GHG intensity of biofuels; instead rely on other studies for these estimates.

We find that the RFS will lead to a diversion of 15% of cropland to biofuel production in 2030. About one-third of this increase is met by converting existing marginal lands, while the rest is met through changes in land use at the intensive margin. The RFS raises corn and soybean prices by 31 and 24%, respectively, in 2030 as compared to the BAU scenario. The impact of the RFS on crop prices is more severe if the costs of producing cellulosic feedstocks are high or the ease of converting land across different crops is low.

The provision of the CBPTC with the RFS promotes the production of second-generation biofuels and doubles the acreage under energy crops relative to the RFS alone. Total cropland for biofuel production under the RFS with the CBPTC is higher than under the RFS alone, but much of the land used for biofuel production is low-quality marginal land; leading to lower corn and soybean prices compared to the RFS alone in 2030. If the RFS is accompanied by a carbon price policy instead of the CBPTC, there is a smaller switch from corn ethanol to cellulosic biofuel. As a result the extensive and intensive margin effects and the crop price effects are somewhat larger than those with the tax credit policy. The addition of the carbon price policy results in similar crop prices in 2030 relative to those under the RFS alone. The addition of the LCFS to the RFS will lead to a significant switch from corn ethanol to cellulosic biofuels by providing implicit subsidies and result in the mandate being exceeded. Since most cellulosic biomass production in the form of energy crops occurs on marginal land, we find crop prices in 2030 in this scenario are lower than those under the RFS alone.

We find that all four policy scenarios considered lead to a reduction in GHG emissions relative to the BAU. The RFS with CBPTC leads to a larger decrease in U.S. GHG emissions than the RFS alone but less than the RFS with the carbon tax policy and the RFS accompanied with the LCFS. US GHG emissions decrease by

2.3% under the RFS, 3.4% under the RFS with CBPTC, 3.5% under the RFS with the carbon tax, and 3.9% under the RFS with the LCFS. These emissions reductions are severely offset by international leakage effects but the change in emissions continues to be negative in the benchmark case. The reduction in GHG emissions achieved after including international ILUC effects is 0.6–2.7% lower than that above, depending on the size of the ILUC effect assumed. Thus, despite the ILUC effect (which is likely to be overestimated here for reasons mentioned above), the policies considered here have the potential to reduce GHG emissions. The rebound effect in the ROW has a much larger offsetting impact on US GHG savings. The reduction in GHG emissions after including the average ILUC effects and gasoline consumption by the ROW is 0.6% under the RFS, 3.4% under the RFS, and CBPTC, 2.3% under RFS and carbon tax policy, and 3.5% under the RFS and LCFS, relative to the BAU. These results are fairly robust across a range of parameter considered.

In summary, the analysis shows that the land use effects of biofuels are dependent on the mix of biofuels produced. We find that policies that supplement the RFS and induce a switch towards cellulosic biofuels, either by directly subsidizing them or by differentially pricing biofuels based on their carbon intensity, can lower the adverse impact of the RFS on crop prices. They also add to the GHG emissions reduction achieved by the RFS both in the U.S. after incorporating leakage effects on the ROW.

One of the limitations of our analysis is that it did not estimate the ILUC effect of biofuels. The estimate used for cellulosic biofuels from energy crops, based on the estimate for switchgrass ethanol from the literature, is likely to overestimate the ILUC effect of cellulosic biofuels since it does not account for the lower land requirements of producing ethanol from miscanthus. Moreover, we assume the ILUC related GHG intensity of corn ethanol is unchanged across policy scenarios, even though the crop price effects differ considerably across policies. Nevertheless, our analysis does show that the extent to which the ILUC effect offsets the reduction in US GHG emissions is smaller than the effect of the increased fuel consumption in the ROW. This global rebound effect is smaller when the RFS is accompanied by the carbon price policy as compared to the tax credit. Our analysis also shows the trade-offs between lower food and fuel prices under the RFS and tax credit policy and the larger GHG reduction under the RFS and carbon price policy.

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Modeling Bioenergy, Land Use, and GHG Mitigation with FASOMGHG: Implications of Storage Costs and Carbon Policy

Robert H. Beach, Yuquan W. Zhang and Bruce A. McCarl

Abstract Biofuels production has increased rapidly in recent years due to heightened concerns regarding climate change and energy security. Biofuels produced from agricultural feedstocks increase pressure on land resources. Competition for land is expected to continue growing in the future as mandated biofuels volumes increase along with rising demand for food, feed, and fiber, both domestically and internationally. In response to concerns regarding impacts such as indirect land use change and higher food prices, U.S. policy is focusing on second-generation (cellulosic) feedstocks to contribute the majority of the mandated increase in biofuels volume through 2022. However, there has been little work exploring supply logistics, feedstock mix, and net GHG effects of combining renewable fuels mandates with climate policy. Using the recently updated Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG), we explore implications of alternative assumptions regarding feedstock storage costs and carbon price for renewable energy production mix, land use, and net GHG emissions. The model is used to quantify the magnitude and regional distribution of changes in the optimal mix of bioenergy feedstocks when accounting for storage costs. Further, combining a volume mandate with carbon price policy impacts feedstock mix and provides substantially larger net reduction in GHG.

R.H. Beach (✉) · Y.W. Zhang
Agricultural, Resource & Energy Economics and Policy Program, RTI International,
3040 Cornwallis Road, PO Box 12194, Research Triangle Park, NC 27709-2194, USA
e-mail: rbeach@rti.org

Y.W. Zhang
e-mail: yuzhang@rti.org

B.A. McCarl
Department of Agricultural Economics, Texas A&M University, 2124 TAMU, College
Station, TX 77843-2124, USA
e-mail: mccarl@tamu.edu

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1 Introduction

There is considerable global interest in the development and implementation of policies encouraging the use of bioenergy in place of fossil fuels. In recent years, many countries have expanded research funding for bioenergy development, provided production subsidies, introduced rules mandating the use of greater volumes of bioenergy use, or otherwise increased incentives for bioenergy production and consumption. The primary drivers are recent increases in petroleum prices along with heightened concerns regarding environmental impacts and energy security associated with traditional fossil fuels. In particular, renewable energy has been playing a major role in climate change mitigation policy, and that role is expected to continue. However, net effects on land use, production patterns, agricultural and forestry commodity markets, greenhouse gas (GHG) emissions, and other key outcomes depend on a complex set of market interactions and can have substantial environmental implications.

Not only will the prices and quantities of those commodities used as biofuels feedstocks be affected, but the effects of increased demand for these feedstocks will be transmitted throughout the agricultural sector, including to other land use activities. Changing returns to production of alternative commodities will lead landowners to alter land allocation across available uses (e.g., crops, pasture, forest), the specific commodities produced, and the management practices employed (e.g., irrigation, tillage). Sectors that use products derived from crops as inputs (e.g., feed use in the livestock sector) will also be affected by changes in the absolute and relative prices of those inputs. Changes in practices may also result in different quantities of by-products and coproducts being produced, which will affect those markets as well. In addition, changes in agricultural production associated with bioenergy production have implications for environmental outcomes by affecting fertilizer use, use of agricultural chemicals, land use, and GHG emissions.

Expanded bioenergy production has affected commodity prices and, in turn, land use domestically and internationally (e.g., Searchinger et al. 2008; Abbott et al. 2009). Food prices and indirect land use effects are now significant policy concerns associated with large-scale bioenergy production. As a result, understanding and mitigating these impacts has become an increasingly important aspect of bioenergy policy design. Both the revised renewable fuel standard (RFS2) required by the Energy Independence and Security Act of 2007 (EISA) (EPA 2010a) and the low carbon fuel standard developed by the California Air Resources Board (CARB 2011) require consideration of net GHG impacts in determining the eligibility of alternative feedstocks and fuel production pathways. The emissions impacts to be considered include not only direct emissions effects of fuel substitution, but also market-mediated impacts on land use and production decisions. Thus, economic models of the forest and agricultural sectors play a vital role in assessment of the potential impacts of alternative biofuels policies and feedstock use.

As a result of concerns associated with the use of feedstocks that have competing demands as food or feed, U.S. policy is focusing on second-generation (cellulosic) feedstock to contribute the majority of the mandated increase in biofuels volume scheduled to take place. Although biofuels produced from these feedstocks are currently produced only in small quantities, ongoing research and development is expected to greatly expand the commercial availability of these feedstocks. Utilizing projections of increasing cellulosic feedstock yields and reduced processing costs, Beach and McCarl (2010) found that the mandates increase in advanced biofuels volumes would be met primarily with switchgrass and corn residue. However, the study did not include some of the higher yielding energy crops that have recently been gaining attention. Another study analyzing implementation of the RFS2 biofuels volumes that incorporated the possibilities of using energy sorghum and miscanthus as cellulosic feedstocks suggests that miscanthus could provide the majority of the feedstock needed to meet the cellulosic ethanol mandate (McCarl and Zhang 2011). However, there has been relatively little work exploring the logistics of supplying second-generation feedstocks or examining feedstock mix and net GHG effects of combining renewable fuels mandates with climate policy.

The competitiveness of a particular renewable energy feedstock is a function of its biomass yield, ease of supply logistics, rate of conversion of biofuels, rate of technological improvement, and the associated costs per unit of energy supplied. Given the interactions between markets and implications for net changes in GHG, it is important to model alternative feedstocks within a consistent framework to assess land competition across traditional crops and dedicated energy crops (Beach and McCarl 2010; McCarl and Zhang 2011). Although cellulosic feedstocks do not have competing uses as food or feed, dedicated energy crops would still compete for land. Results from the prior studies indicate that while energy crops could be grown on less productive lands, they will not necessarily be grown in lower productivity areas if relative returns to energy crops on prime cropland exceed returns to traditional crops. In addition, pasture may be displaced, affecting livestock markets, which then would provide feedbacks to crop markets and, consequently, cropland use. The "iterations" between different sectors, depending on the degree of their mutual dependence, would then continue until the overall market reaches equilibrium—where the land is optimally allocated to alternative uses subject to model constraints on land transfers based on suitability. The primary contribution of this study is to explicitly consider costs associated with storage and transportation of different second-generation feedstocks and implications for net land use change and GHG emissions at both national and regional levels under renewable energy and climate policies.

In this study, we apply the Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG) to explore the implications of alternative assumptions regarding feedstock storage costs and carbon price policy for renewable energy production mix, land use, and net GHG emissions. FASOMGHG is a forward-looking dynamic model of the forest and agricultural sectors that simulates the allocation of land over time to competing activities in both the forest and agricultural sectors and the associated impacts on commodity markets. Having a broad coverage of economic and biophysical systems, this optimization framework enables us to account for competition for land among many alternative first- and second-generation feedstocks produced from both forest and agricultural sources.

The remainder of this chapter will be organized as follows. In Sect. 2, we provide a basic overview of FASOMGHG and recent model updates. We then proceed with a discussion of bioenergy production costs in the model, emphasizing logistics, as well as a brief overview of GHG accounting in FASOMGHG. Section 3 introduces the model scenarios used for this study, and Sect. 4 presents key results. Section 5 concludes and discusses future steps.

2 Model Description

FASOMGHG is a dynamic nonlinear programming model of the U.S. forest and agricultural sectors (see Adams et al. 2005; Beach et al. 2010). The model solves a constrained dynamic optimization problem that maximizes the net present value of the sum of producers' and consumers' surplus across the two sectors over time. The model is constrained such that total production is equal to total consumption, technical input/output relationships hold, and total U.S. land-use remains constant. FASOMGHG simulates the allocation of land over time to competing activities in both the forest and agricultural sectors and the associated impacts on commodity markets. In addition, the model simulates environmental impacts resulting from changing land allocation and production practices, including detailed accounting for changes in net GHG emissions.

The model was developed to evaluate the welfare and market impacts of policies that influence land allocation and alter production activities within these sectors. FASOMGHG has been used in numerous studies to examine issues, including the potential impacts of GHG mitigation policy, climate change, timber harvest policy on public lands, federal farm programs, bioenergy production, and a variety of other policies affecting the forest and agricultural sectors (Adams et al. 2005; Beach et al. 2010 provide references). To avoid using and/or producing impractical production results, FASOMGHG incorporated large data sets specifying discrete, practical production possibilities (budgets) for crop, livestock, and forestry sectors. These discrete production possibilities can be considered as points sampled from the continuous, smooth production surfaces generated by the exponential positive mathematical programming (PMP) cost function approach, as described in Howitt et al. (2010). Other partial equilibrium models, such as the Regional Environment and Agriculture Programming Model (REAP) (Johansson et al. 2007) and the Canadian Regional Agriculture Model (CRAM) (Agriculture and Agri-Food

Canada 1999), are also based on budgets that include a plethora of details on production.

Furthermore, the model has recently undergone substantial enhancements to develop a more detailed representation of the U.S. forestry and agriculture sectors (Beach et al. 2010). Key improvements include an expanded bioenergy sector that models over 20 feedstocks used for the production of biodiesel, starch- and sugar-based ethanol, cellulosic ethanol, and bioelectricity. Land use has also been further disaggregated to account for additional classes of land and the potential for conversion between these land categories. Other improvements on the agricultural side of the model include updates to rates of technological change, input costs, and output prices to reflect the current state of the market.

In the forestry component, there has been further disaggregation from 10- to 5-year time steps[1] and updates to date on timberland stocks, distribution of land ownership, and harvest schedules. Across both agriculture and forestry, the number of GHG categories tracked has been expanded to account for 60 categories of stocks and fluxes. Finally, assumed growth in demand for developed land has been updated to reflect recent projections of income and population growth (Alig et al. 2010).

2.1 Model Overview

FASOMGHG assumes inter-temporal optimizing behavior by economic agents. The model solves an objective function to maximize discounted net market surplus, represented by the dynamic area under the product demand functions less the area under factor supply curves. Such an approach involves solving a nonlinear programming model with endogenous product and factor prices (see Adams et al. 2005, for a detailed description of the model specification). The resultant objective function value is consumers' plus producers' surplus. Landowners base decisions in a given period on the net present value of the future returns to alternative activities. For instance, the decision to continue growing a forest stand rather than harvesting it now is based on a comparison of the net present value of timber harvest from a future period versus the net present value of harvesting now and replanting (or not replanting and shifting the land to agricultural use). Similarly, the model assumes that landowners make a decision to keep their land in agriculture versus afforestation based on a comparison of the net present value of returns between agriculture and forestry. Land can also move between cropland and pasture depending on relative returns. This process establishes land-price equilibriums across the sectors reflecting productivity in alternative uses and land conversion

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[1] The results reported for each 5-year interval are intended to be representative of the average annual results for that 5-year time step. In previous versions of the model, results were generated at 10-year time steps and represented average annual results for that 10-year period.

costs and, given the land base interaction, a link between contemporaneous commodity prices in the two sectors.

The model solution portrays simultaneous multi-period, multi-commodity, multi-factor market equilibriums, typically over 70–100 years on a 5-year time step basis when running the combined agriculture-forest version of the model. Results yield a dynamic simulation of prices, production, management, consumption, GHG effects, and other environmental and economic indicators within these sectors under each scenario defined.

The key endogenous variables in FASOMGHG include

- commodity and factor prices;
- production, consumption, export and import quantities;
- land use allocations between sectors;
- management strategy adoption;
- resource use;
- economic welfare measures;
- producer and consumer surplus;
- transfer payments;
- net welfare effects;
- environmental impact indicators;
- GHG emission/absorption of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O); and
- total nitrogen and phosphorous applications.

FASOMGHG quantifies the forestry and agriculture stocks of CO_2 and non-CO_2 GHGs emitted from the sector and sequestered, plus the sequestered carbon stock on modeled lands converted to developed use. In addition, the model tracks GHG emission reductions in selected other sectors that result from mitigation actions in the forest and agricultural sectors. For instance, the FASOMGHG bioenergy feedstock component accounts for reduced GHG emissions from fossil fuel use in the energy sector due to the displacement of fossil fuels resulting from the supply of renewable bioenergy feedstocks from forestry and agriculture.

2.2 Modeling Land Use

Underlying commodity supply and the associated environmental impacts are the decisions by landowners on how much, where, and when to allocate land across alternative activities. FASOMGHG includes all privately held cropland, pastureland, rangeland, and private timberland[2] throughout the conterminous United

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[2] Although timberland is not explicitly modeled because the focus of the model is on private decision-maker responses to changing incentives, FASOMGHG includes an exogenous timber supply from public forestlands.

States. The model tracks both area used for production and idled (if any) within each land category. In addition, the model accounts for the movement of forest and agricultural lands into developed uses. We recently updated our land use categorization system to represent a more comprehensive range of land use categories. This process included expanding our coverage of pasturelands to explicitly represent multiple forms of public and private grazing lands plus suitability for forest and pasture use (each with different animal unit grazing potential per unit of land). The FASOMGHG land base was developed based on land classifications from multiple sources, with the U.S. Department of Agriculture (USDA) Economic Research Service Major Land Use (MLU) database (USDA ERS 2007) and the Natural Resources Inventory (NRI) published by the USDA Natural Resource Conservation Service (2001) serving as our primary data sources.

Land categories included in the model are specified as follows:

- **Cropland** is land suitable for crop production that is being used to produce either traditional crops (e.g., corn, soybeans) or dedicated energy crops (e.g., switchgrass). This category includes only cropland from which one or more crops included in FASOMGHG were harvested.[3] Cropland used for livestock grazing before or after crops were harvested is included within this category as long as crops are harvested from the land. Data used to define cropland area come directly from the ERS-MLU (USDA ERS 2007).
- **Cropland pasture** is managed land suitable for crop production (i.e., relatively high productivity) or afforestation (in selected regions) that is being used as pasture. The ERS-MLU database defines this area as "used only for pasture or grazing that could have been used for crops without additional improvement. Also included were acres of crops grazed but not harvested prior to grazing." Not requiring additional improvement to be suitable for crop production is a key distinction between cropland pasture and other forms of grassland pasture or rangeland. This land is assumed to be more freely transferable with cropland than other grassland types. State totals for cropland pasture used in the model are drawn directly from the ERS-MLU Web site.
- **Pasture** was defined in an attempt to maintain a consistent definition with the NRI classification of grassland pasture, but to eliminate overlap with ERS cropland or cropland pasture as defined above. For each region, we compute the initial stock of "pasture" algebraically as the maximum of 1) $(\text{Cropland}_{\text{NRI}} + \text{Grassland Pasture}_{\text{NRI}}) - (\text{Cropland}_{\text{ERS}} + \text{Cropland Pasture}_{\text{ERS}})$ or 2) 0. This land cannot be converted to cropland.
- **Private grazed forest** is calculated based on woodland areas of farms reported in the Agricultural Census to be used for grazing (woodland pasture).[4] Woodland pasture is defined as "all woodland used for pasture or grazing during

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[3] Note that FASOMGHG does not include all cropping activities conducted in the United States. For instance, tobacco, vineyards, and most fruits and vegetables are not included within the model.

[4] Data are available at http://www.agcensus.usda.gov/Publications/2002/Volume_1,_Chapter_2_US_State_Level/st99_2_008_008.pdf.

the census year. Woodland or forestland pastured under a per-head grazing permit was not counted as land in farms and, therefore, was not included in woodland pastured." These lands are not included in the private timberland areas defined in the model, and there are no forest products harvested from these lands in FASOMGHG. The area in this category is fixed over time and is not allowed to transfer into alternative uses.

- **Public grazed forest** is computed as the difference between the ERS-MLU total forest pasture stock and the private portion given by the Agricultural Census as described above. This land category is not permitted to move into other uses within the model.
- **Private rangeland** is defined in FASOMGHG using a combination of NRI and ERS-MLU data. Rangeland is typically unimproved land where a significant portion of the natural vegetation is native grasses and shrubs. Thus, rangeland generally has low forage productivity and is unsuitable for cultivation, and it is assumed that rangeland cannot be used for crop or forest production.
- **Public rangeland** includes federal, state, and local sources. It was calculated by subtracting our estimates of private rangeland in each FASOMGHG region from total rangeland in that region. This land category is not permitted to move into other uses within the model.
- **Forestland** in FASOMGHG refers to private timberland, with a number of subcategories (e.g., different levels of productivity, management practices, age classes) tracked (see below for additional details). The model also reports the number of acres of private forestland existing at the starting point of the model that remains in standing forests (i.e., have not yet been harvested), the number of acres harvested, the number of harvested acres that have been reforested, and the area converted from other land uses (afforested). Public forestland area is not explicitly tracked because it is assumed to remain constant over time. Regional timberland stocks, as well as timber demand, inventory, and additional forestry sector information are drawn from the 2005 RPA Timber Assessment (Adams and Haynes 2007).
- **Developed** (urban) land is assumed to increase over time at an exogenous rate for each region based on projected changes in population and economic growth.[5] It is assumed that the land value for use in development is sufficiently high that the movement of forest and agricultural land into developed land will not vary between the policy cases analyzed. Moreover, compared with the total land base modeled, the portion designated to the rapidly increasing developed land [see Nickerson et al. (2011) for recent evidence] remains small. Although it is possible that some urban land could move back into agricultural uses in certain areas, the net movement is expected to be toward urban land, especially at the level of regional aggregation being employed in FASOMGHG. All private

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[5] Note that the developed land category tracked in the model refers to land that was initially in forest or agricultural use in the initial model period only, not land that was already developed prior to that time.

land uses [except Conservation Reserve Program (CRP) and grazed forest] are able to convert to developed land, decreasing the total land base available for forestry and agriculture over time. Land transfer rates vary by land use type over time and are consistent with the national land base assessment by Alig et al. (2010).

- **Conservation Reserve Program land** is specified as land that is voluntarily taken out of crop production and enrolled in the USDA's CRP. Land in the CRP is generally marginal cropland retired from production and converted to vegetative cover, such as grass, trees, or woody vegetation to conserve soil, improve water quality, enhance wildlife habitat, or produce other environmental benefits. State and county-level land area enrolled in the CRP was obtained from the USDA Farm Service Agency (2009).

In FASOMGHG, the initial land endowment is fixed. However, land is allowed to move between categories over time subject to restrictions based on productivity and land suitability. The conversion costs of moving between crop and pasture land categories are set at the present value of the difference in the land rental rates between the alternative uses based on the assumed equilibration of land markets, while movements from forest to cropland reflect costs of removing stumps and otherwise preparing land for cultivation. Because land can move between forests and agriculture, agricultural production faces, in effect, an endogenous excess land supply from forestry. Forestry production, in turn, effectively faces an endogenous excess land supply from agriculture.

In terms of transferability between agriculture and forestry, FASOMGHG includes five land suitability classes:

- FORONLY—includes timberland acres that cannot be converted to agricultural uses.
- FORCROP—includes acres that begin in timberland but can potentially be converted to cropland.
- FORPAST—includes acres that begin in timberland but can potentially be converted to pastureland.
- CROPFOR—includes acres that begin in cropland but can potentially be converted to timberland.
- PASTFOR—includes acres that begin in pasture but can potentially be converted to timberland.

Land can flow between the agricultural and forestry sectors or vice versa in the FORCROP, FORPAST, CROPFOR, and PASTFOR land suitability categories. Movements between forestry and cropland are only permitted within the high-quality forest site productivity class. Changes in land allocation involving pastureland occur within the medium-quality forest site productivity class. In addition, land movements in forestry are only allowed in the non-industrial private forest (NIPF) owner category, reflecting an assumption (and lengthy historical observation) that land held by the forest industry (FI) ownership group will not be converted from timberland to agriculture.

The decision to move land between uses depends on the net present value of returns to alternative uses, including the costs of land conversion. Land transfers from forestry to agriculture take place only upon timber harvest and require an investment to clear stumps, level, and otherwise prepare the land for planting agricultural crops. Agricultural land can move to other uses during any of the 5-year model periods, but when afforested it begins in the youngest age cohort of timberland.

In addition to the endogenous land allocation decision, land also moves out of agricultural and forestry uses into developed uses (e.g., shopping centers, housing, and other developed and infrastructural uses) at an exogenous rate. Rates at which forest and agricultural land are converted to developed uses in FASOMGHG are based on land use modeling for a national land base assessment by the U.S. Forest Service and cooperators. Thus, although land can move between forest, cropland, and pasture, the total land area devoted to agricultural and forestry production is trending downward over time as more land is shifted to developed uses.

An additional potential source of land is CRP land moving back into production. There are, however, environmental benefits associated with land in CRP and plans to retain some portion of that land in the program. In recent analyses, FASOMGHG has generally been applied, allowing CRP land to convert back to cropland under the constraint that a minimum of 32 million acres of land remains in the CRP. This is consistent with the 2008 Farm Bill and USDA intentions to maintain that level of CRP acreage.[6]

2.3 Bioenergy Production

FASOMGHG includes three major types of liquid biofuels for use in transportation: ethanol made from starch or sugar feedstocks, cellulosic ethanol, and biodiesel. Each of these biofuels can be made using a variety of different potential forest and agricultural feedstocks included within the model. Production costs for ethanol are broken into feedstock costs, hauling costs, storage costs, and processing costs. Revenue is derived from ethanol sales at the market price, government subsidies, and the sale of coproducts produced during the processing of certain feedstocks [e.g., dried distillers grains with solubles (DDGS) from ethanol production using grain feedstocks] as well as payments for greenhouse gas offsets under climate

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[6] As noted by an anonymous reviewer for an earlier version of this chapter, there is considerable uncertainty regarding changes to the CRP that may be introduced in the future. However, in this study, we assume that the U.S. would continue supporting CRP indefinitely at acreage levels consistent with the 2008 Farm Bill. We have explored alternative assumptions for the CRP in previous model runs and found that, as expected, allowing greater conversion of CRP land reduces commodity market impacts.

policy scenarios. Production costs for biodiesel consist of feedstock costs and processing costs. Revenue at biodiesel plants is derived only from biodiesel sales at the market price and federal subsidies; however, unlike ethanol production, no state-level government subsidies are included in FASOMGHG, and no valuable coproducts are produced during biodiesel processing (though meals that can be fed to livestock are produced as coproducts to producing the vegetable oils used in biodiesel production). A $1-per-gallon federal subsidy is depicted for both virgin oil and waste oil and greases included in the model.[7] These subsidies are assumed to remain constant at those levels up until 2025 and end thereafter.

In addition to transportation biofuels, FASOMGHG includes both co-firing with biomass at coal-fired plants and the use of dedicated biomass plants. FASOMGHG models the production of bioelectricity using a number of different feedstocks in increments of 100 megawatts (MW) electricity generation capacity, which is assumed to operate at 75% of capacity [producing 657 million kilowatt-hours (kWh)] and to require 9.198 trillion British thermal units (TBtu) of feedstock. For co-firing, the model includes options for co-firing at a standard coal-fired plant size of 750 MW at 5, 10, 15, and 20%, replacing 37.5, 75.0, 112.5, and 150.0 MW of coal-fired generation, respectively.

There are a number of similarities in the assumptions used for bioelectricity production and cellulosic ethanol production, both of which rely on the same set of feedstocks except for the addition of manure as a potential feedstock for bioelectricity. As for liquid transportation fuels, bioelectricity generation costs in the model are broken into feedstock costs, hauling costs, storage costs, and processing costs. However, unlike cellulosic ethanol, all revenue for bioelectricity is assumed to come from the sale of electricity; no government subsidies or coproducts are included in the model. A key driver of bioelectricity production is policy incentives for GHG mitigation. The use of bioenergy feedstocks in electricity production in place of coal enables firms generating electricity to potentially reduce GHG emissions and thus reduce their compliance costs under a GHG mitigation policy.

2.3.1 Hauling Costs

Hauling costs represent the costs of biomass transportation from roadside at the farm to the facility producing ethanol or bioelectricity. These costs are a function of

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[7] The national subsidy included in FASOMGHG is based on the subsidy included in the Emergency Economic Stabilization Act of 2008 (H.R.1424), signed into law in October 2008. The Energy Policy Act of 2005 (H.R.6), which extended the biodiesel credit specified as part of the Volumetric Ethanol Excise Tax Credit (VEETC) under the American Jobs Creation Act of 2004 (H.R. 4520), provided a subsidy equal to $1 per gallon for “agri-biodiesel” (diesel fuel made from virgin oils derived from agricultural commodities and animal fats) and $0.50 per gallon for “biodiesel” (diesel fuel made from agricultural products and animal fats). The Emergency Economic Stabilization Act of 2008 eliminated the distinction between agri-biodiesel and biodiesel such that all biodiesel qualified for the $1-per-gallon subsidy.

distance, biomass yield, density of the biomass being used as a feedstock (defined as the proportion of the land area around an ethanol plant with available biomass of the type being used as a feedstock), and the truck-hauling rate. The dispersion of biomass residues, their bulkiness, and their relatively low energy density suggest that hauling costs may be a limiting factor on plant size as larger plants will need to acquire biomass from an increasing distance. Based on an approach developed by French (1960) and described in McCarl et al. (2000), average transportation costs per ton are calculated as:

$$\mathrm{TC} = \frac{\text{Fixed Cost} + (2 \times \overline{D} \times \text{Cost per Mile})}{\text{Loadsize}},$$

where

$$\overline{D} = 0.4714 \times \sqrt{\frac{M}{\left(640\,\frac{\text{acres}}{\text{sq mi}} \times \text{Den} \times \text{Yld}\right)}}$$

Fixed Cost represents costs that do not vary with distance, including loading and unloading costs and other fixed costs of operating a truck. In addition, a variable hauling cost component is assumed to increase with average distance at the constant rate of *Cost per Mile*. Given a square grid system of roads as described in French (1960), $\overline{D}$ is denoted as an average one-way[8] hauling distance in miles that is calculated based on *M*, the biomass quantity requirements of an ethanol plant[9]; *Den*, the density of biomass residue production (proportion of area surrounding plant with available biomass); and *Yld*, the regional average value for harvestable feedstock yield in wet tons per acre. *Loadsize* is the average load size of a truck in wet tons hauled per load. *Fixed Cost*, *Cost per Mile*, and *Loadsize* for grain crops are assumed to be $45 per load, $1.10 per mile, and 50,000 lbs, respectively (converted into the appropriate unit for a given crop to be consistent with the yield measure, for example, bushels). Costs for crop residues and energy crops are assumed to be twice as high at $90 per load and $2.20 per mile. In addition, because of their higher moisture contents and lower densities, the average load size for crop residues, sweet sorghum, switchgrass, miscanthus, and energy sorghum was assumed to be 40,000 lbs. For processing residues, there are no hauling costs because they are assumed to

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[8] A multiplicative factor of 2 is included in the calculation to represent round-trip costs.

[9] FASOMGHG assumes a standard plant size of 75 million gallons per year for starch-based ethanol and 100 million gallons per year for cellulosic ethanol, with the exception of sweet sorghum, which is assumed to be used in 40 million gallon-per-year plants. The quantity of feedstock required to produce that amount of ethanol varies based primarily on differences in starch/sugar content or potential to convert cellulose to ethanol that lead to variation in ethanol yield per unit of feedstock.

be used at the site where they are generated. Similarly, no hauling costs are included in biodiesel production because they are already included in other stages of production where fats and oils are produced.

Hauling and storage costs for bioelectricity production are calculated in a similar way, except that hauling was assumed to take place in two stages rather than one for co-firing (dedicated plants require only the first stage). In the first stage, feedstocks are assumed to be transported to a central location, just as described above. For co-firing, they are then transported to coal-fired plants that could potentially co-fire biomass in a second stage with increasing transportation costs as the total quantity of co-firing increases. These adjustments were incorporated to reflect the increasing distances between concentrations of agricultural feedstocks and plants where these feedstocks could potentially be co-fired as more co-firing takes place. Unlike cellulosic ethanol production where ethanol plants are located with proximity to forestry and agricultural feedstocks playing an important role in siting decisions, power plants are unlikely to have considered bioenergy feedstock availability in coal-fired plant location decisions. In many cases, existing coal-fired plants and bioenergy feedstocks may be located in substantially different areas within a region because the plants are located near population centers, whereas the forestry and agricultural feedstocks are concentrated in more rural areas. In addition, although feedstock yields and densities are the same for feedstocks whether they are used in cellulosic ethanol or bioelectricity production, the average hauling distance and associated costs per ton will vary based on differences in feedstock quantity requirements for different types of bioenergy plants.

Logging residues can be used in bioenergy producing processes. Logging residue densities were determined for each FASOMGHG region by calculating a weighted average stand rotation volume based on the forest inventory and multiplying by the practical forest density of 0.8. No historical data are available for energy crop densities. All energy crops were assumed to have planting densities of 10%, with the expectation that they would be planted primarily around dedicated plants using these feedstocks. Biomass density for crop residues was calculated using a weighted average of the total acres of corn, sorghum, wheat, barley, oats, and rice produced in the top five counties in each agricultural region relative to the total available acres of land.

Hauling costs will generally decline over time as feedstock yields rise and ethanol conversion rates improve in the case of cellulosic feedstocks. For example, a 25% increase in ethanol conversion rate alone can reduce the total hauling costs by over 10%; if coupled with a 15% increase in feedstock yields, the reduction can be as large as 17%—based on the aforementioned formulas in this section. In these cases more feedstock is collected per acre and less feedstock is needed for cellulosic ethanol production, reducing needed acreage and average hauling distance for a given plant size.

2.3.2 Storage Costs

Storage costs were included for crop residues, energy crops, and processing residues based on the amount of time these feedstocks would need to be stored.[10] It was assumed that wood products, logging residues, and milling residues could be harvested throughout the year; thus, storage costs are assumed to be zero for these feedstocks. Because crop residues and energy crops cannot be harvested year-round and agricultural processing residues are not available year-round, bioenergy producers incur storage costs to ensure availability of sufficient feedstock throughout the year. For crop residues, dedicated energy crops, and agricultural processing residues, storage costs are calculated based on an assumed harvest window, maximum time in storage (which affects storage capacity requirements), costs for placing feedstocks into storage and taking them back out of storage, and a monthly cost associated with feedstock storage calculated based on the average number of months that feedstock is stored.[11]

Traditional annual crops are assumed to have a 2-month harvest window, whereas dedicated energy crops with significant cellulose composition are assumed to have substantially longer windows for harvesting. Thus, including storage costs will tend to increase the costs of using crop residues relative to other feedstocks. While the total duration of the harvest window for a given feedstock may vary based upon geographic and climate conditions in different regions, for the purposes of this analysis we assume a single national value for the duration of the harvest window of each feedstock using a variety of sources (University of Illinois Extension 2011; Gonzalez et al. 2011; USDA REEIS 2011). Costs of storage are assumed to be a fixed cost of $1.00/dry ton of peak storage capacity, $4.59/dry ton to place feedstock into storage and then later take it back out of storage, and $0.30/dry ton per month while in storage. These costs are based on biofuels processing firms and/or farms producing feedstocks constructing storage facilities and paying to finance those facilities.

Table 1 summarizes the assumptions and storage costs for the cellulosic feedstocks with storage costs included in FASOMGHG for the base period. These costs are calculated based on the standard cellulosic ethanol plant size assumed in FASOMGHG, which produces 100 million gallons per year (MGY). Storage costs for standard size plants using cellulosic feedstocks decline over time in the model because cellulosic ethanol conversion rates are assumed to improve over time, requiring less feedstock to produce a given amount of ethanol and thus less storage.

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[10] No additional storage costs are included for grain crops because they are routinely stored for year-round consumption in other markets using a well-established infrastructure and their storage costs are assumed to be reflected in their market prices.

[11] The average number of months feedstock is stored is calculated based on an assumption of equal monthly withdrawals from storage over the number of months that feedstock is stored; that is, if residues are stored for up to 10 months, then it was assumed that 10/12 of total plant feedstock requirements are stored for 1 month, 9/12 for 2 months, and so on. In this example, the average number of months that a ton of crop residues would be stored is 4.5833 months.

Table 1 Assumed storage costs for cellulosic ethanol feedstocks for FASOMGHG standard size plant (100 MGY), base period (2000–2004)

Feedstock	Tons of feedstock required (dry tons)	Harvest window (months)	Needed storage capacity for peak quantity (dry tons)	Average time in storage (months)	Total annual storage costs per plant
Residues					
Crop residues (corn, barley, sorghum, wheat, oats, rice)	1,390,821	2	1,159,017	4.58	$8,391,270
Processing residues (bagasse, sweet sorghum pulp)	1,390,821	2	1,159,017	4.58	$8,391,270
Energy crops					
Energy sorghum	1,390,821	6	695,410	1.75	$4,617,523
Hybrid poplar	1,264,223	8	421,408	0.83	$2,670,462
Miscanthus	1,390,821	6	695,410	1.75	$4,617,523
Switchgrass	1,390,821	3	1,043,115	3.75	$7,395,686
Willow	1,264,223	8	421,408	0.83	$2,670,462

In addition to the direct economic costs for storage, we also assume a 4% loss of volume during inside storage based on Collins et al. (1997), Huhnke (2006), and Shinners et al. (2007).

2.3.3 Processing Costs

Plant-level processing costs are calculated as the sum of costs associated with handling a given feedstock prior to processing at the ethanol or bioelectricity plant (estimated as a cost per wet ton of feedstock) and costs incurred at the plant to convert delivered feedstock to ethanol (estimated as a cost per gallon of ethanol produced). Costs are defined to be consistent with the Environmental Protection Agency (EPA) (2010b). The costs of feedstock preparation and grinding at the ethanol production plant prior to processing for crop residues, energy crops, pulpwood, and logging residues is assumed to be $13.54 per wet ton. For pulpwood and logging residues, a cost of $8.71 per green ton to gather and chip the pulpwood and logging residue is also included in this category, whereas for crop residues and energy crops, the harvesting cost is part of the crop budget and reflected as part of the feedstock cost. Thus, the total cost included in this category for logging residues is $22.25 per green ton. Processing residues (bagasse, sweet sorghum pulp, and softwood and hardwood mill residues) were assigned a $5.00-per-ton handling cost. These costs do not vary over time or across regions. No additional costs are included for handling starch- and sugar-based feedstocks or in biodiesel production.

The second component of processing costs is the assumed cost per gallon of converting delivered feedstock that has been through a grinding process into ethanol or converting fats and oils into biodiesel. This cost is assumed to be $0.62 per gallon for sugar, $1.64 per gallon for sweet sorghum, and $0.71 per gallon for all other starch- or sugar-based feedstocks. These costs are assumed to remain constant over time in real terms. For cellulosic ethanol, production costs are assumed to be $3.29 per gallon for all feedstocks other than sweet sorghum pulp (assumed to be $1.39 per gallon) in the base period, with considerable reductions in costs assumed over time as cellulosic ethanol production technology advances and takes advantage of economies of scale to achieve an economically viable status. Production costs for biodiesel are assumed to be $0.40 per gallon for feedstocks and remain constant over time in real terms.

Annual power plant operating costs were assumed to be $1,838,800 for a 100 MW dedicated biomass plant, and operating costs for the biomass component of co-fired plants were calculated based on the relative feedstock requirements for each level of co-firing included relative to the quantity required per 100 MW of dedicated plant capacity.

2.3.4 Additional E85 Market Penetration Costs

At higher ethanol volumes, increasing use of fuel mixes with higher ethanol concentrations will be required above today's 10% ethanol concentration. This will involve costs with more Flex Fuel Vehicles (FFVs) and distribution infrastructure (transportation, distribution, and dispensing) and/or more stations carrying higher blends. These issues imply an increasing ethanol penetration cost with increasing total ethanol volume in order to reflect the growing share of higher blends.

Data from the Energy Information Administration (EIA) 2009 Annual Energy Outlook (AEO2009) project an increasing divergence between motor gasoline and ethanol prices over time. These data reveal a clear relationship between the differences in these prices. We used this information to estimate a function for the cost of higher blend penetration under the assumption that the difference between the price of motor gasoline and wholesale ethanol should reflect the cost and performance differences between the fuels (according to EIA calculations used to develop AEO2009).

EO2009 assumes that the E10 blending wall is reached around 2013 and that additional ethanol volumes beyond that are E85. Thus, the growing difference between the gasoline and wholesale ethanol prices from 2014 to 2030 can presumably be attributed to the costs of increased production and penetration of E85, and we use the 2014 to 2030 projections of prices and E85 consumption to estimate a relationship that we interpret as the cost of higher blend penetration. Based on the relationships estimated, we incorporated a step function into the model that increases the cost of ethanol production as the volume of ethanol increases, as shown in Table 2. These costs are in addition to the cost of producing and transporting the feedstocks to refineries and conversion to ethanol presented above.

Table 2 Market penetration costs for ethanol

Ethanol production volume (BGY)	Penetration cost ($/gallon)
≤ 5	0
>5–10	0.03
>10–15	0.20
>15–20	0.40
>20–25	0.65
>25–30	0.98
>30–35	1.20
>35–40	1.43
>40–45	1.70
>45	1.80

These costs are likely to decline over time due to innovation as more efficient methods for large-scale distribution of E85 are developed. However, due to lack of data on potential changes in these costs over time, we hold them constant over time at the values shown in Table 2. This is likely to result in an overstatement of the costs associated with expansion of ethanol production volumes, particularly as we move farther into the future.

2.4 GHG Accounting

GHG mitigation opportunities in forestry and agriculture include activities such as afforestation (tree planting), forest management (e.g., altering harvest schedules or management inputs), forest preservation, agricultural soil tillage practices, grassland conversion, grazing management, riparian buffers, bioenergy substitutes for fossil fuels, fertilization management, and livestock and manure management.

FASOMGHG includes a detailed GHG accounting component, quantifying the stocks of CO_2, CH_4, and N_2O that are sequestered by and emitted from the agriculture and forestry sectors along with the stock of lands that are converted for development. In addition, the model tracks changes in GHG emissions in selected other sectors resulting from forestry and agriculture. For instance, FASOMGHG estimates GHG emissions from fertilizer production, fossil fuel use, and bioenergy-related fossil fuel displacement. In total, stocks and fluxes of GHG emissions and carbon sequestration are tracked in 60 different categories. These categories include 18 forest CO_2 accounts spanning forest ecosystem pools, harvested wood products, timber production, fossil fuel use, and developed land. Additionally, there are 42 categories in the agricultural sector tracking sources of CH_4, and N_2O emitted, and sources and sinks of CO_2 emitted and carbon sequestered, including multiple categories for agricultural soils, bioenergy feedstocks, fertilizer use, fossil fuel use, rice cultivation, livestock enteric fermentation, and manure management, among others.

Table 3 summarizes the major categories of GHG accounts, identifying whether these provide opportunities to reduce emissions, sequester carbon, or substitute for fossil fuel use and showing the GHGs affected. Sequestration activities enhance and preserve carbon sinks. They include afforestation, forest management, and agricultural soil tillage practices. Agricultural emissions of CH_4, N_2O, and fossil fuel CO_2 can be reduced through changes in crop management, fertilizer applications, livestock feeding, and manure management. CO_2 emissions can be reduced by substituting renewable feedstocks, such as selected crops, crop residues, switchgrass, and short-rotation tree species, for fossil fuels to generate electricity or transportation fuels.

In the scenarios considered in this analysis, we limit the range of GHG sources/sinks that are directly affected by carbon policies by excluding some GHG emissions/offsets that are more difficult to monitor and verify, such as enteric fermentation and changes in agricultural soil tillage. The categories that receive carbon payments in these scenarios include all fossil fuel use, afforestation, bioenergy offsets, and manure management.

For reporting purposes in this study, these categories are further combined into five major groups: forest management; afforestation; agricultural fossil fuel CO_2, CH_4, and N_2O emissions; liquid biofuels; and bioelectricity.

2.5 Dynamics

FASOMGHG also incorporates a number of assumptions regarding changes in yields, production costs, and demand over time. Assumed rates of technological progress that vary by commodity are included based on historical yield growth and projections of future yields. In addition, certain processing activities, particularly those that rely on relatively new technologies, are expected to experience increases in production efficiency and corresponding reductions in processing costs in the future. For these activities (e.g., cellulosic ethanol production), processing yields (quantity of secondary product output per unit of primary commodity input), and production costs are assumed to change over time at rates that vary by process. Finally, domestic and export demand are assumed to change over time at growth rates that vary across commodities based on historical experience and USDA projections. Beach et al. (2010) provides detailed information on assumed changes in crop yields, livestock productivity, input elasticities, timber yields, bioenergy feedstock conversion rates, and bioenergy processing costs over time.

Simultaneous changes assumed for each of these variables over time are reflected in the baseline simulation. Changes in yield, production and processing costs, and demand over time will alter the relative returns to production of different commodities and will affect producer decisions. Other factors being equal, for commodities where demand is growing faster than productivity, real prices will tend to increase over time.

Table 3 Major categories of GHG sources and sinks in FASOMGHG

Source/sink	Category of potential mitigation	CO_2	CH_4	N_2O
Forestry				
Afforestation	Sequestration	X		
Reforestation	Sequestration	X		
Timberland management	Sequestration	X		
Harvested wood products	Sequestration	X		
Agriculture				
Manure management	Emission		X	X
Crop mix alteration	Emission, sequestration	X		X
Crop fertilization alter	Emission, sequestration	X		X
Crop input alteration	Emission	X		X
Crop tillage alteration	Emission, sequestration	X		X
Grassland conversion	Sequestration	X		
Irrigated/dryland mix	Emission	X		X
Rice acreage	Emission	X	X	X
Enteric fermentation	Emission		X	
Livestock herd size	Emission		X	X
Livestock system change	Emission		X	X
Bioenergy				
Conventional ethanol	Fossil fuel substitution	X	X	X
Cellulosic ethanol	Fossil fuel substitution	X	X	X
Biodiesel	Fossil fuel substitution	X	X	X
Bioelectricity	Fossil fuel substitution	X	X	X
Development				
Carbon on developed land	Sequestration	X		

For commodities where demand growth is slower than productivity improvements, real prices will generally trend downward. These changes in relative returns could lead to shifts in land allocation and production practices until a new equilibrium is reached. In FASOMGHG, annual yield growth is exogenous and assumed to apply across all region/practice combinations for a given crop (i.e., the same percentage increases in yields are applied to starting values that vary across region/practice). However, price changes will induce switching between regions and production practices used to produce a crop in response to changing incentives, which will result in differences in national average yields in response to price changes. As would be expected, yields typically move in the same direction as prices, other things being equal, as landowners adopt more intensive, higher yielding practices when prices are higher.

3 Model Scenarios

Biomass feedstock storage is of importance for successful bioenergy processing (Hess et al. 2007), as harvesting takes place during only a portion of the year. There would be loss of biomass material as well as changes in its composition if the biomass feedstock is not preserved appropriately. For many second-generation cellulosic feedstocks, the unavailability of year-round harvests would require intermediate biomass storage to control the biomass quality and to facilitate streamlined flows to bioenergy processing firms. On the other hand, first-generation feedstocks like grain crops may be stored in existing, established storage facilities and thus do not incur "new" storage costs.

Including storage costs would alter the economic returns to bioenergy production alternatives using different feedstocks. As discussed and presented in Sect. 2, feedstocks having different harvest windows would incur different storage costs. These costs are substantial enough that there are studies in the literature exploring the expansion of harvest windows to reduce storage costs (Gonzales et al. 2011).

Sokhansanj et al. (2009) calculated the logistics costs for large-scale switchgrass production in the Midwest based on both current and future technologies. In either case, the harvest and storage costs account for a significant portion of the total production and delivering costs—above 20%. Stephen et al. (2010) examined multiple factors related to biomass feedstock logistics. They concluded that processed feedstock intermediaries such as densification pellets would be necessary for large-scale bioenergy firms to save on logistics costs, although they focused primarily on transportation costs rather than storage. Nevertheless, it is worthwhile to note that densification would also help reduce storage costs and maintain biomass quality.

An et al. (2011) modeled the supply chain system of lignocellulosic biofuel and included field storage of biomass in their model as it influences material flows. An and Searcy (2012) also estimated the cost of biomass logistics and found it ranging from $19.65 to $41.26 per ton. The estimated costs for logistics can be a large share of the feedstock production cost (or payment to crop growers). For example, in Khanna et al. (2008), the midpoint for farmgate miscanthus production costs in Illinois is about $49 per dry ton so the logistics costs estimated by An and Searcy (2012) could add as much as 40–84% to the cost of producing miscanthus.

Given the potential for transportation and storage to compose a large share of total delivered feedstock costs, these logistics costs will potentially play an important role in the economic competitiveness of biofuels production. However, biofuels feedstock storage costs in particular have not yet been extensively investigated. In this study, we explore potential impacts associated with large-scale expansion of U.S. renewable fuels production under three different scenarios relative to a baseline case. The baseline includes a minimum biofuels volume requirement and assumes that storage costs for cellulosic feedstocks are zero. Under each alternative scenario, the potential domestic agricultural and environmental impacts are examined based on biofuels production sufficient to meet the baseline

Table 4 Scenarios modeled

	Symbol	Biofuels mandate	Storage costs	Carbon price $30
Baseline	RFS2	√		
Storage costs	RFS2storage	√	√	
Cprice $30	RFS2cprice	√		√
Storage costs and cprice $30	RFS2storcpr	√	√	√

biofuels volume requirement under different assumptions regarding feedstock storage costs and carbon price.

The EISA of 2007 calls for 36 billion gallons per year (BGY) of renewable fuels by 2022, but not all of this production is expected to be derived from agricultural and forestry feedstocks modeled in FASOMGHG. For example, EPA (2010b) also considers urban wastes and algae as potential feedstocks for renewable fuels production. Thus, the volume of renewable fuels modeled in FASOMGHG is less than the full 36 BGY [about 30.2 BGY (30.9 BGY in ethanol equivalents because some of this production is biodiesel, which has greater energy density than ethanol)], with the remainder distributed across municipal solid waste, yellow grease, and imported renewable fuels exogenous to FASOMGHG. Following Beach and McCarl (2010), in years after 2022, we assume a floor on ethanol production of 28.7 BGY and on biodiesel of 1.47 BGY. We also constrain starch- and sugar-based ethanol production to total no more than 15 BGY over the modeling period. There is no floor placed on bioelectricity production in any of the scenarios. Relative to Beach et al. (2012), this study focuses more on scenario impacts on the mix of cellulosic feedstocks because production of ethanol from traditional feedstocks is restricted to 15 BGY here, whereas it was permitted to compete with cellulosic ethanol in years beyond 2030 in the previous study.

Table 4 provides a description of the FASOMGHG scenarios employed for this study. In addition to RFS2 under the EISA and storage costs, a dimension of a $30/tCO$_2$e carbon price is also added to investigate the implications of potential regulation over GHG performance.

4 Results and Discussion

As shown in Table 5, under the RFS2 baseline scenario without storage costs, the primary feedstocks for cellulosic ethanol production by 2035 are miscanthus, wood pulp, and crop processing residues in order of declining volumes, with additional contributions from milling and logging residues. The primary feedstocks used for biodiesel production are corn oil and soybean oil. Animal-derived fats also contribute to the biodiesel production. Under the zero-carbon price scenario, the inclusion of storage costs will noticeably raise miscanthus' share and decrease crop

Table 5 Biofuels production by feedstock (Million gallons) 2035

Feedstock	RFS2	RFS2storage	RFS2cprice	RFS2storcpr
Starch-based ethanol				
Corn	14,985	14,985	14,985	14,985
Refined sugar	8	8	30	30
Sweet sorghum	15	0	0	0
Cellulosic ethanol				
Miscanthus	8931	8994	9175	9179
Crop processing residues	959	896	715	711
Logging residues	581	581	630	623
Milling residues	506	507	212	211
Wood pulp	2710	2709	2954	2962
Total ethanol	28,694	28,679	28,701	28,701
Biodiesel				
Animal-derived fats	127	127	127	127
Corn oil	681	681	681	681
Soybean oil	659	659	659	659
Total biodiesel	1467	1467	1467	1467

Note Columns may not sum to totals due to independent rounding

processing residues' share in the biofuel feedstock mix, reflecting the competitive advantage of feedstocks having longer harvest windows.

With carbon price, greater volumes of cellulosic ethanol are derived from miscanthus and wood pulp, with much larger percentage increases from the latter as a result of an increasingly economically competitive forest sector under carbon price scenarios. The addition of storage costs further increases the role of miscanthus and wood pulp in providing ethanol feedstocks, albeit slightly. Meanwhile, again, agricultural processing residues' role becomes diminished. This indicates that when carbon payments are added to the economic returns to biofuels production, the effects of storage costs would become much less meaningful in terms of altering the comparative economic viabilities of different cellulosic feedstocks.

A substantially stronger incentive for using cellulosic feedstocks, especially miscanthus, in bioelectricity generation is manifested under carbon price scenarios, as presented in Table 6. This suggests that in addition to increasing the competitiveness of the forest sector, the presence of a $30/ton carbon price also lends noteworthy support to a bioelectricity sector drawing dedicated energy crops from the agricultural sector as feedstocks. The inclusion of storage costs, however, would reduce the overall bioelectricity generation and decrease the usage of miscanthus.

Slightly more energy sorghum, however, is being used for bioelectricity generation, when storage costs are considered. Taking into account the biofuels production presented in Table 5, this indicates that under carbon price scenarios where the economic returns to both bioelectricity and biofuels production are enhanced, bioelectricity is a more financially attractive alternative than biofuels for energy sorghum. A similar story applies to logging residues.

Table 6 Bioelectricity generation capacity by feedstock (MW) 2035

Feedstock	RFS2	RFS2storage	RFS2cprice	RFS2storcpr
Crop residues (dedicated)	0	0	301	34
Crop residues (co-firing)	0	0	138	136
Miscanthus (dedicated)	0	0	39,027	36,440
Miscanthus (co-firing)	0	0	36,318	35,772
Energy sorghum (dedicated)	0	0	1475	1475
Energy sorghum (co-firing)	0	0	1226	1247
Logging residues (dedicated)	0	0	1475	1486
Logging residues (co-firing)	902	902	0	0
Manure (co-firing)	0	0	263	263
Total	902	902	80,223	76,853

A focused look at the acreages of dedicated energy crops by region in 2035 is presented in Table 7. Under zero-carbon price environments, miscanthus production would take place in the South Central (SC) and Southwest (SW) regions. With carbon price, miscanthus acreage would increase remarkably to satisfy the enlarged biomass demand from the bioenergy sector. Accompanying the overall acreage increases are also the production expansion into new regions across the continental U.S. On the other hand, energy sorghum production would concentrate in the western regions including the SW and the Rocky Mountain (RM). Compared to energy sorghum, miscanthus has a broader coverage because it is assumed to have higher biomass yields in general and is thus more competitive as a cellulosic feedstock.

The effects of storage costs on energy crop acreage would differ between $0 and $30 carbon price scenarios. Specifically, under a $8 carbon price environments, the miscanthus acreage would increase with the addition of storage costs because its relative competitiveness among alternative cellulosic feedstocks improves; under a $30 carbon price, the miscanthus acreage would decrease because adding the storage costs increases the total costs of producing bioenergy.

Figure 1 shows the effects of our scenarios on the distribution of land across FASOMGHG categories at the national level, compared to the RFS2 baseline. The primary shifts in land use observed over time and across scenarios are between forestland and cropland, cropland pasture, and pasture land categories. In scenarios where a carbon price is included, land use shifts significantly toward forestland and away from agricultural uses. There tend to be especially large reductions in cropland pasture and pasture in the next few decades, with smaller reductions in cropland. These changes reflect the changes in relative profitability of forest versus agricultural uses with a carbon price. With a large potential for sequestering carbon in new forests as well as increasing carbon storage in existing forests through changes in management practices, carbon payments encourage a major reallocation of land from agriculture to forests. The addition of storage costs also has noteworthy impacts on the allocation of land between the land use categories—under carbon price scenarios, even larger reallocation of agricultural land to forestland occurs. Consider, the addition of storage costs decreases the economic competitiveness of agricultural

Table 7 Dedicated energy crop acreages by region (Million acres) 2035

	CB	GP	LS	NE	RM	PSW	SC	SE	SW	Total
Miscanthus										
RFS2							3.34	1.05		4.39
RFS2storage							3.37	1.05		4.42
RFS2cprice	9.43	6.71	0.91	0.78	1.72		2.10	0.74	2.83	25.23
RFS2storcpr	9.12	6.34	0.91	0.78	1.33		2.10	0.73	2.83	24.14
Energy sorghum										
RFS2										
RFS2storage										
RFS2cprice					0.36	0.08			0.63	1.07
RFS2storcpr					0.36	0.07			0.63	1.07

CB refers to the Corn Belt region, *GP* the Great Plains, *LS* the Lake States, and *NE* the Northeast U.S

RM presents the Rocky Mountain region, and *PSW* the Pacific Southwest region

SC stands for the South Central U.S., *SE* the Southeast U.S., and *SW* the Southwest U.S

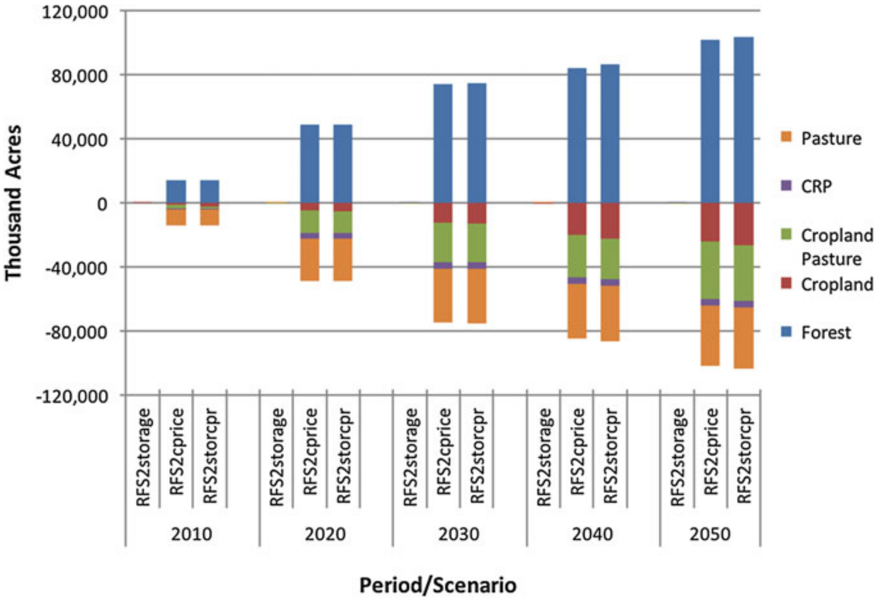

Fig. 1 Land use changes relative to baseline under alternative storage cost and carbon price scenarios

GHG mitigation strategies such as generating bioelectricity using dedicated energy crops, compared to afforestation and/or forest management strategies.

Figures 2, 3, and 4 show the region-specific land use changes relative to the RFS2 baseline under alternative scenarios. We highlight the CB, SE, and SW regions because among the 11 aggregate regions modeled in FASOMGHG for this study, these three regions show relatively large changes that contribute significantly to the overall pattern of changes in U.S. land use. Specifically, the national-level land use changes characterized by the movements from agriculture to forestry are essentially sourced from CB and SE, whereas the land use adjustment within the agricultural sector is largely reflected in SW.

Figure 2 exhibits the simulated land use changes in CB, most of which are the shifts between cropland and forestland over time. The land use shifts in SE shown in Fig. 3, however, are largely between pastureland and forestland. In the agriculture-only SW (as modeled in FASOMGHG), the land use changes are essentially about converting cropland pasture to cropland, as utilizing dedicated energy crops for bioenergy production becomes much more profitable than conventional agricultural activities under carbon price scenarios, and thus, production of feed crops and livestock grazing experience decreases.

Generally speaking, the presence of a carbon price encourages forestry production at the expense of crop and pasture-livestock production. With storage costs, even greater forestland expansion would occur with further contraction of cropland and pastureland, reflecting the alterations in comparative economic returns to land between agricultural and forestry uses under the new equilibrium.

Table 8 shows how the carbon price and/or storage cost-induced land use changes are reflected in the U.S. crop and livestock markets. With no carbon price, the effects of storage costs are minimal. With carbon price, there are substantial increases in commodity prices and decreases in production.

From a land use change perspective, the addition of storage costs shifts more land away from cropland and pastureland to forestry use (as shown in Fig. 1).

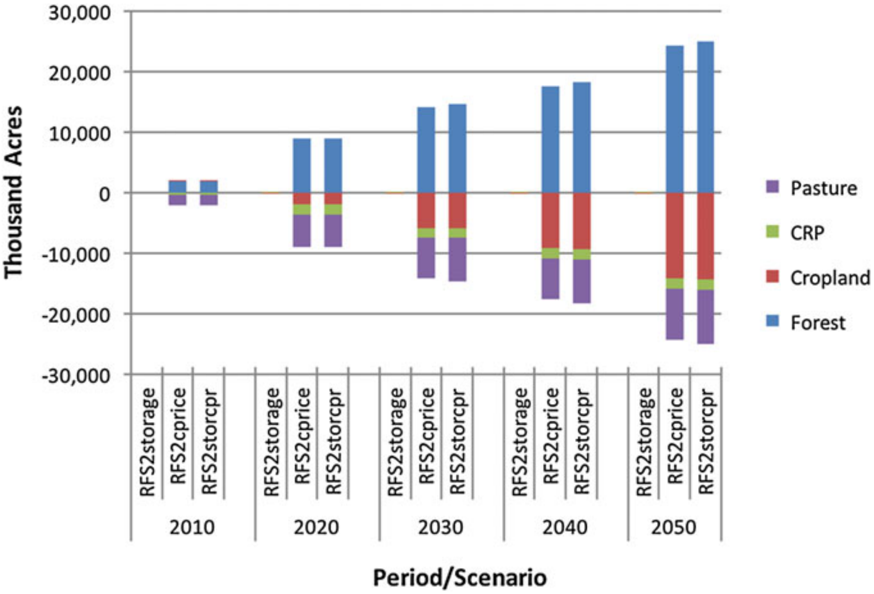

Fig. 2 Land use changes relative to baseline under alternative scenarios, CB region

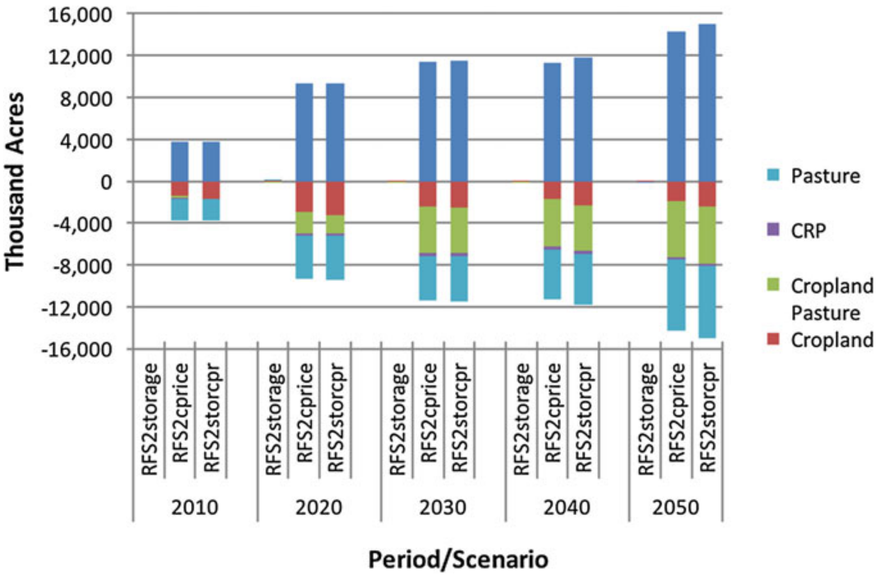

Fig. 3 Land use changes relative to baseline under alternative scenarios, SE region

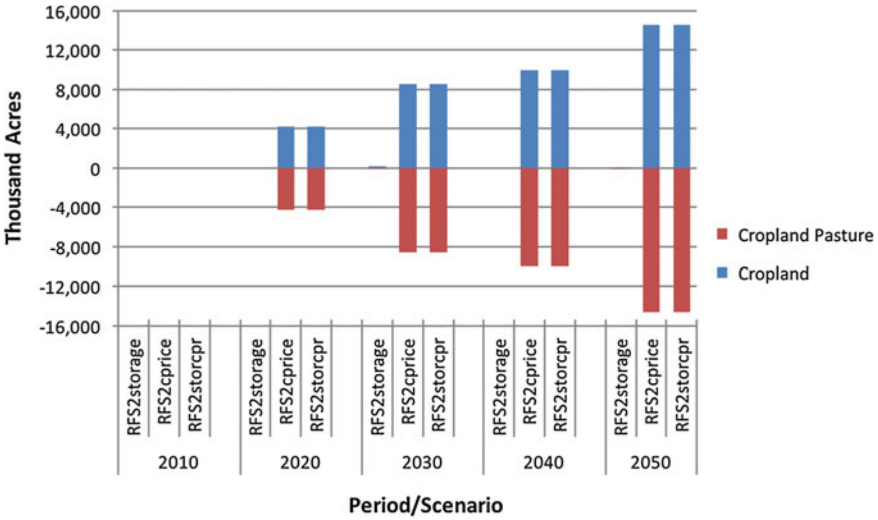

Fig. 4 Land use changes relative to baseline under alternative scenarios, SW region

Thereupon, the livestock economy is expected to be even more negatively affected under carbon price scenarios.

Figures 5, 6, 7 and 8 present how the GHG mitigation potential from the agricultural and forest sectors is influenced by carbon price and/or storage costs at national and regional levels.

Table 8 Changes in commodity production and prices relative to baseline (Percentage changes in fisher indices) 2035

		RFS2storage (%)	RFS2cprice (%)	RFS2storcpr (%)
Grains and Soybeans	Production	0.03	−13.83	−13.98
Grains and Soybeans	Price	0.01	24.70	24.21
Meats	Production	0.00	−6.28	−6.42
Meats	Price	−0.01	8.48	8.63
Livestock	Production	0.01	−7.20	−7.23
Livestock	Price	1.20	6.34	6.61

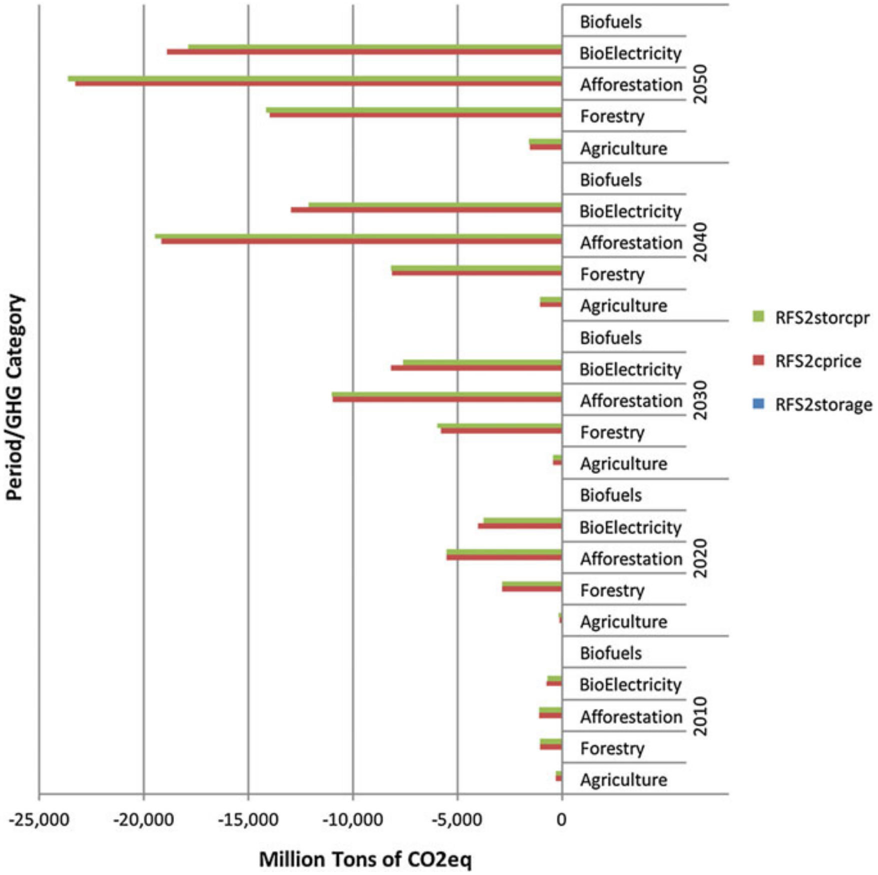

Fig. 5 GHG mitigation potential under alternative storage cost and carbon price scenarios relative to baseline

Not surprisingly, Fig. 5 shows that at a national level, GHG mitigation is largely realized via afforestation, forestry management, and bioenergy production under carbon price scenarios. With storage costs, GHG mitigation would be realized more through afforestation and less from bioelectricity. Consider, the presence of carbon price offers economic incentives for forestry activities, and the inclusion of storage costs penalizes agricultural GHG sequestration strategies such as bioelectricity production that utilizes dedicated energy crops.

Figures 6, 7, and 8 display how regional GHG sinks/emissions are changing over time. Specifically, Fig. 6 shows that in CB, the forestland expansion (shown in Fig. 2) under carbon price scenarios is essentially through afforestation, while Fig. 7 exhibits that in SE, both afforestation and improved management of existing forests contribute to GHG sequestration.

The reduced GHG mitigation potential from biofuels production in SE shown in Fig. 7 corresponds to the decreases in miscanthus acreage in that region under carbon price scenarios (shown in Table 8), as forestland expands over cropland and pastureland. For SW region, the increases in GHG emissions shown in Fig. 8 under

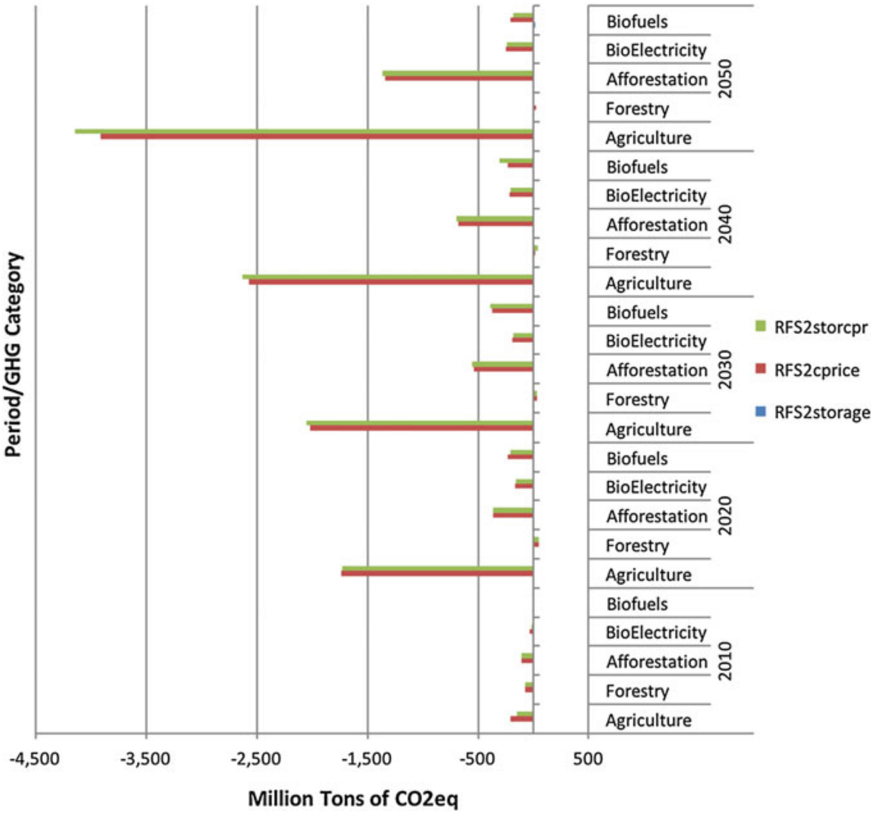

Fig. 6 GHG mitigation potential under alternative scenarios relative to baseline, CB region

carbon price scenarios are a reflection of the cropland expansion (shown in Fig. 4) that accommodates the reallocation of feed crops production and the acreage expansion of dedicated energy crops.

5 Conclusions

While substitution of bioenergy for traditional fossil fuel energy sources can provide benefits for energy security and GHG mitigation, rapid expansion of U.S. biofuels production from corn has raised concerns regarding land use, commodity prices, and the implications of cropland expansion for net GHG emissions. Thus, the focus for future bioenergy use has shifted toward second-generation feedstocks that may alleviate these issues. However, there are a number of technological and logistical hurdles to overcome before cellulosic feedstocks can be used to generate large quantities of bioenergy at competitive costs. In this study, we apply a model covering U.S. forestry, agriculture, and land use to explore the implications of

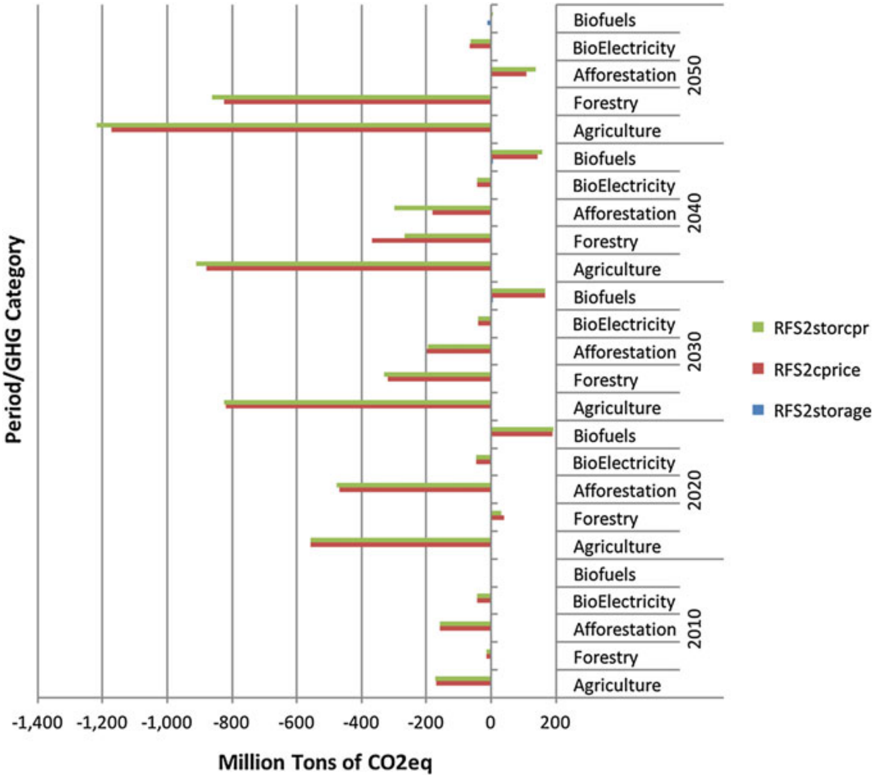

Fig. 7 GHG mitigation potential under alternative scenarios relative to baseline, SE region

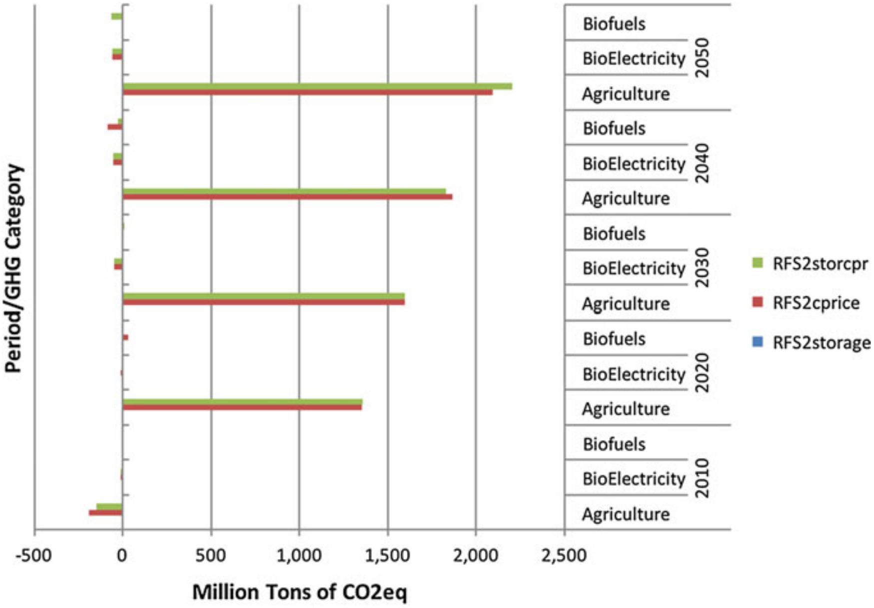

Fig. 8 GHG mitigation potential under alternative scenarios relative to baseline, SW region

including logistical costs of relying on these feedstocks. In addition, we explore the potential distribution across feedstocks with and without storage costs if U.S. biofuels mandates were combined with a climate policy that has an effective carbon price of \$30/ton of CO_2e.

Without carbon price, the effects of adding storage costs to cellulosic bioenergy production activities are minimal across a range of aspects examined in this study, including the national and regional land use change, crop and livestock economy, and the national and regional GHG mitigation potential. The exception is that the addition of storage costs would noticeably increase the shares of cellulosic feedstocks having longer harvest windows in the optimal bioenergy feedstock mix.

With carbon price, the inclusion of storage costs would exhibit noteworthy impacts on land use changes between cropland, pasture and forestland, as well as the associated economic activities and GHG emissions/sinks. Among other effects, adding a carbon price would induce competition in demand for cellulosic feedstocks from the bioelectricity sector. The addition of storage costs would then reduce bioelectricity production and further incentivize forestland expansion. In other words, the effects of storage costs could become significant when biomass-based economic activities are increasingly competing for land.

There are some caveats to consider in interpretation of our study results. We do not have a geographically varying representation of logistics in the model. Using spatially explicit logistics parameters, in particular those pertinent to storage costs, would be desirable for future research delving further into the regional effects of considering storage costs for renewable fuels production. Moreover, region-specific portfolios of logistics possibilities can be developed and included in the model to generate endogenous logistics implications. Another issue common to studies of potential production of cellulosic ethanol is that the assumed rates of technological improvement in cellulosic feedstock yields, cellulosic ethanol conversion technology, and reductions in processing costs play a key role in determining the competitiveness of ethanol produced from these feedstocks over time. In addition, FASOMGHG does not track international land use or GHG emissions, which limits our ability to assess indirect land use impacts. We are also currently in the process of making some additions to the model that increase substitutability between alternative commodities and will cause prices for substitutable products to be more closely linked in future applications.

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Empirical Findings from Agricultural Expansion and Land Use Change in Brazil

Leila Harfuch, Luciane Chiodi Bachion,
Marcelo Melo Ramalho Moreira, André Meloni Nassar
and Miguel Carriquiry

Abstract Agricultural production will play an increasing role in the development of renewable energy sources. Modeling land use changes due to agricultural conversion continues to be a challenge. This chapter contributes by demonstrating an improved methodology to empirically determine elasticities used to compute land use change. It presents an updated land use section of the Brazilian Land Use Model, using secondary economic data, remote sensing information, and improved allocation methodology, especially with extensive margin effects, to better capture multicropping systems, livestock dynamics, and land use dynamics. It shows improved ways for economic and geospatial models to interface with each other, a necessary step in quantifying impacts of dynamic processes. The results of the simulations confirm that agriculture will continue to convert native vegetation, but sugarcane has very little direct impact on natural vegetation due to demand being met through pasture intensification. Also, deforestation rates will decrease compared to those in the past. Finally, policies to ensure compliance with agricultural intensification and guarantees from farmers of compliance with Brazilian forest regulations will be necessary to complement market forces and technological advances in biofuel crop production.

L. Harfuch (✉) · L. Chiodi Bachion · M.M.R. Moreira · A.M. Nassar
Agroicone, São Paulo, Brazil
e-mail: leila@agroicone.com.br

L. Chiodi Bachion
e-mail: luciane@agroicone.com.br

M.M.R. Moreira
e-mail: marcelo@agroicone.com.br

A.M. Nassar
e-mail: amnassar@agroicone.com.br

M. Carriquiry
Universidad de la República, Montevideo, Uruguay

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1 Introduction

Land use changes caused by the constant interaction of humans with the environment are of permanent interest to the international community due to its environmental, economic, and social impacts. (Gibbs et al. 2010). Population growth, combined with rising incomes and urban development, has led to increased demand for food, feed, and fiber production across the world (Alexandratos and Bruinsma 2012; Lambin and Meyfroidt 2011). In addition, energy use globally is also continuing to grow, and because of the nonrenewability of many of these energy resources, there has been a worldwide increase in the demand for agricultural-based biofuels as an alternative renewable energy source. However, its competition for land with other agricultural commodities has raised questions about their impacts on land use changes, greenhouse gas (GHG) emissions, commodity prices, and food security (Nassar et al. 2010a, 2011; Moreira et al. 2012; Ferreira Filho and Horridge 2014).

Brazil has an important role in increasing the global supply of agricultural-based products (Alexandratos and Bruinsma 2012). Almost 30% of its total land area is allocated toward agricultural production, while around 65% remains natural vegetation. Of the remaining vegetation, around 43 million hectares is currently suitable for crop production (which already accounts for land set aside due to national environmental restrictions) and the other 70 million hectares is pasture land that can be converted to crop production with slight modifications to the land. The key question for Brazil is how it will go about increasing agricultural production and the resulting effect it will have on land use, especially considering that land use change has been the main source of GHG emissions in the country.

General and partial equilibrium economic models have been used to measure and anticipate the environmental impacts of changes in land demand. Policymakers have increasingly used these models to develop and implement agricultural, environmental, trade, and climate change policies. However, these models have been criticized for their lack of accuracy in replicating the dynamics of land use change, as several of the parameters are based on expert opinion rather than empirical evidence. The complexity of expansion of agricultural production and its land use impacts presents a major challenge for modelers and the scientific community. Nevertheless, models have been improving over time as new data becomes available and novel methodologies are developed.

This chapter aims to showcase the updated land use section of the Brazilian Land Use Model (BLUM), which has been refined by combining databases and methods from different approaches, including the use of secondary economic data, remote sensing information, and causal-effect derived parameters from allocation methods. In order to assess how the changes in the land use section in the BLUM affect the projections of land use demand for agricultural production, two simulations under the same scenario specifications were performed: one with the previous version of the land use section and the other with the updated version.

The first section of the chapter details the distinguishing features of the analysis. Section 2 explains the methodological approach, followed by Sect. 3 where the empirical results for the recalibrated parameters are presented. Section 4 compares the simulation scenarios of the previous and updated versions of the BLUM. The last section presents some final considerations and implications.

1.1 Distinguishing Features of This Analysis

Global models, such as GTAP (Purdue University), MIRAGE (IFPRI and CEPII), LEITAP MAGNET (Wageningen University), FAPRI-CARD (Iowa State University), and AGLINK (OECD-FAO), are limited in their capability to accurately represent the dynamics of the agricultural sector in Brazil and its effects on land use change, as shown in Nassar et al. (2011), Sparovek et al. (2010), and Babcock and Carriquiry (2010). There are at least seven areas in which existing models have misrepresented Brazilian agriculture: multicropping production systems, livestock sector dynamics, land supply dynamics, competition among crops, linearity assumptions, and environmental legislation.

As discussed by Nassar et al. (2010b), existing models do not properly capture multicropping production systems, which involve double cropping corn over soybean crop area, leading to an overestimation of the land demand for agriculture. Livestock dynamics is also a complex issue in Brazil, and empirical evidence shows that a large share of cropland expansion is occurring on pasture land and is correlated with beef and dairy production increases. Models also fail to incorporate empirical evidence on land use dynamics, which may also include environmental legislation restrictions as pointed out in Sparovek et al. (2010). The refined BLUM, as will be seen throughout this paper, parameterizes each of these important issues in order to reproduce agricultural dynamics in Brazil as accurately as possible.

This paper shows how satellite imagery as well as database and geospatial information can be used to calibrate parameters used in economic models, and incorporates empirical evidence on agricultural expansion and its effects on land use change dynamics (including the calculation of the indirect land use change (iLUC) factor for sugarcane ethanol expansion). We apply this approach to the BLUM, where the parameters and assumptions are based on three sources: remote sensing analysis (Ferreira et al. 2011; Rudorff et al. 2011), geospatial analysis (Sparovek et al. 2011), and an allocation methodology developed by Moreira et al. (2012). The latter source is used due to the lack of remote sensing information for some of the Brazilian regions used in BLUM.

2 Methodological Approach

2.1 Overview of the Brazilian Land Use Model—BLUM

BLUM is a single-country, multiregional, multi-market, dynamic, partial equilibrium economic model of the Brazilian agricultural sector, which is comprised of two sections: *supply and demand* and *land use*. The model includes the following products: soybeans, corn (first and second crop), cotton, rice, dry beans (first and second crop), sugarcane, wheat, barley, dairy, and livestock (beef, broiler, eggs, and pork).[1] In terms of land use, these commodities can be broadly classified between cropland and pasture, while commercial forests are considered as exogenous projections. These three activities combined were responsible for 95% of the total area used for agricultural production in 2008, including pasture activities. Both double-cropped commodities and winter crops, such as corn, dry beans, barley, and wheat do not require additional land for production, as they are planted on the same land as summer season crops, and are included in the national supply.

2.2 The Supply and Demand Section

Demand for agricultural-based products is projected at the national level, and is determined by domestic demand, net exports (exports minus imports), and final stocks. National demand also responds to prices and exogenous variables such as gross domestic product (GDP), population, and the exchange rate. The supply of commodities accounted for in the BLUM is obtained from beginning stocks in each year and an aggregation of regionally projected production, as explained below. The level of supply responds to the expected profitability of each commodity, which depends on costs, prices, and yields.

Land allocation for agriculture and pasture is calculated for six regions[2] (see Fig. 1):

- South (states of Paraná, Santa Catarina, and Rio Grande do Sul)
- Southeast (states of São Paulo, Rio de Janeiro, Espírito Santo, and Minas Gerais)
- Center-West Cerrado (states of Mato Grosso do Sul, Goiás and part of the state of Mato Grosso within the Cerrado and Pantanal biomes)
- North Amazon (part of the state of Mato Grosso within the Amazon biome, Amazonas, Pará, Acre, Amapá, Rondônia, and Roraima)
- Northeast Coast (Alagoas, Ceará, Paraíba, Pernambuco, Rio Grande do Norte, and Sergipe)
- Northeast Cerrado (Maranhão, Piauí, Tocantins, and Bahia).

For a given year, the model equilibrium is obtained by finding a vector of prices that clears all markets simultaneously. A sequence of annual equilibrium price vectors, regional land use and land use changes, national production, prices,

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[1] "Second crop" in this analysis refers to a crop that is double cropped on an existing crop's area.

[2] Grouped Footnotes

The main criteria to divide the regions were agricultural production homogeneity and individualization of biomes with special relevance for conservation.

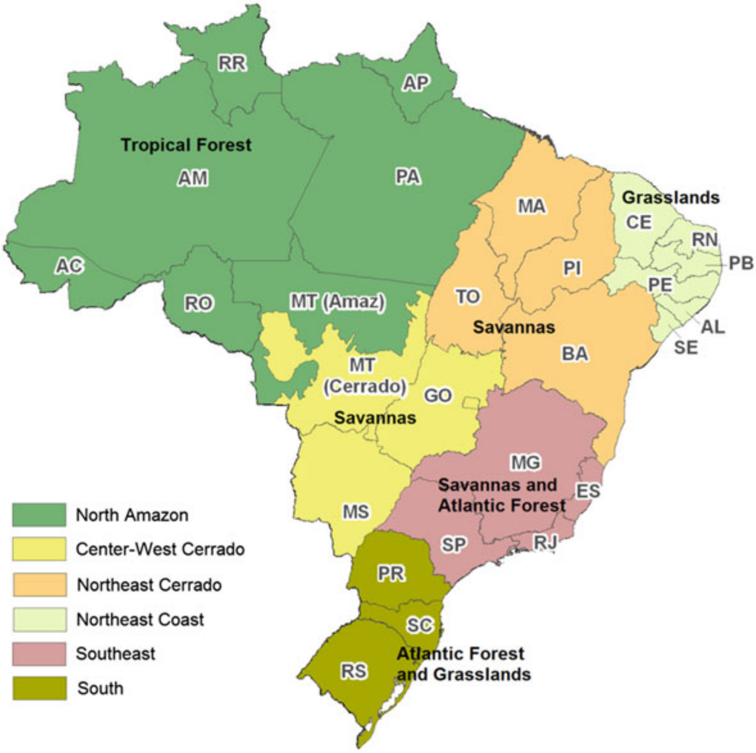

Fig. 1 Regions considered in the Brazilian Land Use Model—BLUM; *Source* IBGE, UFMG, and ICONE

consumption, and net exports is estimated for the next 10–20 years (for the purposes of this paper, we consider a time period of 10 years).

Annual production in each region is calculated as the product of allocated land and yield. National production is the sum of the individual regions' production and the beginning stocks. This relationship guarantees the interaction between the land use and the supply and demand sections of the model, considering that the following identity must be satisfied:

$$\begin{aligned}&\mathit{Beginning\ stock} + \mathit{Production} + \mathit{Imports} = \mathit{Ending\ Stock} + \mathit{Consumption} + \mathit{Exports}\\&\text{or, because } \mathit{Net\ Exports} = \mathit{Exports} - \mathit{Imports}:\\&\mathit{Beginning\ stock} + \mathit{Production} = \mathit{Ending\ Stock} + \mathit{Consumption} + \mathit{Net\ Exports}.\end{aligned}$$

The BLUM also takes into account interactions among different sectors, including both intermediate and derived products. For example, the interaction between the grain and livestock sectors is seen through feed consumption (primarily corn and soybean meal) that is needed for the production of meat, milk, and eggs.

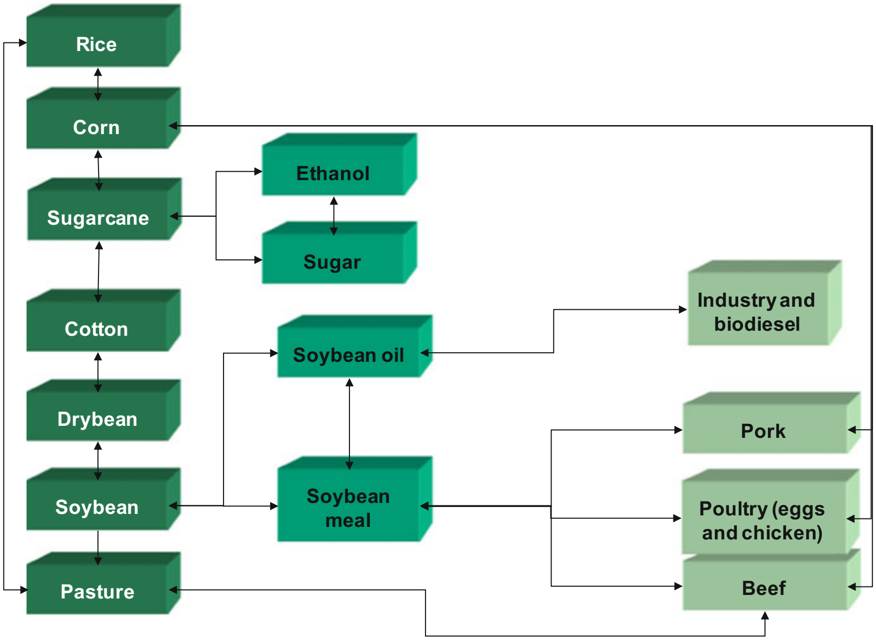

Fig. 2 Interactions between BLUM sectors; *Source* ICONE

Additionally, the relative profitability of beef and dairy production affects the area allocated to feed crops like corn and soybeans. In the case of the soybean complex, soybean meal and soybean oil drive the domestic demand for soybeans and their supply is determined by the crush demand for these derived products. Similarly, ethanol and sugar are the individual components of sugarcane demand (Fig. 2).

2.3 *The Land Use Section*

The land use dynamics incorporated into the BLUM include two effects: *competition* and *scale*. Intuitively, the competition effect represents how different activities compete for a given amount of available land, and the scale effect refers to the way that competition among different activities generates the need for additional land. Replacing areas with natural vegetation to accommodate the expansion of agricultural land is a viable option. In the BLUM, total agricultural area (crops and pasture) is endogenously determined by the scale effect.

The competition effect among the activities in each region is modeled following the methodology proposed by Holt (1999), which uses a system of equations that allocates a share of agricultural area to each crop and/or pasture in each region as a function of its own and "cross" returns. It establishes that for a given amount of agricultural land, an increase in the profitability of one activity will increase the share of land area devoted to this activity (at the expense of one or more of the other activities). The regularity conditions (homogeneity, symmetry, and summation) are imposed so that the elasticity matrices (and associated coefficients) are theoretically consistent.[3] For any set of these coefficients, we are able to calculate own and cross impacts as well as competition among activities. Using this structure, we can run simulations in the BLUM to calculate not only land allocation, but also land use changes. In other words, the model uses these conditions to find the changes in area dedicated to each activity subject to constraints on the amount of total allocated agricultural area. In order to ensure consistency, pasture area is regionally and endogenously determined, but modeled as the residual of total agricultural area minus crop area. In the context of Brazilian agriculture, it is particularly relevant to project pasture both endogenously and regionally, since it represents around 77% of total land used for agricultural production.

Although the competition effect may only represent the dynamics of consolidated regions where agricultural area is stable (and expansion is minimal), Brazil has many regions where agricultural land is expanding, leading to the conversion of native vegetation (Moreira et al. 2012). This effect is captured in the scale section of the BLUM. The scale effect utilizes equations that define how regional returns of agricultural activities determine the total land allocated to agricultural production in each region. More precisely, in each region, total land allocated to agriculture is a share of total area available for agriculture, and this share responds to changes in the average return of agriculture in that region.

The combination of competition and scale effects allows the BLUM to capture both land replacement and land expansion effects, and is essential in allowing the model to represent the reality of Brazilian agricultural land use dynamics. However, scale and competition effects are not independent; they are the two components of the own return elasticities of each activity. Considering a *ceteris paribus* condition, the increase in profitability of one activity has three effects: increase in the total agricultural area (through average return), increase in its own agricultural land share, and, as a result, a reduction in the share of agricultural area of other activities. For competing crops, cross effects of increased profitability on area are negative.

As previously mentioned, the own elasticities of each crop are the sum of competition and scale elasticities. At the same time, regional elasticity of land use with respect to total agricultural returns (agricultural land supply elasticity) is the sum of the scale elasticities of each activity. Therefore, we calculate competition elasticities directly from agricultural land supply elasticities, while total own elasticities were obtained through econometric analysis and a review of the literature. Estimation of agricultural area response to crop return (instead of price) is supported by several studies, as mentioned by Barr et al. (2011).

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[3] The elasticity matrices can be found in the Appendix.

2.4 Land Use Equations in the Previous Version of the Model[4]

In the BLUM land use section, the area *a* of crop *i* in each region *l (l = 1, ..., 6)* in year *t* is defined by the following equation:

$$a_{ilt} = A_l^T * m_{lt} * s_{ilt}, \tag{1}$$

where A_l^T is the total area available for agricultural production in region *l*, m_{lt} is the share of A_l^T that is currently being used for agricultural production (all crops and pasture), and s_{ilt} is the share of the area used by agriculture that is dedicated to crop *i*. A^T is an exogenous variable obtained from GIS modeling (Sparovek et al. 2010). The variable m_{lt} is endogenous to the model, and responds to the average agricultural market return (profitability) index of region $l(r_{lt})$. Thus, the share of area allocated to agriculture can be defined as:

$$m_{lt} = \frac{A_{lt}}{A_l^T} = k r_{lt}^{\varepsilon_{r_l}^{A_l}}, \tag{2}$$

where *k* is a constant parameter and $\varepsilon_{r_l}^{Al}$ is the land supply elasticity (with respect to the average return) for region *l* (results for the Brazilian average are presented in Barr et al. 2011).

In the previous version of the model (Nassar et al. 2009, 2010b; De Gouvello et al. 2010, 2011), r_{lt} was assumed to be the weighted average return of all crops (including pastures) for the period from 2004 to 2009, and was weighted based on the share of agricultural area of each crop:

$$r_{lt} = \sum_{i=1}^{n} r_{it} * s_{ilt} \tag{3}$$

The variable s_{ilt} (the share of area allocated to crop *i* in region *l*) is also endogenous and responds (positively) to the return of activity $i(r_{it})$ and (negatively) to the return of the other activities $j(r_{jt})$. so:

$$s_{ilt} = f(r_{ilt}, r_{jlt}) \tag{4}$$

From Eq. (1), the cross-area elasticity of crop *i* with respect to the return of other crops *j* can be defined as:

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[4] The previous version of BLUM description and applications can be found at Nassar et al. (2009, 2010b), De Gouvello et al. (2010, 2011).

$$\begin{aligned}\varepsilon^{l,i}_{r_{ij}} &= \frac{\partial a_{ilt}}{\partial r_{jlt}}\frac{r_{jlt}}{a_{ilt}}\\ &= A_l^T\left(\frac{\partial m_l(r_{lt})}{\partial r_{lt}}\frac{\partial r_{lt}}{\partial r_{jlt}}s_{ilt}(r_{ilt},r_{jlt})+m_l(r_{lt})\frac{\partial s_{ilt}(r_{ilt},r_{jlt})}{\partial r_{jlt}}\right)\frac{r_{jlt}}{A_l^T m_l(r_{lt})s_{ilt}(r_{ilt},r_{jlt})},\end{aligned} \tag{5}$$

which, when rearranging terms, leads to:

$$\varepsilon^{l,i}_{r_{ij}} = \frac{\partial m_l(r_{lt})}{\partial r_{lt}}\frac{\partial r_{lt}}{\partial r_{jlt}}\frac{r_{jlt}}{m_l(r_{lt})} + \frac{\partial s_{ilt}(r_{ilt},r_{jlt})}{\partial r_{jlt}}\frac{r_{jlt}}{s_{ilt}(r_{ilt},r_{jlt})} \tag{6}$$

The first term on the right-hand side of Eq. (6) can be defined as the scale effect of the cross-area elasticity $\varepsilon^{s_{l,i}}_{r_{lj}}$:

$$\varepsilon^{s_{l,i}}_{r_{lj}} = \frac{\partial m_1(r_{lt})}{\partial r_{lt}}\frac{\partial r_{lt}}{\partial r_{jlt}}\frac{r_{jlt}}{m_l(r_{lt})} \tag{7}$$

The competition effect of the cross-area elasticity $\varepsilon^{c_{l,i}}_{r_{lj}}$ is the second part of the right hand side of Eq. (6):

$$\varepsilon^{c_{l,i}}_{r_{lj}} = \frac{\partial s_{ilt}(r_{ilt},r_{jlt})}{\partial r_{jlt}}\frac{r_{jlt}}{s_{ilt}(r_{ilt},r_{jlt})} \tag{8}$$

One might notice that, since there are six different crops and pasture competing with one another, each region will have a competition elasticity square matrix of the order seven. So, the area elasticity of crop *i* relating to its own return is also formed by the scale and competition effects, and can be written as:

$$\varepsilon^{l,i}_{r_{ij}} = \frac{\partial m_l(r_{lt})}{\partial r_{lt}}\frac{\partial r_{lt}}{\partial r_{ilt}}\frac{r_{ilt}}{m_l(r_{lt})} + \frac{\partial s_{ilt}(r_{ilt},r_{jlt})}{\partial r_{ilt}}\frac{r_{ilt}}{s_{ilt}(r_{ilt},r_{jlt})} = \varepsilon^{s_{l,i}}_{r_{li}} + \varepsilon^{c_{l,i}}_{r_{li}}, \tag{9}$$

where $\varepsilon^{s_{l,i}}_{r_{li}}$ is the scale effect and $\varepsilon^{c_{l,i}}_{r_{li}}$ is the land competition component of the area elasticity of crop *i* with respect to its own return.[5] The land competition component can then be calculated as:

$$\varepsilon^{c_{l,i}}_{r_{li}} = \varepsilon^{l,i}_{r_{lt}} - \varepsilon^{s_{l,i}}_{r_{li}} \tag{10}$$

The link between the regional land supply elasticity ($\varepsilon^{Al}_{r_l}$) and the scale effect of each activity ($\varepsilon^{s_{l,i}}_{r_{li}}$) can thus be observed. The land supply elasticity can be defined as:

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[5] Also explained in Nassar et al. (2009) available at http://www.iconebrasil.com.br/arquivos/noticia/1872.pdf.

$$\varepsilon^{Al}_{r_l} = \frac{\partial m_l}{\partial r_l}\frac{r_l}{m_l} \tag{11}$$

and, rearranging:

$$\frac{\partial m_l}{\partial r_l} = \frac{\varepsilon^{Al}_{r_l} m_l}{r_l} \tag{12}$$

The elasticity with respect to the variation in the return of a given crop i in region l is:

$$\varepsilon^{s_{l,i}}_{r_{li}} = \frac{\partial m_l}{\partial r_l}\frac{\partial r_l}{\partial r_{li}}\frac{r_{li}}{m_l}, \tag{13}$$

which can be rewritten as:

$$\varepsilon^{s_{l,i}}_{r_{li}} = \varepsilon^{A_l}_{r_l}\frac{\partial r_l}{\partial r_{li}}\frac{r_l}{r_{li}} \tag{14}$$

Using Eq. (3), Eq. (14) can be rewritten as:

$$\varepsilon^{s_{l,i}}_{r_{li}} = \varepsilon^{A_l}_{r_l} s_{ilt}\frac{r_l}{r_{li}} \tag{15}$$

Thus, using Eq. (15), if the land supply elasticity is known, the scale effect of activity i can be easily calculated. As a result, the vector containing all land competition component elasticities $\varepsilon^{c_{l,i}}_{r_{li}}$ represents the diagonal of the competition matrix (one diagonal for each region l). After factoring in other restrictions (such as the regularity conditions and negative cross elasticities), the diagonal terms are then used to obtain the cross elasticities in the competition matrix, as shown in Eq. (8).

2.5 *Improving the Land Supply Equation and the Model Elasticities*

According to economic theory, stronger incentives are necessary in order to bring more land into agricultural production, given that it is a limited resource. Thus, the land supply elasticity will not be constant and Eq. (2) can accurately represent land use dynamics. Using the idea described in the land use extension equation defined in the Mirage model (Al-Riffai et al. 2010), a simple way to overcome this problem is to implement a small change in the structure of Eq. (2) as follows:

$$m_{lt} = \frac{A_{lt}}{A_l^T} = kr_{lt}^{\alpha_{lt}\varepsilon_{r_l}^{A_l}} \tag{16}$$

The parameter α_{lt} is positive, can be higher or lower than one, and is defined as:

$$\alpha_{lt} = 1 - \frac{A_{lt} - A_{l0}}{A_l^T}, \tag{17}$$

where A_{l0} is the land used for agriculture in a defined base period. When agricultural land use in period t is close to that of the base period, α_{lt} is close to 1 and has little effect on $\varepsilon_{r_l}^{Al}$. However, if agricultural land use in t is larger than in the base period, the parameter α_{lt} is smaller than one and reduces the effect of $\varepsilon_{r_l}^{Al}$. The opposite occurs when current agricultural land is smaller than A_{lo}, increasing the land supply elasticity.

Given the available data, the weighted average return to agricultural land area seemed to be the best approach to determine agricultural land expansion. However, Morton et al. (2006), Ferreira et al. (2007, 2009a, b, 2011), Sparovek et al. (2010), Rudorff et al. (2011); Rocha et al. (2011) showed that some agricultural activities (notably pasture and certain grains) are very connected with agricultural expansion (scale effect), while others tend to expand on the intensive margin through competition with other activities. This suggests that the activities directly responsible for deforestation would have greater weight in the average return from the expansion of the agricultural land. In the BLUM, this would require r_{lt} to be recalculated, replacing Eq. (3). The new functional form of r_{lt} would no longer be based on the average return weighted by the agricultural area share of activity i, but on evidence that indicates which activities lead to the greatest expansion of the agricultural frontier.

Remote sensing information would provide a vector D representing the respective deforestation rate caused by each agricultural activity. We can then calculate the individual weights of vector d_{li} as follows:

$$d_{li} = \frac{\mathrm{D}_{li}}{\mathrm{D}_l^{\mathrm{T}}}; \text{where } \mathrm{D}_l^{\mathrm{T}} = \sum_{i=1}^{\mathrm{n}} \mathrm{D}_{li} \tag{18}$$

Equation (3) can then be replaced by:

$$r_{lt} = \sum_{i=1}^{n} r_{it} * d_{li} \tag{19}$$

We are able to drop the subscript t since the vector d_{li} does not change over time. Thus, Eq. (14) is now calculated as:

$$\varepsilon_{r_{li}}^{s_{l,i}} = \varepsilon_{r_l}^{A_l} d_{li} \frac{r_l}{r_{li}} \tag{20}$$

Since there are new values for r_{lt}, it is necessary to review the regional land supply elasticities in Eq. (2) and the expansion (scale) elasticities in Eq. (20). In order to keep the original own elasticities, Eq. (10) requires that we rebalance the competition elasticities for each crop. From Eq. (10), we know that total own elasticity equals scale effects plus competition effects. Cross elasticities must also be recalculated to guarantee that the symmetry, homogeneity, and summation conditions presented in Holt (1999) hold.

2.6 Data and Methods

The own return elasticities represented in Eq. (9) were estimated based on a review of the literature [Vado et al. (2004a, b); Shepherd (2006); Moraes (2006); Brescia and Lema (2007); Menezes and Piketty (2007); and Bridges and Tenkorang (2009)]. Specific geospatial analysis was conducted in order to estimate the total potential land available for agricultural production in each region in the BLUM, which is identified as an input in the scale effect section of the model. The database for this analysis was provided by the Agricultural Land Use and Expansion Model —Brazil (AgLUE-BR) (Sparovek et al. 2010, 2011). The extent to which agricultural land can be expanded is restricted by at least two factors: physical suitability characteristics (soil, climate, and land slope) and legal requirements (environmental legislation applicable to private farmland and public conservation parks). Both restrictions were also considered in the geospatial analysis.

Cerrado biome deforestation (which has taken place in the states of Goiás, Distrito Federal, Bahia, Tocantins, Mato Grosso, Mato Grosso do Sul, Maranhão, Piauí, São Paulo, and Minas Gerais) is monitored on a yearly basis by the Laboratório de Processamento de Imagens e Geoprocessamento (LAPIG). Detailed descriptions of the methodology used for detection of deforestation can be found in Ferreira et al. (2007, 2009b), and Rocha et al. (2010). The methodology developed by LAPIG generated the results used in this paper, and can be found in Ferreira et al. (2011).

The main purpose of LAPIG's research was to assess the first use of the land once it was cleared. Three classes of productive uses were defined: annual crops (agriculture), pastures, and sugarcane (a perennial crop). Using LAPIG's database, it was possible to determine the extent of advancement of annual crops and pastures over the Cerrado biome. It is also important to recognize the different land use dynamics among different regions in the same biome. For example, as shown in Table 1, 42% of natural forest was displaced by crops, 3% by sugarcane, and 56% by pasture in the Center-West Cerrado region between 2004/05 and 2006/07. In the Northeast Cerrado region, these rates were 64% for crops, 0% for sugarcane, and 36% for pasture. A similar analysis was developed for sugarcane based on

Table 1 Share of land allocated to different uses after deforestation

Region	Activities	% Deforestation	Crops	% Crops
South	Crops	44	Corn	54
			Soybean	30
			Cotton	0
			Rice	3
			Dry bean	13
	Sugarcane	1		
	Pasture	55		
Center-West Cerrado	Crops	42	Corn	53
			Soybean	45
			Cotton	0
			Rice	1
			Dry bean	2
	Sugarcane	3		
	Pasture	56		
Northeast Coast	Crops	20	Corn	49
			Soybean	0
			Cotton	3
			Rice	3
			Dry bean	46
	Sugarcane	7		
	Pasture	73		
Southeast	Crops	39	Corn	20
			Soybean	74
			Cotton	0
			Rice	1
			Dry bean	5
	Sugarcane	2		
	Pasture	59		
North Amazon	Crops	7	Corn	29
			Soybean	69
			Cotton	0
			Rice	0
			Dry bean	2
	Sugarcane	0		
	Pasture	93		
Northeast Cerrado	Crops	64	Corn	20
			Soybean	34
			Cotton	33
			Rice	3
			Dry bean	10
	Sugarcane	0		
	Pasture	36		

Source ICONE

Rudorff et al. (2010), but it was used to evaluate sugarcane displacement over other, non-forest uses.

Amazon biome deforestation is monitored by INPE—Instituto Nacional de Pesquisas Espaciais. This data, however, only reports the amount of forest cleared, providing no information about the subsequent use of the land after clearing. The use of the cleared land in the Amazon biome was obtained from two sources: the Soybean Moratorium Project (Rudorff et al. 2011) and the Terra Class Project. Based on these projects, we were able to establish the share of cleared land occupied by crops or pasture, also keeping in mind that there was no direct land clearing for sugarcane in the Amazon biome. Excluding nonproductive uses (such as burning and natural forest recovery in newly deforested areas), in 2007/08 the observed shares of pastures and crops in the Amazon biome were 93% and 7%, respectively. These relative shares were used in the BLUM North Amazon region (Table 1).

While the structure of BLUM covers ten different agricultural activities, the remote sensing information gathered from LAPIG, INPE, the Soybean Moratorium Project, and the Terra Class Project addressed only three (annual crops, pasture, and sugarcane). Thus, we had to disaggregate the broadest class (annual crops) into eight agricultural uses. We developed a specific method based on two-step allocation procedures to break down the annual crops category. First, we determined the respective shares of annual crops, pastures, and sugarcane in the conversion of native vegetation using observed remote sensing data. However, the limited ability of remote sensing techniques to interpret images for different classes of cropland required a second step in the analysis: splitting the "annual crops" category into individual crops using the results of Moreira et al. (2012), which are used in Eq. (19) to calculate the average return of agriculture for each region.

Because analyzing agricultural activities in newly deforested areas through satellite imagery is only available for the Amazon and Cerrado biomes (which are found in the Southeast, Center-West Cerrados, Northeast Cerrados, and North Amazon BLUM regions), direct advancement of agricultural activities over native vegetation in the South and Northeast Coast regions, which include the Atlantic Forest, Caatinga (semiarid), Pantanal, and Pampa biomes, was assessed based on the land allocation procedures (as explained by Nassar et al. 2010a). Using regional average returns to agriculture, it is possible to calculate land supply elasticities, as defined in Eq. (11). Because the database for agricultural returns is not currently available, the agricultural land supply elasticity for each region was defined as the average of the point elasticities (the ratio of the percentage change in agricultural land to the percentage change in average return) for the years available in the Cerrado (2004/05 and 2006/07) and Amazon biomes (2007/08). For the regions with no deforestation data available, we compared the observed expansion in agricultural land to the average return from agricultural activities on the expanded land. The share of agricultural expansion over land with native vegetation (with respect to each activity) was calculated using the methodology in Moreira et al. (2012).

Based on the estimated land supply elasticities, it is possible to calculate the scale effect of each activity in each region, as defined in Eq. (20). The competition elasticities were estimated using the elasticity matrices for each region and the regularity conditions explained in the previous section. Competition rankings among only crops as well as among both crops and pasture were defined based on empirical evidence (Nassar et al. 2009; Moreira et al. 2012, and Rudorff et al. 2010) and on the importance of each crop in each region (measured by the land share of crop *i* compared to total agricultural land). The most notable improvement in the refined BLUM is that pasture area is now defined as the most important competitor with crops in the elasticity matrices.

Own and competition (cross) elasticities for the different activities of the BLUM allow us to calculate the land use change caused by relative variations in a given activity's profitability as well as in competing activities' profitabilities. More specifically, the cross elasticities in the sugarcane area share equation represent the variation in sugarcane land share caused by a change in returns to other activities. That is, the cross elasticities determine the portion of sugarcane land share that is lost to other activities. Similarly, the cross elasticities of the other activities share equations, considering that variation in the return on sugarcane is equal to the portion of the other activity's land share that was displaced by sugarcane. The sum of these effects is the net land share that sugarcane loses or gains from other activities, which is equal to the final variation in sugarcane land share. The amount of land allocated to each activity in each region is obtained by multiplying the total agricultural land in each region by the final land share of each crop and pasture. Through simulations, the BLUM shows the effect of the increase in sugarcane production over other activities. The effect is modeled as introducing a shock in each region and the effect can thus be measured by comparing the area allocated to each crop in the shock scenario versus the baseline scenario in 2022, as presented in the results section.

Land use change also often leads to an increase in carbon emissions, which are *ex-post* calculated based on the BLUM results for land use change. The amount of emissions caused by the increase in sugarcane production is the total amount of pasture converted to crops (sugarcane plus grains) combined with natural vegetation that is converted to pastures. These types of land conversions were transformed in region-specific coefficients. These coefficients represent the percentage of each type of conversion taking place in the region (pasture to crops or natural vegetation to pasture), considering the weight of each region in the total land displaced in Brazil. These factors are used to directly calculate the average emission generation associated with each category in each region.

Using the results from the BLUM, the methodology used to transform land use change into CO_2-equivalent emissions is very similar to the one used by the Environmental Protection Agency (EPA) in their Renewable Fuel Standard regulatory impact analysis (EPA 2009). As was the case in the original BLUM analysis, CO_2-equivalent emissions per hectare of sugarcane expansion are calculated using the different emissions factors (for different types of emissions) weighted by the land use change coefficients. However, the land use change coefficients in this refined analysis are calculated differently than in the previous analysis. In the original analysis they were estimated based on past land use change using geospatial analysis, and it was assumed that the same pattern would occur in the future, thus they did not change over time or according to different possible shocks. In other words, the original land use change coefficients were not connected to the economic model.[6] One of the major improvements proposed in our work is that by using the BLUM, the land use change coefficients can be calculated based on the results of the model and, consequently, will be dependent on different scenarios as well as on different economic assumptions.

3 Empirical Results

The first set of results is the revised index of agricultural returns [vector *d* of Eq. (18)], which can be seen in Table 1. The average return comprises the agricultural activities included in the BLUM that compete for land (soybean, corn (first crop), cotton, rice, dry beans (first crop), sugarcane, and pastures). Weights used to calculate the average return are the same as those from Table 1.

Based on Eq. (11) described in the previous section, land supply elasticities were calculated using the data in Table 1. However, the empirical evidence from each year does not always confirm the theory behind the BLUM: for several years returns have been decreasing while agricultural land has been increasing. For this reason, land supply elasticities (at the point) were calculated only for the years with positive variation in market returns. Therefore, land supply elasticities are the average of positive elasticities for a given region. By ignoring negative land supply elasticities, we explicitly assume that the conversion of forest land is driven by agricultural profitability (Table 2). Table 3 compares agricultural land supply elasticities from the previous version of BLUM to the updated ones estimated using the new database. The parameters found using the proposed methodology are smaller than the ones found in the previous analysis. The newly calculated elasticities are still in line with the theory that higher elasticities were found in regions with larger amounts of land available and where the agricultural frontier is expanding (e.g., the North Amazon and Northeast Cerrado regions).

Own price elasticities are presented in Table 4 and competition own elasticities (once the scale effect, which is derived from land supply elasticities, is discounted) are presented in Table 5. The new competition own elasticities show that the competition effect is more significant in the updated version of the BLUM than in the previous one. Updated own elasticities for the competition matrices are larger than in the previous version, indicating that the updated version allows for larger responses of agricultural uses to changes in market return.

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[6] See document EPA-HQ-OAR-2005-0161-0891. Available at: http://www.regulations.gov/search/Regs/home.html#documentDetail?R=09000064809ad1c4.

Table 2 Land allocated to agriculture (1000 ha) and weighted average returns (R$/ha)

	South		Southeast		Center-West Cerrado		North Amazon		Northeast Coast		Northeast Cerrado	
	Area	Return	Area	Return	Area	Return	Area	Return	Area	Return	Area	Return
2002	31,118	261	37,131	202	60,136	213	43,811	69	13,287	129	36,557	342
2003	31,133	309	37,195	281	60,783	269	46,097	88	13,468	148	36,927	416
2004	31,148	313	37,255	246	61,399	246	48,542	73	13,785	146	37,486	466
2005	31,162	294	37,299	191	61,765	168	50,203	52	14,077	159	37,808	323
2006	31,176	165	37,351	143	61,997	98	51,453	28	14,663	151	38,058	174
2007	31,190	120	37,439	172	62,175	104	52,522	26	14,790	124	38,344	132
2008	31,203	218	37,488	215	62,346	167	53,601	64	14,996	106	38,726	152
2009	31,211	253	37,526	173	62,523	162	54,159	57	15,250	135	39,008	193

Source ICONE

Table 3 Land supply elasticities

Regions	Previous version	Updated version
South	0.057	0.002
Southeast	0.067	0.007
Center-West Cerrado	0.180	0.031
North Amazon	0.250	0.103
Northeast Coast	0.010	0.056
Northeast Cerrado	0.100	0.066

Source ICONE

Table 4 Own return elasticities

	South	Southeast	Center-West Cerrado	North Amazon	Northeast Coast	Northeast Cerrado
Corn—1st crop	0.18	0.20	0.20	0.20	0.22	0.19
Soybean	0.43	0.43	0.48	0.45	0.00	0.44
Cotton	0.21	0.21	0.25	0.25	0.20	0.22
Rice	0.15	0.12	0.13	0.15	0.13	0.13
Dry bean—1st crop	0.09	0.10	0.10	0.09	0.10	0.10
Sugarcane	0.40	0.40	0.43	0.20	0.39	0.40
Pasture	0.03	0.05	0.11	0.24	0.01	0.07

Source ICONE

Table 6 shows a regional example for cross-competition elasticities (negative values indicate substitution between two agricultural uses). Numbers in gray (diagonal) in Table 6 correspond to the own elasticities that are found in the competition matrix. Crops "*i*" make up the rows and crops "*j*" the columns, which means that for the South region a 10% increase in the return of soybean will lead soybean to displace 0.572% of corn area (*ceteris paribus*). The next section compares simulations in the previous versus the updated versions of the BLUM.

4 Simulations

To assess how the updated parameters affect land use changes caused by the expansion of biofuels, we simulated a scenario with stronger demand for sugarcane ethanol (i.e., a shock scenario with respect to the baseline scenario). First, a baseline

Table 5 Competition effects (from own elasticities)

	South		Southeast		Center-West Cerrado		North Amazon		Northeast Coast		Northeast Cerrado	
	Previous	Updated	Previous	Updated	Previous	Updated	Previous	Updated	Previous	Updated	Previous	Updated
Corn—1st crop	0.18	0.18	0.20	0.20	0.20	0.20	0.19	0.19	0.22	0.22	0.18	0.19
Soybean	0.40	0.43	0.43	0.43	0.39	0.47	0.40	0.43	0.00	0.00	0.42	0.43
Cotton	0.21	0.21	0.21	0.21	0.25	0.25	0.25	0.25	0.20	0.20	0.20	0.17
Rice	0.15	0.15	0.12	0.12	0.12	0.13	0.13	0.15	0.13	0.13	0.11	0.13
Dry bean—1st crop	0.09	0.09	0.09	0.09	0.10	0.10	0.08	0.09	0.10	0.10	0.09	0.10
Sugarcane	0.39	0.40	0.36	0.40	0.40	0.42	0.19	0.20	0.38	0.34	0.39	0.40
Pasture	0.02	0.03	0.04	0.05	0.05	0.11	0.08	0.17	0.01	0.01	0.05	0.07

Elasticity term regarding the land competition component of the area elasticity of crop i with respect to its own return
Source ICONE

Table 6 Competition elasticity matrix—south region

	Corn 1st crop	Soybean	Cotton	Rice	Dry bean 1st crop	Sugarcane	Pasture
Corn 1st crop	0.1838	−0.2695	−0.0003	−0.0095	−0.0023	−0.0104	−0.0058
Soybean	−0.0572	0.4334	−0.0002	−0.0052	−0.0013	−0.0064	−0.0261
Cotton	−0.0164	−0.0540	0.2087	−0.0015	−0.0009	−0.0055	−0.0093
Rice	−0.0102	−0.0265	0.0000	0.1529	−0.0025	−0.0060	−0.0049
Dry bean 1st crop	−0.0188	−0.0483	−0.0001	−0.0185	0.0914	−0.0031	−0.0104
Sugarcane	−0.0106	−0.0307	−0.0001	−0.0057	−0.0004	0.3998	−0.0047
Pasture	−0.0076	−0.1603	−0.0002	−0.0059	−0.0017	−0.0061	0.0154

Elasticity term regarding competition component of the area elasticity of crop i with respect to its own return and the competition effect of the cross-area elasticity
Source ICONE

scenario was simulated[7] in the BLUM that resembled an expected macroeconomic scenario for 2022 (Brazilian GDP growth of 3.7% per year, population growth of 1% per year, increases in oil prices by US$75 per barrel, 12.4 billion liters of ethanol exports in 2022, and other macroeconomic variable changes). The results of this simulation represent the response of Brazilian agricultural expansion and land use change to these baseline assumptions.

The shock applied to the model corresponds to an additional 9.45 billion liters of ethanol exports in 2022 compared to the baseline. In order to compare the results effectively, the scenario was simulated using the same version of the model, changing only the land supply elasticities, the own competition elasticities, and the cross-competition elasticities. We used the same version of the model used in Nassar et al. (2009), which was a paper submitted to the U.S. Environmental Protection Agency public consultation. In this version, the BLUM runs independently of world markets, and prices are solved for endogenously. Table 7 presents the results for total land used in agriculture. The updated model is more conservative in terms of land use expansion, and as a result projects a lesser advancement of the frontier than the previous version (reference). While the previous version projected an additional 13 million ha for crop production from 2009 to 2022, the updated version projects a 7.8 million ha increase over the same time period. To put this figure into perspective, from 2002 to 2009 total deforestation in the Amazon, Atlantic Forest, and Cerrado biomes was 4.9 million ha, which corresponds to 703 thousand ha/year (Ferreira et al. 2009a; INPE 2012). The previous version of the BLUM projects 1 million ha/year from 2009 to 2022 and the updated version 600 thousand ha/year.

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[7] It is important to note that the results presented were simulated in the BLUM in January 2011 considering the expected macroeconomic scenario for the next 10 years (based on IMF World Economic Outlook projections). The BLUM database is constantly being updated (twice a year) and its structure, parameters, and sectors are improved as new databases and observations become available.

Table 7 Total agricultural land in 2022: crops and pastures (1000 ha)

Regions	2009	2022			
		Baseline		Shock	
		Previous	Updated	Previous	Updated
South	31,743	32,754	31,763	32,775	31,764
Southeast	50,991	52,532	51,222	52,632	51,233
Center-West Cerrado	62,981	67,209	64,205	67,258	64,302
Northern Amazon	51,729	56,212	54,456	56,235	54,421
Northeast Coast	14,986	15,059	15,390	15,063	15,497
Northeast Cerrado	37,231	39,078	40,430	39,088	40,452
Brazil	249,660	262,846	257,466	263,051	257,669

Source ICONE

Table 8 Land use in Brazil: first crops and pasture (1000 ha)

Activity	2009	Baseline 2022		Shock 2022	
		Previous	Updated	Previous	Updated
Corn—1st crop	9285	7678	8214	7442	8134
Soybean	21,557	31,118	31,105	31,026	31,108
Cotton	856	1782	1808	1736	1806
Rice	2894	3033	3155	3025	3153
Dry bean—1st crop	2963	2511	2651	2470	2657
Sugarcane	8120	10,525	10,551	11,558	11,575
Pasture	203,973	206,199	199,982	205,794	199,237

Source ICONE

According to the updated version, three regions cover 92% of total agricultural land expansion in 2022 compared to 2009: Northeast Cerrado (mainly due to soybean and pastures) Northern Amazon (also concentrated in pastures and soybean), and Center-West (with the strongest growth in soybean and largest reduction in pastures). As presented in Table 10, area under corn as a first crop area is decreasing while area under corn as a second crop may increase significantly over this time period. Sugarcane area, in absolute and relative terms, is significantly increasing in the Southeast region but is also expanding in the Northeast Coast, Center-West Cerrado, and Northeast Cerrado regions.

Comparing the shock and baseline scenarios in both the previous and updated versions, it is possible to identify the indirect land use change, as total agricultural land is slightly larger in the scenario with the shock increase in ethanol production. The indirect effect, however, is less than proportional to the expansion of sugarcane area; while sugarcane area is increasing around 1 million ha (shock minus baseline scenario) per year, total agricultural land is expanding by about 200 thousand ha in both versions of the model (Table 7).

The key difference between the previous and the updated versions of the BLUM is the intensification of cattle production (Tables 8 and 9). Due to the fact that

Table 9 Crops and pasture: production in 2022 (1000 tons) for first crops and meat

Activity	2009	2022			
		Baseline		Shock	
		Previous	Updated	Previous	Updated
Corn—1st crop	33,129	35,260	37,221	33,826	36,859
Soybean	57,635	98,174	98,152	97,943	98,220
Cotton	0	0	0	0	0
Rice	12,519	14,683	14,758	14,638	14,746
Dry bean—1st crop	2165	2311	2526	2223	2527
Sugarcane	639,356	969,046	972,087	1,082,989	1,084,699
Biodiesel	1765	3167	3167	3167	3167
Sugar	33,096	43,845	43,879	43,767	43,843
Ethanol	29,048	53,646	53,821	63,188	63,229
Beef	10,211	12,493	12,336	12,493	12,339
Pork	3286	4631	4654	4624	4653
Broiler	11,004	13,163	13,228	13,156	13,234

Source ICONE

cross-competition elasticities are larger in the updated version and using the assumption that pasture is the activity that is first displaced by crops, the updated version allows for more pasture intensification than the previous due to the revision in elasticities. A clear consequence of the heightened competition among crops and pastures is that, for the same level of production, less land is required to be brought into production (and thus less native vegetation is converted), although the marginal land brought into production (shock minus baseline) is almost the same in both the previous and updated models.

In Table 9, one can see that total agricultural production does not change significantly between the previous and updated simulations. However, in the updated version, we see that production of grains does not decrease in the shock scenario, the opposite of which was observed in the previous version. The production of all agricultural sectors between 2009 and 2022 is expanding at rates equivalent to historical ones (from 1997 to 2008). Of the primary agricultural products, soybean and sugarcane are expected to face the largest growth in land area. Of the processed products, production of ethanol and biodiesel are expected to grow strongly compared to 2009. In the baseline scenario of the revised model, ethanol production is expected to grow 85% during the projection period, while in the shock scenario the simulation indicates growth of 118%. As for meats, beef, and broiler, equivalent growth (around 20%) between the two scenarios is expected, while pork may face a larger growth (42%) in the shock scenario (Table 10).

We also solved for the prices needed to clear the market, which are listed in Table 11. When comparing the shock and baseline scenarios, prices lie within an expected range. Because the shock was applied to ethanol demand, ethanol prices increased more than any other product. Sugar prices also increased, as more sugarcane was needed to meet ethanol production needs in the shock scenario.

Table 10 Land use in BLUM regions: crops and pasture (1000 hectares)

Regions	Activity	2009	Baseline 2022		Shock 2022	
			Previous	Updated	Previous	Updated
South	Corn—1st crop	3359	3350	3112	3350	3118
	Soybean	8227	10,865	10,955	10,831	10,956
	Cotton	6	6	10	5	10
	Rice	1294	1450	1376	1443	1374
	Dry bean—1st crop	532	396	417	398	416
	Sugarcane	631	812	803	891	877
	Pasture	17,688	15,875	15,091	15,856	15,013
Southeast	Corn—1st crop	1950	1828	1787	1628	1608
	Soybean	1425	1630	1682	1517	1586
	Cotton	23	5	72	12	72
	Rice	85	5	92	17	91
	Dry bean—1st crop	296	188	274	141	273
	Sugarcane	4950	6450	6502	7159	7217
	Pasture	42,264	42,426	40,813	42,160	40,386
Center-West Cerrado	Corn—1st crop	712	44	535	4	629
	Soybean	7500	10,868	10,530	10,890	10,579
	Cotton	413	1171	1122	1127	1118
	Rice	232	250	267	246	268
	Dry bean—1st crop	73	71	69	71	69
	Sugarcane	990	1274	1252	1375	1349
	Pasture	53,066	53,532	50,430	53,545	50,290
North Amazon	Corn—1st crop	519	46	228	43	258
	Soybean	2484	3973	3912	3991	3930
	Cotton	61	120	117	117	117
	Rice	434	473	522	469	521
	Dry bean—1st crop	175	170	162	170	162
	Sugarcane	142	170	166	179	174
	Pasture	47,914	51,261	49,349	51,267	49,258
Northeast Coast	Corn—1st crop	1517	1557	1484	1566	1458
	Soybean	0	0	0	0	0
	Cotton	31	47	48	47	49
	Rice	65	72	73	72	74
	Dry bean—1st crop	1355	1258	1243	1262	1252
	Sugarcane	1210	1581	1561	1700	1675
	Pasture	10,794	10,545	10,980	10,418	10,989

(continued)

Table 10 (continued)

Regions	Activity	2009	Baseline 2022		Shock 2022	
			Previous	Updated	Previous	Updated
Northeast Cerrado	Corn—1st crop	1227	853	1066	851	1063
	Soybean	1922	3783	4027	3798	4056
	Cotton	322	432	439	428	440
	Rice	785	782	825	780	824
	Dry bean—1st crop	533	429	486	429	485
	Sugarcane	198	239	267	254	283
	Pasture	32,247	32,560	33,321	32,549	33,301
Brazil	Corn—1st crop	9285	7678	8214	7442	8134
	Soybean	21,557	31,118	31,105	31,026	31,108
	Cotton	856	1782	1808	1736	1806
	Rice	2894	3033	3155	3025	3153
	Dry bean—1st crop	2963	2511	2651	2470	2657
	Sugarcane	8120	10,525	10,551	11,558	11,575
	Pasture	203,973	206,199	199,982	205,794	199,237

Source ICONE

Table 11 Producer prices for Brazil

Activity	Unit	2009	2022			
			Baseline		Shock	
			Previous	Updated	Previous	Updated
Corn	R$/ton	388.28	447.59	430.85	452.04	432.99
Soybeans	R$/ton	854.62	1079.84	1082.73	1092.51	1087.64
Cotton	R$/ton	1092.00	1733.05	1709.97	1674.73	1716.10
Rice	R$/ton	698.03	827.12	822.28	811.87	824.25
Dry beans	R$/ton	1050.00	865.99	686.87	877.70	685.77
Sugar	R$/liter	502.99	651.77	642.86	687.31	672.08
Ethanol	R$/ton	0.90	1.39	1.37	1.57	1.54
Beef	R$/kg	5.50	7.54	8.02	7.54	7.98
Broiler	R$/kg	1.48	2.92	2.85	2.93	2.83
Pork	R$/kg	2.87	6.14	6.04	6.17	6.04

Source ICONE

It is important to note that land allocated to sugarcane as calculated in the model is different from total land displaced by sugarcane due to the decrease in the hectarage of grains in some regions. This is because an increase in ethanol demand causes its price to increase, which leads to greater production and reduces excess demand until market equilibrium is reached. In order to expand, sugarcane takes the place of other crops and pasture, decreasing their land shares with respect to total agricultural land. However, part of the grain demand is fixed (net exports are fixed for both simulated scenarios), thus two simultaneous effects were observed as the grain market reached an equilibrium. First, grain prices increased in order to raise production levels to those seen before the ethanol shock. As a result, higher grain prices caused a small decrease in domestic demand. Since the aim of this analysis is to assess carbon intensity while keeping domestic consumer welfare constant, the land that grains lost due to the ethanol shock was incorporated (*ex-post*) into the total area (proportionally to the land use change coefficients).

In the previous version of the model, sugarcane ethanol reduced GHG emissions by 60% [assuming a 30 year time period and no discount rate (EPA 2009)] and the calculated iLUC factor was 21.5 g CO_2/MJ of energy produced from ethanol (assuming the reduction in grain area was included in the indirect effect calculation). In the updated version, GHG emissions reduction was 69% (considering the same time horizon and no discount rate) and the calculated iLUC factor was 13.9 g CO_2/MJ. This result lines up with results from other studies, such as Laborde et al. (2014).

5 Final Considerations

Results derived from all economic models are fundamentally dependent on the assumptions underlying them. In economic modeling, assumptions are translated into parameters, for example elasticities. Although elasticities are easily expressed through derivations, they cannot always be empirically calculated or calibrated, as data may not be available or because empirical evidence does not fit the theory. The main contribution of this paper was to demonstrate how to empirically determine the elasticities that govern changes in land use in the BLUM's land allocation module, as well as to illustrate the sensitivity of model outcomes to changes in these elasticities. The updated version of the BLUM's land use module discussed in this paper is now fully calibrated with observed data from 2002 to 2009, which is used as the base period for the land supply elasticities, cross-area elasticities, and market returns (showed in Table 1 and described in Sect. 2.6).

This paper also contributes to a relatively new field in agricultural economics—the creation of interfaces and connections between economic and geospatial modeling. Although the BLUM is not a spatially explicit model, several of the BLUM's parameters were established based on remote sensing information, which is geospatially defined (as described above). A key advantage of economic models is their ability to quantify impacts. By simulating different scenarios and establishing accurate cause–effect relationships between economic variables, models can indicate positive and negative impacts of policies and private agent decisions. Evaluating the impacts on land use due to the expansion of the agricultural sector, and particularly the biofuel sector, is a fundamental task from an environmental perspective. This paper not only resulted in the improvement of a tool to evaluate land use impacts, but also provided results assessing land use changes caused by the expansion of the agricultural sector. The results are straightforward: in both the previous and updated versions of the model, growing demand for food, feed, fiber, and biofuel will require more land, and deforestation is expected to continue (although at lower rates than those witnessed in the past). The results of the simulations show that the agricultural sector in Brazil will continue to convert native vegetation land not because of ethanol expansion, but because of the expansion of food and feed demand, which we discern because the difference in total area used for agriculture in the baseline and shock scenarios is very similar. This is reasonable given that sugarcane has very little direct impact on natural vegetation and because other sectors, namely pastures, accommodate most of the sugarcane expansion.

Pasture intensification can also help to reduce demand for additional agricultural land, as demonstrated in the results of the updated version of the BLUM. However, unless clear policies to stimulate stronger intensification are implemented (at least from a land use perspective), the market alone will not be able to force the intensification that is needed in order to avoid additional deforestation. The model also indicates that much less forest land will be brought into production in the near future, and that deforestation rates will decrease compared to those in the past. This trend can already be observed in the recently released database on deforestation (see Fig. 3), and shows that the BLUM is supporting empirical evidence. However, pressure to convert forest in Cerrado will continue to be strong. It is the agricultural frontier of Brazil, and the most suitable land and cropland are located there. Environmental requirements and standards in Cerrado compared to the Amazon biome are less intense, and land prices are still lower than in regions such as the South and Southeast. If more Cerrado land is needed for agricultural production, it may be necessary to formulate policies that minimize the negative environmental impacts of conversion. One such policy may aim to require guarantees from farmers that they will comply with Brazilian forest regulations. But, stronger policies to protect areas that are not suitable for crops, and should therefore not be cleared for any reason, are also necessary (Fig. 4).

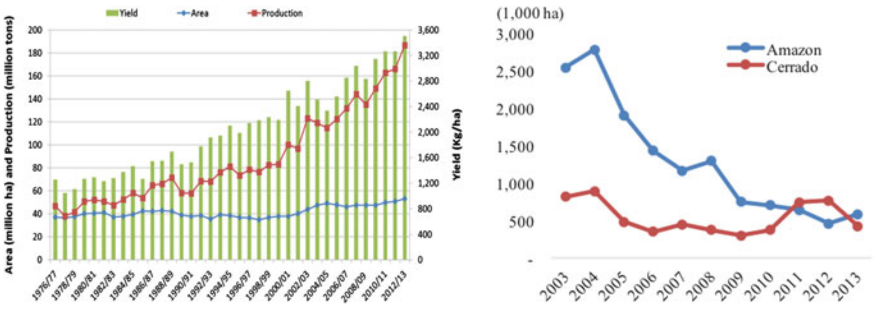

Fig. 3 Area, yield and production for grains in Brazil (*on the left*) and deforestation in Amazon and Cerrado (*right*). *Source* CONAB, INPE (Amazon); LAPIG (Cerrado)

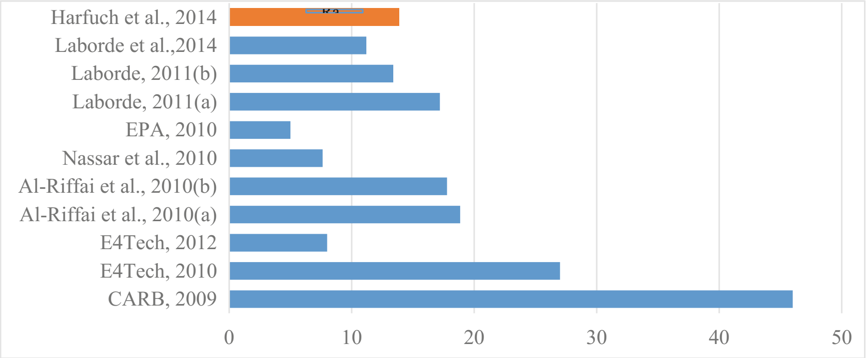

Fig. 4 Sugarcane ethanol iLUC factors in g CO_2/MJ. *Source* authors based on several papers

Although we believe that this paper has contributed to the improvement of methodologies to assess land use changes using agro-economic modeling and empirical evidence, the "art" of modeling always requires improvements. Incorporating new information when it becomes available is essential to update agricultural expansion dynamics. Detailing sectors is another important issue to be endogenously captured in models. Finally, combining different methodologies and databases (especially biophysical models) is also an essential scientific frontier that will enrich land use and carbon emissions analysis.

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Land Use Change, Ethanol Production Expansion and Food Security in Brazil

Joaquim Bento de Souza Ferreira Filho and Mark Horridge

Abstract The concurrence of major increases in ethanol production and world commodity price increases were captured by the 'food-versus-fuel' dilemma around 2008. Brazil is the largest producer of ethanol worldwide and still has vast tracts of natural land available. This paper uses Brazil as case study to simulate food security and environmental impacts, especially on forests, of increased biofuel production. Results show that sugarcane production is concentrated in higher productivity regions so reaching the 2022 ethanol target would require only 0.07 Mha of new land, or 0.02% additional deforestation over baseline. Second, per-area production intensifies as land prices increase, indicating a nonlinear relationship between land area and production. Specifically, results indicate an average indirect land use change effect of 0.083 ha of new agricultural land for every 1.0 ha of additional sugarcane. Current discussions of biofuel expansion miss this critical point of intensification, which results from market forces and technological change. These results are assumed to be driven solely by cost-minimizing behavior, thus leaving significant room for policy to expand agricultural research resulting in greater per unit output and subsequent environmental benefits. Finally, results support historical data that land use change due to biofuel production has little impact on food security.

Keywords Land use Change · Ethanol production · Food security · Brazil

J.B. de Souza Ferreira Filho (✉)
Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo,
São Paulo, Brazil
e-mail: jbsferre@usp.br

M. Horridge
Centre of Policy Studies, Victoria University, Melbourne, VIC, Australia
e-mail: mark.horridge@gmail.com

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1 Introduction

In 1975 Brazil engaged in a massive ethanol production program, in the aftermath of the first oil shock, through the launching of the Programa Nacional do Álcool (National Ethanol Program or Proálcool). Among the many policy measures adopted to stimulate the production and use of ethanol were: subsidized credit for investments; an increase in the at-pump ratio of ethanol to gasoline; guarantee of ethanol prices below gasoline prices; and a reduction of sales taxes on ethanol-engine cars. The production targets at that time were 3 billion liters of ethanol in 1980, and 10.7 billion liters in 1985 (BNDES 2008). The reduction in oil prices after 1985 caused a reduction in the production and use of ethanol in Brazil that lasted throughout the nineties. Ethanol use started to recover again in 2003, led by the introduction of the flex-fuel technology for car engines, which allows the use of either gasoline or ethanol, or any blend of those two fuels. Sugarcane area increased from 4.0 Mha (about 11% of total annual crops area) in 2000 to 9.8 Mha in 2012 (15% of total annual crops area).

The recent expansion of ethanol and sugarcane production in Brazil happened at the same time as world commodity price increases, raising concerns related to the fuel-versus-food dilemma worldwide (Yacobucci et al. 2007; Collins 2008; Elliot 2008; Babcock 2009, Trostle 2008), and the associated land use and environmental issues. As argued by Babcock (2009), “the debate about whether biofuels are a good thing now focuses squarely on whether their use causes too much conversion on natural lands into crop and livestock production around the world.” This debate is particularly important in Brazil, one of the few important agricultural producer countries in the world which still has a vast stock of natural land available. But the induced effect of biofuels expansion on natural land conversion is an indirect land use change effect (ILUC) and so has proved hard to observe directly, as can be seen in the works of Ferez (2010), Nassar et al. (2010), Lapola et al. (2010), Barona et al. (2010), Arima et al. (2011), and Macedo et al. (2012), in the Brazilian context.

In this paper we extend the results by Ferreira Filho and Horridge (2012, 2014) to discuss other aspects of Brazil’s ethanol and sugarcane expansion, using a simulation model to highlight the implications of an ethanol production expansion scenario in two main aspects: the food security impacts and the environmental impact, focusing on deforestation and the indirect land use change. First we present the recent pattern of sugarcane and ethanol expansion as a background for the ensuing discussions. Then we describe our methodology, which we apply to a scenario of future ethanol expansion in Brasil. Finally, we present results and conclusions.

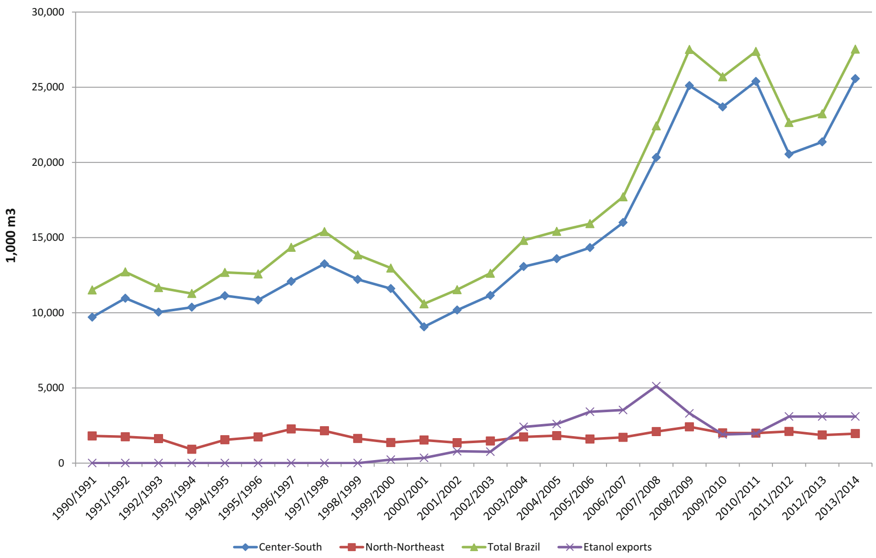

Fig. 1 Evolution of ethanol production and exports in Brazil (1000 m^3). *Source* UNICA and Secretaria de Comércio Exterior do Brasil (SECEX)

2 The Recent Evolution of Ethanol and Sugarcane Production in Brazil

Ethanol production more than doubled between 1990 and 2008, and, as shown in Fig. 1, has been increasing continuously in the period 2000–2008, reaching a peak of around 27.5 billion liters in 2008. Adverse climatic conditions reduced production in 2008/2009 and 2011–2013 periods. The current Brazilian sugar/ethanol production industry has 437 production firms, among which 168 produce only ethanol, 16 only sugar, and 253 both ethanol and sugar. Notice that the increase in ethanol production came mainly from the Center-South region, which produces about 90% of the total.

Sugarcane accounts for a relatively small share in total annual crop area[1] (Fig. 2), although it is the third most important crop in terms of area in Brazil, occupying 9.7 Mha out of 63 Mha of annual crops area in 2012, or 15.3% of the total. The most important annual crops in area are soybeans, with 25 Mha cultivated in 2012, and corn, with 15 Mha. The area of pasture (not included in the figure) tripled between 1970 and 2006 to 160 Mha in 2006 (Brazilian Agricultural Census).

The increase in total cultivated area was accompanied by a steady increase in per-area productivity. The productivity index (tons/ha) grew from 100 in 1990 to

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[1] Permanent crops area accounted for 6.2 million hectares in 2012.

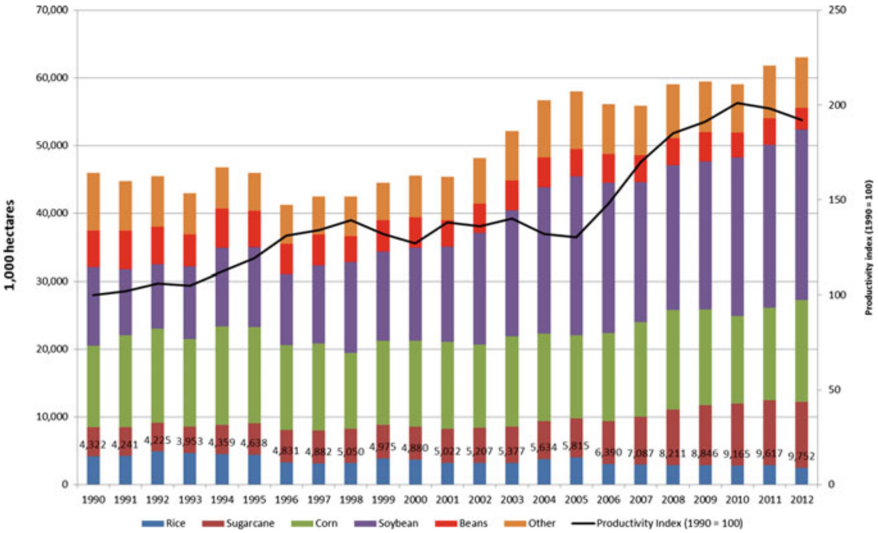

Fig. 2 Evolution of annual crops areas in Brazil and productivity index

192 in 2012, after peaking at 201 in 2010. Livestock productivity also increased, with important gains in animal performance and pasture productivity. As shown by Martha et al. (2012), 79% of the growth in beef production between 1950 and 2006 can be explained by productivity gains.

The regional concentration of ethanol and sugarcane production has important consequences for the points to be discussed in this paper. Looking at regional sugarcane planting over time, Fig. 3 shows that the bulk of the expansion of sugarcane area took place in the state of São Paulo,[2] which in 2013 accounted for 51% of total Brazilian ethanol production. São Paulo's sugarcane area grew from 1.8 Mha in 1990 to 5.2 Mha in 2012, or 53% of total sugarcane acreage in Brazil.[3] The Center-South region (which includes the state of São Paulo) accounted for 93% of total ethanol production and 87% of total sugarcane area.

These figures are central to the ILUC discussion. In São Paulo and most of Brazil's Southern states, the stock of convertible land has basically run out, meaning that the supply of agricultural land is fixed. Hence sugarcane expands only at the expense of other land uses. However, around 18 Mha have been added to total national crop area (annual plus permanent crops) between 1995 and 2006 according to the Brazilian Agricultural Censuses of 1996 and 2006 (14 Mha between 1995 and 2009). An extra 1.8 Mha of planted pasture have been incorporated in the same period (Table 1). The expansion of agricultural area has taken

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[2] São Paulo is the richest state in Brazil, with about 33.5% of national GDP in 2010.

[3] Sugarcane productivity is higher in São Paulo than in other states. Besides, the other Brazilian regions produce a higher share of sugar than ethanol when compared to São Paulo.

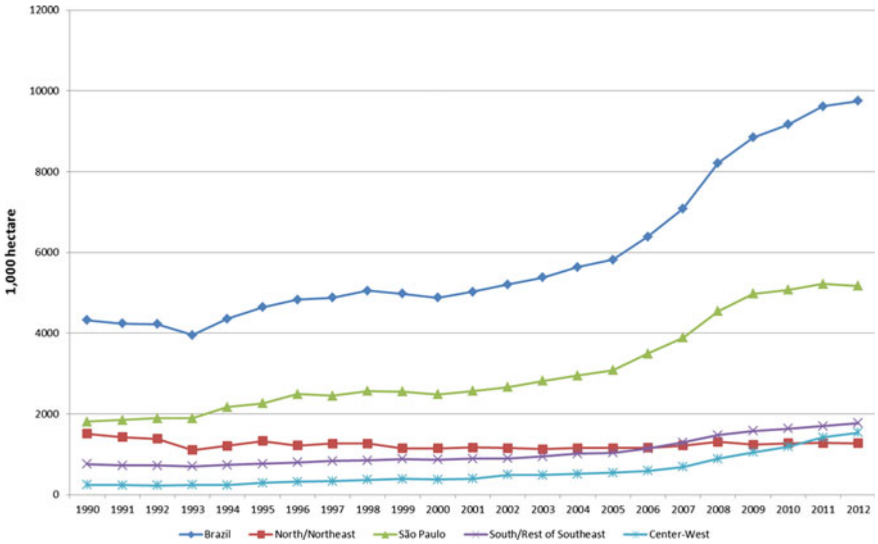

Fig. 3 Evolution of sugarcane planted area in Brazil, by region 1000 ha. *Source* IBGE—Produção Agrícola Municipal

Table 1 Land use variation in Brazil, (1970–2006 Thousands hectares)

	1970	1975	1980	1985	1995	2006	Difference 2006–1995
Perennial crops	7984	8385	10,472	9903	7542	11,612	4071
Annual crops	26,000	31,616	38,632	42,244	34,253	48,234	13,982
Natural pasture	124,406	125,951	113,897	105,094	78,048	57,316	−20,732
Planted pasture	29,732	39,701	60,602	74,094	99,652	101,437	1785
Planted forests	1658	2864	5016	5967	5396	4497	−899
Total var. 2006–1995	189,781	208,518	228,620	237,303	224,891	223,098	−1793

Source Brazilian Agricultural Censuses, various years

place mainly in some states in the Center-west, North, and Northeast, notably those closer to the Center-west Cerrados (tropical savanna) areas.

The simultaneous increase in areas of crops and pasture is possible, of course, due to the increased total area available for agriculture, caused by the expansion of the agriculture frontier through deforestation. We underline the enormous availability of pasture areas in Brazil. Area under planted pasture represents 61% of total

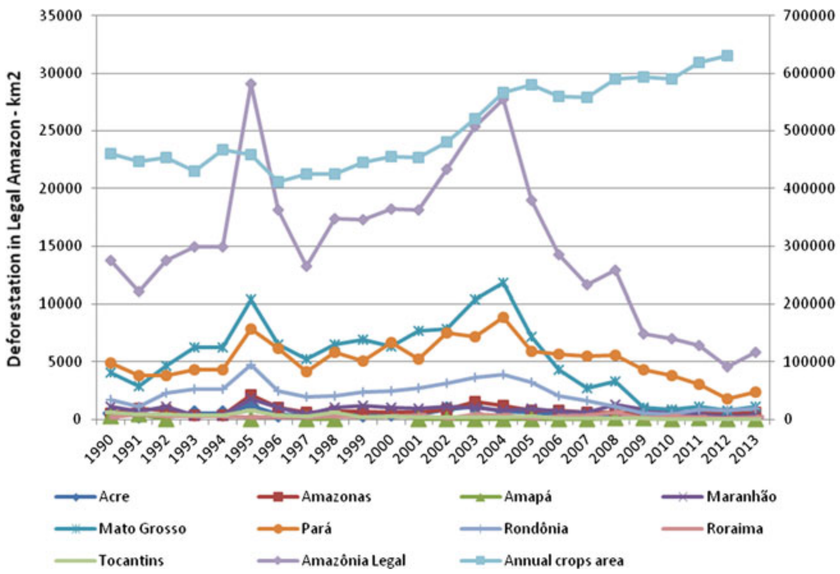

Fig. 4 Deforestation in Legal Amazon and annual crops area evolution (total) 1991–2013. *Source* PRODES (INPE) and Pesquisa Agrícola Municipal (IBGE)

area under production, and the land use change between pasture and crops is traditionally important for agricultural expansion.

In spite of the increase in land used for agriculture and livestock, the rate of deforestation has been reduced considerably in the recent period. Figure 4 shows that the rate of deforestation fell markedly from 27,772 square kilometers (2.77 Mha) in 2004 to 5843 square kilometers (0.58 Mha) in 2013 (IBGE/PRODES).[4] The deforestation values in Fig. 4 refer to the Legal Amazon, an administrative region that includes nine out of the 26 Brazilian states (Rondônia, Acre, Amazonas, Roraima, Pará, Amapa, Tocantins, Maranhão and Mato Grosso). The agricultural frontier, however, is mainly located in Mato Grosso, Rondônia, and Pará, the states on the so-called “Arch of deforestation”.

As seen before, however, the incorporation of new areas and the agricultural expansion do not match exactly in geographical terms, giving birth to the ILUC problem. How much of the agricultural frontier expansion in North and Center-west, for example, is caused by the sugarcane expansion in Southeast Brazil? Furthermore, if one goes deeper into details and looks inside the crops aggregate, how does the sugarcane expansion affects the supply of other types of agricultural products? As showed by Rudorff et al. (2010) using satellite imagery,

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[4] Available at http://seriesestatisticas.ibge.gov.br/series.aspx?vcodigo=IU12&t=desflorestamento-na-amazonia-legal-3-desflorestamento-bruto-anual-na-amazonia-legal.

for example, almost all the land use change for sugarcane expansion of crop year 2008/2009 occurred on pasture and annual crop land. The modeling approach used to analyze these issues is presented next.

3 Methodology[5]

A multi-period computable general equilibrium model of Brazil, based on previous work by Ferreira Filho and Horridge (2014), is used to analyze the ILUC effects of projected sugarcane expansion. The model includes annual recursive dynamics and a detailed bottom-up regional representation, which for the simulations reported here distinguished 15 aggregated Brazilian regions. It also has 38 sectors, 10 household types, 10 labor grades, and a land use change (LUC) model which tracks land use in each state, to be described below. The core database is based on the 2005 Brazilian Input–Output model, as presented in Ferreira Filho (2010).

The model's recursive dynamics consist basically of three mechanisms:

- a stock-flow relation between investment and capital stock, which assumes a 1 year gestation lag;
- a positive relation between investment and the rate of profit; and
- a relation between wage growth and regional labor supply.

With these three mechanisms it is possible to construct a plausible base forecast for the future, as well as a policy forecast—because policy instruments shock variables to different values from the base (e.g., the ethanol expansion scenarios). This difference can be interpreted as the effect of the policy change. The model is run with the aid of RunDynam, a program to solve recursive-dynamic CGE models.

3.1 Modeling Regional Land Use

Increased production of biofuels may arise from technical progress, or using more inputs, such as capital, labor, or land. The last of these, land, is in restricted supply. In order to analyze the importance of an expansion of ethanol production in Brazil, land use has to be explicitly modeled, as described in this section.

For this paper, agriculture and land use are modeled separately in each of 15 Brazilian regions with different agricultural mix, which allows the model to capture a good deal of the differences in soil, climate, and history that cause particular land to be used for particular purposes.

Brazilian land area statistics by the Instituto Brasileiro de Geografia e Estatísticas (IBGE) distinguish three types of agricultural land use, Crop, Pasture, and

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[5] The methodological description is based on Ferreira Filho and Horridge (2014).

Table 2 Transition matrices for land use change (Mha), (Average annual changes)

MatoGrosso	Crop	Pasture	Plant forest	Unused	Total 1996
Crop	8.7	0.2	0	0.1	9
Pasture	1	20.6	0	0.1	21.8
Plant forest	0	0.1	0	0	0.1
Unused	0	0.9	0.1	58.4	59.4
Total 2005	9.7	21.8	0.1	58.7	90.3
Brazil	Crop	Pasture	Plant forest	Unused	Total 1996
Crop	59.2	1.6	0	2	62.9
Pasture	5	153	0.4	2.1	160.5
Plant forest	0	0.9	3.6	0.1	4.7
Unused	0.1	3.7	0.6	619	623.4
Total 2005	64.3	159.2	4.6	623.3	851.5

Source Primary data from IBGE

Plantation Forestry. Each industry in the model is mapped to one of these types. Within each region, the area of "Crop" land in the current year is predetermined. However, the model allows a given area of "Crop" land to be reallocated among crops according to a Constant Elasticity of Transformation frontier, and the same mechanism is used to distribute Pasture land between Livestock cattle and Milk cattle uses. Forestry land has only one use. The total area of each region, of course, considerably exceeds the amount used for agriculture. The difference, called "Unused" in the model, accounts for 73% of Brazil's total area. It includes land which could be used for crops or grazing, but is not yet so used. The North and West of Brazil contain large areas both of cultivable savanna and of forests that could be felled for grazing.

Over time the model allows land to move between the Crop, Pasture, and Forestry categories, or for Unused land to convert to one of these three. Based on the information collected from the Brazilian Agricultural Censuses of 1996 and 2006 (which shows land use changes between 1996 and 2005), a transition matrix approach is used, as illustrated in Table 2. The transition matrices show land use changes in the first year of our simulation. Row labels refer to land use at the start of a year, column labels to year end. Thus the final, row-total, column in each sub-table shows initial land use, while the final, column-total, row shows year-end land use. Within the table body, off-diagonal elements show areas of land with changing use between two consecutive periods. For brevity, the table shows only results for one state, Mato Grosso, and for all of Brazil, but there is one such transition matrix for every region in the model.

In Table 2, row and column values reflect current land use and the average rate of change of land use during the between Census period of 11 years (1996–2005), drawn from the Brazilian Agricultural Censuses of 1996 and 2006. Numbers within the table bodies are not observed but reflect an imposed prior: that most new Crop land was formerly Pasture, and that new Pasture normally is drawn from Unused land (see, for example, Arima et al. 2011; Macedo et al. 2012). The prior estimates are scaled to sum to data-based row and column totals. The transition matrices could be expressed in share form (i.e., with row totals equaling one), showing Markov probabilities that a particular hectare used today for, say, Pasture, would next year be used for Crops.

In the model, these probabilities or proportions are modeled as a function of land rents, subject to a sensitivity parameter. Thus, if Crop rents rise relative to Pasture rents, the rate of conversion of Pasture land to Crops will increase. In the scenario the amount of Unused land was allowed to decrease only in selected frontier regions, namely Rondônia, Amazon, ParaToc (Pará plus Tocantins), MarPiaui (Maranhão plus Piaui), Bahia, MtGrosso (Mato Grosso), and Central (Goias plus the Federal District). In the other, mainly coastal, regions total agricultural land was held fixed.

In summary, the model allows for sugarcane output to increase through:

- assumed uniform primary-factor-enhancing technical progress of 1.5% p.a. (baseline assumption);
- increasing non-land inputs;
- using a greater proportion of Crop land for sugarcane, in any region;
- converting Pasture land to Crops, if Crop rents increase, in any region; and
- converting Unused lands to Pasture or Crop uses, in frontier regions.

The last three mechanisms above characterize the indirect land use change (ILUC) examined in this paper.

4 Model Baseline and Scenario Simulation

As stated before, the model database is for year 2005. The model was run for seven years of historical simulations, using observed data to update the database to 2013, followed by annual runs to simulate the ethanol expansion scenario until 2022. The baseline assumes moderate economic growth until 2022, a 2.5% increase in real GDP per year, with projections for population increase by state by IBGE.[6] As for deforestation, the model is calibrated to give a deforestation path close to the annual average observed values for the period 2009/2013 by PRODES, around 670 thousand hectares per year.[7]

To analyze the ILUC effects of an expansion of ethanol production, we compare the moderate scenario above with a more aggressive one, analyzing the differences in land use in both situations. With this in mind, the baseline projections for ethanol

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[6] This simulation differs from that in Ferreira Filho and Horridge (2014) in two main ways: the baseline historical simulation was updated to 2013, and a revised scenario is used.

[7] The actual average deforestation for 2009/2013 by PRODES is 626 thousand hectares. We have used a value slightly higher because PRODES figures does not include some areas in Piaui state.

entail a moderate expansion in exports (average of 5.5% per year from 2014 to 2022) as well as in household use (around 2.5% per year from 2014 to 2022). These projections result in an average 2.8% per year increase in ethanol production in Brazil in the same period. This inertial growth would result in a baseline production of 37.1 billion liters of ethanol in 2022, or a 133.3% increase above the 2005 production of 15.9 billion liters.

The policy scenario, on the other hand, is based on projections by EPE[8] (2013) in the Plano Decenal de Expansão de Energia 2022 (Decennial Energy Expansion Plan 2022), and comprises an approximate 7.5% per year increase in total ethanol production in Brazil between 2013 and 2022,[9] to reach a total production of 54 billion liters of ethanol in 2022. This scenario is justified mostly by the continuous increase in sales of flex-fuels engine cars in the coming years, which will tend to increase domestic ethanol demand. The policy scenario, then, will be compared to the baseline scenario, which does not incorporate this extra change in the composition of flex-fuels/gasoline engine cars in the Brazilian fleet from 2013, and will allow the identification of the effects of ethanol expansion on the economy. No exogenous technological change was considered for the simulations.

4.1 Closure

An important detail in any CGE model is the closure. Broadly speaking, the closure conditions how the model determines the new solution after a policy shock, establishing the rules for achieving the new equilibrium. In the closure used in this paper, labor is free to move between regions and activities, driven by real wages changes, but not to move between labor categories. Capital accumulates between periods driven by profits, as discussed before. In order to properly approach the sugarcane expansion, a few other closure rules were used in the simulations:

- Capital in the ethanol industry was allowed to accumulate only in some regions, where ethanol expansion is expected to occur (Ferreira Filho and Horridge, 2009). These regions are Minas Gerais (MinasG), São Paulo, Paraná, Mato Grosso do Sul (MtGrSul), Mato Grosso (MtGrosso), and Central. This choice is based on those region's climate aptitude, as well as on their proximity to the most important ethanol consumption regions.
- Exports of agricultural raw products, food, textiles, and mining were kept fixed in the simulations at the baseline levels.

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[8] The Empresa de Pesquisas Energéticas (EPE) is a research center linked to Brazil's Ministry of Mines and Energy.

[9] This value is a weighted average of the EPE forecasts for anhydrous and hydrous ethanol. The value used in the paper is slightly below the EPE forecast, which is around 9.6% per year from 2013 to 2022.

5 Results

As mentioned before, the goal of this paper is to address the potential consequences of increasing ethanol production in Brazil for land use change effects and the food security. Below we discuss the model's results to gain insight about those issues.

The baseline scenario results in a 2.2% increase in deforestation accumulated to 2022 (13.2 Mha), matched by 6.5% increase in total area of crops (5.5 Mha), a 6.1% increase in area of pasture (7.9 Mha), and 3.6% fall in planted forests areas (0.2 Mha). The increase in deforestation, of course, would occur in the frontier states, where the natural stocks of land are still available. The main changes occurred in the states Mato Grosso (−2.3 Mha), Pará and Tocantins (−3.5 Mha aggregated), Rondônia (−0.7 Mha), and Maranhão and Piaui (−1.2 Mha, aggregated).

The increase in ethanol production leads to an increase in sugarcane acreage above the baseline, increasing the total agricultural land required for production. The variation in the broad land use categories is shown in Fig. 5.

Total crops area would increase by 0.16 Mha compared to the baseline, while pasture and planted forests areas would decrease by 0.07 Mha and 0.02 Mha, respectively. The expansion would still require an extra 0.07 Mha of new agricultural areas coming from deforestation. This would imply an average ILUC effect of 0.083 ha of new land for each extra hectare of sugarcane, a result close to that

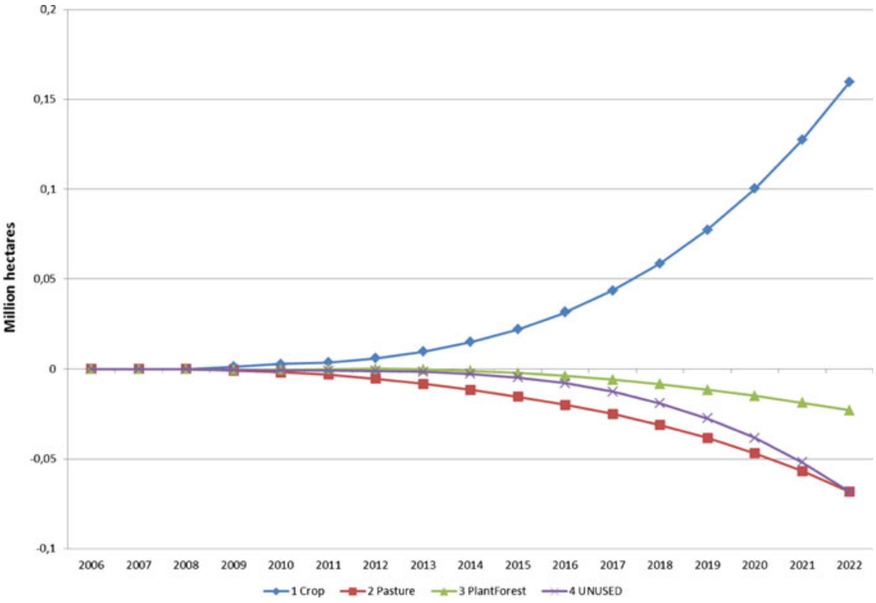

Fig. 5 Simulation results. Land use variation in Brazil. Deviations from baseline, accumulated

obtained (0.14) by Ferreira Filho and Horridge (2014), and slightly higher than the value (0.08) found by Nassar et al. (2010).

The above results show an important point regarding agricultural expansion, which is the advance of sugarcane into pasture areas. As discussed before, Brazil has an enormous area of low productivity pasture, which constitutes a land reserve that can be used for agricultural expansion. The expansion of sugarcane predominantly on pasture was noticed before by Homem de Melo et al. (1981), during the first period of the Proalcool program in the late seventies.

A further analysis into the transition matrix used in the model is useful to clarify the projected land use change pattern. As explained before, the transition matrix was calibrated with data from two Brazilian Agricultural Censuses between 1995 and 2006. There is one transition matrix for each region in the model. The transitions incorporate an important stylized fact of Brazilian agriculture, which is the sequence of transitions from natural forests to pasture first, and then from pasture to crops. This is the more common sequence, although transitions directly from natural forests to crops can also be observed, but in a much lesser extent and in particular biomes. The possibilities of transitions between those broad land use categories, then, are determinant for the results, and can be seen in Fig. 6. In the figure, only transitions from pasture and unused land to crops and from unused land to pasture are presented, to save space.

As Fig. 6 shows, most of the land substitution in the sugarcane expansion regions (MinasG, SaoPaulo, Paraná, MtGrSul, MtGrosso, and Central) comes from the transition of pasture to crops. The regions of MinasG, SaoPaulo, Paraná,

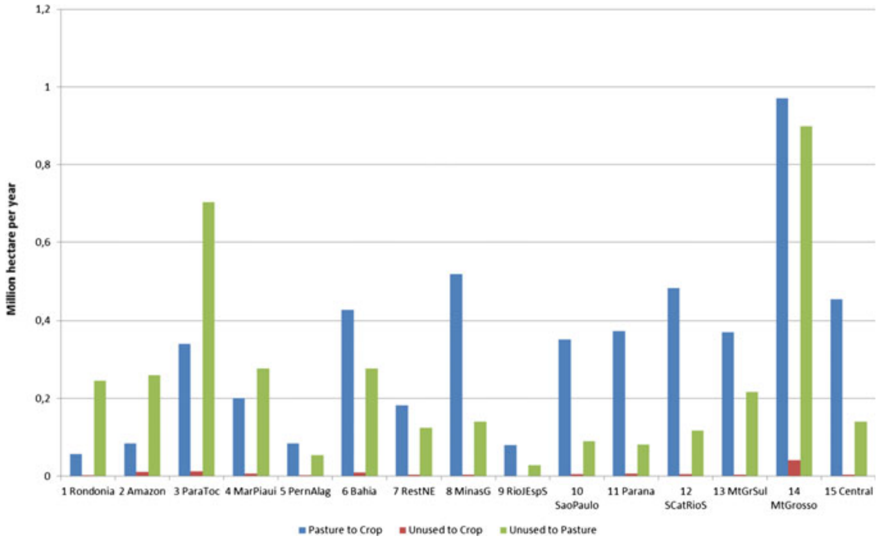

Fig. 6 Land use transitions in Brazil. Million hectares per year. Average between 1995 and 2006

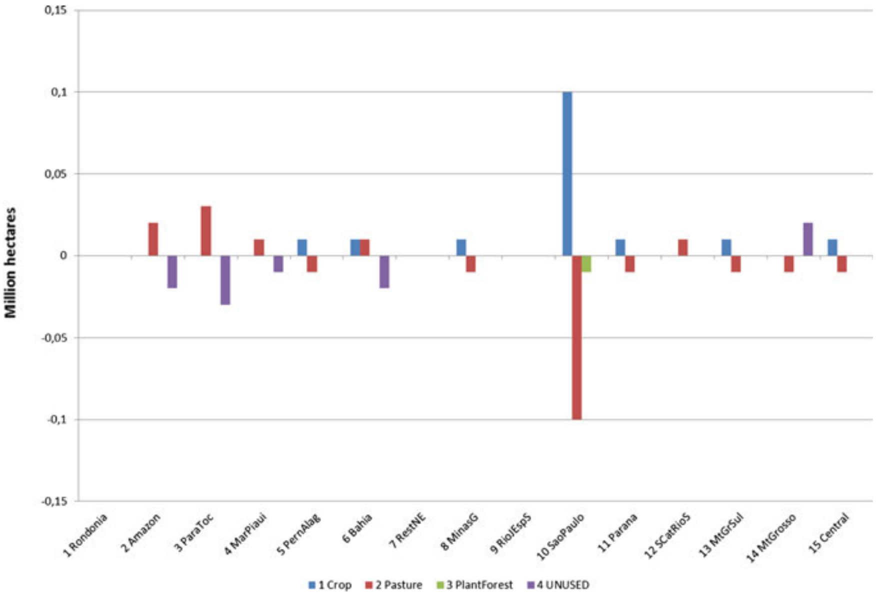

Fig. 7 Broad land type changes caused by increased ethanol production. Million hectares. *Source* Model results

MtGrSul, actually, are regions where no land conversion from natural forests to any other use can occur, since the natural stocks in those regions is already exhausted.[10]

The expansion of sugarcane in regions not located in the agricultural frontier, then, would require both land from pasture for crops expansion and a change in composition of production between different crops, with sugarcane taking over land previously in other uses. This process triggers a complex pattern of substitution and indirect land use change tracked in the model, summarized in the results in Fig. 7.

In the sugarcane expansion regions (MinasG, SaoPaulo, Paraná, MtGrSul, and Central) the increase in crops area happens mostly on pasture—see Fig. 7. Model results show that in São Paulo state, for example, the 0.1 Mha increase in crops area (accumulated in year 2022) would be almost exactly matched by the fall in pasture area.

The exception for this pattern is the state of Mato Grosso (MtGrosso), a frontier state, where an increase in areas converted to forests is actually observed in the simulation; this is caused by a particular feature of that state´s transition matrix. In this case, the transition from pasture to crops (0.971 Mha per year) is higher than the transition from unused to pasture (0.899 Mha per year). The expansion of sugarcane in this state takes more land from pasture (compared to the baseline), but

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[10] Notice that some transition from unused to pasture appears in the matrix in the non-frontier regions, since it's calibrated from past data. In the simulations, however, no deforestation is allowed in those regions, as discussed before.

Table 3 Changes in agricultural production, land use, and productivity per hectare (Cumulative percent deviation from the baseline, 2022)

	Production	Land area	Production/ha
Rice	−0.19	−0.27	0.07
Corn	−0.15	−0.83	0.68
Wheat	−0.62	−1.06	0.45
Sugarcane	20.54	12.44	8.11
Soybean	−0.09	−0.30	0.21
Other agric	−0.61	−1.30	0.69
Cassava	0.13	−0.41	0.54
Tobacco	0.20	−0.10	0.30
Cotton	−0.25	−0.07	−0.18
Citrus fruits	−0.53	−2.08	1.55
Coffee	0.02	−0.53	0.55
Forestry	−0.51	−0.54	0.03
Livestock	0.08	−0.07	0.15
Raw milk	0.11	−0.11	0.22
Other livestock	0.00	0.00	0.00

Source Model results

requires proportionately less forests to be converted to new pasture (compared to the baseline).[11] The increase in pasture will happen elsewhere, in states where the conversion from pasture to crops is smaller than that from unused to pasture, as is the case of ParaToc region (Pará and Tocantins states).

Table 3 summarizes national results for production in crops and livestock, as well as for land use. The increase in ethanol production would require a 20.5% increase [above baseline] in sugarcane production, but only a 12.4% increase in sugarcane area.

Table 3 shows that land use is not proportional to production. The production of sugarcane, for example, increases more than the increase in its area. Sugarcane production is concentrating in Southeast Brazil, where the productivity per hectare is the highest in the country. In this case, each additional hectare of sugarcane adds to production more than the national average or, conversely, less land is required for each ton of sugarcane.

Likewise, in the cases where a fall in cultivated area is observed, the pattern is that production falls less than area. This difference is caused by an induced increase in productivity per hectare, caused by (limited) substitution of land by other inputs in the simulations: as land prices increase more fertilizer and other inputs would be used per unit of area, increasing productivity.

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[11] This means that some land previously under pasture would be set aside, as is indeed observed from the data. A different (observed) transition matrix in the Second Brazilian Communication to the United Nations Convention Frame (Brasil 2010) estimates that 1.3 Mha of land was set aside between 1994 and 2002 in Brazil, 0.27 Mha of which was in the state of Mato Grosso.

The exception to this rule is cotton: productivity actually falls, due to a particular regional combination of results. Cotton is mostly cultivated in the state of Mato Grosso more productively than elsewhere in Brazil. Our simulation shows a decrease in cotton area in that state, causing a fall in productivity not compensated by the increase in other states where the culture expands, like Minas Gerais and Bahia, for example.

Thus the ethanol expansion scenario proposed by EPE (2013) would be easily accommodated, in terms of land use change. The ethanol production target of approximately 54 billion liters in 2022 would be met with an extra 0.07 Mha of new land, representing just 0.02% more deforestation than the amount projected in the baseline.

And finally it is important to analyze also the impacts of the projected ethanol expansion on Brazilian food supply. The expansion of biofuels production worldwide has been associated with recent food price increases by many authors (Yacobucci et al. 2007; Collins 2008; Elliot 2008; Babcock 2009; Trostle 2008). The issue has been analyzed also in relation to the welfare and poverty impacts in Brazil, by Ferreira Filho (2010) and Ferreira et al. (2011).

Table 3 shows that the increase in ethanol production would cause a small reduction in the area of land used for other agricultural products. This would affect their market prices, with potential impacts on household welfare. Notice, however, that incomes would also change with the policy shocks, and the net result on household consumption will depend on the balance between incomes and the consumption bundle prices changes, as shown in Fig. 8. In this figure the variation in real consumption of the 10 different households in the model is displayed, where POF1 stands for the poorest household and POF10 for the richest.

The ethanol expansion raises consumption levels for the poorest households (relative to the baseline). This result is driven by the increase in real incomes, which can be understood by analyzing the relation between household incomes and the labor wages of different occupations. The expanding agricultural sector is intensive in less skilled workers, who mostly come from the poorest households. When sugarcane expands, besides expanding labor demand (and wages) directly in the activity, an increase in land prices occur, inducing a change in input demand in all land-using activities, away from land and toward labor and capital. This further increases wages in agriculture, increasing the wages of the poorer households. Model results point to a positive net effect on real incomes, increasing real consumption of most of the household groups.[12]

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[12] The reduction in consumption of the richest household is linked to the fall in production of activities intensive in more skilled labor, like the oil industry (gasoline), whose consumption would fall when ethanol consumption increases (substitutes).

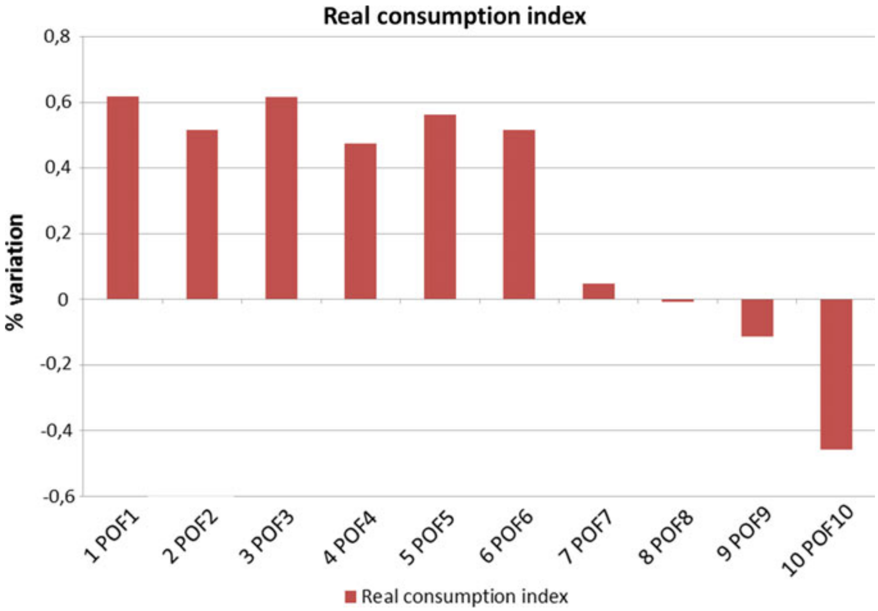

Fig. 8 Model results. Real consumption by household group, accumulated in 2022. Percent deviation from baseline.

6 Final Remarks

The expansion of biofuels worldwide fueled a debate recently about its consequences for deforestation and food security. In this paper we argue that none of those issues represent serious challenges in the case of the Brazilian economy.

The concentration of sugarcane in regions with higher productivity (the Southeast region) is one of the first aspects to be taken into consideration when analyzing the associated land use change issues. Each hectare of sugarcane in regions with above average productivity reduces the induced need for new areas drawn from natural forests, or ILUC. Considering that most of the modern ethanol production units are already located in the Southeast region, this seems to be the trend for the expansion. The recent spillover of sugarcane areas to the center-west regions is happening with the same technological standards observed in Southeast Brazil, what means that the trend for land use discussed here is likely to be stable in time.

The second important point raised by the simulation results is the endogenous intensification of per-area production induced by land prices increases, suggesting a nonlinear relation between the reduction in land areas and production levels, a point frequently misunderstood in discussions about biofuels expansion. This means that one extra hectare of biofuel crop does not require one extra hectare of cleared forest. Actually, in the Brazilian case this effect combines with a high availability of low productivity pasture to generate a low ILUC effect on natural forests, which in this paper was estimated to be around 0.084 ha of cleared forests for each additional hectare of sugarcane.

Our results also suggest that the LUC impacts on food security in Brazil are very small; this is supported by historical data. On the contrary, the expansion of agriculture-based activities which use high shares of low skilled labor is likely to have positive distributional impacts, with potential to increase the real consumption level of the poorer households.

Finally we stress that no additional exogenous technological change was assumed for the policy scenario analyzed in this paper. The productivity increases due to intensification were assumed to arise from cost-minimizing behavior with given production functions. The continuous expansion of ethanol and sugarcane production above the levels analyzed in this study may eventually start to reduce the average sugarcane productivity, a point which certainly deserves attention for the future. Public policies toward agricultural research are likely to have a higher payoff not only in terms of agricultural output, but also in terms of land sparing, with corresponding environmental benefits.[13]

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Lessons from the ILUC Phenomenon

Michael O'Hare and Richard J. Plevin

Abstract The impact of greenhouse gas emissions on climate change occurs both through direct life cycle emissions and direct land use change as well as through indirect land use change (ILUC). The latter, in particulars are uncertain and front-loaded: land conversion leads to a large initial discharge that is paid back through reduced direct carbon intensity relative to fossil fuels in the future. This chapter discusses approaches to make policy decisions about accounting for ILUC effects in the presence of uncertainty about the magnitude of the effect and the need to balance a precautionary desire to delay investment till the uncertainty is resolved with the cost of delaying a switch from fossil fuels to biofuels. Given the temporal variation in the trajectory of emissions, policymakers should consider using metrics other than the cumulative discharges to capture the impact of emissions on the climate and the time profile of that impact and costs of positive and negative errors in incorporating ILUC effects in policy implementation. It is also important to recognize the presence of other market-mediated effects such as the fuel rebound effect that can also offset some of the direct savings in carbon emissions from switching to biofuels.

Keywords Biofuels · Indirect land use change (ILUC) · Uncertainty · Life cycle assessment (LCA) · Climate policy

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M. O'Hare (✉)
Goldman School of Public Policy, University of California at Berkeley, Berkeley, CA, USA
e-mail: ohare@berkeley.edu

R.J. Plevin
Institute of Transportation Studies, University of California at Davis, Davis, CA, USA

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1 Introduction

Among the most debated issues raised by biofuels is greenhouse gas (GHG) discharge caused when forest and pasture are cleared and cultivated in response to the demand for land to grow bioenergy crops. Recognition of this discharge, commonly called ILUC [for *indirect land use change* (emissions)], in several fuel regulations has engendered a lively debate over its actual size for various biofuels, and methodological progress in estimating it. It has also led to insights about how ILUC emissions, and other consequences, should be recognized and incorporated in policy design and implementation. These insights, which have implications beyond biofuels and even energy policy, are among the most interesting unanticipated consequences of studying the ILUC phenomenon. The present essay describes them and draws analytic implications that challenge some aspects of conventional energy policy analysis.

We do not discuss ILUC estimation methodology, which is well covered elsewhere in this volume, nor the size of ILUC for any fuels. Our discussion begins with the recognition that an increase in crop-based biofuel production induces a GHG discharge from land use change, (approximately) at the beginning of that production, whose size, though uncertain, is potentially large enough to affect societal preferences across competing fuels (Plevin et al. 2010). Uncertainty about the magnitude of ILUC emissions, across and within different models that estimate it, is small enough not to put biofuels completely off the table but large enough to demand attention to decision-analytic methods and explicit attention to the goals of fuel policy (Plevin et al., 2015). In addition, the distinctive time profile of ILUC emissions, nearly all at the beginning of biofuel production, makes conventional metrics of fuel climate effects like total GHG discharge intrinsically ambiguous and problematic. For example, when ILUC occurs, substituting energy-equivalent amounts of a biofuel for a fossil fuel can reduce total GHG discharge but still increase GHG-induced global warming for a long period (O'Hare et al. 2009).

2 Implicit Biofuels Policy Assumptions Have Been Challenged by ILUC

Policies promoting biofuels were initially motivated by a variety of objectives, including (in Brazil and the US especially) national independence from imported fossil fuels, and the desire of agribusiness players to expand their markets. To further support existing subsidy and quantity mandates, advocates of increased biofuel use seized on growing concern about climate change to point out that as biofuels carbon is captured from the air, their use (at least in concept) presented an opportunity to capture solar energy in a closed cycle that does not increase atmospheric GHG. Note that the present discussion applies to crop-based biofuels whose feedstocks (including some cellulosic feedstocks) compete with food, feed and fiber for arable land, not biofuels from wastes or residues; these generally do not have ILUC-like discharges and require a different kind of analysis.

The carbon directly released from burning a fuel is not the only climate effect of interest, as shown by life cycle analyses (LCAs) that count the GHGs emitted in growing, transporting, and converting the biomass (e.g., by fermentation and distillation) to a liquid fuel. Some studies have shown that these emissions greatly diminish or actually vitiate the climate benefits of, in particular, a corn ethanol system (Crutzen et al. 2007; Plevin 2009; USEPA 2010; Reay et al. 2012). Attention to this issue also highlighted large differences among the climate "greenness" and net energy content of biofuels made using different farm and refinery technologies. Debating the comparative carbon intensity of fuels at this period concealed three important assumptions, as discussed below.

2.1 GHG Intensity as a Property of a Substance

Underlying the early discussion of biofuels, and the design of biofuels policies like the California Low Carbon Fuel Standard and the US Renewable Fuel Standard was an implicit assumption that the differential climate effects of producing different fuels could be captured, well enough for policy making, by calculating each fuel's *global warming intensity* (GWI), using attributional LCA (ALCA). This is usually measured in g CO_2e MJ^{-1}, representing the "GHG [scaled to equivalent amounts of CO_2 using the IPCC's GWP methodology (Ciais et al. 2013)(IPCC)]" released by (i) making and using an amount of fuel providing one megajoule of energy, and (ii) only doing that. ALCA is a bookkeeping exercise tracing all the inputs to the final product back to their energy use, based on physical input–output relationships. The accounting stops when quantities are deemed small enough to ignore.[1] For example, the diesel fuel used in corn production is counted, but the analysis does not extend to the effect on livestock industry and its GHG discharges from either raising the price of corn or diverting it from feed. More important, as an accounting of existing practice, ALCA does not measure indirect effects across the economy of a significant change in the assortment of goods made and consumed (Ekvall and Weidema 2004; Finnveden et al. 2009). We emphasize here the implicit idea that GWI is a measure of climate effect that can be appropriately *attributed to a fuel* (perhaps a particular batch of fuel from a particular place) like its density or energy content (DeCicco 2012).

The models summarized and aligned in a widely cited 2006 meta-analysis seemed to indicate that from this perspective, corn ethanol promised modest climate and net energy benefits over fossil fuel (Farrell et al. 2006): driving a vehicle one

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[1] A small quantity of a substance can have a large environmental effect. Although cut-off criteria are typically applied in an LCA, there is no theoretical basis suggesting that the neglected elements of the life cycle are, in fact, of little significance (Plevin et al. 2013).

mile using the former would cause less global warming than driving a similar vehicle one mile on gasoline. The same paper, however, recognized that "…several key issues remain unquantified, such as…the carbon effects of conversion of forest to agriculture."

2.2 *Fuel Substitution on an Energy-Equivalent Basis*

Also implicit in the debate of the period were the assumptions that policies forcing or subsidizing biofuels into the fuel marketplace would cause replacement of fossil fuels by biofuels on a MJ-for-MJ basis, or closely enough not to matter. Some economists have questioned this MJ-for-MJ substitution rate (Drabik and de Gorter 2011; Bento and Klotz 2014) and the response of the fuel system as a whole to biofuel policy has become more salient recently under the rubric of "rebound effect" discussed below (Smeets et al. 2014) .

2.3 *Total GHG Discharge as a Policy Criterion*

Even more tacit in this early discussion was the assumption that a unit reduction in GHG discharge, no matter how or when achieved, was as good for the climate–or for some broader measure of policy objectives, like "social welfare" broadly conceived–as reducing any other unit. This would mean that total GHG discharges up to an analytic time horizon, standardized to g CO_2e MJ^{-1}', would measure fuel systems, climate effects well enough to direct policy.

3 Land Use Change and Global Warming Intensity

In 2008, important papers (Fargione et al. 2008; Searchinger et al. 2008) extended the LCA concept for biofuels outside the production sequence framework, recognizing the central phenomena that (i) incompatible "uses", including natural vegetation, compete for a fixed land resource, (ii) fairly inelastic, international, food commodity markets transmit causal price signals from agricultural interventions around the world with behavioral consequences, and (iii) bringing land into cultivation from wild or pasture conditions releases significant amounts of GHG when existing plant materials–especially including very high carbon stock forests–burn or decay. The authors of these papers claimed that if new biofuel is driven into the market by any mechanism, a GHG discharge is triggered that is not recognized by ALCA, but that should be attributed to that biofuel just like the tractor's diesel consumption.

Conventionally, this discharge is characterized either as *direct land use change (Fargione)*, as non-cropland is planted with a biofuel crop, or *indirect land use* *change (Searchinger)* to describe the changes that are induced anywhere away from the biofuel production site. ILUC is commonly triggered by a sequence of "falling dominos" as different crops succeed each other and eventually forest or pasture is cultivated for (usually) a food crop. Generally the size of this discharge is estimated by an economic model that transmits a biofuel production increase shock into markets affecting natural and other land cover, and a land use model relating changes in cover to GHG discharges.

This chapter is not mainly concerned with the science of ILUC estimation, but the logic can be summarized in the following greatly simplified vignette (see, for example, Hertel et al. 2010 for a full explanation). In order to obtain feedstock for new corn ethanol production, a US refiner must outbid parties who wish to use corn for feed or food. This increases the price of corn, and some farmers grow less soybeans and more corn, while corn and soybean exports decrease. Remaining world demand for corn and soybeans induces conversion of pasture to crop production in (e.g.) Brazil, and conversion of Amazon forest to cattle raising to replace the lost pasture. At the same time, overall food consumption decreases. The land required for the new corn ethanol production is thus supplied by a combination of increased yields on existing cropland, reduced food consumption, and land conversion from natural conditions (Searchinger et al. 2008).

One result important for the present discussion is the broad agreement that a climate effect "of making and using more of a fuel" not visible in an ALCA should "count" in assessing policies promoting particular fuels. Standard analysis of biofuels' climate effects has thus been expanded from ALCA to a *consequential* life cycle analysis (CLCA) whose analytic boundaries comprise predictable effects of a change in practice, whether inside or outside the production process. CLCA importantly changes the substrate of which GHG discharge is properly predicated, from a *substance* such as bioethanol, to an *action*, such as making and using some amount more of the substance, or a *policy*, such as subsidizing use of that substance, and this change fits awkwardly at best with the basic structure of a lot of biofuel policy, both in implementation and advocacy (Plevin et al. 2013).

Furthermore, ILUC has turned out to be not just another CLCA-scored dimension, but because of distinctive qualities of its occurrence and analysis, it has drawn both scholarly and (to a lesser degree) policy attention to climate issues requiring new kinds of analysis and policy tools. Specifically,

- The GHG discharge, and consequently also the climate-forcing, time trajectories from using a biofuel and either an energy-equivalent *or a GHG-discharge-equivalent* amount of fossil fuel are very different (Kendall et al. 2009; O'Hare et al. 2009; Anderson-Teixeira and Delucia 2010; Levasseur et al. 2010; Cherubini et al. 2011).
- ILUC cannot be observed, but only predicted by complex models with many parameters, so its estimates are subject to wide uncertainty bands (both ways) (Plevin et al. 2010; Laborde and Valin 2012 Plevin et al. 2015).
- ILUC discharges are not unique to biofuels, but result from any activity that competes with food (at least commodity food) for land.

4 Application of GHG Estimation

Before turning to the lessons of the ILUC debate as presented by the foregoing qualities, it is worth reviewing who can or should do what with estimates of direct and indirect GHG discharges. There are at least four salient decisions facing players in this biofuel theater. For policymakers:

- Should use of a given type of fuel be encouraged in place of (typically) fossil fuel, especially for transportation where liquid fuels have especially high form value? If "yes",
- What policy mechanisms (subsidy, performance obligations, quantity obligations, etc.) should be used as levers, and how vigorously?
- What properties of which fuels qualify them for such leverage?
- And for participants in the market: what amounts, of what kinds of fuel, should I buy and use at current prices and under current rules?

Presumably, policymakers should make those decisions to maximize social welfare, and market participants will seek to maximize profit or utility. As the decisions at hand differ by locus and possibly purpose, we should note that different actors might rationally require different measures, even under the rubric of "climate effect", for different kinds of choice. The concept of "life cycle GHG emissions", for example, can be operationalized many different ways, producing different ratings and fuel preference orders, as is the case for regulatory rating systems implemented in California, British Columbia, and Europe (Plevin et al. 2013).

This decision structure highlights the comparative nature of the choices under consideration. Even if a GWI could be assigned to a given fuel with complete and uncontroversial certainty, no action by anyone follows from such a number; what matters is at the least, a pair of such measures for two competing fuels. For practical purposes, a judgment that "fuel A is good for the climate" is vacuous or depends on a tacit counterfactual: since the production of biofuels results in positive GHG emissions, these fuels contribute to GHG emission reduction only to the extent that their use results in the avoided use of fuel systems with greater GHG emissions (Plevin et al. 2013). In the pages that follow, we will for convenience talk about criterion measures that might be predicated of a specific fuel, or policy, but we assume that such measures are always to be used to compare alternatives.

More important is a growing recognition that the climate effects of expanding production and use of a given fuel are not properties of the fuel, or even the industrial system that produces it (DeCicco 2012), but of the policy that induces the change in fuel use. Important climate effects follow from factors that cannot be captured in a description of a fuel's life cycle (Plevin et al. 2013).

5 Uncertainty and Choice

As we observed above, one of the salient properties of ILUC measures is their inherent uncertainty (Plevin et al. 2015; Khanna and Crago 2012). Different modelers have found different values for what is putatively the same thing (Warner et al. 2013), and increasingly, analysts are providing not only central estimators of these values but also explicit estimates of the uncertainty associated with them (Plevin et al. 2010, 2015; USEPA 2010; Laborde and Valin 2012). Because ILUC cannot be observed directly, and because the scientific basis (parameter values and structure) of the models used to estimate it is always incomplete, this uncertainty has shown itself to be refractory: a decision-maker's best knowledge of the ILUC for a given fuel is and will always be a probability distribution whose variance is neither enormous nor small enough to ignore (Plevin et al. 2015).

What policymakers should do with this uncertainty was a topic of debate from the initial discovery of ILUC: one line of political advocacy, fortunately much less pursued than it was a few years ago, has been the remarkable idea that because ILUC is not known with complete precision or accuracy for any fuel, policymakers should act as though it is known with certainty to be zero (Plevin et al. 2010).

5.1 Decision Theory as a Framework

The formalism of statistical decision theory provides a good framework in which to think about the implications of uncertainty for a policy decision (Raiffa and Schlaifer 2008). Consider, for example, the relatively simple context of a *low carbon fuel standard* (LCFS) *a la* California. This policy requires the average GWI of California vehicle fuel to fall incrementally over a decade, and its mechanism of operation requires that the state's Air Resources Board (ARB) assign each fuel i in the California market a GWI G_i that is used to calculate an energy-weighted average GHG intensity for each fuel wholesaler's annual production (CARB 2009). The ARB has determined that this GWI shall be the sum of (i) a fuel's average production chain GWI as calculated using a version of GREET (Wang 1999), and (ii) the marginal ILUC emissions induced by increasing production of this fuel, as predicted using an adaptation of the GTAP model (Hertel 1997; Taheripour et al. 2008) combined with a GHG accounting model (Plevin et al. 2014). We note that both the production chain GWI and ILUC are uncertain, and that the sum of these two quantities estimated this way, though both measured in g CO_2e MJ^{-1}, may conceal some important double-counting. (Plevin 2015) Other jurisdictions confront the uncertainty in ILUC in the context of other consequential regulatory actions. For example, USEPA is obliged by statute to recognize ILUC, but only needs to classify fuels into a few categories based, in part, on GWI to implement the Renewable Fuel Standard (USEPA 2010), but the principles and issues presented by the seemingly straightforward LCFS apply in those cases as well. Our focus for the moment is on the uncertainty surrounding the "true value" of the ILUC emissions induced by the increased production of any fuel.

In the decision theoretic framework, a *decision-maker* must select one of several possible *actions* and will experience a payoff that depends on (i) the chosen action and (ii) the *state* of a system which is known to him only imperfectly, for example the value of a random variable that cannot be observed, if at all, until after he commits to an action. The decision-maker can assign a *probability density function* (PDF) to the possible values of the random variable. The simplest corollary to this exercise is a bet that pays off if the decision-maker correctly chooses the number or color of the next roulette wheel spin.

The key policy implementation step in the LCFS case is thus selection of operational values for the G_i's that fuel wholesalers must use in their reporting. If ILUC were a feature of a stationary system, and modeling presented an extremely narrow PDF for a fuel's ILUC emissions, like the distributions laboratory analysis gives us for things like a fuel's specific gravity, the implied action might seem to be to choose any of the very closely spaced central estimators of this value, such as the mean, as G_i, for each fuel. However, there is no unique, "true" value for ILUC emissions; there is a range of plausible "true" values obtainable under alternative futures (e.g., under different fuel price and policy regimes, and other stochastic developments in the economic system). A unitary decision-maker might assign subjective probabilities to these alternatives and combine them to produce a single PDF, but this PDF would only represent one decision-maker's belief about the "true" value for ILUC emissions. Nor is there consensus on how to combine ILUC emissions with the remainder of GHG emissions associated with producing and using a given fuel to produce a summary GWI. Under these circumstances, the choice of action becomes more complicated and entails attention to the decision-maker's belief about the respective *cost* of taking the right and wrong actions.

ARB's best information about the ILUC emissions associated with a fuel as defined by its chosen modeling framework is currently a PDF that has substantial variance and is also asymmetric, with a longer tail on the high side (Plevin et al. 2010; Plevin et al., 2015); including other estimates from other models as data in a Bayesian framework would increase this variance. Decision theory provides some standard results about the statistic of such a PDF that should be "bet" on, all of which depend on the *cost of being wrong* as a function of the error $e = G^*_i - G_i$. Usually the decision criterion is to minimize the expected loss, defined as appropriate for the decision. For example, if it is as bad for G_i to be ten grams per megajoule below G^*_i as ten grams above, and twice as costly to be wrong by twenty grams as ten (symmetric linear cost function), the median of the PDF of G^*_i is the optimal choice; if losses are quadratic in the absolute error, the best choice is the mean.

5.2 What Does It Mean to Act Conservatively?

The cost, however defined as the policy objective, conditional on $G*_i$, of choosing one or another value for G_i, is probably not so simply related to e. In the first place, it may not be symmetric. In the second place, what happens in the world when the regulator issues an operating value depends on the response of a large, complex system to that choice: when the regulator publishes a schedule of G_i's the fuel economy responds with a quantity of total fuel consumed and a mix of component fuels that depend on the prices of those components and the compliance benefit each provides. The correctly formulated decision in principle is to choose a vector of $\{G_i]$ that maximizes the objective

$$O = E\left[V\left(\{G_i\}, \{G_i^*\}, R\{G_i\}\right)\right],$$

where V is the net benefit of the outcome, and the expectation is not only over the probability distributions of the $G*_i$ but in principle also of R, the response of the economic system to the choice of the G_i's. We can relax the assumption that policy should maximize this expectation, and consider alternative rules such as minimizing maximum loss, but the complexity of the decision is not much reduced.

For the moment, let us assume that V is adequately measured in total GHG discharge in the California fuel system over thirty years (we relax this assumption below). If a given G_i is 10 g CO_2e MJ^{-1} below the real value, "too much" of fuel i will be used: are we indifferent between that outcome and using "too little" if G_i is too high, even if the extra GHG emitted is the same either way in the first year? It might appear so, but ILUC is more or less irreversible, and land use change has important biodiversity costs. Correcting the fuel mix when better information is available does not retrieve either of these costs, while underutilizing biofuel for a year only causes a year's worth of over discharge. Perhaps choosing G_i for biofuels on the "high side" is the prudent path.

On the other hand, giving current biofuels too high a G_i may cripple the development of an ethanol infrastructure that would greatly enhance the climate benefits of future cellulosic ethanol, and the safe action is one that deliberately advantages biofuel. Either way, the problem for the LCFS regulator has thus evolved far from turning the crank on the best available model and implementing "the number" it delivers, and the lever that forced it in this direction is the refractory uncertainty in the magnitude of ILUC emissions.

Lest the foregoing discussion seem arcane, we emphasize that choosing a best estimate (whatever *best* means) of the "true value" of the global warming intensity (e.g., g CO_2e MJ^{-1}) of a particular fuel is not the same as implementing a value for that fuel's GWI to be used in a regulation. Allowing an asymmetric cost function to displace an *operational value* from a *most likely* value is completely conventional in health and safety contexts. For example, a structural engineer is legally obliged to use a value, called a *design strength*, in sizing a steel beam that is much smaller than the average failure strength of such beams in a test laboratory.[2]

Policy debate about climate stabilization generally recognizes, though awkwardly, the need to compare the costs of being wrong in each direction; that is the implicit basis of a debate about whether to protect the current economy by waiting for more evidence of climate change, or move quickly to avoid possible catastrophes. The analysis of biofuel policy implementation, however, is only beginning to accommodate the implications of significant uncertainty in the size of ILUC emissions (and other GHG releases) and the need to consider what the "safe side" of regulatory practice is.

5.3 Decision-Making in the Real World

Our decision model departs significantly from the real world of the regulator. Decision theory assumes a unitary decision-maker who can assess his probabilities for each state of the world, and who knows his utility function over outcomes. In fact, energy policy is made by multiple actors in a political environment, actors whose utility structures differ and who have different data and therefore different probabilities for states. Sharing data helps bring these probabilities to be more alike, but to make people's outcome/payoff functions match requires deal-making and mechanisms to share gains and allocate risk.

If the uncertainty in the climate effect of a fuel (or policy) were owing only to variation in estimating predictive models' parameters, or even uncertainty about the environment in which the models' future would unfold, it would be relatively tractable. However, there is no consensus model of the global economy. The existing modeling systems vastly simplify a global economy, and rely on many assumptions known to be false in the real world (e.g., perfect competition, perfect information flow, market clearing, no savings, no unemployment, entire aggregated market sectors respond in unison to price changes). Key assumptions differ across models primarily because none has been shown to be superior to others (Ackerman and Nadal 2004; Laborde and Valin 2011). Consensus on how to model global climate impacts is not forthcoming, and events, in a world without control conditions, will not make it possible to observe which model is "best" even after years of

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[2] Safety factors are common throughout engineering, not only forcing us to behave as though materials are not as strong (and chemicals not as safe) as we know they are, but to overestimate likely loads (probably the most uncertain dimension of a structure's operating environment). We do this because we recognize a cost function in which a beam that is too weak will kill and injure people, or at least cause very expensive damage to property, while a beam that is too strong will only make a building cost more. Where cost functions have a different degree of asymmetry, for example where the structure in question is an airplane rather than a building and extra weight is especially costly, we knowingly adopt smaller safety factors; for brittle materials whose failure is not preceded by deformation that would warn users to evacuate, we adopt larger ones.

observation. Consequently, epistemic uncertainty about how "correct" any given model really is dominates the usual sources. In this situation, policymakers are well advised not to expect that more science will relieve them of the hard work of making choices that are deeply political and judgmental.

These conditions are not a counsel of despair, however. In the first place, a policy does not require everyone to agree on everything, but only on the policy to be adopted. In the second place, decisions properly framed are inevitable: it is not possible not to have any fuel/climate policy, or to have more than one at a time, so society has to bite the bullet and make choices. Third, public deliberation moves more fluidly if stakeholders' concerns can be recognized and correctly described. Also, while model predictions of ILUC vary for any given fuel, the finding that ILUC significantly reduces the LCA-estimated advantage of biofuels is consistent across a wide variety of approaches (Warner et al. 2013). Putting the issue of prudence and safety factors forward in policy implementation, as the uncertainty issue asks us to do, is likely to make it easier to analyze policy choices than forcing them to be debated as though we know more about G^*_i's than we really can.

6 Discharge Trajectories and Time

To this point, we have treated the costs and benefits of using one fuel or another as being adequately measured by the sum of life cycle GHG emissions. However, a key difference between ILUC and direct emissions' respective time trajectories of release, forces us to look behind that assumption. We find that total GHG is neither an unambiguous benefit measure nor serves as good of a proxy as it might appear.

One important time consideration that we will not examine closely here is presented by the different atmospheric lifetimes of GHGs with different radiative efficiencies. Under the Kyoto Protocol, different greenhouse gases are combined into a single "CO_2-equivalent" value using *global warming potentials* (GWPs) which represents the radiative forcing produced by 1 kg of a gas relative to that produced by 1 kg CO_2 over a chosen time horizon. For the present discussion, GWP scaling will suffice, but it is notable that the GWP for a gas other than CO_2 changes significantly depending on the time horizon used to construct the GWP (Ciais et al. 2013) and that counting a discharge with a GWP whose period extends beyond an analytic horizon (for example, using GWP_{100} for a discharge 50 years before the analytic horizon) is intrinsically incoherent. More important for the present discussion, what summing GWPs over a chosen analytic horizon does not account for is the *forcing at a given time as a function of when the GHG is emitted* during that analytic period. An alternative CO_2-equivalency metric, Global Temperature Potential (GTP) estimates the relative change in temperature produced *at a future point in time* (note that the point selected is a policy decision) by non-CO_2 gases or particles relative to the temperature change caused by an equal mass of CO_2 (Shine 2009; Tol et al. 2012; Ciais et al. 2013).

To implement a program like the LCFS, or to determine which of two fuels is "better" (perhaps to subsidize or regulate substitution of one for another) imposes the non-negotiable discipline of a scalar measure of merit. Multidimensional metrics are useful for many purposes, but a vector can only be *larger than* another vector if a defined function maps both into real numbers. From the start, ILUC analyses confronted a dimensional accounting problem posed by time of discharge: most of the emissions from ILUC from an increase in biofuel production occurs at the onset of the new production, is only partially and very slowly reversible, and is proportional to the size of the increase no matter how long it is sustained, while the other GHG releases of the biofuel system, and of the fuels for it is usually assumed to be substituted, are almost all proportional to, and occur with, the ongoing fuel use. The accounting problem of combining the one-time ILUC discharge with the ongoing direct discharges is analogous to the problem of combining the one-time capital cost of a factory with ongoing labor and materials costs to calculate the "cost of an item" produced in it. As they have different units (g CO_2e MJ^{-1} of additional *production capacity* for the first and g CO_2e MJ^{-1} of *fuel use* for the second) ILUC and direct discharges cannot be summed directly.

The early convention for including ILUC emissions in fuel GWI assumed a production period, implying a total quantity of biofuel produced over that production period, and allocated the ILUC discharge linearly over this quantity: on the assumption that the ethanol production triggering ILUC would continue for 30 years at constant fuel yield, for example, Searchinger et al. added 1/30th of the ILUC release to direct corn ethanol discharge, a calculation the California ARB still uses (Searchinger et al. 2008). In contrast, EU regulations "amortize" ILUC emissions over 20 years (European Parliament 2009). Obviously the assumed length of the production period has a large effect on the unit ILUC discharge value assigned to a fuel this way, and should: if an ethanol production increase lasted only a year or two, its GWI counting ILUC would be enormous. So far no persuasive analysis has demonstrated the "correct" production period to use in this calculation: should it be the average lifetime of an ethanol biorefinery? The time until widespread electrification of the fleet, or hydrogen fuel cells, or natural gas, make liquid fuels obsolete? More fundamentally, the choice of time horizon is not a scientific question but a political decision informed by a variety of kinds of market expertise. Whatever value is used, facilities may in fact produce more or less fuel. There's simply no way to know this in advance.

Another early analysis of land use change dealt with this problem as though the initial land use change discharge burdened the biofuel with a "carbon debt" that it repaid over time through its GHG advantage over fossil fuel in direct emissions (Fargione et al. 2008). But this number gives a regulator little help in implementing a policy like the LCFS. A fuel with a shorter payback period is "greener" than one with a longer period, *ceteris paribus*, but the payback period does not translate easily into a GWI score. In any case, what is an "acceptable" payback period, and what if the ethanol production in fact does not continue that long? And how would we compare biofuels to fossil fuels, which have an infinite payback period?

Melillo et al. (2009) suggested that if a carbon charge can be instituted as an overarching climate policy, biofuels should simply be taxed on their total first-year discharge GWI, including ILUC, leaving it to the financial system and subsequent year's market advantage to pay a literal carbon debt.

6.1 Discharge Trajectories

The implications of differing discharge profiles for different fuels are even more complicated than capital cost accounting, because GHGs have different atmospheric lifetimes and cause warming while they remain in the air. A gram of CO_2 emitted now will have caused more accumulated forcing (temperature increase) by 2050 than the same gram emitted in 2040 (Kendall et al. 2009; O'Hare et al. 2009). Figure 1 shows discharges, atmospheric GHG concentration (cumulative discharges less decay), and cumulative forcing over time for a fossil fuel and an energy-equivalent quantity of biofuel, *each of which emits the same total amount of*

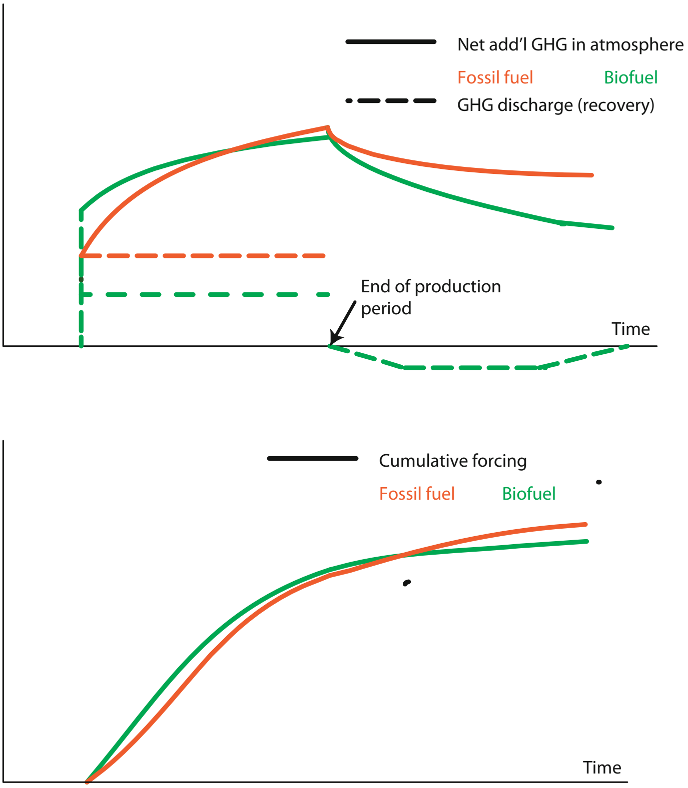

Fig. 1 Time discharge profiles and forcing for a biofuel and a fossil fuel

CO_2 during the production period. For example, this might represent a biofuel with 60 g CO_2e MJ^{-1} (of fuel use) direct discharge and 1050 g CO_2e MJ^{-1} (of production capacity) for ILUC, produced over 30 years, and gasoline with 95 g CO_2e MJ^{-1} direct discharge used for the same period. In this sketch, biofuel production begins with ILUC, fossil and biofuel use continue for the production period, and the land where ILUC occurred then begins to regrow to natural conditions, recapturing CO_2 from the atmosphere (if it does not, the failure to recapture cannot be "blamed" on the biofuel). Meanwhile, emitted GHGs accumulate in the air and decay out. This picture of discharges solves the problem of combining ILUC with direct discharges, but only by combining them into one or another function of time, not a scalar measure.

Note that with our assumption of regrowth sequestration, MJ-MJ substitution of any biofuel whose direct GHG discharges are lower than a fossil fuel's, grown for any production period, will eventually have emitted less total GHG than the fossil fuel, and eventually cause less cumulative forcing. However, "eventually" may be a very long time. The significance of this figure is that all the fossil and biofuel pairs of time trajectories cross at some time in the future.

Which fuel is more climate-friendly? If the trajectories did not cross, the answer would be simple (though how much "greener" the biofuel is would still require analysis). But as they do, the answer to that question requires a policy decision about what criterion–that is, *what scalar function of which trajectory*–should be used to assess them. Even if the criterion is as simple as "total GHG emissions", it remains to choose a time up to which that integral (of emissions) is evaluated, because moving the *analytic horizon* beyond the crossing point will switch our preference between the fuels.

Neither policy analysis nor political theory gives us a solid basis on which to choose such a horizon. Perhaps the right date is the end of the current governor's or president's term? A date by which nearly everyone now alive on earth will be dead, say 100 years? The most likely date by which the Greenland ice cap will have melted into the oceans? The 500 years of the IPCC's GWP_{500}?

Using very long analytic horizons without discounting (see below) leads to absurd policy implications. A 500-year analytic horizon, for example, would mean that Drake should have considered the effects, including climate effects, on a twenty first century industrial world he could not even imagine, with the same weight as its contemporaneous effects when he burned the Spanish timber stores at Cádiz (Mattingly 1989).

Even if some operational time horizon were adopted within which discharges were simply summed, we would still not be out of the woods with a defensible, coherent practice. Recall, in particular, that the reason we care about GHG emissions is not for their own sake but for their climate-forcing effect: if fuels policy is about global warming, it seems important if a policy minimizing GHG emissions for a given period actually results in more warming for decades, and it would seem appropriate to infer the criterion from the forcing, or at least the cumulative atmospheric concentration, trajectory rather than discharges alone. No current policy implementation, to our knowledge, does this. In the context of crop-based biofuels with ILUC, it is important that moving the criterion assessment from total discharge, to cumulative atmospheric GHG, to cumulative forcing successively extends the time until a given biofuel will score “better” than a fossil fuel.

Since the original paper on discharge time accounting for ILUC (O’Hare et al. 2009), several improvements and alternative approaches have been presented, both for liquid fuels (Kendall et al. 2009; Levasseur et al. 2010) and forestry, where long intervals between harvest/combustion (discharge) and regrowth are important (Cherubini et al. 2011). However, policy design and implementation in this area still use simple discharge summation over an arbitrary production period as the operational criterion.

6.2 Discounting

There remains the issue of comparing costs incurred now with costs in the future. If we score fuels on the basis of cumulative forcing–certainly a better proxy for social cost than emissions totals–over a long period, we have to ask whether we are really indifferent between increasing planet temperature by a degree F during the decade 2050–2059 and doing the same for the decade 2020–2029; both would add the same amount to the cumulative index as of $t > 2060$. Economics provides us a model, exponential discounting, with which individuals and societies conventionally compare costs and benefits now to costs and benefits in the future. This model, widely used in benefit/cost analyses of all kinds, counts a consequence with an economic interpretation (not necessarily a money value) in year t with $(1 - r)$ of the weight of the same consequence occurring in year $t - 1$. Here r is a discount rate, whose size is itself a policy decision requiring analysis. With this accounting, things that will happen later count less in a benefit/cost assessment than things that happen sooner.

A nonzero discount rate can portray a variety of considerations, including so-called “pure time preference,” the psychological principle that we prefer benefits sooner than later; actual financial trading outcomes in markets across time; and uncertainty about predicted events. (A further complication is introduced by the *social cost of carbon* (SCC) correction advocated by a US government working group (Interagency Working Group on Social Cost of Carbon 2013), which counts GHG discharges as *more* costly (before discounting) insofar as they occur later, because they affect a larger population and economy. Analytically, this correction can be captured by subtracting the annual SCC growth rate from the chosen discount rate.)

To date, almost no researchers have incorporated discounting in their models of discharge time profiles. We consider this an important opportunity to improve both scholarship and policymaking. Even though the right discount rate for such analyses is arguable, using a rate anywhere in the plausible range of about 3–10% greatly increases the plausibility and legitimacy of this kind of model.

Note that discounting only applies to economic values (not necessarily values measured in money, though they have to be measured in some consistent way) that can actually be traded across time. The classic example is a financial instrument such as a bank deposit that trades control of funds from one time to another. It is not generally meaningful to discount physical quantities: a bucket of water in January is worth less, not more, than the same bucket in June if its purpose is to water a summer garden; if used to put out a fire in January, discounting does not measure how much more valuable it is then than in June. Consequently, discounting GHG discharges across time implicitly assumes that those quantities are close enough proxies for social cost incurred at the time of discharge. For effects spread over decades and centuries, this is not the case and discounting should be applied to more appropriate indicators like annual forcing.

Even a small discount rate accumulates large effects when time periods get long; for example, discounted at 3%, a dollar's worth of benefits in 2034 counts as only about 50c now; a 2114 dollar, 5c. At 5%, a 2064 dollar is worth less than 8c now. Instead of the kind of "angels on the head of a pin" reasoning required to contemplate 100 or 500-year analytic horizons, it seems wiser to accept infinite horizons and discount the relevant trajectories. This automatically, elegantly, and defensibly makes events in the conjectural, far, future count for very little and makes consequences during futures we can reasonably analyze salient. For an example of the effect of discounting on discharge profiles, see O'Hare et al. (2009).

The "discount rate debate" in the climate context has mostly been focused on the trade-off between incurring costs for stabilization now and receiving benefits years or decades in the future when climate change would otherwise be more severe. Advocates of faster investment in stabilization typically argue for smaller discount rates. It is not possible to provide a complete analysis of the role of discounting in climate policy here (Schelling 1995; Guo et al. 2006; Stern 2006; Nordhaus 2007); for the present context, we accept that conventional discounting is required for rational policy analysis.

6.3 Time Displacement Accounting

We return briefly to the question of the assumed production period for a biofuel system, which as noted above, is extremely difficult to estimate with confidence and greatly affects the unit contribution of ILUC to a biofuel's GWI. An insight from Kløverpris and Mueller (2012) provides an opportunity to sidestep this issue completely. They note that agricultural expansion for all purposes (such as increased food demand) is greater in a given year than the expansion needed for projected biofuel production, so the effect of producing biofuel for one season is merely to cause the biofuel ILUC to occur a year earlier than it otherwise would.

The model they construct on this insight has many of the problems discussed above, but treating ILUC as merely accelerating land clearing that is already going to happen leads to a shortcut calculation we can call *time displacement accounting* that avoids almost all the complexity of complete time profile models and does not require an assumed production period. Note that in this framing, all the discharges from the biofuel and comparable fossil fuel occur within a year, so most of the issues raised by the difference between forcing and discharge trajectories are avoided: for discharges less than a year apart, any pound of GHG (scored as IPCC GWP), however discharged, has about the same social cost as any other, so we can reasonably use total GHG discharge in GWP terms over this short period as proportional to social cost.

Causing the ILUC to occur a year earlier than it otherwise would has a social cost of about *r* times the social cost of the ILUC, just as paying a dollar a year early costs about 5c at 5%. Furthermore, this effect is independent of production period; no matter how long or briefly production continues (again, assuming land conversion worldwide annually exceeds biofuel land needs), each year of production independently causes this acceleration of clearing discharge. Accordingly, it is a reasonable approximation and a tractable protocol to simply multiply total ILUC by *r* and add it to direct emissions to calculate GWI: at 5%, for example, a fuel with ILUC of 500 g and direct emissions of 60 g could be reasonably assigned a GWI of $60 + (0.05 \times 500) = 85$ g. The uncertainty in estimating ILUC itself remains to be dealt with as in the previous section, and a regulator needs to settle on an appropriate discount rate (which we have argued is the case no matter what) but much of the difficulty in accounting for time issues is avoided.

6.4 Discharge Profiles and ILUC Beyond Biofuels

We now briefly note two implications of the analysis of ILUC whose application is broader than biofuel GWI estimation. The first is that, as Bruce Dale has noted in conversation, ILUC is not just caused by biofuel production but by anything that competes with food for land. This includes state parks, highways on arable land, and, importantly, suburban development on what would otherwise be farmed. Developers like to build on flat land, and every acre of (say) Chicago suburbs displaces corn from food markets and must have an even larger ILUC discharge (because it produces no feed byproducts) than an acre of corn used for ethanol instead of feed or food. The ILUC effect of putting farmland to any other uses deserves analysis and recognition in land use regulation.

The second lesson is that discharging GHG early in an energy production system causes more forcing for a long time than discharging it later. Nuclear power and hydropower, for example, are generally scored as low carbon, but the carbon discharges attributable to the large amounts of steel and concrete used to build dams and reactors occur at the very beginning of the systems' operational life and represent a much larger fraction of those technologies' total forcing than time-ignoring calculation of discharge quantities indicate.

7 Beyond ILUC

7.1 Non-land-Use Climate Effects

The big lesson from ILUC research–that everything in the world is connected, albeit with bungee cords rather than chains–presents policymakers and analysts with the likelihood that a large biofuel production increase will indirectly generate still other, non-land use, GHG discharges not counted in an ALCA. Two of these have been identified and shown to be considerable, the "rebound" effect on petroleum use and N_2O releases from increased fertilization of all crops. A strong case can be made that, if ILUC is real and should "count" in scoring fuels for climate, these other indirect climate effects should be counted as well (Khanna et al. 2011).

The rebound effect, sometimes called *indirect petroleum use change* (IPUC), is the failure of biofuel forced into a particular market, such as the US, to displace fossil fuel MJ-for-MJ worldwide (Rajagopal and Plevin 2013). The displacement that does occur reduces fossil fuel prices worldwide and increases petroleum use everywhere outside the biofuel program jurisdiction, an increase that partly offsets the climate gains from the domestic substitution. Estimates of this effect show it to be in the range of 30–70% of MJ-MJ substitution amounts (Hochman et al. 2011; Chen and Khanna 2012; Bento and Klotz 2014; Chen et al. 2014).

Increases in world food prices motivate farmers to increase yields, though the size of this effect, which is an important factor in the size of ILUC, has been strongly debated. One way to increase yields on existing cropland is to fertilize more heavily, especially with nitrogen, and this additional application generates added releases of N_2O, a potent greenhouse gas (Crutzen et al. 2007; Melillo et al. 2009; Reay et al. 2012).

7.2 Non-climate Costs and Benefits

Our discussion to this point has emphasized the difference between total GHG discharge and climate forcing, generally indicating that scoring biofuels by the latter (better) proxy for social cost makes them look less attractive from a climate stabilization perspective. But *social cost*, what policy should tautologically minimize, comprises much more than climate change, and biofuels expansion has important non-climate effects (as does fossil fuel extraction). Some of these dimensions of social cost are accounted for by the market prices of biofuels and their competitors and do not present an especially difficult problem. LCA, as we noted, counts the diesel fuel the corn farmer's tractor uses, but not the gas that cooks his eggs in the morning nor the cost of the eggs themselves (but see (Giampetro 2009) for analysis that incorporates energy costs of human labor). However, those costs, energy and other, are reflected well enough in the price he requires for his corn that we can consider them as accounted for in the social decision system.

Other costs, however, are not well reflected in market prices. One example is the effect on nutrition that the ILUC-estimating models present along with their land use results: using land for energy instead of food makes food more expensive and reduces its consumption (Searchinger et al. 2015) . Some of that reduction may benefit the overweight, or represent less meat in the diet of the middle class, and may be no great concern, but some of it is less food overall consumed by people who are already nutrition insecure. Biofuel production requires water that is scarce in some regions and usually not priced efficiently (Fingerman et al. 2010).

ILUC forest clearing not only releases GHG but also reduces biodiversity (Fargione et al. 2010). Changes in agricultural practices, especially in developing countries, affect social structures, rural employment, and local politics.

In principle, these additional costs (and benefits) of biofuel expansion and production should be included in analysis of the optimal choice of G_i discussed under uncertainty, and the GWI values chosen to minimize a discounted indefinite stream of net benefits of all (identifiable) kinds. Also in principle, or in theory, all of them could be estimated by modeling and otherwise, priced by the benefit–cost analysis heuristics and devices used to account for nonmarket goods, converted to units of GHG by a carbon price, and added directly into the GWI calculation for a fuel, thus measuring a variety of costs in units of GHG emissions in order to conform to the administrative structure of a fuel policy.

It is not clear that this would be a good idea, however, even if it were analytically tractable. The LCFS, for example, is subject to general expectations of increasing social welfare, but it is also a fuel carbon intensity policy. A constant challenge to implementing enacted programs with a specific scope and purpose is the natural desire of advocates of other goals to hang their own concerns on it, until the policy in question becomes an unmanageable, uncoordinated Christmas tree of good intentions. Nevertheless, and recognizing the risk of second-best problems, it does seem reasonable to integrate large non-climate effects into GWI measures where it can be done easily.

Two examples of this integration apply to food and water. Hertel et al. (2010) included in their analysis a model framework that constrained food consumption to remain constant during a biofuel production increase shock, and observed about 40% more ILUC. Using this value is not an improvement in the estimate of ILUC, but a policy decision not to "count" climate benefits resulting from food deprivation. A recent extension of the GTAP model for ILUC incorporated a restriction of agricultural expansion to regions where irrigation water is available, and ILUC increased about 27.5% (Taheripour et al. 2013). This amendment represents a better description of what using more of a biofuel will actually do in climate terms, not a judgment about the value of water.

8 Conclusions

Fuel policies affecting or depending on crop-based biofuels cannot properly be implemented or analyzed merely by summing GHG discharges as the designers of (for example) the LCFS or RFS implicitly assumed. The distinctive properties of the ILUC discharges induced by increased production of these fuels, especially including the refractory variance in estimates of it, and the mismatch between the GHG release profile of fuels with ILUC and competing fossil fuels, require attention to considerations that are still novel in both research and policy implementation. Among these are the cost of being wrong about a fuel's GWI and the failure of summed GHG emissions to reflect social cost when time trajectories of fuel GHG releases do not match.

It is too early to make firm recommendations for policy that account for all these implications of ILUC research. It may become necessary to redesign the policies substantially so they do not require fuel-specific GWI values. However, for the near future, and as research and policy design proceed, some action recommendations can be advanced with confidence.

First, the operational merit index for fuels—their GWI—should be more sophisticated about time than merely summing discharges over an arbitrary production period, preferably time-aware, and should be based on discounted cumulative forcing, with or without a social cost of carbon (SCC) correction. Implementing agencies should "bite the bullet" and (i) adopt a discount rate to address the time profile of ILUC emissions and (ii) analyze probable production periods to identify a sound assumption so as to make this possible. If forcing is discounted, it is not necessary to choose an analytic horizon. Alternatively, if the assumptions behind time displacement accounting are supported with further research, it is an acceptable and reasonably accurate heuristic that avoids much of the complicated time-aware modeling and can adequately compare fuels with GHG discharge estimates directly.

Second, implementing agencies should confront the issue of safety factor and prudence by (i) a systematic analysis of the cost of positive and negative errors in assigning GWI values, and (ii) an affirmative decision to choose values relatively far from the chosen GWI distribution's central estimators if that is indicated. Sophisticated approaches to addressing uncertainty and risk are therefore required to incorporate ILUC emissions into regulations properly (Plevin et al. 2013; Witcover et al. 2013).

Third, water and food considerations should be incorporated into GWI values (for policies where GWI is the operating mechanism) by means such as the constrained models described above.

Outside fuel policy, the lessons of ILUC for food-competitive land use and early discharge trajectories should be adopted into policy and climate analysis of energy sources.

Fourth, and generally: the most important lesson of ILUC analysis is that indirect effects of many kinds affect the climate benefits of fuel substitution, and effects such as rebound and noncombustion releases like methane from changing cattle and rice production, and N_2O releases from increased fertilizer use should be recognized and counted as well as possible.

Appendix: The LCFS Mechanism

The most uncertainty-intolerant biofuels policy framework at present is the California Low Carbon Fuel Standard (LCFS). The machinery of the LCFS is simple in principle: every fuel distributor in the state annually calculates his annual *average fuel carbon intensity* (AFCI) as a sum of the fuels combined into motor fuel, weighted by their respective officially published GWI values. If this AFCI is below the gradually declining standard specified in the regulation, the fuel distributor has allowances to sell to other distributors; if higher, he must pay a fine or purchase allowances.

Specifically, for a fuel distributor (approximately, wholesaler) j in year t who blends Q_i units of fuels $i = 1, 2, 3\ldots$ with GWI values G_i, the fine (or sale of credits) C_{jt} at a "price" of P when the standard is S_t will be:

$$\begin{aligned} \mathrm{AFCI}_{jt} &= G_p Q_p + G_b Q_b \\ C_{jt} &= \left(S_t - \mathrm{AFCI}_{ji}\right) P Q_i. \end{aligned}$$

In this example, p is petroleum and b is a biofuel, and calculations are all per MJ of available fuel energy (diesel and electric energy receive an adjustment to account for their higher efficiency). Assuming biofuel costs more than fossil fuel and it is not being blended to the limit to minimize product cost, a lower value for G_b will lead to cheaper compliance for the distributors. Though it was widely expected when the LCFS was developed that the main compliance paths for gasoline and diesel would be admixtures of maize ethanol and soybean biodiesel, the requirements of this policy are quite stringent. For example, if the "blend wall" for ethanol into gasoline is 20% (twice the current legal limit) and there is little market penetration of so-called E85 or flex-fuel vehicles (that can operate on any ethanol percentages) during the LCFS' period of operation, compliance with a 10% carbon intensity reduction from gasoline's 96 g CO_2e MJ^{-1} requires "45-g" ethanol, a value almost no current domestic bioethanol can be shown to have *even ignoring the indirect discharges from ILUC (Liska).*

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Part III
Feedstocks for Cellulosic Biofuels: Production Risks and Risk Management

Innovation in Agriculture: Incentives for Adoption and Supply Chain Development for Energy Crops

Madhu Khanna, David Zilberman and Ruiqing Miao

Abstract The literature on technology adoption provides key insights that can explain the incentives and barriers to the adoption of new energy crops for producing biofuels to displace fossil fuels. Energy crops are perennials with high upfront costs and establishment lags. They also differ from conventional crops in their riskiness. Their production involves foregoing returns from existing uses of the land. These features differ spatially and across farmers due to difference in farmer risk and time preferences. Understanding patterns of adoption is important for designing farming systems, supply chains, and policies. The literature investigates the influence on the adoption decision of many sources of heterogeneity across time and location including differences in the characteristics of technologies, farmers, market conditions, and policy incentives. Factors likely to influence adoption are explained using the example of two high-yielding and promising energy crops: miscanthus and switchgrass. Energy crop adoption decision is shown to be based on monetary factors (profit and costs) and the composition of mechanisms to address risk and uncertainty available to a region, as well as the risk and time preferences, attitudes, and beliefs of farmers. The paper ends with a discussion of market mechanisms and policy incentives to induce adoption and create supply chains needed to engender this industry.

Keywords Adoption · Energy crops · Miscanthus · Supply chain · Switchgrass

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M. Khanna (✉)
Department of Agricultural and Consumer Economics, University of Illinois
at Urbana-Champaign, Urbana, IL, USA
e-mail: khanna1@illinois.edu

D. Zilberman
Department of Agricultural and Resource Economics, University of California at Berkeley,
Berkeley, CA, USA
e-mail: zilber11@berkeley.edu

R. Miao
Department of Agricultural Economics and Rural Sociology, Auburn University,
Auburn, AL, USA
e-mail: rzm0050@auburn.edu

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1 Introduction

There is growing interest in the use of energy crops for replacing fossil fuels for transportation, power generation, and heating. The use of energy crops for cellulosic biofuel production will require guaranteed feedstock supply from farmers. Knowledge about the factors that contribute to the decision of producers to grow energy crops is important to establish policy changes needed to induce production of biomass. Since cellulosic biofuels, defined as those obtained from cellulosic feedstocks, are currently not economically competitive relative to fossil fuels in either the transportation or the electricity sectors, the use of bioenergy to replace fossil fuels is entirely driven by policy. The US and the EU are providing a variety of policy measures that seek to provide incentives for biomass production. These policies differ in the mechanisms through which they provide incentives; some policies directly subsidize farmers for producing biomass while others indirectly create incentives by requiring energy providers to demand bioenergy at a price higher than the energy equivalent value of the fossil fuels they displace. In order to understand whether these policies will be effective in creating a market for biomass, it is important to examine the type of incentives they provide and the risks and uncertainties they mitigate and to juxtapose these with the factors that will influence the willingness of farmers to produce biomass. To understand the incentives provided by these policies, it is also important to recognize other numerous agricultural policies that are currently in place and provide competing incentives to continue conventional agricultural production.

The next section of this chapter provides a short review of the main strands of the literature on technology adoption and their implications for the adoption of energy crops. Section 3 introduces the features of energy crop production and provides a review of research on key factors that will affect the profitability of bio-crops and their adoption in various locations. Section 4 includes a review on findings regarding how energy crop adoption is affected by other economic factors such as risk and uncertainty, as well as by noneconomic factors such as technology attributes, farmers' concerns for environmental stewardship, and demographic characteristics. The last section concludes.

2 Previous Literature on Agricultural Technology Adoption

There is a large literature investigating the adoption of innovations in agriculture. This literature has sought to explain the observed trends in adoption of several major technologies. In this section we first present the conceptual insights from this literature, and then introduce the factors that affect technology adoption and discuss empirical findings in the literature related to these factors.

The literature on technology adoption was inspired by the realization that there is a time lag between the moment a new innovation is available and the time it is

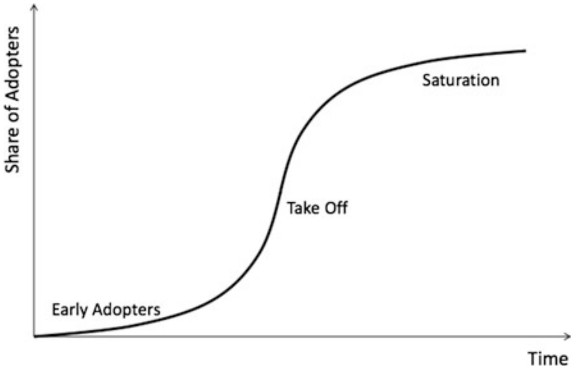

Fig. 1 The diffusion curve

adopted by a large share of its intended users. This literature distinguishes between adoption and diffusion processes (Feder et al. 1985). Adoption occurs when a farmer starts to use a new innovation; adoption may be partial or full, and a farmer may allocate only part of her land to a new variety while keeping the rest in the traditional one. Diffusion is defined as aggregate adoption, measured by the fraction of farmers that adopt a new technology, by the fraction of the land that is utilized with the new technology, or the fraction of the output that is produced with the new technology. The literature on adoption was started by sociologists (Tarde 1890) and some of its main findings are presented in Rogers (1983). Early studies found that diffusion curves are S-shaped as a function of time (see Fig. 1).

Rogers (1962) introduced the imitation model to explain the S-shaped diffusion curve. In this model, interactions among individuals from a homogenous population lead to imitation. The imitation model of adoption has been criticized because it is not consistent with economic behavior. David (1975) has presented an alternative to the imitation model called the threshold model. This model consists of three elements: micro-level decision rules, identification of sources of heterogeneity, and dynamic processes that affect adoption decisions. At the micro-level, individuals may pursue profit maximization or make choices according to a combination of profitability and riskiness of each alternative. Because individuals are different, they may decide to adopt at different periods. The sources of heterogeneity may be location, the size of enterprise, education levels, risk perceptions, time preferences, and risk preferences. At each moment, there is a threshold level of a source of heterogeneity that separates adopters and non-adopters. The dynamic processes that affect diffusion are processes like “learning by doing” which lowers the cost of adopting a new technology, “learning by using” which increases the benefits from a technology, and “statistical learning” that allows adopters to observe the properties of the technologies and update their assessment of it, thus reducing some of the risks associated with adoption. The threshold model explains the S-shaped diffusion curve because sources of heterogeneity tend to have uni-modal distribution (Sunding and Zilberman 2001).

The empirical literature has identified several major factors that explain adoption patterns (Feder et al. 1985; Sunding and Zilberman 2001; Foster and Rosenzweig 2010). First are the characteristics of technologies. Two features that are associated with technology adoption are their potential to enhance profits through increased yield or reduced operational cost. Technologies that are environmentally friendly may be adopted when government policies either penalize negative environmental side effects, subsidize environmental benefits (e.g., emission reduction), or set an upper bound on pollution per unit of output. Some technologies may augment resources like land quality (e.g., drip irrigation enhances water holding capacity) or human capital, and may be adopted in regions where these resources are scarce. Other technologies may be adopted because they control risk (e.g., integrated pest management or vaccination of animals). Finally, farmers frequently adopt technologies that enhance product quality or contain features for which consumers are willing to pay a premium price.

Second, adoption may vary across farmers because of differences among farmers. The literature identifies scale of operation (e.g., larger farms or farmers with multiple activities), education, wealth, health, age, and location as key sources of heterogeneity. Farmers also differ in their perceptions of their ability to succeed and endure (i.e., self-efficacy).[1] There are also differences among communities and regions that may affect adoption. For example, communities with high level of social capital and strong networks of information sharing and mutual support are more likely to adopt technologies. Similarly, regions with more developed credit systems as well as lower regulatory and transaction costs may induce higher rates of adoption. Finally, risk considerations are major determinants of adoption behavior. They include degree of risk faced by farmers in terms of yield, output price, and input availability and cost. High rates of risk aversion contribute to reduced likelihood of adoption of new technologies.

Third, market conditions and policy incentives are important determinants of adoption. Farmers' concerns about risk may be mitigated by various forms of insurance, including crop insurance, as well as government policies such as decoupled income support and disaster assistance. A related set of policies are inventory policies that stabilize prices both to farmers and consumers. Government may affect adoption also by credit subsidies and guarantees, as well as production mandates that guarantee demand.

3 Energy Crop Production

The decision to produce an energy crop is based on a variety of costs and benefits, including the price of biomass, biomass yield, the costs of various field operations, and the cost of storing and transporting it to a processing facility. The profitability

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[1] Wuepper and Lybbert (2017) provide a survey of this recent line of research.

of energy crops is expected to differ across locations, time, and feedstocks. We focus in particular on two dedicated energy crops, switchgrass (*Panicum virgatum*) and miscanthus (*Miscanthus x giganteus*) that have been identified as the most promising energy crops due to their low-input and high-dry matter yield per hectare in the US and Europe.

Switchgrass is a warm season perennial grass with a stand life of 10 years or more. There are several varieties of switchgrass including the Cave-in-Rock cultivar, an upland variety well suited for the upper Midwest, and Alamo and Kenlow, lowland varieties most suited for southern US. Miscanthus is a perennial rhizomatous grass with a stand length of 15 or more years reaching maturity after about two years. The yields of these perennial grasses vary considerably across varieties and locations. In the fall, perennial grasses undergo senescence and translocate nutrients from the above-ground plant canopy to the roots. Delaying harvest until after senescence reduces need for nutrient application in the subsequent year, reduces drying time, and improves the quality of the biomass. However, waiting to harvest until after senescence also decreases harvestable yield as compared to peak yields. This reduction is estimated to be as much as 20 to 50% by various studies (Clifton-Brown and Stampfl 2004; Jain et al. 2010; Smeets et al. 2009). As a result the delivered yield of biomass from energy crops is typically substantially smaller than the peak biomass yield estimated by crop growth models.

With dedicated energy crops, typically perennials, the costs and returns occur over a long time horizon and differ with the age of the crop. Comparing returns of perennial crops to annual crops requires application of a discount rate to convert profits over time to a net present value or to an equivalent annualized profit per year. If the conventional crop yields a harvestable residue, then any profits from it would also need to be included in the profits from the conventional crop and it becomes a part of the opportunity cost of using land to produce a dedicated energy crop. Alternatively, the landowner could determine the annualized break-even price of biomass needed to cover his annualized costs of production, including the cost of land. This represents the minimum price or a threshold price that a farmer must receive to make it in his self-interest to switch land from a conventional use to biomass production. If the market price of biomass is greater than this annualized break-even price, then it is profitable to produce biomass.

In this section we apply the findings on technology adoption described above to analyze the economic factors likely to influence the decision to produce biomass assuming perfect certainty and full information about yields, prices, and demand in the future. In Sect. 4 we discuss the implications of risk, uncertainty, and learning for biomass production decisions.

3.1 *Yield of Bioenergy Crops*

Yields for bioenergy crops depend on the type of bioenergy crop and the location where the crops are planted since these locations differ in their climatic conditions,

Table 1 Simulated delivered yields of bioenergy crops in the US

(Metric Ton Dry Matter ha^{-1})					
Region	Miscanthus	Upland variety of switchgrass	Lowland variety of switchgrass	Corn stover	Wheat straw
Atlantic States	31.6	10.9	16.4	2.60	2.18
Midwestern States	23.8	9.5	10.2	2.86	2.23
Plain States	19.8	7.3	11.0	2.36	1.42
Southern States	30.2	10.1	15.2	2.50	1.95
Western States	–	–	–	3.29	2.11

Note: Delivered yields are obtained from peak biomass yields by including harvest losses of 20% for miscanthus and switchgrass and 7% loss during storage (Chen 2010)

soil quality, terrain, and other biogeochemical conditions that impact a plant's ability to produce biomass. Simulated post-harvest (delivered) biomass yield of miscanthus is found to be about two times the yield of switchgrass in much of the rainfed US, with the exception of the north where minimum temperatures are extremely low and in the south where the absence of frost prevents senescence of the miscanthus plant needed for its long-term growth. Rainfed perennial grasses are not viable in the western part of the US. The variability in yields of various biomass feedstocks across regions in the US is shown in Table 1. Yield variations are due to differences in the length of the growing season in the various sites' studies across Europe (Clifton-Brown and Stampfl 2004). Figure 2 shows the variability in yields across the US (Since yields of crop residue are much smaller than those of energy grasses, the legends in this figure are different across maps).

Yield estimates are based on experimental plots or crop growth models. Average farm yields achieved in a region or country are inevitably smaller than yield potential, sometimes significantly so. Lobell et al. (2009) note that this is because achieving the maximum potential yield requires near perfect management of crop and soil and climatic factors that influence plant growth and development throughout the crop growth cycle. On average, the ratio of county average yield to the technical potential for corn in the US, reported by the U.S. Department of Agriculture (USDA), was 65% across all sites and years for rainfed maize and 75% for irrigated maize.

3.2 *Cost of Producing Biomass*

The costs of producing biomass differ with the feedstock being used to produce the biomass and across locations for a given feedstock. For energy crops, annualized costs of producing biomass consist of several components including establishment, maintenance, harvest, storage, transportation, and the cost of land (i.e. the foregone profits from an alternative use of that land). In the case of crop residues, costs

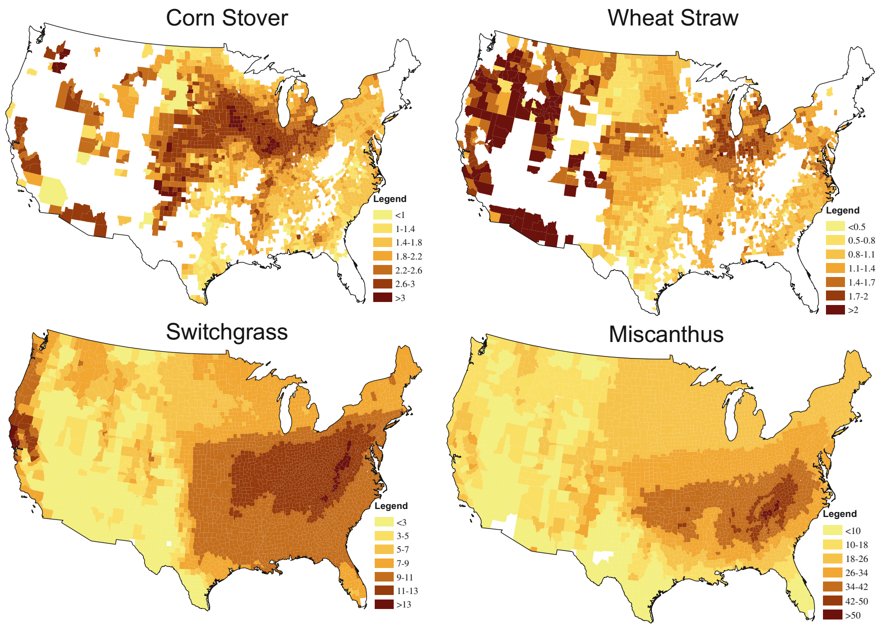

Fig. 2 Delivered yields of feedstocks in the US (metric ton/year/ha)

include replacement fertilizers that need to be applied and annualized costs of harvesting, storage, and transportation. These costs could also include an opportunity cost of land, if it leads a landowner to switch from a more profitable tillage or rotation option to a less profitable one.

Biomass can be stored after harvest in several ways including on-farm open air, on-farm covered, or storage in a centralized covered facility. The loss in biomass is highest when biomass is left unprotected and lowest in the enclosed structure. These losses depend on the number of days the biomass is stored and need to be weighed against the costs of installation, land, labor, and materials as well as the biomass quality that is needed by the biorefinery. A centralized covered storage facility could be shared by many farms but would require producers to incur biomass handling and transportation costs to move the biomass from the farm to the refinery. The optimal choice of storage facility is likely to depend on the volume of biomass and the length of time that it has to be stored, the price of biomass, the quality of biomass required, and the weather conditions within the region.

Biomass transportation from the farm to the refinery is likely to be by trucks. Transportation costs include the amortized capital cost of the truck, operating costs which include labor, fuel, maintenance, insurance, and repairs. Additionally, loading and unloading costs and waiting time for the driver also need to be factored in. Costs of transportation will vary across farms depending on their distance to the refinery and the collection area of the refinery. With high-yielding feedstocks, a refinery can obtain its feedstock from a smaller collection area. The greater the distance that the biomass has to be transported, the smaller the farm gate returns to biomass producers. Thus incentives to grow bioenergy crops are likely to be higher in the vicinity of the refineries.

When energy crops are grown on cropland, the opportunity cost of land is the foregone profits from the conventional crops that would otherwise be grown on that land as well as any value from the crop residues that might be harvested for bioenergy. When dedicated energy crops are grown on marginal land that is currently idle, there is likely to be a cost of upgrading and converting the land to grow an energy crop and its foregone profits from an alternative low value crop, such as hay, that could be grown on that land. The costs of land can be high, particularly in the Midwestern US which is very productive for producing corn and soybeans, and are estimated to range from \$200–\$300 per hectare in the South to \$700–\$800 per hectare in the Midwest (in 2007 prices). One of the benefits of perennial grasses is their ability to be productive on low-quality land, as evidenced by switchgrass field experiments (Varvel et al. 2008). Production of bioenergy crops is therefore more likely to occur on marginal land with lower opportunity costs. Currently, idle cropland or cropland pasture represents marginal land categories that are in and out of crop production, depending on crop prices (Khanna et al. 2011). The opportunity cost of marginal land is estimated in the range of \$100–\$300 per hectare across various rainfed regions in the US. In a study estimating the cost of production of miscanthus and switchgrass in Europe, Smeets et al. (2009) determine the price of land considered suitable for energy crops to be €10/ha in Lithuania, €45/ha in Del-Dunantal, Hungary, €50/ha in Lubelski, Poland, €201/ha in Devon, UK, and €232/ha in Lombardia, Italy.

Some costs are fixed and do not vary with the yield of biomass (e.g., the cost of establishment and the cost of land); but others do. Thus, the stand life of a perennial crop, the biomass yield per unit of land, and the growing season for the crop all potentially impact the cost per dry ton for biomass residues and dedicated energy crops. There are several other factors that are expected to influence the costs of producing biomass, including the size of the farm, the number of harvests, the timing of harvest, the harvesting horizon, and the method of storage. The harvesting operation is capital intensive and requires equipment such as a tractor, mower, rake, baler, and bale transporter. Other costs include labor and fuel. The large fixed cost component implies economies of scale if the harvesting equipment can be used over a larger acreage. Labor and fuel requirements for baling may also increase as tonnage increases (Jain et al. 2010; Thorsell et al. 2004).

3.3 Heterogeneity in Break-Even Costs Across Locations

The costs of producing miscanthus and switchgrass in the US are estimated by Jain et al. (2010) under two different scenarios: a low-cost and a high-cost scenario. The two scenarios differ in their assumptions about nutrient requirements, ease of establishment of the grasses, and harvest-related loss in yields. In each case, these

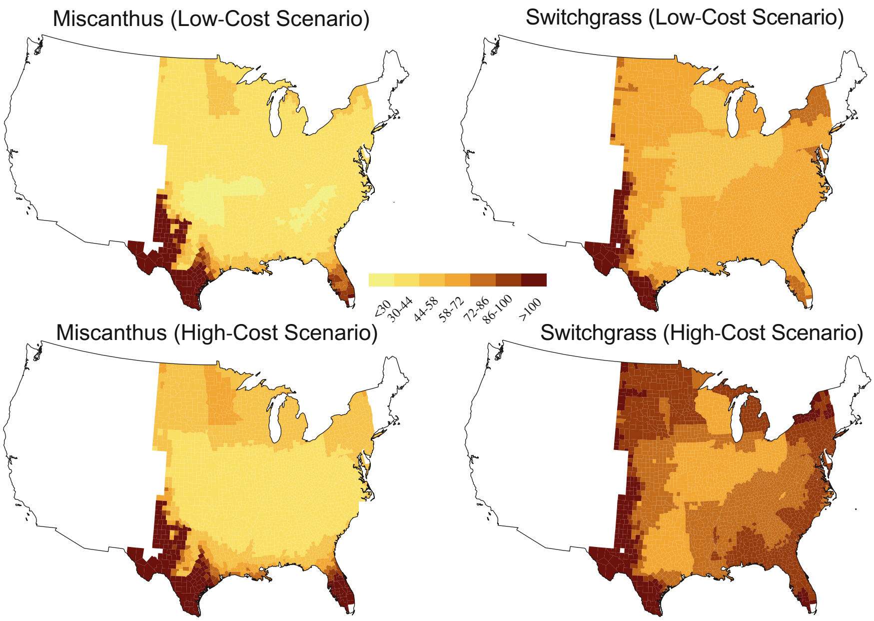

Fig. 3 Production costs of miscanthus and switchgrass ($/metric ton)

costs differ over the life of the crop and across space due to differences in yields, costs of field operations, input prices, and implicit opportunity cost of land. The costs of feedstocks vary across locations due to differences in yields per hectare and the cost of land across locations as shown in Figs. 3 and 4. In the low-cost scenario, the cost of miscanthus production ranges from under $40 per MT to over $100 per MT, while switchgrass is from under $50 to over $95 per MT. Under a low-cost scenario, miscanthus has a lower cost of production compared to switchgrass in most states, except in some southern and northern regions.

Figure 4 shows the costs of corn stover across different states for alternative rotation and tillage choices. In areas where corn–soybean rotations are the most profitable, the cost of corn stover is low if rotation corn is planted using no-till. Continuous corn with conventional tillage leads to the highest costs per ton of corn stover in most states.

The lowest average production costs of corn stover occurs under corn–soybean rotation and non-tillage practice, which is $44/DMT, while the highest occurs under corn–corn rotation and conventional tillage practice, which is $79/DMT. Figures 5 and 6 depict the relationship between production cost ($/DMT) and delivered yield (DMT/ha) for energy grasses and corn stover based on county-level cost and yield information, respectively, from which we can see that there is a clear trend that production cost decreases in yield. This implies that increasing yield can contribute to lowering the production cost of biomass.

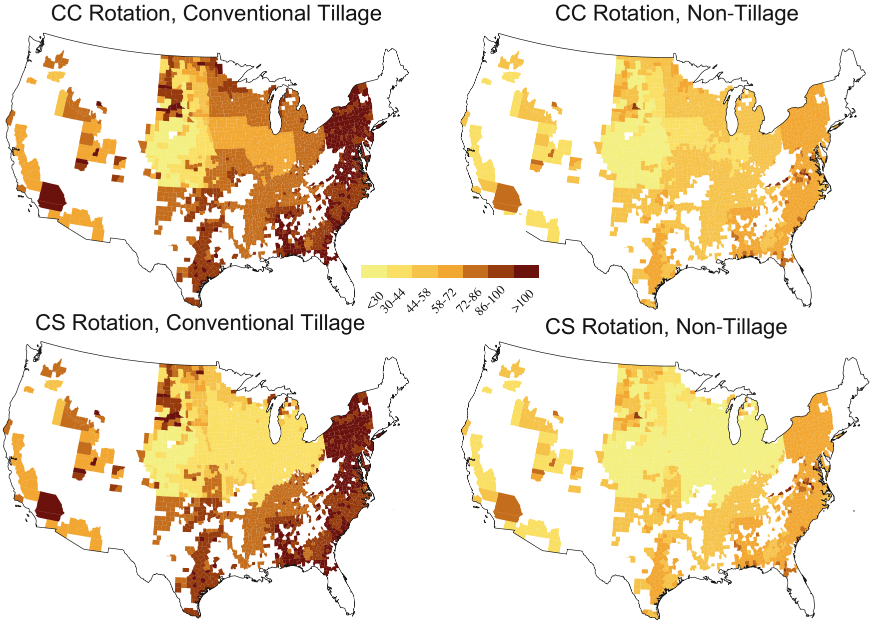

Fig. 4 Production costs of corn stover ($/metric ton)

Khanna et al. (2011) study the pattern of biomass production in the US if the price of biomass is $50/MT, assuming a relatively low cost of production of energy crops. Much of the corn stover will be produced in the Midwest and in the Plains. In contrast, of the total miscanthus produced, 38% is in the Plains, 27% in the Midwest, 20% in the Atlantic, and 14% in the Southern states. Switchgrass production occurs in the Southern Plains and in some northern states, while wheat straw production is mainly in the Northern Plains and the West. Their study shows that if switchgrass and crop residues production is under low-cost scenario while miscanthus production is under high-cost scenario, then there is no production of miscanthus at a price of $50/MT, instead switchgrass production will be viable primarily in the southern Plains and the southern Midwest. They also show that if corn stover collection rate is relatively high then stover production is more than twice as large as compared to otherwise and occurs primarily in the Midwest and the Plains. For studies regarding heterogeneity of energy crop production costs in Europe, we refer readers to Styles et al. (2008), Smeets et al. (2009), and Bocqueho and Jacquet (2010).

These results suggest that the least-cost feedstock for biomass will differ across locations and thus it is very likely that a mix of feedstocks will co-exist in the US and in the EU, but with regional specialization.

4 Drivers of Energy Crops Adoption: A Review

Drivers of a typical technology adoption apply in the case of energy crop adoption. As we have discussed in Sect. 2, drivers of technology adoption include technology characteristics, farmers' characteristics, risk, uncertainty, market conditions, and policy incentives. In this section we provide a survey of current literature on energy crop adoption from the perspective of these drivers.

4.1 Characteristics of Energy Crops

Agronomic Characteristics: The technical complexity of adoption, compatibility with current operations, ability to use existing farm equipment, length of the rotation period, need for specialized machinery, and impact on the landscape can play an important role in the decision to adopt energy crops (Paulrud and Laitila 2010; Villamil et al. 2008). Surveys of farmers in the US and in Sweden show that farmers are more likely to switch to an energy crop if existing machinery on the farm can be used for the new crop, if farmers are able to avoid scheduling conflicts between on-farm and off-farm activities, and if energy crops can be harvested during off-season for conventional crops. The longer the rotation period of the crop, the lower the willingness to grow such a crop because of the inflexibility it leads to in terms of farmer's ability to grow alternative crops on that land in the future. Many farmers are also reluctant to grow crops with a height of over 4 meters because high crops limit the view and change the aesthetical impression of the landscape (Hipple and Duffy 2002; Paulrud and Laitila 2010).

Environmental Effects: Biomass production has several environmental effects that depend on the specific feedstock. The harvesting of crop residues can reduce soil fertility and organic matter and contribute to an increased risk of soil erosion. Energy crops have the potential to sequester a large amount of soil carbon, reduce nitrogen leaching and runoff, and improve soil fertility. However, the production of energy crops like miscanthus and switchgrass, under rainfed conditions, can change the water balance of an area by changing evapotranspiration, runoff and percolation compared to the agricultural land that is replaced. This may have adverse hydrological impacts such as reduced aquifer recharge and stream flow that feed reservoirs, wetland, and other ecosystems. These grasses can also impact biodiversity, with several studies finding that ground flora diversity, diversity of soil microorganisms and soil fauna and number of mammals, birds, beetles, and spider species being larger in miscanthus and switchgrass fields as compared to annual crops (Smeets et al. 2009). On the other hand, there are concerns that large monocultures of these high-yielding grasses on land under native vegetation and mixed prairie grasses could reduce biodiversity. Smeets et al. (2009) consider 10–20% of a farm as being the optimal share of land to be allocated to energy crops given other demands for it and its environmental impacts.

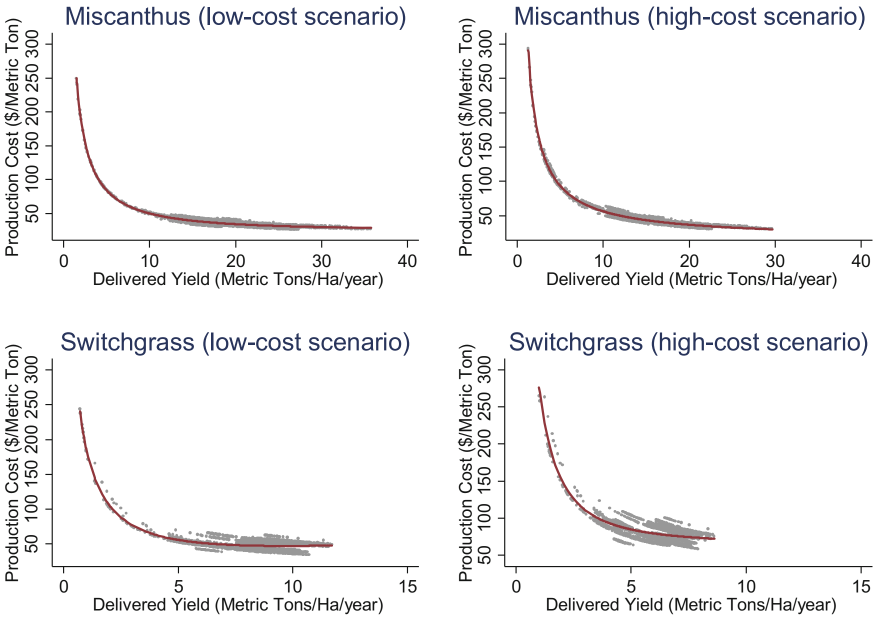

Fig. 5 Miscanthus and switchgrass: relationship between production cost and delivered yield

The environmental characteristics of biomass feedstocks relative to that of existing land use can lead to regulations that affect the ease of conversion of land to produce these feedstocks. The negative impact of crop residue harvesting has also led to recommendations for the share of residue that can be sustainably harvested. These regulations can influence the acreage devoted to biomass production. It is also possible that policies that provide payments for the ecosystem services provided by agriculture may be established; these would affect the profitability of energy crops and sustainable biomass production techniques that generate these services. The environmental benefits of energy crops could also motivate some farmers who believe in environmental stewardship to adopt them. Focus groups suggest that the reduced need for chemicals and pesticides as well as ability to reduce soil erosion, improve soil quality, and provide wildlife habitat can be expected to be important motivators for some farmers to adopt these crops (Hipple and Duffy 2002).

Complementary Technologies: The technology for producing energy crops is likely to consist of several components that need to be adopted together to establish the crop, such as seeds/rhizomes, fertilizers, and pesticides. These components may be sold individually or as a combined package. Studies show that farmers often prefer to adopt technologies sequentially, based on profitability and risk considerations. Byerlee and de Polanco (1986) found that not all farmers will adopt all

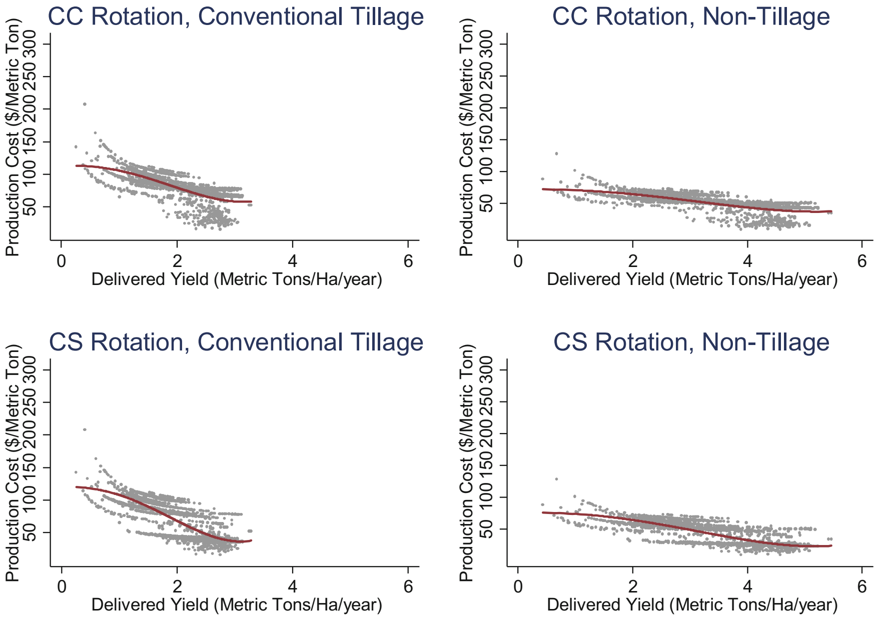

Fig. 6 Corn stover: relationship between production cost and delivered yield under different rotations and tillage practices

components of the package but some will adopt part of the technology package. Furthermore, components may be adopted sequentially, as farmers learn how to utilize them. In the presence of uncertainty, farmers may want to reduce the irreversible investments they need to make upfront and to adopt multiple components of the new technology gradually as new information about the benefits of those components becomes clearer. The ability to adopt technologies gradually or incrementally, thereby allowing for "trialability," increases the incentives for adoption (Hipple and Duffy 2002). Khanna et al. (2000) shows that the adoption of nitrogen soil testing and variable rate nitrogen application technologies did not always occur as a package. Farmers that adopted the more capital intensive variable rate application technology were larger farmers with more human capital and the potential for learning from soil tests.

Adoption of energy crops requires establishing new supply chains to store, transport, and process the biomass. It requires investment in infrastructure to support farms, storage facilities, and refineries, such as roads, railroads, water treatment facilities, and biomass storage facilities. Thus, new technologies often require the adoption of complementary technologies by others making adoption of technology a multi-faceted activity. This suggests that the introduction of new technology will be associated with multidimensional supply chains that provide not only the immediate component of the new technology, but also complementary assets as well as training to integrate the elements of the new technology effectively. Lack of availability of complementary technologies, in the case of bioenergy crops, the lack of secure, reliable, developed markets, and marketing assistance to link potential adopters with processing facilities, could limit adoption of new and untried energy crops.

Economics of Scale and Scope: The nature of the downstream technology for processing biomass will also influence the extent of adoption, the type of biomass feedstocks produced, and the location of production. More specifically, whether the biorefinery can achieve economies of scale and scope will determine whether there are many small firms or a few large firms in the supply chain and the types of feedstocks they can process.

Industrial technologies can exhibit decreasing returns to scale (marginal costs of production increase as production increases) or increasing returns to scale (marginal costs of production decrease as production increases). When technologies have decreasing returns to scale, industries consist of many small firms, but with increasing returns to scale, we may expect a small number of firms that can control the market (Arthur 1994). Biorefineries are likely to exhibit economies of scale since they involve large investments and the development of supporting infrastructure for biomass storage and transportation. There will be limits to scale, however, since large refineries will need to collect biomass from a larger distance. Thus refinery size will be determined by weighing the trade-offs between lower capital costs and higher feedstock transportation costs. The scale of the refinery will influence the demand for acreage under biomass production in that region. It will also influence the market structure that emerges. Industries characterized by decreasing returns to scale lead to competitive market outcomes while those characterized by increasing returns to scale favor monopolistic structures. This has implications for the pricing of biomass, the bargaining power between refineries and growers, and the type of contracts that emerge in this market.

The ability of biorefineries to process multiple feedstocks will affect the mix of feedstocks grown in a region. If a biorefinery's conversion process is limited to processing a single feedstock only, then that will determine the choice of feedstock in that region and the acreage dedicated to its production. If there are economies of scope, which allow refineries to process multiple feedstocks at a point in time or during different seasons, it will provide more flexibility to landowners to choose among feedstocks. With differences in harvesting schedules for different feedstocks, it will also reduce the length of time that biomass has to be stored and thus the costs of storage for landowners and refineries.

4.2 Farmers' Characteristics

Velandia et al. (2010) find that farmers in Tennessee generally had a positive attitude toward growing switchgrass. But they do not find a strong correlation between personal attitudes and intentions to continue growing switchgrass after their contracts had expired. However, perceived inability to successfully adopt the alternative practice (i.e., self-efficacy) and social pressures from important referent groups were major factors contributing to the inability of farmers to convert positive attitudes toward a practice into adoption behavior. In the case of switchgrass farmers in Tennessee, the opinions of the county extension agents and their family (and not the opinions of other farmers) that they continue growing switchgrass to diversify their farming operation were important in influencing their decisions to continue to grow switchgrass. This indicates that social pressure is an important determinant of the intention to continue to grow switchgrass. Neighbor's opinions about their farming operation were not found to be important by Villamil et al. (2008). Based on a survey on about 2000 Swedish farmers and choice experiment method, Paulrud and Laitila (2010) found that farmers account for energy crops' visual impact on landscape when considering the adoption of these crops. Also, they showed that farmers' attitude can affect the adoption decision regarding energy crops. Effect of social norms regarding visual appearance of the crop (orderly rows and weed free trials) and being considered to be an indicator of the success of a farmer could also constrain technology adoption.

Educating and involving community and extension personnel in private bioenergy feedstock initiatives may have a positive impact on farmers' decisions to make long-term commitments to grow dedicated energy crops, since family and extension personnel opinions seem to influence farmers' production decisions. Community perceptions about bioenergy crops and university extension support can have an important influence on farmers' intentions to make a long-term commitment to produce biomass feedstock. This suggests the need for social interest in innovations that provide societal benefits such as environmental benefits or national needs for bioenergy as a motivator of farmers' decisions about energy crops. Government policies alone may not be a sufficient to induce adoption; adoption of alternative farming systems that rely on government policies and programs can be negatively affected by skepticism and distrust of the government to provide appropriate incentives.

Focus group interviews suggest that personal beliefs about climate change and fossil fuel dependency affect attitudes toward energy crops and could motivate adoption in the future (Sherrington et al. 2008). According to Vanclay and Lawrence (1994) when environmental thinking enters the social infrastructure, mass adoption is likely irrespective of the disadvantages. The lack of supportive social infrastructure was the main reason for the failed development of a biomass electricity plant in the UK (Upreti and Horst 2004). Environmental justification at the national level may not be sufficient to convince local residents; promoting bioenergy requires interactive communication, public participation, and collective learning among stakeholders. Moreover, public concerns about the visual impact of energy crops, the potential invasiveness of some crops, and their impact on biodiversity could provide mixed messages about the environmental effects of energy crops from different organizations. Consistent information about the environmental benefits of energy crops based on sound research could increase social acceptability of these crops (Sherrington et al. 2008). Farmers who were practicing no-till and those with greater desire to provide wildlife habitat were more willing to convert land to switchgrass (Jensen et al. 2007). Adams et al. (2011) and Mattison and Norris (2007) find that farmers' view of biomass production as a contributor to climate change mitigation and reducing dependency on fossil fuels (which is a primary input in agricultural production) was a driver of energy crop adoption. Sherrington et al. (2008) found that beliefs about the benefits energy crops on the farmers' land are important determinants of the adoption decision.

A number of studies have examined the effects of demographic and socio-economic factors on adoption of energy crops and found mixed evidence. Sherrington et al. (2008) find that older farmers may be more likely to adopt energy crops because it enables them to maintain farm production while scaling back daily involvement; the potential to contract out the crop production process would make it attractive to this population of farmers. On the other hand, the survey of farmers in Illinois by Villamil et al. (2008) shows that potential adopters of miscanthus have less farming experience and farm more land than potential non-adopters. Jensen et al. (2007) also found that younger farmers with more education were more likely to grow switchgrass in Tennessee. But they found that smaller farmers were more likely to grow switchgrass, possibly because switchgrass could be grown on marginal acres and with low-input requirements. In contrast to these studies, Velandia et al. (2010) find that demographic characteristics (e.g., age, experience, percentage of income from farm activities, and number of acres in cropland) were not correlated with the intention to continue producing switchgrass in Tennessee after the current contract expires.

Surveys also show that famers had a larger share of leased land were less willing to convert hectares to switchgrass, possibly due to insecurity of land tenure (Jensen et al. 2007). Jensen et al. (2007) also shows that farmers do consider the opportunity cost of their land, equipment, and time when deciding whether or not to grow energy crops. Farmers with a higher percentage of income from off-farm sources were more likely to convert land to switchgrass, suggesting that off-farm income provides a way to offset income risks from a new crop. However, the new crop could also be a competitor for time, although the low-input requirements of switchgrass may reduce this concern. Farmers with a higher net return per hectare and those owning livestock and thus needing hay and pasture were less willing to convert land (because they had a higher opportunity cost of land). Farmers owning hay equipment and thus facing a lower cost of equipment were more willing to convert since the equipment can be readily adapted to harvesting switchgrass.

Larger farmers and farmers growing a larger number of crops (and thus in less need for diversification) were likely to convert fewer acres to switchgrass production. Farmers that are members of grower/commodity organization are also less likely to convert land to switchgrass production, possibly due to commitment to produce a particular commodity (Jensen et al. 2007).

In addition to the demographic characteristics of landowners, the decision to produce energy crops will strongly be influenced by the location of bioenergy processing facilities. Concerns about truck movements to transport biomass, pollution and nuisance, odor, and emissions from the plant could lead to opposition to site such facilities in an area that might otherwise be well suited to produce biomass (Upham and Shackley 2007). Similarly, Upreti (2004) finds that public opposition to locating biomass energy plants in a community is a key obstacle to promoting biomass energy. Even though local communities may value the environmental benefits of bioenergy and bioenergy facilities to have fewer environmental impacts than plants that use fossil fuels, concerns about local impacts on ecology and landscape, perceived risks, mistrust of developers and of the government, and a not-in-my-backyard-attitude could prevent the implementation of bioenergy projects (Upreti and Horst 2004). The demographic characteristics of the community, the weight attached to economic development and employment, and the level of knowledge about the true risks and benefits of bioenergy production can affect willingness to allow the locating of bioenergy plants and this will affect decisions of landowners to grow bioenergy feedstocks. Jensen et al. (2007) found that landowners located in a county with a coal-fired plant were more likely to convert a larger acreage to switchgrass production. A survey of farmers in Missouri found that farmers located in the same county as a biomass pelletizing facility were significantly more likely to harvest biomass as compared to those located in distant counties (Freeh 2011).

4.3 Time, Risk, and Uncertainty

Since energy crops are typically perennials, a comparison of their profitability relative to annual crops depends on the rate of discount used by landowners to discount future returns and compare them to upfront costs of establishment. Khanna et al. (forthcoming) use a choice experiment to examine the effects of the risk and time preferences on energy crop contract choice of farmers in five states in the US. A high discount rate would create disincentives for foregoing current returns and incurring high costs of establishment in exchange for returns over a 15–20 year period. Principles of rational behavior would suggest that investors should evaluate alternative investments at a common discount rate, equated with the market rate of interest on standard financial instruments such as government bonds. However, potential investors might rationally demand higher rates of return compared to other investments if they consider energy crops to be a risky investment or to involve hidden transactions costs. The latter will depend on the institutional arrangements under which bioenergy crop production occurs and the ease with which producers can find markets for their product. High discount rates may also be used for decision making if farmers lack information about the costs and benefits of growing energy crops and the experience with these crops needed to make rational decisions. The length of the time horizon used by farmers when considering investment in an energy crop could also affect their estimate of returns (Ghadim and Panell 1999; Khanna et al., forthcoming). A longer time horizon to assess the benefits of energy crops and low discount rates will lead to higher estimates of the profitability of adoption than if farmers have a smaller time horizon and are more impatient about realizing the returns on their investment in establishing the crops. A longer planning horizon will also be more conducive to investment in learning about these crops and for developing the skills needed to adopt them. Khanna et al. (forthcoming) find that farmers with a high discount rate are less likely to grow an energy crop and will allocate less land to its production and that farmers prefer shorter contracts; however, the negative effect of contract length on the crop adoption decision is smaller for farmers with a higher discount rate because the discounted effect of the contract on future risks and returns becomes smaller.

Perennial crops have a lengthy establishment period before they begin to generate revenue. High upfront costs and negative revenue streams during the establishment phase have been identified by several studies in Europe as major barriers to adoption of energy crops (Paulrud and Laitila 2010; Sherrington et al. 2008; Sherrington and Moran 2010). These studies argue that uptake of energy crops will continue to be slow without a grant regime to support farmers during the initial years of production. Sherrington and Moran (2010) report that farmers prefer upfront support through establishment grants to contracts that guarantee income over the lifetime of the energy crop, even if the contract price for biomass is high. They propose addressing income stability concerns through insurance schemes or contracts that directly lead to smoothing of farmers' cash flow.

Liquidity constraints further bias preferences toward regular incomes over irregular incomes. Moreover, if the upfront investment in energy crops is very costly, it will be important to have sources of long-term finance and the capacity to obtain finance for investment. Programs that provide subsidized credit or access to cheap sources of credit are likely to increase the adoption of perennial crops or technologies that require long-term investment. Alternatively, contracts that smooth out the establishment costs of perennials and reduce liquidity constraints will increase the incentives to adopt energy crops. Analysis by Bocqueho and Jacquet (2010) examines the incentives to switch to miscanthus and switchgrass from annual crop rotation of wheat/barley/rape in the Eure-et-Loir region of France. They find that neither energy crop is profitable to produce, with or without liquidity constraints, unless all subsidies to wheat/barley/rape are eliminated. They find that the provision of loans is more effective in inducing production of energy crops than the fixed output price, given their assumptions about price risk for energy crops. Availability of loans is particularly important for miscanthus that has a much more irregular return profile than switchgrass.

In making decisions about allocating land for energy crops, farmers have to consider a number of risks, such as variability in yields due to weather or difficulties in establishing the crop, volatility in biomass prices because they are indexed to energy prices or due to fluctuations in supply and demand for biomass, lack of outlets to sell their crops, or the risk of shut down of the processing facility during the lifetime of the energy crop. They also have to compare among alternative risky choices, since the production of annual crops is also subject to a number of risks related to crop prices and yields. To the extent that the risks facing energy crops and annual crops are less correlated, farmers may choose to plant some of their land under energy crops as a diversification strategy.

Bocqueho and Jacquet (2010) simulate the effect of independent price risks for energy crops and annual crops and show that risk-averse farmers will find it profitable to grow miscanthus and switchgrass as a diversification strategy even though it was not profitable to grow them under perfect price certainty. These results depend strongly on the farmer's perceptions about the price volatility for different types of crops. Fixed price contracts can mitigate these risks. On the other hand, fixed price contracts can be undesirable if farmers perceive that the price of traditional crops would increase relative to energy crops. The high expected price of wheat in the UK was identified as a barrier to farmers' acceptance of fixed price contracts for bioenergy crops (Sherrington et al. 2008). When farmers face both price volatility and liquidity constraints, the type of contract that would be most effective in inducing adoption depends on their risk, time preferences, and inter-temporal preferences for income smoothing. Farmers are more likely to grow these crops if they have low discount rate, low rates of risk aversion, and are offered long-term contracts that share production and price risks with the processors.

Velandia et al. (2010) surveyed existing switchgrass farmers in Tennessee and found that over 80% of farmers believed that switchgrass production would help to stabilize farm income and also enable them to better allocate their resources during off-season time. About 75% of farmers believed that it was likely that switchgrass production would help them diversify their farming operations. In a survey of farmers in Tennessee, Jensen et al. (2007) found that farmers with a more diversified crop portfolio had a reduced need to diversify and thus were less willing to adopt an energy crop. Villamil et al. (2008 surveyed farmers in Illinois and found that 44% of the potential adopters of miscanthus were motivated by its potential to provide a supplementary source of farm income (not only from the biomass but also from possible carbon credits in the future) and 36% by its potential to diversify the crops they grow. Focus group discussion in the UK suggests that energy crop adoption was viewed as a diversification strategy rather than a replacement for primary crops (Sherrington et al. 2008).

While growers and scientists have accumulated immense knowledge of production and economics of traditional crops like wheat and rice, there remains significant uncertainty about the basics of the new bioenergy crops, including how to establish them, their input requirements, and suitable varieties. The production uncertainties are compounded by uncertainties about the technology and economics and the existence of a supply chain since many bioenergy processing technologies are in their infancy. Uncertainties about crop prices, energy prices, yield, biofuel technologies, and energy policies can create significant barriers to the adoption of energy crops, particularly since they involve long-term decisions.

Lack of personal experience and production data from other sources creates uncertainty about production costs and yields, which implies uncertainty about profits. Uncertainty in the market prices for energy crops and the workings of the bioenergy market in general have been identified as barriers to adoption of energy crops, especially for production outside of noncontractual arrangements

(Adams et al. 2011). Since energy crops are usually perennial crops, the long-term commitment also adds to the uncertainty of recovering upfront investments from future revenue streams. Concerns about flexibility, insufficient knowledge about production, and risks associated with the market were also expressed by farmers interviewed in Sweden, UK, and Italy (McCormick and Kåberger 2007).

Uncertainty can affect not only the choice of whether or not to adopt an energy crop but also when to adopt it.[2] Farmers may prefer to wait if they expect prices to increase or costs to decline in the future. Timing of adoption can be an important issue when considering technologies that involve a fixed investment upfront that can be used for a number of production periods, e.g., purchase of specialized new machinery for harvesting or baling energy crops. With uncertainty about prices, yields, and market demand, there is an option value associated with postponing the investment (Song et al. 2011). The timing of adoption of technologies with long economic life, like perennial crops which increase yield or save variable input costs, will depend on expectations about energy prices, costs of adoption, and energy policies in the future.

Farmer surveys indicate that farmers are taking a “wait and see” attitude toward switchgrass as an energy crop and they need more information on anticipated costs, equipment needs, market demand, as well as the profitability of energy crops relative to conventional crops (Hipple and Duffy 2002). Farmers indicated that they prefer to “test the waters” and commit a small percentage of their acreage to energy crops before making a larger commitment. Perceptions that returns to energy crops would increase in the future as the government increases incentives for growing energy crops to combat climate change could create incentives for some farmers to delay adoption. On the other hand, it could motivate some farmers to adopt at an early stage and be better placed to benefit later on (Sherrington et al. 2008). Thus, the timing of adoption of energy crops may vary across regions and farmers, depending on their costs of adoption, the biomass price in their region, their discount rates, and expectations about the future.

Increased complexity of farming and lack of adequate information, guidance, role models, and training were stated as a disincentive for adoption by survey respondents in Iowa (Hipple and Duffy 2002). Based on case studies in six countries in Europe, McCormick and Kåberger (2007) identified knowledge, skills, and institutional capacity as barriers to energy crop adoption. In Gubin, Poland, farmers expressed a need for more demonstration projects for energy crops. Pilot projects in

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[2] McWilliams and Zilberman (1996) analyzed the timing of adoption of a technology (computers) whose price declines over time. They found that larger firms, with more educated entrepreneurs and more complex businesses, are likely to be early adopters of computers while firms that do not have the sufficient scale or human capital tend to wait and make lower investment. Khanna et al. (2000) find that adoption of site-specific crop management technologies (precision farming) is likely to occur first on farms with high soil quality and high variability in soil fertility and quality. This is because the profit differential is sufficiently high on such farms and it is able to offset the disincentives to adoption due to price uncertainty and investment irreversibility.

Murek, Austria and Enkoping, Sweden were found to be important in building capacity and increasing knowledge about processes.

Villamil et al. (2008) find significant variability in preferences for the preferred channels for information about energy crops. Over 65% of respondents in Illinois identified farm/agricultural organizations, agricultural newsletters, other farmers and neighbors, the Internet, and newspapers as the top five information channels. There were also significant differences in the type of information about energy crops that farmers in different regions in Illinois were seeking. In some regions there was greater demand for information on the agronomy and markets for energy crops while in others there was greater interest in information about the possibility of reducing input use and the environmental services that miscanthus could provide. A survey of biomass producers in Missouri shows that farmers were more likely to harvest biomass for sale if they had a neighbor who was also growing them (Freeh 2011).

4.4 Market Conditions and Policy Incentives

The price of biomass is likely to be influenced by several elements: its energy content relative to the fossil fuel it will displace, the cost of processing and converting it to a final product, the price of substitute fossil fuels, market power that would allow supplier to charge a price above the marginal cost of production, and policy incentives. Policies differ in the incentives they provide; some policies such as mandates for the share of renewable energy in fossil energy increase demand for biomass and create a willingness to pay a higher price for the biomass than its energy equivalent value. Other policies can lower the cost of producing biomass and reduce the cost of uncertainty about future returns.

Renewable fuel or renewable electricity mandates create an incentive to produce bioenergy beyond the level that a competitive market would support. The difference between the energy equivalent value of biomass and its marginal cost of production is implicitly met by energy providers (oil blenders or electric utilities) who need to comply with the mandate. This additional value will partly cover the additional costs of biomass processing facilities and the remaining will be transferred to biomass producers and ultimately to the landowners. This is because the additional demand for biomass leads biomass producers to bid up the price of land. By increasing competition for cropland, it increases the price of cropland and crop prices; by increasing the demand for idle/marginal land that is suitable for some energy crops, it raises the returns to that land. The provision of tax credits or subsidies for blending biofuels with gasoline or for generating electricity from renewable sources will not lead to an increase in biofuel production if the mandate is binding; it would simply lower the price of energy for consumers. If, on the other hand, the mandate is not enforced then the subsidy for using bioenergy could lead to the mandate being exceeded and it would contribute to an increase in demand and additional willingness to pay for biomass.

Policies that seek to promote biofuels by rewarding them for their lower GHG intensity such as a carbon tax or a low-carbon fuel standard (LCFS) differ in the mechanisms through which it creates incentives to blend biofuels with liquid fossil fuels. A carbon tax would make fossil energy more expensive compared to bioenergy and therefore lower the price differential between the two. It will create incentive to produce feedstocks that are both low-cost and low-carbon intensive. Given the current high costs of producing cellulosic biofuels, the analysis by Chen et al. (2011) shows that very high carbon prices (over \$100 per ton of CO_2) would be needed to induce the production of cellulosic feedstocks. On the other hand, the use of bioenergy for co-firing with electricity could be induced even at relatively low carbon prices (Khanna et al. 2011).

Production subsidies that are provided per ton of biomass supplied or per unit of land on which biomass is produced directly benefit producers and lower their opportunity costs of production. It might also increase the willingness of biomass producers to supply biomass at a price somewhat lower than the cost of production, thus benefiting processors and consumers as well. Establishment cost share subsidies not only reduce the opportunity cost of switching land use but also help to smooth the income stream from energy crops. This is particularly the case when these cost share subsidies are accompanied by annual payments that cover the foregone returns from the land during the establishment phase. These production subsidies and establishment cost share subsidies also help overcome the “chicken and egg” dilemma facing biomass producers and processors. Farmers have limited incentives to invest in energy crops without the certainty of demand from potential users; and processors are reluctant to invest in the technologies needed to develop these markets if feedstock supply is limited and uncertain. These subsidies are also likely to change the mix of feedstocks that is economically viable: subsidies provided per ton of feedstock or per liter of biofuel create incentives to produce relatively higher yielding feedstocks and to switch away from lower yielding feedstocks. Subsidies to share a portion of the establishment costs will favor energy crops with high establishment costs.

Khanna et al. (2011) examine the land use effects of various biofuel and climate policies and find that the mix of policies will affect the pattern of land use for crop residues and for energy crops. They show that under the biofuel mandate in the US, corn stover would be produced mainly in the Plain States (Kansas, Nebraska, North Dakota, and South Dakota) in 2022, while 80% of wheat straw acreage is collected in the Western States (including Arizona, California, Idaho, Oregon, and Utah). About half of the switchgrass acreage in 2022 is in Texas and 15% is in Missouri. Miscanthus is more competitive than switchgrass in terms of break-even costs of production, and its production is fairly concentrated in the Great Plains (Oklahoma), in the Midwest, and along lower reaches of the Mississippi river. The provision of biofuel subsidies like the volumetric tax credit and the Biomass Crop Assistance Program (BCAP) significantly expands the acreage under the high-yielding crop miscanthus and reduces acreage under lower yielding switchgrass and crop residues. This is because miscanthus and switchgrass compete for marginal land in the same locations and the BCAP increases the relative profitability of miscanthus. As shown in Khanna et al. (2011), switchgrass production is profitable in Texas, Louisiana, Florida, and Georgia and parts of Wisconsin and North Dakota. Corn stover is collected in Nebraska while the production of wheat straw occurs in Oregon. Moreover, the BCAP also makes the production of switchgrass and miscanthus viable earlier than under the RFS alone.

5 Conclusions

The review suggests that several factors are likely to be important in influencing a landowner's decision to grow energy crops. First is the profitability of growing these crops as compared to other land uses determined by crop yield, energy crop production costs, and existing policy support. Locations where the yield of energy crops is high and where productivity of conventional crops is low are likely to be the first to be used for energy crop production. Heterogeneity in yields and costs of land across locations and across bioenergy crops will lead to a mix of feedstocks being produced in a region.

The production of energy crops is subject to numerous risks and uncertainties which will delay energy crop adoption unless the gain in profits is large enough to provide a risk premium that compensates farmers for the additional variability in their income and an option value premium that offsets incentives to wait for more information and favorable market conditions. Diversification strategies may increase adoption of energy crops even absent increased profit. Crop insurance, long-term contracts, and policies that assure long-term support for bioenergy crops can reduce risks. Additionally, uncertainty about markets and technologies for using bioenergy encourages farmers to take a "wait and see" attitude toward energy crops. The lack of knowledge and variability of outcome increase the perceived risk of potential adopters, which implies a critical role for inducing learning among farmers and diffusion of information through extension services, demonstration projects, and social networks.

There is growing evidence that adoption choices depend not only on monetary benefits but also on non-pecuniary benefits as well. Beliefs about the societal benefits of energy crops and social pressures are likely to be important determinants of the adoption decision. Educating and involving community and extension personnel in private bioenergy feedstock initiatives may have a positive impact on farmers' decisions to make long-term commitments to grow dedicated energy crops. Environmental justification at the national level may not be sufficient to convince local residents; promoting bioenergy requires interactive communication, public participation, and collective learning among stakeholders. Moreover, public concerns about the visual impact of energy crops, the potential invasiveness of some crops, and their impact on biodiversity could provide mixed messages about the environmental effects of energy crops from different organizations and reduce incentives to adopt.

Some of these noneconomic factors may be related to the socio-demographic characteristics of farmers (e.g., age, ownership of land, nonfarm income, and hay equipment ownership). The decision to produce energy crops will strongly be influenced by the location of bioenergy processing facilities, where the attitude and public opinion of the community will play a key role. Furthermore, the agronomic characteristics of energy crops, their compatibility with conventional agriculture, and the environmental benefits of energy crops could also influence farmer decisions. The technology for producing energy crops is likely to consist of several components that need to be adopted together to establish the crop, and to store, transport, and process the biomass. This requires investment in infrastructure, supply chains, and market development to support energy crop production by farmers.

In sum, our review highlights the need for more in-depth studies that examine the complexities of the adoption decisions arising from the presence of risk, uncertainty, attitudes, and perceptions, in addition to technical and agronomic research and benefit–cost analysis. It also emphasizes the importance of facilitating societal learning about the costs and benefits of energy crops to promote their social acceptability. Finally, it identifies an important line for future research on the design of the supply chain and contractual arrangements that will actually induce adoption that can be investigated through surveys, experimental studies, and investigation of arrangements in related markets such as those for sugarcane in Brazil.

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Effects of Liquidity Constraints, Risk and Related Time Effects on the Adoption of Perennial Energy Crops

Géraldine Bocquého

Abstract This chapter highlights the crucial role of liquidity, risk, and related time effects in explaining farmers' willingness to grow perennial energy crops as a renewable energy source. I first review the scarce empirical evidence from surveys and focus groups about how liquidity constraints hinder adoption, and present additional results from simulation approaches based on optimization models. Then, I evaluate the extent to which perennial energy crops can be considered as a risky enterprise, and emphasize the importance of assessing risks at farm level to uncover potential diversification benefits. I also show how time considerations generate further related issues, due to intertemporal fluctuations in the income stream, investment irreversibility, and land reallocation. This chapter also highlights relevant policy and contract schemes to overcome the barriers to adoption described above. Establishment grants and cash advance systems are widespread and efficient ways of limiting liquidity effects on adoption as long as moral hazards are managed and conversion back to conventional crops is discouraged. Risk barriers are mostly managed through private long-term production contracts between farmers and biomass processors.

Keywords Agricultural innovation · Herbaceous energy crops · Advanced biofuels · Farmers' behavior · Land allocation choices

JEL Codes Q16 · Q12 · D81

1 Introduction

In 2009, through the Renewable Energy Directive, the European Union adopted ambitious mandatory targets of 10% of transport fuels from renewable sources by 2020 in each Member State. However, in subsequent years, biofuels became

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G. Bocquého (✉)
LEF, AgroParisTech, INRA, Nancy 54000, France
e-mail: geraldine.bocqueho@inra.fr

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increasingly controversial. Indeed, those derived from the sugar and oil contained in food crops like corn and rapeseed can result in worse greenhouse gas performance than the fossil fuel they replace (Crutzen et al. 2008). They can also engender conversion of areas of high carbon and biodiversity value such as forests and peatlands (Searchinger et al. 2008; Fargione et al. 2008; Melillo et al. 2009) and drive up food prices (Zilberman et al. 2013). After much debate, the European Union finally reached an agreement in June 2014 on the amendment of the Renewable Energy Directive. The new iLUC Directive reduces the indirect land-use change impacts of biofuels by limiting the way Member States can meet the 10% target of renewables in transport fuel by 2020. In particular, it sets a cap of 7% on the contribution of food-based biofuels. The remaining 3% is expected to be mostly fulfilled by the so-called second-generation biofuels. These advanced biofuels are derived from nonfood feedstock, including agricultural and forest residues like straw and manure, organic waste like urban organic waste and sewage sludge, by-products of the wood industry like sawdust and black liquor, as well as dedicated feedstock sources such as woody and lignocellulosic crops.

However, second-generation biofuel technologies face major technical and economic obstacles (see Carriquiry et al. 2011 for a review). The main concern is the cost and the efficiency of the cellulose transformation process, a recent and sophisticated technology. The second concern is the availability of a sustainable feedstock at a competitive price, for which transportation and storage costs are critical because of the low energy density of cellulosic biomass. Among the potential feedstock sources, residues, waste, and by-products have an advantage over dedicated sources because they do not create an additional demand for land. But they are often geographically scattered and/or difficult to access, and some of them are already used for nonenergy purposes. Achieving important volumes in a short time period would then require the use of dedicated energy crops. Even if they do compete with food crops and forest areas for land (e.g., Lange 2011; Havlík et al. 2011), they yield more energy per hectare than traditional energy crops, need few chemical inputs, are labor extensive, and can adapt to low-quality soils. Furthermore, perennial species such as switchgrass, miscanthus, and fast-growing tree species—e.g., poplar, willow, eucalyptus—develop extended root systems and cover the ground in winter, which offers several environmental benefits: carbon sequestration (Hansen et al. 2004; Brandão et al. 2011), soil conservation (Kahle et al. 2001), and wildlife habitat (Bellamy et al. 2009; Semere and Slater 2007).

The crucial question of farmers' willingness to produce biomass at a reasonable price for the biofuel industry is more complex for perennial crops than for food and annual crops. First, growing perennial energy crops is an innovative activity for farmers as cellulosic biomass is a new product, perennial species require new production methods, and farmers are unfamiliar with the energy market. As a result, farmers lack knowledge and face uncertainty about the crop profitability. Furthermore, the cellulosic energy market is only emerging and mostly local, meaning that few opportunities exist and that market risk is particularly high. Second, perennial energy crops exhibit important up-front costs for plantation, while yields reach their maximum potential after 2 years at best, implying that a return on the investment takes several years. This feature has several consequences. Financial resources need to be available to cover the establishment period and are tied up for several years. Thus, farmers who face liquidity constraints may be particularly unwilling to adopt perennial energy crops. Moreover, there is additional uncertainty with respect to crop profitability because the varying economic and legislative context makes future incomes and opportunity costs difficult to estimate. The crop life span is often more than 10 years depending on the species. In addition locking up land and financial capital in a long-term project reduces farmers' flexibility: switching to another activity because of disappointing results or better alternatives is unlikely to be profitable as long as up-front sunk costs are not recovered. This inability to review decisions in light of new information, or at a high cost, reduces the expected profitability of investing into perennial energy crops. Third, the amount at risk in case of a production or market accident is significant, especially in the first years, which is also when accidents are more likely to happen. It increases farmers' risk exposure and the probability of incurring a high loss, and thus further decreases expected profitability.

The challenges posed by novelty and delayed returns, and describe above, explain that liquidity constraints and risk appear to be critical barriers to farmers' willingness to grow perennial energy crops. In this chapter, I summarize the main findings on the relationship between liquidity constraints, risk, related time effects and adoption of perennial energy. David's (1969) threshold model is the first theoretical framework with a focus on the individual decision-making process and how farmers' heterogeneity can explain contrasted adoption decisions. In particular, the threshold model can accommodate individual drivers such as farmers' resource constraints and preferences.[1]

In Sect. 2, I investigate the relationship between liquidity constraints and adoption while in Sect. 3 I focus on risk issues. In Sect. 4, I show how time considerations generate further related issues, due to fluctuations in the income stream, investment irreversibility, and land reallocation. I discuss in Sect. 5 relevant policy and contract options to relax liquidity constraints and overcome risk barriers. Sect. 6 concludes.

2 Liquidity Constraints

The life cycle of perennial energy crops includes an initial establishment period—at a minimum two years for switchgrass and miscanthus, up to 10 years for woody crops—that produces very little yield, while planting costs are very important, for instance in the case of miscanthus and woody crops. The planting material is the main cost item but farmers also resort to expensive machinery or contracting

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[1] See Sect. 2.1 of Chap. "Innovation in agriculture…" for a review of theories on technology adoption.

services because planting efficiently miscanthus rhizomes and wood stem cuttings demands specific equipment. If the area planted is small, as it is often the case for trial plots, individual farmers are unable to take advantage of scale economies. Planting costs of switchgrass are much lower because it reproduces by seeds.[2] Other establishment costs include preparing the ground during the first year, applying potential herbicides and fertilizers, and cutting back the growing plants in the case of woody crops. Thus, farmers who face liquidity constraints may be particularly reluctant to grow perennial energy crops. In this section, I review the scarce empirical evidence from surveys and focus groups, and then present additional results from simulation approaches based on optimization models.

2.1 Empirical Evidence

The link between technology adoption and liquidity problems has been mostly studied in developing countries where the majority of farmers have a limited access to credit and/or capital markets do not operate efficiently. However, farmers from developed countries are also exposed to credit constraints and rationing. For instance, Blancard et al. (2006) showed that two-thirds of their sample of French farmers were credit constrained in the long run. As highlighted by Barry and Robison (2001), the farm sector experiences chronic liquidity problems and cash flow pressures due to relatively low, but volatile, rates of return on farm assets and lengthy production periods. It is a special challenge for financial markets because it reduces farmers' debt servicing capacity and creditworthiness. Other challenges include the geographical dispersion and small size of farms, leading to loans with high interest rates to offset large servicing costs, and the availability of a reliable financial information, making the assessment of borrowers' creditworthiness more difficult than in other economic sectors. Furthermore, the strong reliance on reputation, personal familiarity, and social closeness which typically characterizes the relationship between agricultural borrowers and their lenders is mostly relevant for local funding, while such funding is in general scarce (Barry and Robison 2001).

Obtaining a credit to plant perennial energy crops may be even more difficult because of uncertain rates of return and delayed payoffs. In addition, lenders are likely to be especially concerned about adverse selection problems because they do not have access to farmers' information channels.

Even if establishment costs have been repeatedly cited as a barrier to the adoption of perennial energy crops (e.g., Sherrington et al. 2008; Mola-Yudego and Pelkonen 2008; Jensen et al. 2011a), providing a quantitative estimate of the relationship between adoption and liquidity constraints per se is not straightforward. Farmers' situation as regards liquidity constraints is indeed difficult to measure in

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[2] The large up-front costs of miscanthus are offset by a high productivity compared to switchgrass (Heaton et al. 2008; Smeets et al. 2009; Boehmel et al. 2008).

the field, which calls for the use of proxies. The amount of credit that a farmer can borrow depends on a mixture of individual characteristics, such as reputation, farm profits—ability to repay the loan—and value of the assets pledged as collateral—security for the loan—(Ciaian and Swinnen 2009). In developing countries, due to the lack of reliable information, land is generally used as collateral (Feder 1980; Binswanger and Sillers 1983). In developed countries, collaterals are more diversified, and may include other assets such as grain stored, herd size, and nonfarm assets. Thus, liquidity-constrained farmers are likely to have smaller farms, a lower income or wealth, and a higher debt level than non-constrained farmers. Another reason for small farms to be more liquidity constrained is the proportionally larger transaction costs of small loans. These costs are charged by the lender to the borrower through a fixed fee or an increased interest rate (Binswanger and Sillers 1983).

In addition to identifying relevant proxies, the search for empirical evidence comes across two further problems in the case of perennial energy crops. First, in many countries perennial energy crops have been planted for commercial purposes only very recently, meaning that these countries are only in the early phase of the diffusion process. At this stage, farmers usually implement new crops as small-scale trials to gain information about crop performance, and only afterwards decide whether to switch to full-scale adoption (Abadi Ghadim and Pannell 1999). Thus, the value of the investment to grow a few hectares is kept within reasonable limits, and liquidity shortage may not be as critical as in a further stage. In other words, credit constraints may not be binding at this early adoption phase.

Empirical studies led in areas where perennial energy crops are already produced on a large scale come across the second problem. The longer the experience with the new crop, the more confident the lender, and the less stringent the credit conditions. In addition, in those areas, the large adoption was generally made possible through important grants covering part or all of the up-front costs and/or improved credit conditions. It is typically the case in the United Kingdom (Sherrington et al. 2008) and Sweden (Helby et al. 2006). However, these experiences do advocate for the importance of relaxing liquidity constraints to enhance adoption. As reported by Sherrington et al. (2008) from a focus group: Very few farmers said they would consider growing energy crops without the establishment grant.

These two ways of circumventing liquidity constraints partly explain why most authors have failed to measure in the field any effect on the decision to adopt perennial energy crops. For instance, Jensen et al. (2007) was unable to show a significant relationship between Tennessee farmers' indebtedness and willingness to grow switchgrass. Likewise, in Breen et al. (2009), the effect of either farm income or farm solvency on Irish farmers' interest in producing energy crops is non significant. As regards the off-farm income proxy, it was found to have no significant effect on switchgrass adoption in Tennessee (Jensen et al. 2007). Qualls et al. (2012) did show a negative effect on willingness to produce switchgrass in the southeastern United States, but only for the lowest level of off-farm income. There is much more evidence in favor of a positive farm size effect (Rämö et al. 2009;

Roos et al. 2000; Villamil et al. 2008; Breen et al. 2009; Rosenqvist et al. 2000), but farm size is a surrogate for a large number of other factors such as capacity to bear risks, wealth, access to information (Feder et al. 1985). This proxy is thus sensitive to confounding effects, and cannot alone justify clear-cut conclusions about the liquidity effect.

2.2 Simulation Approaches

Alternatively, the effect of liquidity constraints on adoption at farm level can be assessed through simulation approaches with mathematical programming models. Contrary to econometric models, those models articulate the objectives and constraints of representative farmers and calculate an optimal solution for the use of resources under the assumption of complete rationality. The most straightforward method to account for cash flow problems is to define explicit financing constraints which express the trade-off the farmer's household faces between borrowing, investing and consuming. Typically, an *investment constraint* defines the financing options at each time period, either external credit or self-funding:

$$I \leq B + M,$$

where I is the amount invested, B the amount borrowed, and M the cash available. The amount borrowed is constrained by the farmer's exogenous borrowing capacity K in a *credit constraint*:

$$B \leq K.$$

A *cash balance* expresses the cash available to the farmer for self-funding as a function of total income R, total savings S and expenses for production E, for consumption C and for debt service D:

$$R = M + S + E + C + D.$$

In addition, a dynamic framework enables cash transfers between time periods.

Ridier (2012) provided an example with a multi-period model aiming at assessing the potential farm level supply of short rotation woody crops in south-western France. The farmer is assumed to maximize the discounted sum of the expected utility of household consumption per period, plus the expected utility of net wealth at the end of the planning horizon. This objective function is subject to technical, institutional and financing constraints. Under the assumption of no risk and an area subsidy of 260 €/ha, Ridier (2012) showed that a wheat and sunflower farmer is willing to convert 39% of his or her land to short rotation willow—the total farm area is 35 ha. This is made possible by an important borrowing capacity

—100,000 €—which allows the farmer to cover establishment costs ranging from 2000 to 3000 €/ha.

Another option is to apply like Lychnaras and Schneider (2011) a general technical constraint on land conversion. In this study, the potential supply of arundo,[3] miscanthus, switchgrass, and cardoon in central Greece is investigated through a multi-farm model. Based on a farm survey, the authors limit the share of energy crops per farm to 50%—the mean farm size is 30 ha. This constraint accounts for liquidity problems, as well as several other farm-level barriers such as risk.

Other authors simply disregard barriers to adoption and investigate theoretical uptake. This is the case of Sherrington and Moran (2010) when investigating willow and miscanthus adoption in the United Kingdom. Their findings suggest that, at current prices, willow remains less competitive than conventional crops, whereas returns to miscanthus should have encouraged adoption on a wider scale than at present. As an explanation, the authors highlight the importance of barriers to adoption, including disruption to cash flow.

Other approaches account for liquidity constraints indirectly, for instance through decision-makers' aversion to intertemporal fluctuations—see Sect. 4.1.

3 Risk

Perennial energy crops are innovative species and the market for the biomass produced is mostly local and immature, which makes them particularly risky for farmers. In addition the lag between establishment costs and payoffs reduces farmers' flexibility in resource allocation and increases the amount at risk in the first years as compared with annual crops. There is abundant theoretical and empirical literature exploring the link between risk and technology adoption in general (e.g., Koundouri et al. 2006; Serra et al. 2008; Just and Zilberman 1983; Abadi Ghadim et al. 2005).[4] However, as highlighted by Feder et al. (1985) and Marra et al. (2003), few empirical studies have properly treated risk factors because these factors are difficult to observe and measure. The literature about adoption of perennial energy crops is no exception. In this section, I investigate the way risk interacts with the adoption process in a static framework. I first focus on the extent to which perennial energy crops can be considered as a risky enterprise, and then emphasize the importance of assessing risks at farm level to uncover potential diversification benefits.

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[3] Tall perennial cane suitable for the Mediterranean region.

[4] See section "Risk and uncertainty" of chapter "Innovation in Agriculture: Incentives for Adoption and Development of a Supply Chain for Energy Crops" for more details.

3.1 Risk at Plot Level

The main problem when analyzing risk issues relative to perennial energy crops is the lack of reliable agronomic and economic data to objectively identify probability distributions and measure farmers' risk exposure. An alternative is to rely on farmers' own perceptions, i.e., subjective measures of risk which depend on individual settings. Information quality and previous experience with innovations and/or perennials are some of the factors that are known to influence individual perceptions. Unfortunately, they are difficult to control, which threatens the external validity of measures based on such proxies. However, risk perceptions have the advantage of directly underlying the decision-making process, and thus the potential to better explain adoption heterogeneity.

Focus groups are common methods to capture farmers' opinion in a qualitative way. Sherrington et al. (2008) showed with this method the importance of tackling risk issues to further enhance adoption of willow and miscanthus in the United Kingdom. More particularly, the authors highlighted farmers' uncertainty about financial returns, market opportunities, and cost of returning land to alternative production. Villamil et al. (2008) studied specifically information needs and preferred information channels among potential miscanthus adopters in Illinois. They also tried to better qualify concerns over risk. Of the 26 focus group participants, 21 rate miscanthus production as a *moderate risk* enterprise and the rest of the participants as a *big risk* enterprise.

Attempts to provide quantitative measures of farmers' risk perceptions usually rely on Likert-type survey questions. For instance, Jensen et al. (2007) asked to 1259 Tennessee farmers to indicate the extent to which they agree with a number of statements regarding the production and marketing of switchgrass, including:

> Production risk for switchgrass is lower than other crops or products I currently produce.

The scale they use is as follows: 1 = *strongly agree*, 2 = *disagree*, 3 = *no opinion*, 4 = *agree*, and 5 = *strongly agree*. The authors reported an inconclusive mean rating of 2.84 for the above statement. However, there is a significant difference at the 95% confidence level between the mean rating by those who are willing to grow switchgrass and those who are not willing. Surprisingly, willing farmers give a lower rate than unwilling farmers, meaning that they perceive switchgrass in a more negative way. However, the rating has no significant impact on the share of farmland potentially converted.

Bocquého (2012) investigated more thoroughly the topic by distinguishing 16 different types of risk French farmers may face, and compared the relative scores of miscanthus and wheat. The sample is composed of farmers who have actually decided to grow miscanthus and farmers who have taken the opposite decision. Farmers are asked to account for total risk exposure, i.e., both the likelihood of the given risk item and the ensuing income variation. In addition, they are told to consider their own production environment. In most cases, farmers have benefited from establishment grants and long-term contracts that provide a fixed price, a cash advance and technical assistance (see Sect. 5). The results are summarized in Table 1. From the first column it can be seen that, on average, all miscanthus risks are perceived at maximum as *moderately important*. Most important risks relate to market opportunities, plot value after miscanthus removal, and changes in the relationship with the land lessor. Uncertainty of biomass price and a potential failure of the contract counterparty are also important concerns to farmers. The fourth column indicates that miscanthus is viewed as significantly more risky than

Table 1 Risks of growing miscanthus as perceived by French farmers—adapted from Bocquého (2012)

	Mean	SD	Obs.	Mean score difference miscanthus-wheat	Mean score difference adopters-non-adopters
Production risk					
Disease	1.3	0.5	88	– ***	+
Pests	2.3	1.1	88	– **	–
Climatic accident	2.0	1.0	99	– ***	+
Weed	2.0	1.1	104	– ***	+ ***
Fire	2.2	1.3	102	+	–
Management or harvest	2.0	0.9	101	– ***	+ *
Plot choice	2.4	1.3	103	+ ***	–
Market risk					
Output price	2.6	1.6	91	– ***	– *
Market opportunities	3.1	1.5	99	+ ***	–
Economic risk					
Input price	1.9	1.1	100	– ***	– **
Labor costs	1.7	0.8	52	+	–
Credit costs	2.2	1.4	51	+	–
Plot value after removal	2.9	1.6	98	+ ***	– *
Institutional risk					
Relationship with land lessor	3.0	1.5	85	+ ***	– **
Environmental policies	1.8	1.1	102	– ***	–
Contract counterparty failure	2.6	1.4	102	+ ***	– *

The importance of each risk item is assessed in the context of farmers' production conditions on a 5-point scale: 1 = *not important at all,* 2 = *of little importance,* 3 = *moderately important,* 4 = *important,* 5 = *very important*. The statistics are adjusted for the stratified random sampling procedure

SD standard deviation *Obs.* Number of observations

*significant at the 10% level, **at the 5% level, ***at the 1% level wheat regarding most of these risks—market opportunities, final plot value, relationship with land lessor, counterparty failure—as well as plot choice. It means that miscanthus is viewed as more risky that wheat only for the risks that are miscanthus specific. On the contrary, most miscanthus production risks as well as input price risk are seen as rather low, both in absolute and relative values. The risk of changing environmental rules and output price risk are also perceived as low as compared with wheat. These last results are certainly explained by the grants and contracts offered to farmers, which are used as risk mitigation tools. The fifth column gives the sign of the relationship between perception of miscanthus risks and adoption decision. In general, the relationship is negative, meaning that farmers having adopted miscanthus perceive less risks than other farmers. It may be partly explained in the case of early adopters by the knowledge and skills they have gained *by doing* and *by using*.[5] However, one exception is weed risk that adopters perceive as significantly more important than non-adopters at the 1% level. This may reveal unexpected weed problems in the study area.

A more sophisticated approach to the estimation of risk perceptions is the direct elicitation of subjective probabilities from farmers. Grisley and Kellogg (1983) showed in an experiment that farmers from Northern Thailand are able to formulate probabilistic expectations about the outcome of risky events in crop production and marketing. In this study, the authors used Anderson et al.'s (1977) *visual counter* method:

> Each farmer was asked to reveal his beliefs about minimum and maximum values that each uncertain event (price, yield, and net income) could take at harvest time. This range was divided into five equal, discrete intervals and presented to the farmer on a sheet of paper. (…) He was then asked to distribute [25 coins] among the five intervals in accordance with the strength of his beliefs about their occurrence at harvest.

Applying a similar method to perennial energy crops with farmers and/or experts would be extremely valuable to improve our understanding of how risk influences the adoption process.

In general, in the studies that seek to measure risk perceptions, there is too little control on respondents' characteristics such as experience with the innovation, contractual arrangements, market environment, quality of technical assistance, type of land.[6] The type of land is of utmost importance in the case of perennials because their resistance to adverse growing conditions can make them relatively less risky—and profitable—compared to annual crops on low-quality land (Bocquého et al. 2015).

The way risk impacts decision-making not only depends on agents' exposure to risk, but also on how they respond to risk, in accordance with their individual preferences. A few recent studies showed that farmers from developed countries are

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[5] See section "Risk and uncertainty" of chapter "Innovation in Agriculture: Incentives for Adoption and Development of a Supply Chain for Energy Crops" for more details about the role of information acquisition and experience in reducing uncertainty.

[6] See Hardaker and Gudbrand (2010) for a review of challenges in eliciting probability expectations.

mostly risk averse but exhibit heterogeneous preferences (e.g., Bocquého et al. 2014; Reynaud and Couture 2012; Serra et al. 2008; Herberich and List 2012; Menapace et al. 2012). Several demographic and socioeconomic characteristics are known to influence risk aversion, including age, education level, farm size and off-farm income. This heterogeneity can explain part of the differences in the adoption decision. In the absence of any specific risk mitigation tool, and as explained in Sect. 1, perennial energy crops tend to be more risky than competing crops, which implies that more risk-averse farmers are expected to be more reluctant to grow these crops.

3.2 Risk at Farm Level and Diversification Effect

In reality, farmers care more about total farm income and total farm risk than about income and risk of each farm activity in isolation. At this broader scale, the negative impact of risk on utility is weaker and the relationship between risk preferences and adoption may become ambiguous. Indeed, multiplying the number of activities is a well-known technique to manage risk at farm level. This behavior is formalized by the portfolio theory: under the mainstream assumption that decision makers maximize expected utility, in the overwhelming majority of cases, it is optimal to diversify portfolios so as to average probabilities and reduce overall risk exposure (Samuelson 1967). This behavior is also summarized in the popular recommendation *Don't put all your eggs in the same basket*.

The higher the initial farm risk and the lower the risk on a new crop, the stronger the diversification potential and the larger the crop uptake. In this context, risk aversion is expected to have a positive effect on adoption as long as the optimal diversification area is not reached. Furthermore, a low correlation between the initial and new sources of risk increases diversification benefits. It is typically the case with perennial energy crops. Indeed, production risks are induced by human errors—such as planting miscanthus rhizomes in flood-prone areas—rather than natural hazards, and the biomass energy market is partly disconnected from the food market.[7]

Jensen et al. (2007) provided empirical evidence of diversification as one of Tennessee farmers' motivation for growing switchgrass. They reported that the number of crops grown has a negative effect on the share of farmland converted. It means that the potential of switchgrass to further stabilize farm income is lower for farmers who already exhibit a diversified crop portfolio. Qualls et al. (2012) drew the same conclusion with data from southeastern United States. They tested the impact of the opinion variable *importance of switchgrass as an opportunity to diversify farming operation*. They found that its marginal effect on both the

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[7] Time series econometrics have shown that the linkage between fuel and food prices depends on location, the food and fuels considered, the modeling specification, and whether the data is daily, weekly, or monthly. See Zilberman et al. (2013) and Janda et al. (2012) for a review.

probability of interest and the share of farmland converted is rather strong and highly significant: a one-unit increase in the 5-point rating scale increases the probability of interest by 14% points, and the unconditional share of land by 4% points. Swedish farmers also mention in a series of focus group interviews the potential of energy crops for better risk management (Jonsson et al. 2011).

Bocquého and Jacquet (2010) assessed with a farm optimization model the extent to which the diversification effect can enhance adoption. Perennial energy crops are assumed to compete with cereals and risk to operate on prices only, prices having a similar volatility but being independent. The authors found with a net present value calculation that switchgrass and miscanthus are both less profitable than conventional crops in the French agronomic and economic conditions. However, the diversification effect makes perennial energy crops attractive for a risk-averse farmer: the optimal switchgrass acreage ranges from 24.6 to 34.5 ha—the farm size is 100 ha—and the optimal miscanthus acreage from 0 to 20.7 ha, depending on price volatility and farmers' risk aversion. These figures are valid under the assumption that other barriers to adoption such as liquidity constraints are tackled by governments or processors. Larson et al. (2008) also used a farm optimization model to quantify potential biomass supply in Northwest Tennessee. The authors showed that if biomass crops are priced annually based on the energy equivalent price, they do not enter into the optimal crop mix of the grain farm for any risk preference level, except the most risk-averse one. But in this case, only 36 acres of switchgrass out of 2400 are planted—i.e., around 14 ha out of 971.

4 Time Considerations

In previous sections, I analyzed the role that liquidity constraints and risk play in the adoption of perennial energy crops. Now, I focus on their interactions with time issues, in connection with the late return on investment. I show in a first part how intertemporal fluctuations in the income stream may act as a barrier to adoption. In a second part, I explain how investment irreversibility can encourage farmers to delay the adoption decision in order to get better information. In a third part, I consider farmers' option to convert land back to conventional crops before the end of the crop life span.

4.1 Intertemporal Fluctuations

A stream of income which fluctuates over time can proceed from two phenomena. The first one is uncertainty about future returns at the moment when the cropping decision is made. Even if the expected value of payoffs is assumed to be equal at each time period, it is unlikely that realized payoffs will be the same from one year to another. This is true for both annual and perennial crops. However, in the case of perennials, the planning horizon is much more than one year: the life span of switchgrass, miscanthus, and woody crops are respectively about 10 years, 15 years, and up to 25 years. Thus, some payoffs occur far in the future and are particularly uncertain due to market and/or policy hazards. In other words, the spectrum of possible returns farmers perceive when they assess the different crop options gets wider over time. On the contrary, in the case of annuals, it is likely that the width of the probability distribution they perceive is similar between time periods because the time lag between decision and payoffs never exceeds one year. As a result, fluctuations in the crop income stream may be particularly high in the case of perennials.[8]

The second phenomenon that creates intertemporal fluctuations is independent from risk issues. It is directly linked to the dynamics of the crop economic cycle which creates a long time lag between costs and benefits. The higher the costs compared to benefits, the more jagged the income stream. This is typically the case of miscanthus production, the costs of which are clumped together in the first year and payoffs spread over time on an annual basis as of the second or third year. This is also the case of woody crops, which are harvested every five to ten years. The income stream of switchgrass is more regular as plantation costs are relatively low and the establishment period relatively short.

Intertemporal fluctuations have two major kinds of consequences. The first one is an increase in overall risk exposure because of high potential losses. For instance, in the case of perennial energy crops, an establishment that fails or market opportunities that disappear are not unlikely, especially in the first years and when their diffusion is at an early stage. It has the potential to jeopardize farmers' capacity to make a return on investment and in the worst case to cancel all future benefits. In both situations, farmers are expected to incur a sizable loss because the investment in planting the crop is a large sunk cost.

The second consequence of an irregular income stream is the transmission of income variability to consumption when credit markets do not operate perfectly. But farmers and people in general dislike irregular consumption streams, a behavior also known as aversion to intertemporal fluctuations (Lence 2000; Frechette 2005). Very few authors have analyzed intertemporal fluctuations as a barrier to adoption of perennial energy crops. Bocquého and Jacquet (2010) and Ridier (2012) are two noteworthy exceptions. In Bocquého and Jacquet's (2010) farm model, farmers are assumed to have no access to credit to finance switchgrass and miscanthus plantations and their aversion to intertemporal fluctuations is captured by a concave utility function applied to each dated income flow. The authors found that, in the miscanthus baseline scenario, the positive diversification effect is completely outweighed by the negative effect of intertemporal fluctuations. As for the optimal switchgrass acreage, it drops from 32 to 1.2 ha—farm size is 100 ha.

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[8] If the perennial is a new crop, the experience the farmer gains over time can mitigate these increasing fluctuations.

Ridier (2012) used a similar modeling approach but households' saving and consumption decisions are explicitly represented, besides production decisions. Farmers' intertemporal preferences with respect to consumption fluctuations are captured by a concave function applied to each dated consumption flow. The results suggest that farmers choose the woody crop with the highest harvest frequency because it evens out incomes and improves farmers' ability to smooth out consumption.

4.2 Investment Irreversibility

As briefly mentioned in Sect. 3, acquisition of new information is key to understand the dynamics of the adoption process because it reduces farmers' uncertainty about the profitability of the new technology. The value of gaining additional information is particularly significant for innovations requiring a lump-sum sunk cost to start the production cycle, like perennial energy crops. Indeed, the asymmetry between a sure initial loss and uncertain future gains implies a high risk exposure. One strategy to reduce it is to wait until more information is available on future gains, and thus on investment profitability. By investing now, the farmer loses the option to collect more information and make a better decision later.

Real option methods (Dixit and Pindyck 1994) are one way of uncovering optimal decision rules in this setting. Song et al. (2011) developed a real option model to study farmers' willingness to grow switchgrass instead of corn and soybean in the north-central United States. The authors demonstrated that delaying land conversion has a significant option value even when a net present value threshold is passed. They estimated that, under the real option rule, returns from switchgrass have to exceed double the breakeven net present value before the crop is adopted.

If the innovation is divisible, another strategy is to go for partial adoption to trial the innovation at a low cost, and gain additional on–site information through learning. In a further step, farmers may switch to full adoption depending on trial outcomes. This strategy is well documented by Abadi Ghadim and Pannell (1999) and Abadi Ghadim et al. (2005) who applied a multistage decision model to the case of chickpeas in Western Australia.

4.3 Land Reallocation

Farmers' concerns over farm business flexibility when growing perennial energy crops were highlighted in a number of empirical studies (e.g., Sherrington et al. 2008). Indeed, perennial crops reduce farmers' flexibility in reallocating resources to other enterprises for two key reasons. First, as already mentioned in Sect. 4.2, the initial investment for establishing the plantation is irreversible, which means stopping current production does not allow the farmer to recover the financial capital invested. Second, recovering the land for conventional activities implies significant conversion costs. Miscanthus and switchgrass develop extensive root systems that require clearing by tillage and/or herbicides, while stools of woody energy crops must be removed with forestry mulchers. Drainage systems restored if necessary. Nevertheless, the option to revise the adoption decision is open if switching to another activity is perceived by farmers as marginally more profitable than pursuing with perennials. Although, generally speaking, technology disadoption has been scarcely investigated in the agricultural literature, a few authors have recently tried to develop models to investigate the decision to abandon perennial crops.

As the plantation gets older, farmers may revise their yield and return expectations and consider replanting the crop in a different place, with different methods, or at a different time period. They may also wish to switch back to conventional crops. Mosquera et al. (2013) built on the famous Faustmann (1849) model originally designed to determine the optimal rotation length of trees grown for timber. In their study, they investigate the optimal period to remove a palm oil standing. The interesting feature of Faustmann-like models is that they account for economic returns beyond the first rotation. As explained by Amacher et al. (2009), in the original Faustmann model the landowner is assumed to maximize land value, defined as the net present value of harvest profit over an infinite cycle of rotations, where harvesting and establishing a new stand is assumed to continue forever. They note that when land markets operate perfectly, the land value represents the market equilibrium price of bare forest land. The optimal rotation age is when the marginal return of delaying harvesting for one time unit—and getting larger trees—is just equal to the foregone interest based on the value of the stand and the land. This foregone interest is the opportunity cost associated with tying up capital in standing timber and land. Its first component is rent the landowner can capture by harvesting earlier and investing the resulting benefit at interest rate r for one period. Its second component is the land rent, i.e., the present value of investment returns lost by not beginning a new sequence of rotations on the land at the current period (Amacher et al. 2009).[9]

Mosquera et al. (2013) adapted the Faustmann model to palm trees by considering income from yearly sales of output—fruit—as opposed to selling all output—wood—in the final period. The authors found that the optimal rotation length is when the marginal benefit of waiting one more period to replant palm trees, i.e., the benefit from selling fruit in that period, is equal to the interest on the whole stream of profits plus the land rent which is the interest on the value of bare land. A similar

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[9] Amacher et al. (2009) gave a very good review of Faustmann models, including assumptions and properties. The authors also provide a comparison with alternatives such as the single-rotation model.

model could be built to determine the optimal rotation period of perennial energy crops when switching to another activity is not an option for the farmer.

In a second step, Mosquera et al. (2013) assumed a disease model where disease impacts the yield function and additional costs are supported due to adoption of control strategies. The disease model also differs from the disease-free model in that it starts when the disease is first detected and considers a scrap value instead of profits from perpetual rotations. At the end of the rotation farmers are allowed either to stop producing palm oil or to replant palm oil trees. The scrap value measures the value of land considering its highest valued use which may or may not include additional rotations. In this context, the grower's problem is to find an optimal level of control strategy to keep the number of diseased trees at an acceptable level, such that the net present value of the rotation is maximized. The authors showed with an optimal control approach that the opportunity cost of a one-period delay in cutting the stand corresponds to the sum of total costs for disease control and foregone interest from land value that is not received due to postponed removal of trees. Following Mosquera et al.'s (2013) example, the Faustmann rotation model could be adapted specifically to the case of perennial energy crops to investigate disadoption behavior. A scrap value function would accommodate all types of cropping decisions subsequent to stopping producing the energy crop.

Faustmann rotation models can also be combined to land allocation models, rotation length and land use being the choice variables. In the example suggested by Amacher et al. (2009), only two land-use forms compete, agriculture and forestry. However, land is of varying quality, and can be divided into a continuum of uniform parcels. The farmer must allocate this land in a way that maximizes the present value of returns from land. Solving this problem involves identifying optimal production in each parcel for both uses and then allocating parcels to the use that yields the higher return. This model can be adapted to the disadoption problem by allowing a land switch between the energy crop and another land use in a dynamic framework. Land quality would be a way to account for the ability of perennials to outperform annuals on marginal land.

Song et al. (2011) introduced stochastic revenue streams through real option methods in a model applied to switchgrass production in the north-central United States. The authors allowed for land conversion in two directions, i.e., a farmer who decides to convert to energy crops is allowed to take into consideration the future possibility of converting land back to traditional crops under plausible market conditions. However, flexibility in land use is submitted to sunk conversion costs—for crop plantation and crop removal. Song et al. (2011) found that, under their assumptions, the threshold return for converting from corn–soybean to switchgrass more than triples the threshold when two-way conversion is not allowed, which renders farmers' greater reluctance to adopt perennials when there is no possibility to switch back to conventional crops.

5 Policy and Contract Options

As outlined in the above sections, liquidity, risk and related time effects greatly influence the adoption process. For perennial energy crops to be grown on a long-term basis, liquidity constraints need to be relaxed, and expected income to compensate for extra income variations proceeding from extra risk and intertemporal fluctuations, for the option value of delaying adoption, and for the opportunity cost of using resources. As perennial energy crops appear to be less attractive than conventional annuals in most growing conditions,[10] a simple annual subsidy or price premium would have to be substantial. In this section, I review some other policy and contract options that may enhance production of cellulosic biomass in a more cost-effective way.[11]

5.1 Establishment Grants and Cash Advance Systems

Establishment grants are standard government interventions in favor of perennial energy crops. As highlighted in Sect. 2.1, they have backed the large-scale expansion of miscanthus in the United Kingdom and willow in Sweden, and were revealed as a necessary promotion tool in these two countries (Sherrington et al. 2008; Helby et al. 2006; Mola-Yudego and Pelkonen 2008).

In the United Kingdom, different grants have been implemented since the early 2000s. In England, farmers were offered £ 1000/ha for willow and £ 920/ha for miscanthus until 2006, and since 2007 establishment grants covering 50% of establishments costs. In Scotland, willow and poplar were eligible for payments of £ 1000/ha between 2005 and 2006, and in Northern Ireland a fund was established for willow between 2004 and 2006 with an average rate of assistance of £ 1920/ha (Sherrington et al. 2008). Since 2007, in both Scotland and Northern Ireland, farmers have been able to apply for grants covering 40% of establishments costs for short rotation willow or poplar, up to a maximum of £ 1000/ha. In Wales, a grant for willow has also been available to landowners, but at only £ 600/ha. This policy resulted in a total miscanthus and short rotation willow area of about 17,000 ha in 2008 in the United Kingdom (Sherrington and Moran 2010).

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[10] See for instance Monti et al. (2007), Larson et al. (2008), Khanna et al. (2008) and Bocquého and Jacquet (2010) for switchgrass; Khanna et al. (2008), Deverell et al. (2009) and Bocquého and Jacquet (2010) for miscanthus; Gasol et al. (2010) and Kasmioui and Ceulemans (2012) for woody crops; and Carriquiry et al. (2011) for a general cost review.

[11] Policy and contract tools that are not specifically targeted to liquidity or risk issues are out of the scope of this chapter. Crop insurance schemes and indirect funding through support to renewable energy production are not considered either. A wider range of tools to overcome barriers to adoption is described in Sect. 4.4 of Chap. "Innovation in agriculture…" and in Chap. "Contracting farming in biofuel sector…".

In Sweden, a specific subsidy for willow planting was introduced in 1991, which covered approximatively establishment costs (Helby et al. 2006). The amount of the subsidy decreased in 1997, but increased again in 1999 to reach 5000 SEK/ha—equivalent to € 373 at 1999 exchange rate—, i.e., half of the 1991 amount. This policy, along with investment in research and development and a low wheat price before 1995, led to an area of more than 14,000 ha of short rotation willow as of 1996 and at least until 2002 (Helby et al. 2006).

In France, there is no dedicated program, but the government has supported perennial energy crops as part of a broader development plan in selected areas. For instance, between 2009 and 2011, following the reform of the European sugar regime, farmers from eastern France were eligible to diversification incentives from a national program for the reorganization of the beetroot sector (Bocquého et al. 2015). Miscanthus and switchgrass were some of the diversification activities supported. For farmers, main benefits were subsequent establishment subsidies (40% of the incurred costs as a minimum, with a cap at 70,000€, which corresponds roughly to 22 ha).

In the United States, the USDA Biomass Crop Assistance Program was created through the 2008 Farm Bill (USDA 2012). It provides an establishment grant covering up to 75% of the planting costs, in addition to an annual rental payment while producers wait for the crop to mature—up to five years for herbaceous biomass, and up to 15 years for woody biomass. Part of annual payments can be converted into matching payments at a rate of $1 for each $1 per dry ton paid by a qualified biomass conversion facility, in an amount up to $45 per dry ton. Matching payments are limited to two years, and are designed to assist with the delivery of biomass directly from land to the conversion facility—collection, harvest, transport and storage costs. The program was reauthorized by the 2014 Farm Bill albeit with some changes.

Establishment grants serve to counteract the negative liquidity balance during the first years, leading to a higher investment capacity, and a lower year-to-year variation in the crop income stream. By decreasing up-front sunk costs, they also reduce the risk and option premia, and increase expected profitability. They are sometimes referred to as conversion subsidies because they lower land conversion costs.

Ridier (2012) compared the effect of an establishment grant—covering 50% or 60% of costs—to an annual payment of 300 €/ha on the adoption of woody crops in southwestern France. The author found that the annual payment represents the highest level of incentive, under the assumption that it is granted throughout the 21-year time horizon with certainty. However, as establishment costs range from 2000 to 4700 €/ha, the establishment grant is worth less than the sum of all payments over the crop lifespan, even when a proper discount rate is applied to future payments. Thus, the annual payment may not be the most cost-effective tool.

One advantage of establishment grants is their immediacy, as opposed to annual payments that farmers perceive as uncertain in the future (Sherrington et al. 2008). Nevertheless, a few authors highlighted unintended consequences of targeting the establishment period. For instance, Helby et al. (2006) reported that in Sweden the grants allocated to planting rather than production and sale of willow supported short-term opportunistic behavior rather than long-term production. In addition, the survey results reveal moral hazard problems that contribute to undermine the subsidy efficiency. Those farmers who are strongly motivated by the planting subsidy are indeed less active in weed control and use less external advice. Moreover, Song et al. (2011) tested in a real option framework the effect of a 50% establishment grant, under the assumption that land-use conversion is possible in two directions, i.e., from traditional crops to switchgrass and vice versa. They showed that the grant encourages conversion both into and away from the biomass crop, and in the long run does not affect much proportions of land in switchgrass. It only makes the peak switchgrass acreage occur at an earlier time.

When establishment grants from the government are not sufficient or available, energy suppliers may propose cash advance systems in exchange to a supply commitment formalized in a contract, as in eastern France (Bocquého and Jacquet 2010) or in the United Kingdom (Sherrington and Moran 2010). Such systems may also be provided by public authorities in the form of low-rate loans. Like establishment grants, cash advances counteract liquidity issues and intertemporal fluctuations, but they do not reduce the overall risk of a large loss because the advance has to be repaid. In the best case, the advance is interest free, and expected profitability is slightly improved due to the benefit of delaying costs for a couple of years.

Bocquého and Jacquet (2010) investigated the impact of reducing income fluctuations with such cash advance tools on the uptake of switchgrass and miscanthus in a 100 ha cereal farm in central France. The authors found that it can be a powerful mean of stimulating farmers' willingness to grow the new crops. Under the assumption of neutrality to risk but aversion to intertemporal fluctuations, the optimal acreage in the baseline scenario jumped from 0 to 40.4 and 2.8 ha for switchgrass and miscanthus respectively—other assumptions include an interest rate of 1.5% on the advance and an individual discount rate of 5%.

5.2 Dedicated Risk Mitigation Tools

Aside from establishment grants and cash advance systems, complementary incentives may be necessary to tackle specifically risk issues in adoption. Farmers' uncertainty about the profitability of perennial energy crops is usually tackled by processors through long-term production contracts. This win-win arrangement secures in the long term both a market for farmers' biomass and a steady supply for processors. The design of an optimal contract is complex, and should address the specific challenges of perennial energy crops. Alexander et al. (2012) provided an insightful survey of relevant concepts and research from the contract theory literature. They explained in particular how contracts should maximize the processor's profit while meeting farmers' participation and incentive compatibility constraints.

The participation constraint expresses the need to design contracts that farmers will accept. It requires that

> the contract compensates the farmer in such a way that his/her payoff from producing the energy crop will be at least as high as the payoff from the next best use of the land.

The incentive compatibility constraints are set up specifically to

> ensure that a farmer operating under the contract has more to gain from meeting contract objectives than not meeting the objectives,

Typically yield or quality objectives such as moisture content. In other words, compatibility constraints are ways to address moral hazard problems. In practice, they are often implemented as pay-for-performance systems which ensure that the more the farmer complies with the objectives, the higher the payment. As linking payment to performance increases farmers' risk and raises production costs—e.g., limiting moisture implies storage protection—the contract payment should compensate for these extra costs. Otherwise, farmers will refuse to participate.[12]

The contract payment scheme for perennial energy crops should mitigate the most important risks and fluctuations borne by the farmer in order to ensure participation. The most radical way is to offer a fixed area payment, which eliminates all risks and year-to-year income variations from the farmer's side. However, more elaborated schemes have the potential to better match both farmers and processors' preferences and perceptions. For instance, payments indexed on the price of an alternative crop such as corn hedge farmers against land price risk. The variability of the opportunity cost of land is indeed of great concern to farmers who tie up land for several years into biomass production. The hedging can be total or partial depending on the correlation between the payment and the price used as an index. Yield payments are another example. Because processors' first objective is to ensure biomass supply in quantity, they usually prefer this scheme to area payments. In this case the payment depends on the volume delivered, based on a per ton biomass price. As farmers bear all production risks, processors often provide technical assistance to reduce these risks which result from a lack of knowledge or experience. In addition, by allowing contractors to control farmers' practices, this provision is a further way to mitigate moral hazards and ensure a steady quality besides incentive compatibility constraints. Another option to reduce farmers' burden with respect to production risk is to share the costs of replanting in case the crop fails to establish. It is a feature of some of the contracts found in France.

In practice, farmers are heterogeneous in their risk preferences, and processors do not have information about farmers' individual degree of risk aversion—or loving. Thus, processors will most likely offer suboptimal contracts, leading either to farmers' nonparticipation—biomass is underpaid—or a profit loss—biomass is overpaid and farmers get a rent. This situation is a typical adverse selection

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[12] For more theoretical insights about contract farming, please refer to section "A theoretic perspective of contract farming" of chapter "Contracting farming in biofuel sector: A survey".

problem. One solution described by Alexander et al. (2012) is a screening contract mechanism under which farmers voluntarily choose the contract that is best suited for them in a well-designed menu. With data relative to switchgrass and miscanthus production in southern Illinois, Yang et al. (2015) found that offering a menu of contracts results in greater expected profits for the processor but not necessarily for farmers as compared to cases when the processor offers only one contract type. In addition, they highlight the need for the processor to weigh benefits of offering multiple contracts against additional transaction costs.

A growing number of studies assess the efficiency of different contract designs in mitigating risks and enhancing adoption of perennial energy crops. In a farm land allocation model, Bocquého and Jacquet (2010) assume that risk operates on prices only and food prices are uncorrelated with energy prices. They found that a contract featuring a fixed-price yield payment makes French cereal farmers convert 91 ha to switchgrass instead of 32 ha in the no-contract scenario—out of 100 ha—, and 34 ha to miscanthus instead of 7 ha. However, the authors showed that the fixed-price mechanism is generally less efficient than cash advance systems in fostering adoption when intertemporal fluctuations are accounted for.

Yang et al. (2015) examined how risks from multiple sources interact and jointly determine optimal contract terms. They considered the fixed-price contract mechanism, as well as two alternative schemes: a land-leasing contract under which the biorefinery leases land from landowners through a fixed area payment and a revenue sharing contract with the price indexed to the biorefinery revenue. They demonstrated that under the conditions prevailing in southern Illinois, more risk-averse farmers prefer the land-leasing contract to avoid exposure to yield and price risk. As the level of risk aversion decreases, preferences shift toward the fixed-price and revenue sharing contracts since farmers can gain higher payoff in exchange for the higher risks they are bearing.

Larson et al. (2008) assessed the potential to supply biomass feedstocks under alternative contract arrangements for a northwest Tennessee 2400 acres—about 971 ha—grain farm. The four alternative types of contracts reflect different marketing strategies and offer increasing levels of risk sharing with the processor: (i) a spot market contract where biomass is priced yearly as a substitute for gasoline and all risks from biomass production—output price, yield and input price—are borne by the farmer, (ii) a standard marketing contract with a penalty for production underage and a partial shift of output price risk to the processor as excess production only is sold at the spot market price—(iii) an acreage contract which provides a guaranteed annual price per ton of biomass produced on the contracted acreage and thus totally shifts output price risk to the processor—but the farmer still incurs the entire yield and input price risks—and (iv) a gross revenue contract which provides a guaranteed annual gross revenue per acre of biomass and thus totally shifts output price and yield risks to the processor. As expected, under risk aversion and for a given biomass price, the gross revenue contract generally induces more switchgrass production than other arrangements.

Based on survey data, Jensen et al. (2011b) analyzed factors influencing farmers' interest in marketing switchgrass through contracts and/or joining a cooperative that harvests, transports, stores, and markets switchgrass in the southern United States. The authors found that, among farmers who are willing to grow switchgrass, those who farm more area, have facilities where they can store switchgrass, and have substantial off-farm income are more interested in contracting and/or joining a cooperative. According to the authors, these results suggest that marketing arrangements such as contracts and cooperatives are not only risk management tools, but also ways to optimize the use of physical assets and limit time commitment through access to technical advice and market knowledge.

However, if the contracts described above can be efficient tools to mitigate the risks linked to biomass production itself, they fail to address counterparty risk, particularly high in long-term contracts. Indeed, farmers may fear that processors go bankrupt before the contract ends, which holds potential for dramatic impacts on their income if the payback period is long and other market opportunities are scarce. At the same time, processors may be concerned that farmers switch back to a conventional crop if market conditions are favorable. New information may induce both parties to look for a more profitable contract arrangement. As reported in Table 1 and by other authors (e.g., Sherrington et al. 2008), farmers perceive counterparty risk as quite important. One solution described by Alexander et al. (2012) is to incorporate foreseeable renegotiation into the initial contract to increase its credibility—also known as renegotiation proofness constraints. Other options are price-indexed contracts which foresee adverse price shocks, and cap-and-floor contracts which mitigate the risk of incurring very large losses.

The counterparty risk problem can also be addressed with insurance schemes. For example, farmers would engage into producer groups where the loss borne by a farmer due to a counterparty failure is absorbed by the rest of the group members. To keep costs manageable, it requires that farmers in the group are numerous enough and supply biomass to a variety of processors, which means small-scale processors or farmers from a wide geographical region. Until the market becomes mature, one can also call with Sherrington and Moran (2010) for governments to act as guarantor, or at least be more actively involved in providing a form of insurance.

6 Conclusion

This review highlights the crucial role of liquidity, risk, and related time effects in explaining farmers' willingness to grow perennial energy crops. First, despite well-established credit markets, farmers from developed countries are often exposed to credit rationing. Credit conditions for financing a new technology are even more stringent, and, as a consequence, farmers are strongly concerned about the high establishment costs of perennial energy crops. However, providing a quantitative estimate of the relationship between the adoption decision and liquidity constraints is challenging for several reasons: measures of credit constraints often rely on the use of proxies, constraints may not be binding at an early stage of the diffusion process due to the small size of plantations, and at a later stage constraints are likely to be relaxed by establishment grants and improved credit conditions. Simulations with farm optimization models are an alternative, liquidity problems being for instance accounted for through explicit technical constraints.

Second, farmers face a number of additional risks when growing perennial energy crops without support, including production risk, market risk, economic risk and institutional risk. Likert-type survey questions are the most popular means to measure farmers' risk perceptions, those which matter in the adoption process, as opposed to objective risks. To improve our understanding of how farmers perceive the risks of perennial energy crops, more control on respondents' characteristics and environment such as experience, market conditions and land type is needed. Farmers' preferences are the other risk component impacting the adoption decision. In the absence of risk mitigation tools, as most farmers are risk averse, risk is expected to be a significant barrier to adoption. However, the potential of perennial energy crops for diversifying income sources and stabilizing the global farm income qualifies this last result.

Third, time issues specific to perennials make the analysis even more complex. Irregularity in the income stream due to uncertainty about future events and time lag between costs and returns is expected to hinder adoption because credit markets are imperfect and farmers are averse to intertemporal fluctuations. In addition, the irreversibility of investing into establishing perennial crops gives a value to postponing the decision and thus keeping the option to make a better one in the light of new information. Moreover, land reallocation decisions, for instance conversion back to conventional crops, depend on opportunity costs and conversion costs such as establishment and removal costs.

This chapter also highlights relevant policy and contract schemes to overcome the barriers to adoption described above. Establishment grants and cash advance systems are widespread and efficient ways of limiting liquidity effects on adoption as long as moral hazards are managed and conversion back to conventional crops is discouraged. As regards risk barriers, they are mostly tackled through private long-term production contracts between farmers and biomass processors. To secure a steady supply and quality, the optimal contract must at least cover the opportunity cost of land, plus some premia to compensate for additional uncertainty, and include pay-for-performance systems. In addition, to ensure the contract is credible, the counterparty risk inherent to long-term commitment must be addressed properly, for instance through incorporating foreseeable flexibility in contract terms or supporting specific insurance systems.

The importance of liquidity, risk and related time effects in the adoption of perennial energy crops should not mask farmers' technical constraints such as soil suitability, storage capacities and incompatibility with existing activities. Non-pecuniary factors like social and personal beliefs or values are also major determinants of adoption choices.[13] As for policy options, those with a focus on environmental goals can further incentivize the production of cellulosic biomass, while fostering cultivation methods that limit adverse side effects like competition with food crops. Such levers include payments for ecosystem services to remunerate contribution to, e.g., renewable energy supply and carbon sequestration.

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[13] See Sect. 3 and 4 of Chap. "Innovation in agriculture…" for a complete review of factors affecting energy crop adoption.

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Contracting in the Biofuel Sector

Xiaoxue Du, Madhu Khanna, Liang Lu, Xi Yang
and David Zilberman

Abstract To accommodate rapid technological change in agriculture, contract farming has emerged as a market response to manage and share risks along the supply chain. Contract farming strengthens vertical coordination for producers and processors motivated by desire to decrease randomness, overcome credit and risk constraints, assure production targets, and address environmental considerations. Using contract theory perspective, this paper shows why multiple contract forms exist to address different types of risk, market size and maturity, and other constraints. Our findings suggest that, in the case of biofuels, contract design depends on land quality, output prices and markets, farmers' risk preference, and other constraints. In establishing a refinery, the decision-maker must determine the size of refinery, quantity of in-house feedstock production, and strategy for purchasing additional feedstock. When facility capacity exceeds in-house production, the processor needs to rely on external feedstock. Processors and producers with higher land quality are shown to benefit from vertical integration, while lower land quality should result in conversion to biofuel production due to lower opportunity cost. As second generation feedstock production grows and matures, policies must consider contract design, technology adoption, and vertical integration.

Keywords Contract farming · Mechanism design · Biofuel · Energy crop

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X. Du · L. Lu · D. Zilberman (✉)
Department of Agricultural and Resource Economics, University of California at Berkeley, Berkeley, CA, USA
e-mail: zilber11@berkeley.edu

X. Du
e-mail: duxiaoxue1515@gmail.com

L. Lu
e-mail: lld2x1515@berkeley.edu

M. Khanna · X. Yang
Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Urbana, IL, USA
e-mail: khanna1@illinois.edu

X. Yang
e-mail: xyxiyang9@gmail.com

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1 Introduction

Contract farming has emerged as a market response to managing and sharing risks through the supply chain by processors and producers in modern agriculture. In the United States, the share of agricultural production through contracts was 39% of the total value of agricultural production in 2008, up from 11% in 1969 (MacDonald and Korb 2011). In this chapter, we look at the various factors that have contributed to the growth in contract farming in modern agriculture, characterized by product differentiation, technology innovation, risks and uncertainties both on the supply and demand-side of the market.

One of the early papers, Cheung (1969), focused on how contract farming could induce risk-sharing and improve efficiency. Risk, a parameterized (variance and higher order moments of past corn price for instance) random variable, is the most restricted form of uncertainty. However, there are risks that are immeasurable—the so-called Knightian uncertainty. Many Knightian uncertainties exist in modern agriculture: when a new fruit variety is introduced to the market, little is known about the profitability of the product and the risk is not measurable. Similarly, when farmers make the decision of whether or not to grow second generation biofuel feedstock, they have no idea about its productivity, nor do they know the degree of learning-by-doing effect in the future. Under such circumstances, lack of knowledge of basic parameters may lead to contracts that share risks.

Later papers such as Knoeber and Thurman (1995), Goodhue (2000), and Hueth and Ligon (2002), analyze the contractual relationship in a supply chain. Here, the randomness takes another form: at least one party in the contract does not have perfect information about its counterpart (e.g., a manufacturer may not know a producer's productivity or land quality), which is known as the asymmetric information problem. Contracts, in the form of a tournament rewarding system, provide a way to resolve the issue.

Another function of contract farming is that it helps to overcome constraints due to thin markets. Processors seek to overcome credit constraints while producers face management limitations. Contract farming establishes a partnership where one party provides complementary input to the other. Meanwhile, with product differentiation, product markets get thinner and more susceptible to 'hold up', a problem described below. For example, fruit processors and producers are both in need of a timely transaction. Contract farming allows strengthening of vertical coordination in a supply chain.

Reliance on contract farming differs across different agricultural sectors. According to MacDonald and Korb (2011), less than 20% of corn and cattle production is sold through contract farming, but over 90% of poultry and sugar beets are produced under contracts. Moreover, among the sectors that are using contracts intensively, the forms of contracts being used are different. For instance, marketing contracts dominate the fruit sector, while production contracts are almost the exclusive form in poultry production.

The goal of this chapter is to utilize the learning gained from existing literature to analyze how the biofuel sector could benefit from contract farming. Both the goal of energy independence and the desire to lower greenhouse gas emissions have triggered the search for alternate energy sources. Despite economic viability and technology availability of grain crop ethanol, the production of first generation biofuel has increased food prices As a consequence, the Energy Independence and Security Act of 2007 mandates that corn ethanol production cannot exceed 56 billion liters per year after 2015 and sets a goal of producing 39.7 billion liters of cellulosic ethanol per year after 2020, which often involves utilization of dedicated perennial grasses as feedstock. The transition to advanced biofuels requires adequate supply of biomass feedstocks to meet this goal. However, uncertainty in production technology and unpredictable market conditions of cellulosic feedstocks make it crucial that biorefineries adopt certain types of institutional mechanisms to guarantee smooth input supply. In this case, the situation is more complex: both the biorefineries and feedstock growers face uncertainty in production technology; refineries may not have the information on farmers' productivity and land quality; the market is quite thin in that farmers may find only one refinery to sell the product and refinery may find few farmers in the region that are willing to grow cellulosic biofuels; and upon building the processing facility, refineries may find themselves facing tight credit constraints. We address the importance of contract farming in overcoming these obstacles.

The remainder of this chapter is arranged as follows. In the next section, we will discuss the motivations for contract farming and some advantages and disadvantages of contract farming. Following that we will use a contract theory perspective to examine why different forms of contracts exist. We then compare existing types of contracts in agricultural sectors and discuss some recent findings on optimal contracts for the biofuel sector. Finally we give some concluding remarks and closing comments.

2 Why Contract Farming

2.1 Contract Types in Agriculture

There are many types of contracts that have been used in the agricultural sector. To get familiar with contract farming, we first introduce some well-adopted types of contracts. Meanwhile, since scholars have been categorizing contract farming using different terminologies, we first introduce the definition of some important terms used in this chapter, which are mainly adopted from Hayenga et al. (2000), Bijman (2008), Vermeulen and Cotula (2010), and MacDonald and Korb (2011).

Spot market or *cash market*, is the fundamental type of market structure where ownership and decision-making are completely separated at each stage of the commodity production process. With spot markets, farmers own the land and make the planting decisions while processors own the processing facilities and buy the raw crops at instantaneous market price.

Vertical integration is characterized by unified ownership of the upstream and downstream process. Joint venture is a classic example of vertical integration. Under vertical integration, a processing company may purchase/lease the land and grow the crop by itself, or gain ownership of intermediary firms that provide centralized storage of biomass to reduce collection and transportation costs.

Contract farming sets either a formal or informal agreement between farmers and buyers. The agreement may include but is not limited to the following predetermined terms on the crop: price, quantity, quality, specific characteristics, and other transaction details. Meanwhile, buyers may also specify in the agreement the inputs and technical advice that they could provide farmers.

From the definitions above, under vertical integration farmers lose their independence, but, at the same time, face the least financial risks. As Acemoglu et al. (2009) suggest, vertical integration is more likely to occur in capital-intensive industries and when the contracting cost is higher. Therefore, while vertical integration is less common in agriculture (Hayenga et al. 2000), contract farming constitutes 39% of the value of U.S. agricultural production (MacDonald and Korb 2011) and is widely accepted worldwide (Angeles et al. 2008). Hayenga et al. (2000) compare the different conditions that farmers face under different business models. The result is presented in Table 1.

Based on the involvement of contractors in production activities, farming contracts can be divided in two categories: namely, marketing contracts and production contracts (MacDonald and Korb 2011). In marketing contracts, growers and buyers must agree on ‘what is to be made’ and ‘what are the commitments for future sale’ (da Silva 2005). Namely, market contracts specify the quantity and quality of the designated crop in the transaction and set either a predetermined price for the crop or a formula for pricing based on market price at the time of transfer.

In the case of production contracts, arrangements are made on ‘how to produce’ certain products (da Silva 2005). Buyers are more involved in the production process under production contracts. They may specify inputs to be used in production and share risks in both production and sale price with growers.

Bijman (2008) mentions another way to categorize different types of contracts, namely formal and informal contracts. He explains the reasons for most agricultural contracts being informal: (a) it is often hard for a third party to precisely measure if the desired characteristics of the commodity are met and (b) the involvement of a third party will incur higher transaction cost. A consequence of such a

Table 1 Comparison among business models

	Independence	Financial risk	Access to capital
Cash market marketing Contract production contract	Highest modest/low	Highest modest/low	Low/modest highest

Source Hayenga et al. (2000)

categorization is that Bijman (2008) explicitly reveals the importance of reputation in informal contractual relations. This is especially relevant to perennial crops, since by the end of first contract term, the producers' productivity and ability to meet certain crop criteria and the contractors' fulfillment of payment are observable to both parties. Therefore, in such a repeated game environment, the trustworthiness of both parties in early stages often determines the possibility of contract renewal in later stages.

2.2 Motivations for Contract Farming

There is a growing literature analyzing the effects of risk aversion on contract choices. Using a simulation model, Buccola (1981) shows that the share of output a farmer (processing firm) would sell (buy) under a fixed price or cost-plus pricing contract and on the spot market depends on the degree of risk aversion of the farmer and the firm and the covariances between market price of the raw product, the final product, and production costs. Anderson et al. (2004) show that preferences for a contract may differ between a principal and an agent due to differences in the risks they face and in their risk aversion; they find that while pasture owners prefer grazing contracts to owning cattle as their risk aversion increases, cattle owners prefer leasing land to contract grazing because the risk reducing benefits of contract grazing are insufficient to compensate for its costs. Other studies use survey data to show the importance of risk aversion as a determinant of contract choice.

Katchova and Miranda (2004) find that highly leveraged (more risk) crop producers were more likely to adopt marketing contracts and that marketing contracts were used not only to reduce price risk but also to have an outlet for the harvested crop. Reliance on fixed contracts instead of the spot market has been found to be significantly related to the level or price risk, risk aversion, and risk perception among hog producers (Franken et al. 2009). Much of this research has focused on a producer's choice between a contract and selling on the spot market. Zheng et al. (2008) analyze the choice among alternative types of contracts by hog producers and find that the most risk averse hog producers prefer production contracts that are less risky than marketing contracts. They also show that forcing risk averse farmers to choose the more risky marketing arrangements could lead to significant welfare losses.

Bocqueho (2012) estimates the risk preference of French farmers under both cumulative prospect theory and expected utility theory. The findings support the usage of cumulative prospect theory and suggest that farmers are risk averse as well as loss averse. Farmers exhibit an inverse S-shaped probability weighting function, which shows that farmers overweight extreme events and low probabilities, while under-weighting high probability events.

As Boehlje et al. (2006) claim, with consumers increasingly emphasizing commodity quality, the agricultural sector faces an increasing need for products with certain characteristics. This need has triggered a rapid growth in technology innovation. The innovation not only brings about uncertainty into the market but also makes markets thinner, meaning that only a few consumers and suppliers exist within a market. Consequently, the uncertainty and thin market provide an incentive for each stage of production to make coordinated decisions. In fact, manufacturers may find contracting appealing because of benefits from risk-sharing, relaxed credit constraint, environmental consideration, etc. From growers' perspective, contracting may also be attractive in that contracting brings about more stable income than doing business through spot markets. Contracts in agricultural production can be viewed as a tool that allows risks to be transferred from less risk tolerant farmers to the risk neutral players in an industry. For instance, in biofuel production, new energy crops may have to be introduced to produce greater quantities of biomass to meet the need of biofuel production. A production contract may assuage farmers' concerns about growing new varieties. Moreover, by contract farming, producers could gain greater access to capital and more advanced growing technology. Bijman (2008) notices that at the social level, government subsidized contract farming may lead to better technological adoption for society, which is referred to as the 'donor's ambition'.

As a result of these benefits to all parties involved in production, we have witnessed the transition from spot market transactions to vertically coordinated production either in the form of vertical integration or contract farming during the last century. Acemoglu et al. (2009) suggest that vertical integration is more likely to occur in capital-intensive industries and when the contracting cost is higher. Therefore, vertical integration is less common in agriculture (Hayenga et al. 2000). In the following subsections, we discuss some of the major incentives for contracting in greater detail.

2.2.1 Randomness

It has long been known to economists that when people are making decisions under risk, not only the expected payoff matters but also their attitude toward risk. Risk arises in many forms in agricultural production: farmers may incur risk in the output quantity and quality while both farmers and buyers face risk in spot market prices.

The motivation for marketing contracts becomes clear: when the crop price becomes risky, a risk averse farmer may prefer to set a predetermined price with buyers rather than selling their crops on the cash market even if the latter could generate higher expected return. On the other hand, manufacturers receive more stable input prices under contracts though they might be able to purchase the crop at a lower price in the spot market. Cheung (1969) first observed that the rationale behind sharecropping contracts is that both parties share the risk of yield variation. It should be noted, however, unlike the case of price uncertainty, the risk of yield variation can only be shared by the two parties rather than eliminated. In fact, Stiglitz (1974) proves that the relatively risk averse party bears less than its proportion of risk.

When a crop is relatively novel for producers, there is technology uncertainty associated with the production of the crop. Sunding and Zilberman (2001) discuss technology adoption decisions in agriculture. It should be also noticed that despite the fact that the use of contracts can reduce price and production uncertainties, it generates its own risk: the risk of either party defaulting the contract, i.e., producers may sell the product to other buyers on the spot market when they see a higher spot market price and buyers may refuse to purchase the amount indicated in the contract (Suzukiab et al. 2008).

Knightian uncertainty often is involved in situations where the event is completely unanticipated (Just 2001). Typically, the uncertainty gives incentive for producers to acquire information on the unknown parameters and leads on incentives to establish contracts (Wright 1983). The asymmetric information case will be introduced in the next section.

2.2.2 Transaction Cost

In the biofuel industry, a crucial question facing a biorefinery is how to guarantee the supply of biomass. A biorefinery could collect biomass from hundreds of farmers, but the high transaction cost, which could include searching cost, negotiation cost, and measurement cost, associated with this process is the key issue. Here transaction cost refers to the costs of establishing and administering the relationship between the refinery and farmers, including costs associated with opportunistic behavior and haggling ex-post. Compared with other row crops, a unique feature of bioenergy crops is large transaction-specific investments, which mean these investments cannot be used in other production processes. The biorefinery and the farmers are generally located together to avoid high inventory and transportation costs, which may cause site specificity. The bioenergy crops cannot be used for other purposes, which may cause asset specificity (Williamson 1983). Both farmers and biorefinery are hesitant to enter the biofuel industry unless appropriate contracts are designed to solve these hold-up problems, as introduced earlier. Contracting provides a way to mitigate the transaction cost associated with biomass acquisition.

The transaction cost literature started from the seminal paper of Coase (1937), which explains how to use vertical integration to deal with the transaction cost problem. Transaction costs refer to various costs associated with market transactions such as search cost, bargain cost, and enforcement cost. One way to avoid those costs is vertical integration and production within a firm. Cheung (1969) extends the literature to explain the agriculture sharecropping behavior in Taiwan and shows that contract choice will not influence the outcome when transaction costs are zero. Since then, transaction cost theory has been used to explain contract choices.

The input sharing problem is especially important for bioenergy crops mainly because of the high establishment cost at the early stage of the crop's life cycle. An important question is to understand the mechanism by which cost sharing affects contract design. The majority of sharecropping literature concentrates on output sharing instead of input sharing. Some exceptions include the work of Braverman and Stiglitz (1986), which shows that cost sharing contracts have a decided advantage over contracts which specify the level of inputs when there are asymmetries of information regarding production technology between the landlord and the tenant.

Allen and Lueck (1995) compare the importance of risk aversion relative to transaction cost in affecting contract choice. They summarize the empirical evidence in several industries including agriculture, gold mining, natural gas, and timber and their conclusion is that the transaction cost framework rather than risk preference theory is more reliable for explaining the existence of sharecropping contract. An increase in crop risk decreases the probability of sharecropping contract because greater exogenous shock makes crop measurement more difficult and cash-rent contract more likely.

The dominance of contract production in broiler industry can also be explained from the perspective of transaction cost theory (Knoeber 1989). One feature of the broiler industry is that the high cost of transporting feed and mature broilers led the integrator and growers to locate near each other. Both broiler houses and processing facilities are relation-specific assets because of their site specificity. There are two important contract arrangements on broiler industry: the first one is tournament payment scheme which means a grower's payments depend on his performance relative to the average performance of growers. This scheme is a way to adapt to the changing productivity without negotiating prices and shifts many production risks to the integrator.

Another contract arrangement is that the growers need to provide chicken houses, which creates a bond between growers and integrators. This also provides incentives for growers to guarantee a minimum level of performance because the returns to investment depend on the performance. Besides agriculture production, transaction cost method can also be used to understand the contract behavior in other industries. Leffler and Rucker (1991) find evidence from timber harvesting contracts, which favors the transaction cost explanation. The timber harvesting contracts can be divided into two categories: lump-sum contract and per unit harvest contract. The main transaction cost examined in this paper includes the cost of enforcing desired harvest level and presale measurement cost. The objective of timber owners is to minimize the transaction cost through the choice of payment scheme. They develop a transaction cost model and generate two testable hypotheses: likelihood of adoption of per unit contract increases with tract-level heterogeneity and unreliability of timber sellers presale information; the other hypothesis is that per unit contracts are more likely to be used when the seller's monitoring cost is low. They test these hypotheses using private timber sales contract in North Carolina. The result provides support for the transaction cost model against alternative models, such as risk aversion model which predicts that a per unit contract is less likely when a tract is more heterogeneous and the quality of seller provided information decreases.

For biofuel feedstock production problem, almost all the above conditions are met. First, dedicated bioenergy crops, such as switchgrass and miscanthus, require special investments. Initial investments are specific to biofuel feedstock production. Farmers are unfamiliar with the planting methods and market conditions of bioenergy crops. Moreover, energy crops are perennial plants, with a lifespan of ten years or more, and are thus difficult and costly to switch. The farmers and biofuel refineries have a certain degree of monopoly power. A long-term contract can guarantee the profits and specific assets of those farmers. Second, the uncertainty of bioenergy crops is high compared to traditional crops such as corn. Since biofuel is considered as a substitute for fossil fuels, biofuel feedstock prices are also correlated with gasoline prices. Gasoline prices exhibit high volatility and price uncertainty associated with biofuel feedstock is high. Based on these characteristics, a high degree of vertical integration is considered a good choice in terms of contract design.

2.2.3 Moral Hazard

Another problem with bioenergy crop production is the moral hazard problem (or hidden action), which means farmers may shirk responsibility in the production, harvest, transportation, and storage processes especially when monitoring is hard or impossible. In most agricultural contracts, it is relatively easy to observe a farmer's characteristics, but hard to monitor the behavior of farmers. Moral hazard may have negative effect on the profitability of biorefinery when product quality is hard to measure. A biorefinery can fix this problem by providing farmers with incentive-based contracts such as share contracts and tournament contracts. It is important to identify the potential moral hazard problems in the production of bioenergy crops and understand how moral hazard interacts with asymmetric information and adverse selection.

From the perspective of a biorefinery, contract design is important to mitigate moral hazard problems. With fixed wage payments, agents receive a fixed amount of income regardless of effort hence they lack incentives to exert additional efforts. Because monitoring is costly and difficult, incentive-based contracts, such as fixed rental contracts and performance-based payment, are likely to reduce undesirable outcomes from moral hazard problems.

The moral hazard literature was developed by Spence and Zeckhauser (1971) and Mirrlees (1976). Stiglitz (1974) analyzes the problem in a sharecropping setting. Stiglitz (1974) demonstrates that sharecropping achieves the right balance between incentives to agents and insurance to agents since rental contracts do not provide an appropriate sharing of risk, while fixed wage contracts do not provide enough incentives for farmers to exert their full effort.

Basu (1992) proposes a technique to address the moral hazard problem which states limited liability would lead agents to adopt too much risk in the production process. The limited liability in the agrarian context means that if the weather fails and the harvest is sufficiently poor, the landowner would not be able to claim his full rent. In this case, the tenant is protected from downside risk when harvest falls below a threshold level. The landlord chooses sharecropping instead of fixed rent to direct the tenant's choice of projects toward less risky ones with the underlying tenancy contract serving as an implicit limited liability clause. Ghatak and Pandey (2000) extend the literature by showing that joint moral hazard in effort and risk justifies sharecropping contract, not moral hazard in effort or risk alone. A sharecropping contract is designed to balance the trade-off between providing incentives to tenants and discouraging risk-taking due to limited liability. They analyze two extreme forms of incentive-based contracts. If the incentive to earn profit is too high, agents tend to adopt risky cultivation technologies, which may be harmful to the principal. Low incentive contracts will lead farmers to supply a low level of effort. Thus a sharecropping contract provides a good balance between moral hazard effects on effort and risk considerations.

The literature also analyzes the effect of a combined moral hazard problem and adverse selection problem on contract design. Goodhue (2000) proposes explanations for two puzzles in the broiler industry: processors control inputs and use an inefficient relative compensation estimator to calculate grower's compensation. The finding of this work suggests the input control decision and relative compensation measure is a processor's response to grower heterogeneity, grower risk aversion, and systematic uncertainty. In the presence of moral hazard-adverse selection problems, the processor is shown to benefit from sharing income risk with growers.

Another implication of moral hazard assumption is that workers with full insurance against risks will not exert their full efforts. Contracts address this problem by having farmers retain some of the uncertainty and establish payments based, in part, on effort. In the case of bioenergy crop production, the biorefinery would achieve a socially optimal result most likely with performance-based contracts. For example, a contract based on the quality and quantity of bioenergy crop output gives better incentive to farmers to induce their efforts than a fixed acreage payment, all else equal.

In addition, we may also observe ex-post opportunism due to contractual incompleteness and costly monitoring and enforcement. Either party may take advantage of the situations not covered in the contract in the event of contractual incompleteness. Costly monitoring and enforcement may create incentives for both parties to take advantage of information asymmetries and shirk their responsibilities specified in the contract. Crocker and Reynolds (1993) consider a contract efficient if the marginal benefits and costs of completeness are equal. Sykuta and Parcell (2003) claim that even economically efficient contracts leave potential for opportunistic behavior.

2.2.4 Overcoming Constraints

Here, we discuss how contract farming could help overcome credit constraints, which also applies to overcoming other constraints. Jaynes (1982) illustrates the credit problem in landlord-tenant contracts. It is easy to see that if a manufacturer is under tight capital constraint, it may prefer to set contracts with farmers, to balance the trade-off between expanding its processing facility and in-house input production. Moreover, as explained in Tsoulouhas and Vukina (1999), credit constraint will push manufacturers to choose marketing contracts rather than production contracts since the latter will incur higher possibility of credit shortage for contractors.

The contract can also be used to address the liquidity constraint problem of bioenergy crop adoption. Compared to traditional crops, bioenergy crops require a large up-front investment in a refinery, increasing in complexness when transitioning from sugarcane or corn feedstocks to cellulosic feedstocks, such as miscanthus. With no cash return for the first two years, farmers need access to financial support in order to plant bioenergy crops. Contracts serve as a source of credit enhancement for establishing a refinery.

Key and Runsten (1999) find that compared to formal banks, agro-industries are in a better position to provide credit to the farmer because of the ability to monitor and enforce the contract. They use Mexican frozen vegetable industry as an example to study the effect of contract farming on smallholders and large growers and evaluate the effect of contracts. Transaction costs, especially enforcement and to a lesser extent monitoring, are shown to decrease further by combining credit contracts with production contracts. The conclusion of this study is that contract farming may benefit farmers by providing financial resources, especially smallholders that tend to exhibit more risk averse behavior and have less access to financial markets.

Bierlen et al. (1999) test several contract choice hypotheses using eastern Arkansas data set and provide empirical support for the credit constraint hypothesis. They find that the probability of choosing a cost-share contract increases with operating expenses, cash rent, and landlord financial strength. The probability of choosing a crop-share contract decreases as equity increases because bankers are more likely to lend to tenants with higher equity levels.

Bocqueho and Jacquet (2010) use net present value framework to study the effect of liquidity constraints and risk preferences on the adoption of switchgrass and miscanthus by farmers. They conclude that switchgrass and miscanthus are less profitable than the traditional crops unless appropriate contracts are offered to farmers. But they do not explicitly solve for the optimal contract that would trigger production of switchgrass or miscanthus. While they consider heterogeneous characteristics of the farmers such as soil quality and uncertainties, they do not consider initial investment as a sunk cost and irreversibility of these investments.

As mentioned above, when farmers have a tightened budget, they may also be more interested in contracting with processors in that contracting could allow them to access greater capital than without contracts. Bocqueho and Jacquet (2010) confirm that capital constraints affect EU farmers' willingness to grow switchgrass and miscanthus.

2.2.5 Assuring Production to Specification

With greater innovative manufacturing technology and deeper legislation on food safety and other requirements, processors today often request products with certain characteristics, which may not exist in the market otherwise. Therefore, quality and quantity control are important factors in contracts. Manufacturers could rely on contract farming to obtain products that meet their specific needs. Rehber (1998) shows that contract farming is a mechanism for buyers to gain control over specific commodity characteristics. Not surprisingly, a processor could gain such control either by setting a higher predetermined price for producers through marketing contracts or signing production contracts with farmers under specific production provisions.

Goodhue et al. (2003) shows that protecting quality is an important motivation for vertical integration. They study wine grape production contracts in California and find that formal contracts are more widely used with high quality wine grape growers. Moreover, the content of contracts for high quality grapes and low quality grapes are different. The contracts for high quality grapes often stipulate production practices that affect subtle wine attributes while for low quality grapes stipulations are for easily identified properties such as sugar content. Hennessy and Lawrence (1999) also document the importance of quality in the hog production contract design. They survey the industry participants and find that quality is a key determinant in the reorganization of the hog industry.

Sykuta and Parcell (2003) surveyed contract design structures in identity-preserved, nongenetically modified soybean production. They also documented the importance of using contracts to guarantee the quality of soybean. The contracts used to produce identity-preserved, GMO-free soybeans pay farmers a premium per bushel provided GMO content is below a specified threshold. In order to prevent contamination from other crops, the contracts also include a list of production and management such as filling certification forms, ensuring harvest, transportation, and storage equipment is appropriately cleaned and storage facilities are clearly marked for segregation from other crops, minimum border row widths of 20 feet to reduce cross-pollination potential.

2.2.6 Environmental Consideration

Environmental consideration is another factor on which contracting parties may diverge. Eaton and Shepherd (2001) explain that contractors often are interested in a single crop, while producers frequently manage a multicropping system. Moreover, producers bear most of the cost and effort to comply with environmental legislation. As a result, contract farming allows a contractor to achieve environmental considerations by tapping into the producers experience with the local ecology.

Ogishi et al. (2003) use animal waste pollution to demonstrate why contract farming could lead to over production and why legislation should take into account industry reform. Under current regulations, small farms are not penalized for their livestock production. However, contract farming integrates the production possibility of those farms which leads to over production for the society as a whole and makes the regulation ineffective. Morvaridi (1995) found similar environmental risks in contract farming in Cyprus.

3 A Theoretical Perspective on Contract Farming

3.1 Why Different Forms of Contracts Exist

Extending the investigation of contracts, economics ask why different forms of contracts exist. Isn't there a uniform formula that could guarantee the optimal welfare for both parties involved in the contract? Our discussion thus far shows that different contract forms address different motivating factors of all parties involved. For example, marketing contracts better address price stability while production contracts allow the producer to address credit concerns and the manufacturer to address environmental issues. We summarize these conclusions in Fig. 1.

Cheung (1969) first addressed the question of different contract forms by comparing fixed wage, land lease, and sharecropping contracts. He argues that fixed wage or land lease contracts could bring about lower transaction costs, while sharecropping (or profit-sharing) contracts lead to risk sharing. Consequently, trade-off between risk-sharing and transaction costs becomes one of the determinants for which type (or mixture) of contracts to use. However, Rao (1971) used

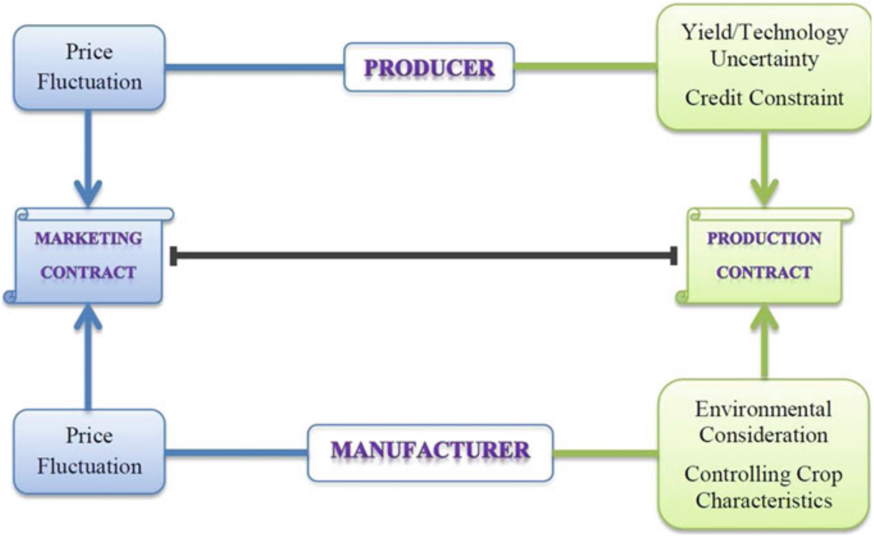

Fig. 1 Factors that generate different contract forms

sharecropping data in India to empirically test this statement and the results were not in favor of Cheung's arguments. Stiglitz (1974) explained the existence of multiple types of contracts by introducing asymmetric information and claimed that the different forms of contracts help contractors to sort the farms' abilities which is unobservable for the contractors. But, Eswaran and Kotwal (1985) argued there is no reason to believe that in most rural areas, the assumption of ignorance of farmers' ability is inappropriate. Yet, an important contribution of Stiglitz (1974) is showing that fixed wage or land lease contract could exist if and only if farmers or producers are risk neutral. Moreover, Cheung (1969) looks at contracting from a risk-sharing perspective while Stiglitz (1974) adds effects of asymmetric information in his analysis.

Later works are more in favor of the following explanation: the nature of randomness or constraints that different parties face determines the type of contract chosen. From this perspective, Stiglitz (1974) viewed the unknown producers' inner ability as the dominating risk faced by a contractor. Recently, Yang et al. (forthcoming) discuss the importance of asymmetric information, such as land quality, which is known to farmers but unobservable for processors. Another type of risk involves risk in output quality over time. Martinez (2002) observed that, in the poultry sector, lower transportation distances are advantageous to reduce time to slaughter, thus reducing weight loss and risk of egg contamination. As a consequence, the tighter relationship between manufacturers and producers leads to the predominance of production contracts. In pork industry, however, such timeliness is not necessary which partly explains the existence of other forms of contracts. In other contexts, Allen and Lueck (1995) found that when risks come from yield variation, high-variance crops are often grown under fixed price contracts whereas low-variance crops are produced using sharecropping contracts.

Tsoulouhas and Vukina (1999) analyzed the effect of manufacturer size on the choice of contract forms and found that large manufacturers could bear more risks resulting in greater use of production contracts than for small manufacturers. This finding confirms the claim in Stiglitz (1974) that a risk averse contractor bears a lower share of the risk. Finally, many processors choose to hold a portfolio of contracts. Buccola and French (1979) simulate the expected utility maximizing portfolios of three different pricing contracts that a tomato processing cooperative, tomato growers, and a tomato paste distributor would hold under price and output uncertainty and show that a risk averse firm prefers to hold two or three price contracts simultaneously given price and output uncertainty.

3.2 A Mechanism Design Perspective

Contract theory seeks to explain contract design and analyze equilibrium and welfare outcomes. Contract theory is a subfield of game theory, focused in large part on issues arising from incomplete and asymmetric information. Alexander et al. (2012) provide a comprehensive review on (static) contract theory and explain its

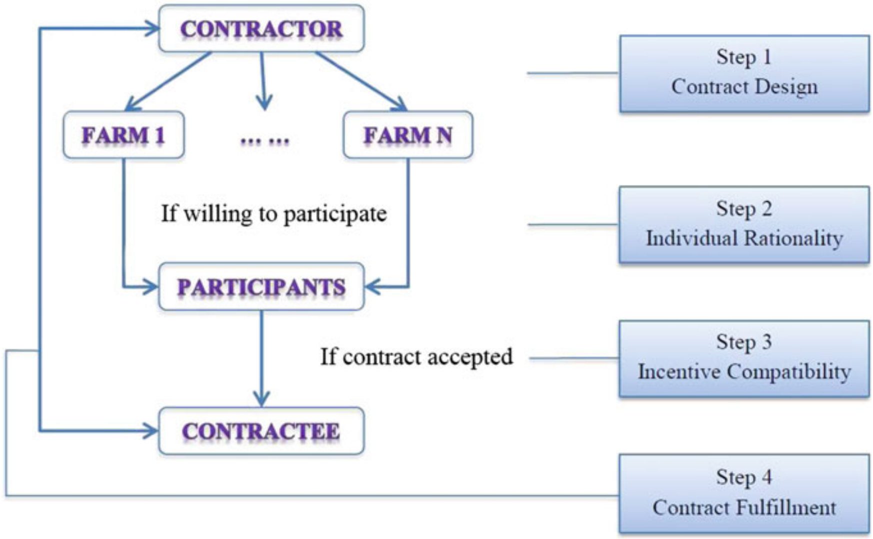

Fig. 2 Illustration of contracting process

implication in perennial energy crop production. The design of a contract typically has four steps (Fudenberg and Tirole 1991): first, the principal designs a contract or mechanism to maximize his expected payoff; second, the agent chooses if he will participate in the mechanism (this is the so-called participation or individual rationality constraint); third, all the agents that choose to participate simultaneously decide if they will accept the mechanism or not; forth, agents accepting the mechanism will fulfill the contract. The contracting process is illustrated in Fig. 2. Contract design should consider the participation constraint and the incentive compatibility constraint (Khanna and Zilberman 2012). The latter constraint suggests that contractors should provide growers an incentive greater than they can earn absent the contract. It should also be noted that although the contract is offered in the first step, the designer of contracts should derive the optimality condition in a backward fashion (known as backward induction). This means the contractor determines the type and conditions of a contract that targeted participants will be willing to sign the contract.

A strong result given by Green and Laffont (1977), well known as the revelation principle, indicates that when designing a contract in order to maximize expected payoff, the contractor should consider only those mechanisms that (a) are incentivize compatibility with all the willing-to-participate agents and (b) make all agents self-willingly reveal any private information they have in the process of fulfilling the contract. This finding significantly reduces the time for searching for optimal contracts. In fact, as pointed out in Alexander et al. (2012), an optimal contract can be obtained when the marginal cost from tightening one constraint (either incentive compatible or participation) meets the marginal benefit of relaxing the other.

Both Khanna and Zilberman (2012) and Alexander et al. (2012) address the issues of ‘moral hazard and ‘adverse selection’, which are problems when asymmetric information is present. The key issue is that when growers can have hidden moves or private knowledge about the crops being produced, they may utilize such asymmetric information to gain ‘information rent’. For example, the situations described in Stiglitz (1974) and Yang et al. (forthcoming) are such that producers have private information on their productivity and land quality, respectively.

Other examples may involve improper use of designated inputs. An optimal contract design considers these factors and may approach them through incentive payment and tournament payment when using contracts.

There are other gaps in the field of contract farming. For instance, Khanna, Zilberman and Miao (this book) observe the absence of discussion on technology diffusion in contract farming. Technology adoption is a key factor to stabilize crop price and quality. Nevertheless, it is evident that farm size has an impact on farmers’ decision to adopt a technology; evidence on the direction of this impact is however mixed and technology-specific (Khanna et al. forthcoming). In contract negotiation with smallholders, technology inducing contract or technology adoption could benefit both parties in the long run. Although, we observe that production contracts are dominant in livestock production and are less common in other areas of agricultural production (MacDonald and Korb 2011), it remains unclear under what conditions marketing contracts or production contracts will be used. Nor do we know if any sector-specific factors determine the dominating type of contract in that sector.

4 Biofuel Feedstock Contracting

4.1 Characteristics of Feedstock

The growing concern on both energy security and climate change has increased demand for alternative energy sources. Although traditional energy crops such as corn and sugar cane provide an alternative energy source, such inputs are also important food sources and feedstock for major livestock. This triggered the so-called food versus fuel debate, which impacted prices of these energy crops, at least in the short-run (Zilberman et al. 2013). Second generation energy crops address institutional, political economic, and efficiency considerations. Dedicated perennial crops, especially switchgrass and miscanthus, have been found to be ideal feedstock for biofuel production, and in some cases co-products such as fine chemicals and fiber (Khanna et al. 2008). However, adoption of switchgrass and miscanthus requires an establishment period in which no return can be expected (Bocquého 2008). Moreover, technology availability (for production and processing), nonexistent output markets, and lack of institutional support (e.g., credit, insurance) are additional barriers to the establishment of these feedstocks.

Table 2 Comparison of yields in different parts of U.S

Region	Miscanthus	Lowland variety of switchgrass	Upland variety of switchgrass	Corn stover	Wheat straw
Atlantic states	31.6	16.4	10.9	2.60	2.18
Midwestern states	23.8	10.2	9.5	2.86	2.23
Plain states	19.8	11.0	7.3	2.36	1.42
Southern states	30.2	15.2	10.1	2.50	1.95
Western states				3.29	2.11

Source Chen (2010)

A detailed estimation on the yield and production cost of switchgrass and miscanthus can be found in Chen (2010). Table 2 gives a summary of estimated yield of different feedstocks in different locations of the U.S. Intra-crop yield could vary considerably across location and land quality. Further, the cost structure of these feedstocks is quite different. In order to reach adequate supply levels, switchgrass most likely will require dedicated land on these crops (i.e., no inter-cropping or multicropping), thus introducing cost of land into its total cost estimation. In the case of corn stover and other crop residues, the cost is only the additional effort on collecting residues. Moreover, the rate of conversion of these feedstocks to productive end use varies greatly. All of these critical characteristics of feedstock imply that commercial scale second generation feedstock production will require dedicated refineries. Thus, in business model design, stability of input supply will require adequate compensation to address these risks and sources of uncertainty.

Yoder (2010) compares four different types of contracts based on degree of stochastic dominance. The results from this study suggest the $/acre plus yield bonus contracts reduce farmer risk the most, followed closely by the $/acre contract. Moreover, the contracts that compensate farmers on a $/acre basis in the establishment stage and then on a $/ton basis in the remaining years reduces risk more than the $/ton contracts. In fixed price contracts, farmers need to bear yield risks, while they need to bear yield risk and market risk in the indexed contract. The combination of both yield and market risk results in a substantial increase in standard deviations of the indexed contracts. It is shown that a per acre base payment plus per ton payment can significantly reduce production risk to farmers by shifting yield risk to the plant and indexing contracts significantly increases investment risk to both farmers and biorefinery while reducing default risk.

4.2 Farmers' Willingness to Grow Energy Crops

Recall that a successful contract design requires consideration of farmers' individual rationality constraint. That is, in order to provide an incentive compatible contract, contractors have to first make sure that farmers are willing to participate in the contractual relationship. Therefore, understanding farmers' willingness to grow energy crops becomes urgent.

A survey by Smith et al. (2011) in Minnesota shows that in order for farmers to be willing to supply biofuel feedstock, it is important that the net income yielded from growing biofuel feedstock must be at least high enough to compensate for loss of their current net income. The authors summarized that, if expected income does not decrease, then 48% of farmers in the survey would be willing to produce short rotation woody crops while 72% would be willing to produce perennial grasses. Only 17% of the respondents would be willing to grow perennial grasses under lowered expected income. They also explained that the reason of farmers preferring grasses to short rotation woody crops may come from the fact that the latter crop needs longer commitment time, longer return periods, more specific machinery, and cost of reconversion. Another survey that aims at understanding willingness to grow switchgrass for farmers in 12 southern states is provided by Jensen et al. (2011). Their survey results imply that farm size, ability to create jobs, on-farm storage, and off-farm income are positively related to farmers' interest to join in a contractual relationship while conflicts in planting and harvest time generates negative impacts. Villamil et al. (2012) found empirical evidence in Illinois that potential biofuel users have much higher willingness to grow energy crops. Both Villamil et al. (2012) and Ostwald et al. (2012) conclude that an important barrier for farmers to adopt feedstock production is the lack of relevant knowledge of the crop.

A choice experiment conducted by Paulrud and Laitila (2010) in Sweden suggest that not only do farmers care about their expected income, they also take crop characteristics such as length of rotation period, machinery being used, and the impact of the crop on landscape into account. Moreover, they found that contract form has insignificant influence on farmers' planting decision, but farmers' age, farm size, and geographical area are important determinants.

Besides impact on income and crop characteristics, Fewell (2013) and Bergtold et al. (2014) find that contract length, cost share, financial incentives, insurance, and custom harvest options are also important contract attributes for farmers in Kansas to be willing to grow advanced biofuel feedstock such as corn stover, sweet sorghum, and switchgrass. Khanna et al. (forthcoming) look at the disincentives for energy crop production. Using a choice experiment in five states in the Midwestern and South-central regions of the US, their results suggest that high discount rates, up-front establishment costs, and crop-specific investments are factors that reduce incentives for farmers to adopt energy crops.

4.3 Policy Impacts

Current U.S. biofuel policies take many forms: mandates require that the supply of retail fuel must be mixed with certain percentage of biofuel (the blend wall) and USDA has set aside conservation land at no cost for farmers to produce second generation biofuel feedstocks. Finally, subsidies on first generation biofuel have been discontinued recognizing that producers have been able to operate at profitable level.

Changes in the agricultural sector show that in order for governments to achieve certain policy goals, they must take into account structural changes in agricultural production. Otherwise, the effectiveness of policies becomes limited. For example, Ogishi et al. (2003) found that one of the reasons for limited effectiveness of policies aiming at protecting water quality is that the policies are not adjusted to the structural change in livestock production where contractual relationships have become a dominant business model.

4.4 Optimal Biofuel Contract Design

As claimed in Vermeulen and Cotula (2010), there is no single contract form, nor single business model, that will promise a successful supply chain. Contract design has to incorporate numerous factors such as the nature of the crop, availability of technology, demographic factors, and contractor and contractee characteristics. Based on earlier discussions, we provide some general guidelines as follows.

The optimal decision-making for manufacturers begins with identifying the ideal type of feedstock in the given region. At this stage, manufacturers should be aware of the yield potential and relevant processing costs of different crops and their relative adverse effects on landscape. At the same time, it is crucial to figure out the machinery cost for planting the feedstock even if the cost is not covered by the contract.

Then, the manufacturer must assess the benefits and costs between in-house production and contract farming. In the case of vertical integration, manufacturers simultaneously decide the optimal size of processing facility, which determines the processing capacity and the optimal level of land to be purchased for feedstock growing. Another important choice for manufacturers to make is technology adoption, which affects the manufacturer's immediate cost structure and has dynamic impacts. Namely, technology affects future decision making since the maturity of advanced technology will lower production uncertainty which may increase farmers' willingness to be involved in contract farming. Therefore, the benefit of adopting more advanced technology is not merely potential higher yield of feedstock but also discounted sum of future gain in yield and in lowered uncertainty. Under vertical integration, processors should pay special attention to the credit constraint they face while both exogenous spot market price risk and productivity uncertainty should also be assessed.

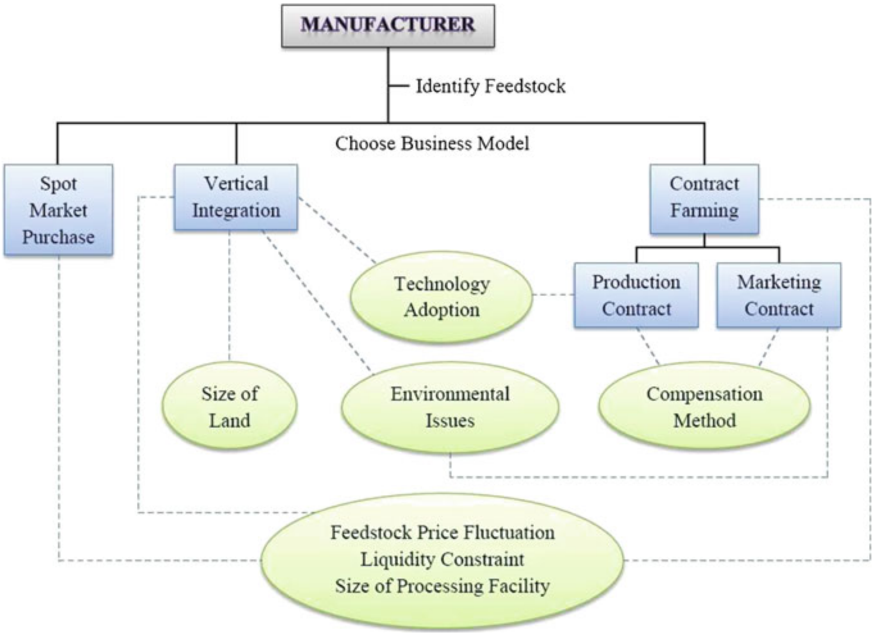

Fig. 3 Manufacturer's decision tree

When contracting is most desirable, the manufacturer should gather information on growers' current income level and keep in mind that no matter what contract is to be provided, the farmers' profit margin cannot be lower than their current level. The specific contract form will depend on farmers' attributes such as the size of the farm, risk attitudes, and their liquidity condition as well as nature of the feedstock such as its rotation period and adverse effect on the landscape. Moreover, the manufacturer has to look into specific government policies on feedstock production, ecological regulations, and government payment for instance. An illustration of manufacturer's decision tree is demonstrated in Fig. 3.

Recent articles such as Yang et al. (forthcoming) assess the optimal contract design for biofuels. Their results suggest that farmers possessing low land quality have better incentive to grow biofuel feedstock since their opportunity cost of producing such crops are relatively lower than farmers with high quality lands. They also demonstrate that as farmers become more risk averse, they prefer fixed price contracts so that the risk of output price is shifted to manufacturers. Heterogeneity in farmers' risk attitudes suggests that multiple forms of contract should be made available to producers to fit risk profile.

The high level of uncertainty about feedstock production suggests that there may be few farmers that are willing to grow the feedstock; it may be more cost effective for the refinery to undertake in-house production or purchase the feedstock on spot market. Although in-house production implies higher initial cost, as processors accumulate knowledge on production technology, production contracts may become plausible because of the effect on lowering production quantity uncertainties over time and attracting potential contract farming.

An interesting question in biofuel contracting is whether a cooperative will emerge in the bioenergy crops production sector and substitute part of the function of contracts. Cooperatives are found in many areas and in a wide range of agricultural sectors. Cooperatives are institutions owned by farmers and the goal is to maximize total welfare of its members. Cooperatives can be considered as fully vertically integrated institutions providing incentives to its members since it repays them all the profits from vertically integrated production.

Recently, EPA passed a rule, which allows for cellulosic biofuels made from two invasive species, Arundo donax (giant reed) and Pennisetum purpureum (napier grass) to qualify for credits under the Renewable Fuel Standard (RFS). To reduce the risk of invasiveness of these feedstocks, EPA also requires additional registration, recordkeeping, and reporting efforts. To be more specific, EPA requires that renewable fuel producers demonstrate that the growth of these invasive grasses will not pose a significant potential of spreading beyond the planting area or that such a risk will be minimized through an EPA approved Risk Mitigation Plan (RMP). The RMP includes a wide variety of plans including plans for early detection and rapid response to potential spread, best management practices, continuous monitoring and reporting of site conditions, site closure and post-closure monitoring, and identification of a third party auditor who will evaluate the performance of the RMP on an ongoing annual basis.

A crucial question here is how to use agricultural contracts to minimize the potential of invasiveness of these grasses to guarantee the benefits of introducing these species outweigh the harms to the local ecosystem. Scott and Endres (2013) claim that careful contract design can help protect landowners' property from spread of invasive species. They propose several practical contracting strategies to combat the challenge of invasiveness of these feedstocks, such as a neutral third party should determine whether or not an invasion has occurred because farmers may hesitate to acknowledge the invasion if they have to bear the cost of plant eradication. Prevention requirements should also be incorporated into the contract, such as establishing and maintaining a minimum 25-foot setback or border around feedstock stand to allow for monitoring and management of spread, covering biomass during the transportation process and disposing excess live plants at the edge of field, in field borders or in landfills. In addition, contract terms should also be clearly defined, such as what constitutes invasion, what constitutes eradication, who should take financial and physical responsibilities of eradication in the event of invasion. The bioenergy crops production contract should be a long-term contract based on transaction cost theory because the production involves large relationship-specific investments such as planting and harvest equipment and skills. A long-term contract is a way to protect both parties and their assets.

5 Concluding Remarks

In this chapter, we first looked at the existing types of contracts in agriculture sector and focused on the two dominating types: marketing contracts and production contracts. We compare the difference between vertical integration and contracting farming. Past literature has shown that factors such as randomness, overcoming constraints, assuring production to specification, and environmental consideration are some main reasons for contract farming. Disadvantages include the risk of defaulting and loss of farmers' independence. We then observe that different types of risks faced by different parties and farm size are some factors that could explain why multiple forms of contracts exist.

From a contract theory perspective, we notice that a successful contract design requires the contractor to keep in mind the individual rationality constraint and incentive compatibility constraint. Also, renegotiation proof condition has to be satisfied if the contract is used in a repeated manner.

In Sect. 4, we looked at some mature contract relationships in other sectors especially the case of production contracts in broiler sector and marketing contracts in fresh fruits and vegetable sectors. Meanwhile, we summarized some important farmer attributes and nature of crops that will enhance farmers' willingness to grow biofuel feedstock.

In the last section, we show that a refinery's business model depends on differences in contracting parties' management effort, and generates different optimal contracts. In the biofuel context, land quality and farmers' risk preferences are important, as are dynamic impacts due to technology adoption. We conclude that modeling optimal contract design must incorporate impacts of technology adoption and vertical integration.

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Part IV
Conclusions

Conclusion

David Zilberman, Madhu Khanna and Ben Gordon

Abstract Agriculture, while one of the oldest industries, has had a high rate of technological change during much of the twentieth century. Every few decades a new sector is added to agriculture and affects the rest of the agricultural sector, primarily by adding a competing demand for land and affecting the prices of crops. The biofuel sector was introduced within the past 30 years and expanded during the first two decades of the twenty-first century. It is a major part of the bioeconomy, which can be broadly defined as "one based on the use of research and innovation in the biological sciences to create economic activity and public benefit," as described by the US White House, National Bioeconomy Blueprint (2012). With the advance of modern molecular biology, the bioeconomy has expanded from the production of food and fiber to also include fine chemicals and energy, and is likely to grow further. This handbook overviews and analyzes some of the major aspects of the biofuel sector. It also provides a framework to analyze and address other sectors of the bioeconomy and the economics and policy associated with new industries in general.

Keywords Biofuel policy · Biofuel environmental impact · Brazil · United States

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D. Zilberman (✉) · B. Gordon
Department of Agricultural and Resource Economics,
University of California at Berkeley, Berkeley, CA, USA
e-mail: zilber11@berkeley.edu

B. Gordon
e-mail: benjamingordon@berkeley.edu

M. Khanna
Department of Agricultural and Consumer Economics, University of Illinois
at Urbana-Champaign, Urbana, IL, USA
e-mail: khanna1@illinois.edu

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1 The Biofuel Sector in the United States and Brazil

The first section of the book provides an overview of the modern biofuel sector in two countries, the United States and Brazil. It includes the history of the sector (in Chapter "US Biofuel Policies and Markets" for the U.S., Chapter "The Sugarcane Industry and the Use of Fuel Ethanol in Brazil: History, Challenges and Opportunities" for Brazil), its regulation, and a short summary of its impacts (in Chapter "US Biofuel Policies and Markets" for the U.S. and Chapters "Incentives and Barriers for Liquid Biofuels in Brazil" and "Prospects for Biofuel Production in Brazil: Role of Market and Policy Uncertainties" for Brazil). It emphasizes the importance of heterogeneity and diversity within the biofuel sector. In particular, the biofuel sector relies on different types of feedstocks that are used to produce multiple types of fuel (mostly ethanol and biodiesel). The selection of feedstocks and biofuel type vary by location, reflecting differences in biophysical, bioclimatic, and socioeconomic conditions.

The results from both the US and Brazil suggest that the factors motivating the development of the biofuel economy in both countries were largely similar. High energy prices, domestic fuel security, and balance of trade considerations played an important role in the establishment of a biofuel sector in both countries. In the case of Brazil, lack of foreign currency reserves for the import of fuel sources prompted the creation of a domestic gasohol industry that sold ethanol blended gasoline. When energy prices were low in the late 1980s, the Brazilian government almost abandoned the biofuel sector. But in response to rising energy prices after Desert Storm in 1991, support was renewed and the flex-fuel car was introduced. With the rising energy prices during the new millennium, support continued, but the interest in biofuels lost its primacy when Brazil discovered its own oil reserves and more recently with the decline in global oil prices. In the case of the US, the major drivers were the rising energy prices in 2005 and concern about a worsening balance of trade in 2007–2009.

There was a difference in the role of environmental considerations in the establishment of the biofuel sectors in both countries, which has led to circular trade of biofuels between the two countries. In Brazil, environmental considerations have not played any explicit role in the development of biofuels while in the US, different types of biofuels have been mandated based on their greenhouse gas (GHG) intensity. The Renewable Fuel Standard (RFS) in the US sets quantity mandates for different types of biofuels that are categorized based on their GHG intensity relative to gasoline. The Low Carbon Fuel Standard (LCFS) in California sets a target for reducing the GHG intensity of transportation fuel and encourages the use of lower carbon biofuels, such as sugarcane ethanol produced in Brazil. This has led to trade shuffling between US and Brazil with the US exporting the relatively lower cost corn ethanol to Brazil and importing the higher cost but less carbon-intensive sugarcane ethanol from Brazil.

Roles of the government were very similar in both countries in terms of setting policies but in Brazil the government also actively participated in developing the retail infrastructure for distribution of hydrous ethanol and promoting growth of flex-fuel cars. Brazil created government programs to address fuel security and balance of trade concerns. When Brazil was ruled by a dictatorship, command, and control was used to initiate investment in biofuel infrastructure and the government fixed the price of oil sold domestically. After the transition to democracy, market forces played a more important role but the recent socialist government has used energy policy to reduce inflation, as well as to achieve certain distributional outcomes.

In the US, government mandates and subsidies provided the incentive to expand the biofuel sector since 2005. The government assured demand for biofuels by establishing mandates and subsidizing investment in refineries early in the life of biofuels. The US government recognized the limited capacity of the US to produce first generation biofuel, which uses corn, sugarcane, and other food crops, and therefore provided strong incentives (subsidies and tax credits) for second-generation biofuel, which processes cellulosic materials from grasses and wood production. One major difference is that Brazil was able to avoid the blend-wall (the upper bound on concentration of ethanol in fuel) while in the US that has become a binding constraint that is now leading the US EPA to scale back the mandate for corn ethanol. Easing the blend-wall by allowing conventional cars to use higher concentration blends and supporting the development of infrastructure to market fuel with high ethanol content (e.g., E85) as well as a shift in the vehicle mix to flex-fuel vehicles are two avenues to increase adoption of ethanol in the US. However, neither is likely to be introduced given the current economic climate with low oil prices.

Agribusiness played similar roles in both countries as the agricultural sector provided significant support in favor of a growing biofuel sector. Biofuel was an important avenue to expand the sugarcane sector in Brazil and increase its income. In the US, biofuels led to the growth of income and earnings of the corn sector and triggered rural development. Biofuel mandates in the US and Brazil implicitly penalize oil consumption while subsidizing biofuel consumption. As a result, the oil industry can be expected to oppose blending requirements for biofuels. However, in Brazil, the consumption of biofuels indirectly benefited the major state-owned oil producer, Petrobras, by freeing up oil that could be exported to the world market at the international price that was often higher than the domestic price. As a result, the role and attitude of the oil industry to biofuel were different in the US and Brazil. The oil industry in the US opposed biofuels whereas in Brazil it tacitly supported it because the state-owned oil producer could be forced to increase biofuel production and benefit from it. The support of biofuels by the Brazilian oil sector was stronger earlier in the process when Brazil was a major importer of biofuel. But with the discovery of large reserves near its coast, the oil sectors' major priority became to develop this reserve and biofuels became a lesser priority. Petrobras gained from biofuel mostly as the provision of biofuel to the domestic markets allowed it to earn more income by exporting domestic oil (Khanna et al. 2016).

Both the Brazilian and the US experiences with biofuel policies hold several important lessons. First, the introduction of the biofuel sector had a significant impact on the rest of agriculture. One major concern was the impact of biofuels on food prices. This impact was especially salient in corn and soybean ethanol where biofuel production resulted in reduced acreage and other resources for the production of food for human consumption even though there was an increase in overall acreage of corn. The reduced supply of corn and grain for food/feed resulted in a significant increase in the price of corn and soybean, especially during 2007–2008 after the implementation of the RFS in 2007. However, this effect has dissipated over time due to increased production and market adjustments. The introduction of biofuels also tends to reduce gasoline prices and while biofuels may reduce GHG emissions compared to the fossil fuels that it replaces, the rebound effect may lead to added contribution of GHG emissions, which suggest that biofuel policies that aim to reduce GHGs need to be harmonized globally.

Second, the evolution of biofuels in both countries suggests the importance of technological change and innovations. Learning by doing reduced the cost of biofuels significantly in both countries over a span of two decades or so and increased conversion efficiency, which has resulted in a decline in the GHG emissions intensity of corn ethanol. The importance of technological change has been a major factor leading to policies that aim to support second-generation biofuels. However, at least in the case of the U.S. biofuels mandate, the expectations of fast breakthroughs that will make second-generation biofuels more cost effective within 10–15 years were not fulfilled and realistic understanding of the technology and its capacity are important elements of policies that enhance technological change.

Third, the history of biofuels in both countries shows the importance of policies that enhance both demand and build up supply. The government in Brazil initiated and mandated the building of infrastructure for the distribution of anhydrous and hydrous ethanol and initiated policies that led to rapid expansion of flex-fuel cars in the vehicle fleet. It also created demand for biofuels through mandates, fuel taxes and credits. The U.S. government subsidized research on biofuel technologies, as well as investments and tax credits for biofuel refineries. In addition, mandates, fuel taxes and tax credits were introduced to explicitly and implicitly penalize the consumption of gasoline and reward the consumption of biofuels. Analysis of biofuel policies also indicates that some policies perform better than others on various performance metrics, emissions reduction, terms of trade improvement, energy security, and welfare gains.

Fourth, the evolution of the biofuel sector shows the importance of market forces. The biofuels sector thrived during the period of high energy prices and reached crises during periods of low energy prices. There is a limit to the effectiveness of government policies; these policies are much more effective under the right economic environment. The biofuel sector has inherent instability because it is dependent on both food and fuel prices and biofuel refineries are prone to experience significant variability and fluctuation in prices. For example, during periods of high feedstock and low energy prices refiners may lose money, while during periods of high energy and low food prices they are significantly profitable. Thus, investment in the sector is likely to increase when some degree of profitability is assured. This explains the important role of various types of mandates in establishing the biofuel sector in both the US and Brazil. In addition, it suggests the potential role of crop insurance and futures markets, especially in the case of second-generation biofuels. The historical case analyses in the first section and their lessons provide an important background to some of the more detailed discussions in the rest of the book.

2 The Impact of Biofuels on the Environment: Methodologies and Findings

Section two presents some of the methodologies used to quantify the impact of biofuels on the environment, in particular GHG emissions and land use change, as well as the results obtained using these techniques. Much of the research on biofuels has been directed at these concerns and is presented in this section. Because of the importance of environmental considerations and the scientific challenge associated in assessing them, introduction of new sectors in the bioeconomy will benefit from conducting this type of research as well as refinement of methodologies employed. There are several major questions associated with assessing the environmental impact associated with biofuels along with different methodologies to address them. We will address some of them below.

2.1 Relevant Environmental Impacts

Production of biofuels may affect various indicators of environmental quality including water quality, land quality, biodiversity, etc. But since the major motivation to introduce biofuels has been reduction of GHG emissions, it becomes the most important environmental impact of biofuels considered by policy makers. An understanding of the impact of biofuels on GHG emissions also requires an understanding of its impact on land use. The land use effects are also important because they are strongly correlated with impacts on biodiversity. This impact on biodiversity is one driver for the special concern of the impact of biofuel on deforestation, in particular in the Amazon. The analysis in Chapter "Empirical Findings from Agricultural Expansion and Land Use Change in Brazil", for example, suggests that the impact of sugarcane ethanol on deforestation in the Amazon is minimal while the impact of soybean production on the savannahs in Brazil is significant. There is evidence that biofuels also affect water quality, such as the deposition of nitrates, as well as water availability. All environmental impacts of biofuels depend on the feedstock used, biophysical characteristics of its location, and method of production, and these choices are affected by economic conditions and policies (Chen and Khanna, Chapter "Land Use and Greenhouse Gas

Implications of Biofuels: Role of Technology and Policy"). For example, the nutrient runoff of perennial feedstocks, such as miscanthus, is lower per unit of energy produced than corn ethanol (Housh et al. 2015).

The analysis in Chapter "Lessons from the ILUC phenomenon" suggests the need for research on all the environmental impacts of biofuels to assess their magnitude and dynamics. The reality of implementation is complex and some of these impacts, for example on water quality, may be adequately addressed by existing regulation. In other cases, the cost of measurement and implementation may outweigh the benefit of additional regulation. In theory, the regulatory challenge is to develop implementable polices that enhance social welfare, measured by discounted net social benefit taking into account the cost of implementation and enforcement. Quite often political reality does not allow introduction of first best policies and much of the policy analysis in this book is of policies implemented or considered by policy makers. Because GHGs are a major global problem, the GHG impacts of biofuel (and the related land use effects) are likely to be part of their environmental impacts everywhere, and therefore have been emphasized in this book.

2.2 *The Use of Life-Cycle Analysis (LCA) for Biofuel Policy*

In an ideal world, the GHG effects of biofuel should be addressed by penalizing carbon emissions throughout the supply chain of biofuels. But in reality the GHG effects of biofuel have been regulated downstream in the supply chain and under existing regulations the sellers of fuels are accountable for the GHG emissions throughout the biofuel supply chain. This reality necessitates the use of a technique like life-cycle analysis (LCA). This technique requires a proficient understanding of the processes used at each stage of the supply chain, including and transportation. Ideally regulation would be based on GHG emissions per unit of energy of biofuel at the micro-level, but these impacts vary across heterogeneous producers and are difficult to monitor and regulate. Policy analysis relies on representative estimates of the direct GHG emissions and on measures of indirect effects estimated at the macro-level. The latter are aggregate estimates of coefficients, measured at either the regional or country level and vary for different feedstocks used for biofuel. One of the major challenges of LCA is to develop practical and accurate aggregation procedures to obtain meaningful estimates. Current LCA practices have been developed within the context of engineering. Much of LCA is attributional, meaning it acts as an accounting system to allocate the environmental side effects of activities to the different stages of production. But consequential LCA is needed for biofuel policy, as well as environmental regulation, because it takes into account the market-mediated or indirect effects on GHG emissions that are caused by the food and fuel price changes as a consequence of biofuels displacing food and fuel production. The attributional LCA approach however assumes fixed proportion technologies in which the input–output ratios are not sensitive to market forces. It does not consider the potential for GHG emissions per unit of energy or fuel to change over time as a result of technological changes and in response to changes in prices. The analyses in both Chapters "Biofuel Life Cycle Analysis" and "Lessons from the ILUC phenomenon" recognizes that the technology coefficients must be adjusted both to reflect changes in prices as well as innovation that leads to changes in key coefficients.

2.3 The Inclusion of Indirect Effects of Biofuel in LCA

One of the major challenges in the application of LCA to regulate biofuels is the inclusion of indirect effects, and in particular, indirect land use change (ILUC). Early LCAs of biofuel assumed a fixed technological coefficient that relates input to output at the various stages of the supply chain leading to production and use of biofuels. The weighted sum of these coefficients captures the direct environmental effect of biofuels. For example, the direct GHG emissions effect of one unit of biofuel is represented by the net GHG emissions associated with the production inputs, such as fertilizers, growing and processing of feedstocks, conversion of these feedstocks to fuel and transportation of feedstocks and fuel at different stages of production. The direct gain from biofuels thus reflects the difference between the GHG emissions associated with producing the biofuel subtracted from the direct emissions associated with the production of its fossil-based alternative.

The work by Searchinger et al. (2008) suggested that when the allocation of land to biofuel production increases the price of corn it leads to an expansion of acreage allocated to its production, which further increases GHG emissions. These extra emissions are the ILUC effect of biofuels. The original estimates of ILUC by Searchinger et al. (2008) suggest that biofuels are a net contributor to GHG emissions. However, much of the research in Chapters "Effect of Biofuel on Agricultural Supply and Land Use"–"Land Use Change, Ethanol Production Expansion and Food Security in Brazil" raises doubt about the magnitude of Searchinger's findings and provides alternative results, as described below.

The ILUC effect of biofuels is not the only market-induced indirect effect of biofuels. There may be other market-mediated effects of biofuels on GHG emissions. For example, the introduction of biofuels changes the supply of transport fuel, which may affect the price of fuel as well as the use of fossil fuels (Rajagopal et al. 2011). The exact magnitude of this indirect fuel use change (IFUC) effect depends on the type of policy used and pricing mechanisms. The extent to which this and other indirect effects are included in LCA for policy purposes is a major policy decision. One objection to the use of IFUCs is that the indirect effects are not technical externalities (where the managerial decisions cause the damage) but rather pecuniary externalities mediated through the market. However, similar market-mediated effects are considered in design of other policies (Zilberman et al. 2011). There is strong justification for including these effects if they are large and can be estimated with a high degree of confidence. There is less justification for their inclusion if their average effect is small and highly uncertain and the computation and regulatory costs are high.

The computation of the ILUC effect is challenging for several reasons. First, the ILUC of different biofuels may vary because of differences in the feedstock, location, and agronomic practice (Chen and Khanna, Chapter "Land Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy"; Beach et al., Chapter "Modeling Bioenergy, Land Use, and GHG Mitigation with FASOMGHG: Implications of Storage Costs and Carbon Policy"), and the type of co-products produced. The extent to which this variability is recognized in decision-making depends on the trade-off regulators are willing to make between regulatory precision and cost of implementation.

Second, to incorporate ILUC coefficients for regulations such as the RFS and LCFS, it is useful to compute the annualized coefficient (GHG/unit of energy/year). However, the GHG emissions due to the ILUC of biofuels vary substantially over time compared to the emissions of direct effects. For example, deforestation may cause large, immediate GHG emissions while the emissions of feedstock production and processing are more evenly distributed over time. The discounting of damages of GHG emission over time is also not straightforward. These issues require further research—and while agencies need to rely on the best knowledge available in determining their regulatory procedure to compute ILUC coefficients, these coefficients may change with new understanding of ILUC dynamics.

A third challenge associated with incorporating ILUC into regulation is the high degree of uncertainty of these impacts, which are only simulated, but cannot be observed and measured directly. Estimates vary by methodology of the model employed (whether it is a computable general equilibrium model, positive dynamic programming, or partial equilibrium; whether the model is static or dynamic), assumptions used (regarding key parameters such as elasticities of supply and demand), etc. There is a growing tendency to report the distribution of estimated impact (e.g., a confidence interval around each mean), and policymakers may make choices that will reflect their risk aversion (O'Hare and Plevin, Chapter "Lessons From the ILUC phenomenon". The variability and uncertainty of ILUC estimates have led to substantial research effort. However, extent to which ILUC effects should be used in policy is still an open question. The EU currently does not consider ILUC while the US does take it into consideration. Much of the analysis in this section of the book covers the methods used and magnitudes of ILUC coefficients assessed.

3 The Impact of Biofuels on Land Use

The estimated impacts of biofuel on land use and other environmental impacts depend both on the method used for analysis, and the policies used to induce production of biofuels. One major conclusion of several of the studies on the impacts of biofuel on land use is that these impacts evolve over time and thus use of static ILUC analysis may lead to biased results that overestimate the ILUC effects of biofuels.

Most of the literature on ILUC of biofuels consists of numerical simulations of mathematical models based on expert opinion rather than empirical estimates of key parameters, such as input/output coefficients and elasticities (Khanna and Crago 2012). These models tend to be static and depict outcomes within a narrow timeframe. But, economic development and conversion of land use among activities are dynamic processes that evolve over time and a long-term perspective on this evolutionary process can provide fuller understanding of timing and location of changes in land use in response to the introduction of biofuels. The impact of biofuels on land use change will vary across location because of differences in land availability and current uses that are a result of historical processes. It is important to keep in mind that at each location land resources are finite. The conceptual dynamic models in Chapter "Effect of Biofuel on Agricultural Supply and Land Use" suggest that agricultural development tends to begin with an expansion of the agricultural land base (extensive land use) and then in an increase in productivity through investment in variable inputs and technology (intensive land use). For example, the work of Cochrane (1979) suggests that throughout the eighteenth and especially nineteenth century production in US-based agriculture expanded mostly due to an expansion of land use, while yield per acre did not increase much; while during the twentieth century, the vast majority of yield increases were driven by intensification driven by investment in equipment and research as well as increased use of fertilizer and irrigation. Overall land use in agricultural crop production peaked in the 1920s and declined to a small degree thereafter. Historically, significant rises in agricultural prices led to major investments in increased supply and resulted later on in reduced food prices. Thus conceptual analysis suggests that the increased demand for agricultural products associated with biofuels would lead to changes both at the extensive and intensive margins. In countries where there is significant opportunities to expand crop land, the increase at the extensive margin will be substantial, while regions that are close to constraints of arable land the expansion of agricultural land use for crop production will be limited. The GHG emission effects of expanding agricultural crop land is likely to be much smaller if the conversion is from pasture to crop rather than forest to crop.

Some countries are close to reaching their practical limit of land suitable for agricultural use (China, India, EU, and US) and thus in these countries much of the impact of biofuels is through intensification. For example, land in the Conservation Reserve Program in the US is one of the only sources of extra land available for expansion of corn ethanol. Yet, there are vast tracts of unutilized, arable land in Brazil and Africa. In Brazil, much of this reserve is used for extensive grazing. Thus, the conceptual analysis and stylized facts in Chapter "Effect of Biofuel on Agricultural Supply and Land Use" suggest that the magnitude of ILUC is likely to be small relative to direct effects of biofuels.

Indeed, research following the work of Searchinger et al. (2008) showed that they overestimated the ILUC of biofuels. The estimate of ILUC tends to decline as the number of sectors included in the analysis increases, when technological change in feedstock production and processing is introduced, and when the GHG benefits of coproducts from biofuels, for example Distillers Dried Grain Solubles (DDGS), are considered (Khanna and Crago 2012). Chapter "Global Land Use Impacts of U.S. Ethanol: Revised Analysis Using GDyn-BIO Framework" develops a dynamic computable general equilibrium (CGE) framework, called GDyn-Bio, to analyze ILUC and compares their results to the static CGE model called GTAP-BIO, which has been used to assess the impact of biofuels within California's Low Carbon Fuel Standard. They compare the two models to assess the mandated expansion of U.S. ethanol production between 2004 and 2030 within a global context that includes land use for crop production, pastoral land, and forest. Compared to the static model, their dynamic analysis indicates a lower expansion of cropland over time because of (i) technological innovation, (ii) introduction of intensification possibilities in all sectors, including food processing, livestock, and forestry, (iii) lower long-run supply response elasticities to crop prices, and (iv) accumulation of physical and human capital over time. Their analysis suggests that the inclusion of dynamic considerations will reduce average land use expansion compared to the static model by more than half and the reduction will be especially significant during later years of the process. Since the static model that is used by California has ILUC coefficients that are a quarter or less of the magnitude of Searchinger's figures, incorporating dynamic considerations would result in ILUC coefficients that are one-tenth of Searchinger's figures.

Two empirical studies of the ILUC of the Brazil biofuel program support the results of the conceptual analysis. The multi-period CGE model presented in Chapter "Land Use Change, Ethanol Production Expansion and Food Security in Brazil", finds that the deforestation resulting from the biofuel expansion will be very small (0.02%) compared to deforestation in a baseline analysis. The chapter also finds that each hectare expansion of sugarcane production may lead to of 0.08 hectare of cleared forest. These estimates are smaller than those of previous CGE models, which did not incorporate dynamic considerations and some of the major features of agriculture in Brazil in terms of technology and regional heterogeneity. The chapter finds that the targeted increase for ethanol production in 2022 (by 37 million liters) will result in a larger increase in production than overall land use of sugarcane. The model recognizes that increased ethanol production will lead to intensification of production and growth of capital, a small reduction in areas of other crops and reallocation of land among crops. The chapter also finds that since agriculture is intensive in less skilled workers, increased biofuel production will have a positive effect on rural income and the income of the poor and their consumption levels. Most of the land expansion resulting from increased biofuel will come from conversion of land from pasture to farming. This is not surprising, given that Brazil's pastureland is 2.5 times as large as cropland; and sugarcane is likely to expand in regions with high reserves of pasture land.

Chapter "Empirical Findings From Agricultural Expansion and Land Use Change in Brazil" estimates find that including dynamic considerations in modeling land use change reduces the GHG emissions of sugarcane ethanol in Brazil (direct and indirect combined) by 1/3 from 21.5 gCO_2/MJ to 13.9 gCO_2/MJ. The dynamic version of the Brazilian Land Use Model (BLUM) is a partial equilibrium multi-product and multi-market model that incorporates specific features of Brazil not counted in previous models. These include multiple cropping, environmental legislation, and technological and capital accumulation in both the crop and livestock sectors, and technological and resources change over time. These extra features of modeling suggest that as biofuel production increases, there is a relatively larger reliance on changes at the intensive margin rather than the extensive margin, so that less land will be needed for each incremental increase in biofuel production. In addition, the expansion of the biofuel area will be mostly into pasture land, with low impact on tropical forest. Their estimates reflect the role of regional heterogeneity and stricter enforcement of environmental regulation in explaining the reduced level of ILUC. This enforcement resulted in significant reduction of deforestation during 2005–2010 when biofuel expanded. Yet, the estimates of ILUC due to ethanol production in Brazil presented in Chapter "Empirical Findings From Agricultural Expansion and Land Use Change in Brazil" are consistent with those of other recent studies and suggest that the early studies of ILUC due to ethanol ignored technical and institutional adjustments and overestimated these impacts.

Another important conclusion is that the land and environmental impacts of biofuels are policy dependent. Chapter "Land Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy" applies a dynamic, multi-market, nonlinear mathematical programming model (BEPAM), to compare the impact of several policy designs aimed to achieve the objectives of the Energy Independence and Security Act of 2007 (EISA) that requires the blending of 136 billion liters of biofuels with petroleum fossil fuels by 2022, while setting a limit on use of corn ethanol. Their analysis suggests that changes in policy design results in a different composition of the biofuel portfolio and distribution of land among activities. It further results in a different pattern of commodity prices and distribution of impacts among groups and in meeting policy objectives. They found that the use of the RFS by itself would result in the largest increase of corn and soybean production and prices, while contributing the least to the reduction of GHG emissions among the policies considered. The production of second-generation biofuels, in particular miscanthus, will increase when the RFS is combined with a subsidy for second-generation biofuels or under the LCFS, where biofuels are priced based on their GHG emissions factor. These two policies will result in the largest reduction in US GHG emissions per liter of biofuel produced. Because second-generation biofuels are very expensive, a low carbon tax is unlikely to incentivize their production. Instead it achieves a reduction in GHG emissions by raising the price of gasoline compared to the benchmark.

While Chapter "Land Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy" does not compute ILUCs explicitly, it relies on other studies to estimate the rebound effects, reflecting the responses of other countries to the changes in food and fuel prices due to US biofuel policies. When these effects are taken into account, the global GHG emissions reductions due to US biofuel policies are much smaller. This finding is consistent with the finding of Rajagopal et al. (2015) and suggests that the impact of biofuels policy unilaterally by one country is significantly diminished due to the countervailing responses of the rest of the world. This situation suggests the importance of international agreements that would harmonize biofuel policies so that they can reinforce one another. Another related conclusion from Chapter "Land Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy" is that while second-generation biofuels are appealing due to their significant contribution to GHG emission reductions, their economic viability is limited without subsidies. Thus there is a further room for research and development to reduce their processing cost in order to make them more economically competitive even under moderate carbon taxes.

Another important lesson of this section is to consider a wide range of technology options in assessing biofuel policies. In particular, it stresses (i) the importance of including storage costs in assessing the impact of alternative biofuel policies and (ii) that policy analysis should consider a wide range of sources of feedstocks, including both agricultural and forestry products as well as use of feedstocks to produce both liquid fuel and electricity. Chapter "Modeling Bioenergy, Land Use, and GHG Mitigation With FASOMGHG: Implications of Storage Costs and Carbon Policy" applied FASOMGHG, a dynamic model of the forest and agricultural sectors, to assess the impacts both of storage costs and carbon price on the choice of biofuels in agriculture and forestry to achieve the renewable energy use targets of EISA 2007. Because feedstocks are cumbersome and voluminous, and feedstock producers have different degrees of freedom with regards to the timing and location of harvest, some feedstocks, such as sugarcane or miscanthus, have much higher storage costs than forest-based feedstocks. If the biofuel targets are pursued without pricing carbon, storage costs will increase the share of miscanthus relative to crop residue in the production of second-generation biofuels because it has a longer harvesting window. Adding in a carbon price will increase the share of biofuel derived from the forest sector compared to agriculture and the use of biofuel to produce electricity rather than in the production of transport fuels because of the larger GHG emission gains associated with replacement of fossil fuels, such as coal.

The analyses of the impacts of biofuels on ILUC and GHG emissions were conducted using a diverse set of models with different sets of assumptions and covering different products, locations, and time frames. While the authors present several consistent conclusions, they also suggest that there is a continuous challenge to integrate different models and databases to develop mechanisms that allow models to speak to one another and allow for a more complete set of findings as well as improved verification of reliability and consistency of results. Furthermore, with the uncertainty regarding model parameters and structures, it is important to develop further studies that would allow for more rigorous assessment of the range of reasonable outcomes one can expect under different predictions.

4 Overcoming Constraints on Introducing Cellulosic Biofuels

As the importance of cellulosic biofuel has increased, the interest in using energy crops, such as miscanthus, switchgrass, etc., as feedstock to produce it has risen. Chapter "Land Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy" shows that energy crops like miscanthus and corn stover can produce significant amounts of energy with a relatively small land footprint. The use of such crops is likely to expand the potential utilization of biofuel while reducing the tradeoffs between food and fuel. However, production of biofuel from energy crops is raising several challenges. They include the technical challenges of converting energy crops to fuels, and the efficient production, harvesting and transport of these feedstocks. Also important are the institutional challenges of establishing policies and incentives that will induce farmers to invest in producing cellulosic feedstock and in establishing refineries. Establishment of new industries like cellulosic biofuel may require the creation of diverse supply chains that integrate production and processing of feedstock. These incentives are provided in part by the government and others by refineries through contracts or other arrangements.

Chapter "Contracting in the Biofuel Sector" presents an analysis of the establishment of a refinery that suggests that three key questions are the size of the refinery, the extent of in-house feedstock production, and the strategy for purchasing additional feedstock. These decisions depend on resource ownership, credit constraints, risk aversion, geography, and institutional arrangements. When the organization that establishes the refinery owns sufficient land, then vertical integration of production and processing is optimal. But if the feedstock required by the processing facility is larger than the in-house production, then the processor needs to rely on external sources of feedstock. For example, in the case of corn ethanol in the US, refineries typically rely on existing markets to source feedstock. But in the case of second-generation, perennial biofuels, refineries may need to sign contracts with farmers who commit to invest in providing the feedstock. The challenge of contract design is to address the uncertainty of future prices of feedstock and biofuel, as well as performance of farmers. The rich literature on contract farming provides criteria to guide establishing incentive compatible contracts to obtain feedstock. But the implementation of such contracts remains a challenge. Therefore, refineries may benefit from insurance mechanisms and futures markets for biofuels. Further, government intervention in terms of mandates and/or subsidies may be required to assure sufficient production capacity if social benefits are not fully captured by the private sector.

Chapter "Innovation in Agriculture: Incentives for Adoption and Development of a Supply Chain for Energy Crops" emphasizes that successful introduction of biofuels required the recognition of heterogeneity across locations, targeting the regions where they are likely to be profitable compared to other land uses. Inducing landowners to grow energy crops, especially perennials, will remain a challenge because of the time lag between planting and harvesting, and the uncertainty about yields and prices of the feedstock. Therefore, locations where yields of energy crops are high, while the yields and profitability of traditional crops are low (and therefore land prices are low), are most appropriate for production of energy crops. This means that significant amounts of miscanthus and mostly switchgrass have good potential in the southern states of the US. Corn stover is naturally more likely to be produced mainly in the Midwest and the Great Plains. Miscanthus may be able to compete with food crops in parts of the Midwest and the Great Plains if energy prices are sufficiently high.

Both Chapters "Innovation in Agriculture: Incentives for Adoption and Development of a Supply Chain for Energy Crops" and "Effects of Liquidity Constraints, Risk and Related Time Effects on the Adoption of Perennial Energy Crops" emphasize that adoption of perennial energy crops will be constrained by liquidity and risk considerations. These two issues are related—risk of technology and prices as well as performance of the farmer makes it difficult for lenders to assess creditworthiness and therefore provide capital for investment. Moreover, the capacity to use the land and other assets associated with investment in perennial crops as collateral is limited because of the uncertainty about the value of the investment, especially when perennial crops are planted on land that has low alternative use. Thus commercial credit limitation may stymie the development of perennial energy crops unless there is sufficient self-finance or government programs are established to address these issues.

Even when credit is available, risk and risk aversion are likely to reduce the willingness to invest in perennial energy crops. Since investments in many of these crops are irreversible and the price of biofuels and feedstocks fluctuate, Chapter "Effects of Liquidity Constraints, Risk and Related Time Effects on the Adoption of Perennial Energy Crops" emphasizes that one may expect significant investment in biofuels during periods when prices of fuel and biofuels are high and the expected payback period is relatively short. Given the variability of fuel, food, and input prices, one may expect, without intervention, an unstable industry with periods of boom and bust.[1] Furthermore, given that the processing cost of cellulosic biofuel is relatively high, the industry is likely to remain small without further research and development to lower the conversion costs of biofuel production.

Both the liquidity constraints as well as the uncertainties about energy crops may require government intervention if there is social gain in establishing these policies. These societal values will depend on the potential for biofuels to reduce GHG emissions, improve water quality, and enhance energy security, as well as by the recognition that the cellulosic biofuel industry is in its infancy with the potential to gain from the process of learning by doing and learning using associated with utilization of these emerging technologies (Khanna and Crago 2012). Social intervention may be in the form of subsidies for investment in perennial energy crops as well as price support, mandates, investment in R&D, and investment in infrastructure.

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[1] This is consistent with the analysis of Hochman et al. (2008). This paper presents a situation in the U.S. before the introduction of the Energy Independence and Security Act of 2007.

5 Concluding Remarks

The various chapters of this book demonstrate that two biofuel sectors—corn ethanol in the U.S. and sugarcane ethanol in Brazil—have emerged and achieved maturity. Political economic motivations led to the establishment of these industries and they reflect different weights given to energy security, reduction of GHG emissions, food security, and biodiversity. The analyses also suggest that there is significant potential to increase the production of biofuels both in the form of sugarcane in Brazil as well as through the introduction of cellulosic biofuels. However, the evolution of the industry and its future depends heavily on government policy choices. Selection of policy instruments depends also on regulatory procedures and measurement criteria. While political economic considerations have and will continue to weigh heavily on policy choices, the analysis in this book suggests that some policies have resulted in significant unintended effects on food and fuel markets. Policies that augment market processes and reflect societal values on measurable outcomes, for example a carbon tax, tend to result in more efficient outcomes. It also seems that there is societal gain from investment in research to improve the production and processing of biofuels. However, the political economy implications may not be desirable, nevertheless, the various chapters of the book were able to identify policy designs that allow for the improvement over current policies both of economic welfare as well as of other societal objectives. Nevertheless there remains a large space for future research that informs policy choices as new information is discovered.

The book also suggests that one of the main constraints for the development of the biofuel sector is the debate about ILUC. The bulk of the analysis in section two suggests that the early estimates of ILUC were overestimated and that the lion's share of the GHG emission impact of biofuels is captured by its direct effects. Thus, it is likely that sugarcane ethanol and some forms of cellulosic ethanol (especially as their processing becomes more efficient) will make significant contribution to reduce GHG emissions; while corn ethanol will continue to make a modest contribution to reduce GHG emissions compared to the fossil fuels it replaces. Thus, GHG emission considerations should not serve as barriers to further utilization of biofuel technologies but should rather be incorporated in policy design so that biofuel feedstocks can be rewarded based on their relative merit.

While the analysis of this book suggests that the magnitude of ILUC is rather modest, other rebound effects through fuel markets are quite significant. Since climate change is a global issue, local policies that aim to address climate change may be less impactful. This prompts the need to develop a coordinated framework in order to achieve the common goal of reducing GHG emissions globally.

One of the important features of biofuels is that their production requires a sequence of processes that are carried out by several industries. Therefore, unlike more traditional analyses of environmental and resource issues, the analysis in this book emphasizes decisions made along supply chains and their design. In particular, an understanding of the economic considerations of alternative designs of a supply chain is important for the adoption and evolution of different forms of biofuels as well as design of policies to induce and regulate the biofuel sector. Understanding supply chains also serves to develop a more comprehensive and effective life-cycle analysis of the various impacts of biofuels. The emphasis on supply chains and interconnectedness between different segments of the biofuel sector can provide insights and lessons for analysis of other sectors of the economy.

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