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S. Niggol Seo

Micro-Behavioral Economics of Global Warming

Modeling Adaptation Strategies in Agricultural and Natural Resource Enterprises

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Preface

This book presents the foundation of the micro-behavioral economics of global warming. An empirical model, named the G-MAP model (geographically scaled microeconometric model of adapting portfolios in response to climatic changes and risks), is developed and applied to observed decisions of agricultural and natural resource enterprises in sub-Saharan Africa and South America. Major findings from the five versions of the G-MAP model are explained coherently throughout the book: the G-MAP animal species, the G-MAP agricultural systems, the G-MAP natural resource enterprises, the G-MAP climate risk, and the G-MAP public adaptations.

The micro-behavioral economics of global warming and the G-MAP models are evaluated against the three alternative modeling traditions each of which is known to have some level of limitations in capturing adaptation behaviors. The first is the Agro-Economic Models (AEMs) that are based on crop simulations or field experiments on selected crops under elevated CO_2 conditions. The second is a family of econometric studies of grain yield changes caused by yearly weather fluctuations. The third is the Agro-Ecological Zone (AEZ) methods in which the impacts of global warming are entirely hinged upon the AEZ classifications.

The author casts a fresh look at the traditional economics of global warming by unraveling a great array of adaptation strategies adopted by individuals who manage agricultural and natural resource enterprises in sub-Saharan Africa and South America. The book demonstrates the nature of the micro-behavioral economics as a cohesive dynamic integration of multiple disciplines, including economics, psychology, climate science, ecosystem studies, agronomy, and animal science, into the decision-making framework of one who makes decisions. The G-MAP models will provide a guide map of adaptation strategies to humanity's enduring journey of battling global climatic changes in this century and beyond.

The author began working with Prof. Robert Mendelsohn at Yale University in the summer of 2001, and the fundamentals of the micro-behavioral economics were established by May 2006 through the present author's PhD dissertation at Yale University titled "Modeling Farmer Responses to Climate Change:

Measuring Climate Change Impacts and Adaptations in Livestock Management in Africa" (Seo 2006). The empirical model of the micro-behavioral economics was later named the G-MAP model (Seo 2010).

For the development of the field this book engages, Prof. Robert Mendelsohn has been the primary intellectual force in the background. The seed of the micro-behavioral economics was sown when the highly influential Ricardian analysis was published two decades ago by him and his colleagues (Mendelsohn et al. 1994). Professor William Nordhaus, a frontiersman in the economics of global warming and a distinguished scholar of the economics of many big social issues (Nordhaus 1977, 1991), has given over the years not a few kind encouragements and critical comments. Like many scholars in the profession, I am grateful for his far-sighted guidance. The World Bank supported both projects of climate change in Africa and Latin America from which rural household surveys that are used for this book were collected. In particular, I am thankful to Prof. Ariel Dinar, lead economist at the World Bank then.

This book will turn out to be a thought-provoking treatise to those who are grappling with the unprecedented challenges posed by the advance of global warming. To many more contemplative readers, this book will come as a witty essay on how human beings should get along with natural beings, presented through the looking glass of global warming (Thoreau 1854, Leopold 1949, Carson 1962).

Dabo Hall, November 2014 S. Niggol Seo

Keywords Micro-behavioral economics of global warming · Adaptation to climate change · G-MAP model · Agricultural and natural resource enterprises · Sub-Saharan Africa · South America

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About the Author

S. Niggol Seo Professor is a natural resource economist who specializes in the study of global warming. Born in a remote rural village in South Korea in 1972, he studied at a doctoral degree program at the University of California at Berkeley and received a Ph.D. degree in Environmental and Natural Resource Economics from Yale University in May 2006 with a dissertation on micro-behavioral models of global warming. While at Yale, he learned from Robert Mendelsohn and William Nordhaus on the economics of global warming. Since 2003, he has worked with the World Bank on various climate change projects in Africa, Latin America, and Asia. He held faculty positions in the UK, Spain, and Australia since 2006. Currently, he is Professor of Environmental Studies at Nalanda University, the oldest University in the world and one of the most influential institutions in human history revived recently by the East Asian Summit. He can be reached at niggol.seo@aya.yale.edu.

Chapter 1
Introduction to the Micro-behavioral Economics of Global Warming

Abstract This chapter provides an introduction to the book which presents the Micro-Behavioral Economics of global warming with applications to adaptation decisions made by individuals who manage agricultural and natural resource enterprises in Sub-Saharan Africa and South America.

Keywords Global warming · Micro-behavioral economics · Adaptation · Sub-Saharan Africa · South America · Ecosystems

During the past half century, climate scientists have reported a steep increase in the atmosphere in the concentration of Carbon Dioxide, a major byproduct of burning fossil fuels for industrial activities and cutting forests (Keeling et al. 2005). During the same time span, global average temperature has risen gradually in an ups-and-downs fashion by about 0.6 °C from the 20th century average temperature (Hansen et al. 2006; IPCC 2014a). Concerns on the warming Planet have steadily increased over the past three decades as scientific knowledge have accumulated and been refined (IPCC 1990, 2001, 2014a).

Not far behind, policy efforts at the global level to contain the rising greenhouse gas emissions, including Carbon Dioxide, Methane, Nitrous Oxides, and Fluorinated Gases, from anthropogenic activities have gradually taken shapes and increasingly gained scientific and public supports (Nordhaus 1994, 2013; UNFCCC 1998, 2011a). While the world's citizens are still divided on how the humanity should meet the challenges from the warming Earth, concerned climate communities and policy circles have made arduous efforts to put together a global legal framework in which all the parties of the Convention take shared responsibilities in ensuring that the global temperature increase be kept under the 2 °C threshold while addressing justice concerns with regard to whom should bear the costs (UNFCCC 2011a).

Among the long list of concerns on the warming Earth, food security has remained to date at the very top of the list right from the twilight days marked by the establishments of the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC) (IPCC 1990, 2014a). Climate researchers as well as policy negotiators have

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placed agricultural vulnerabilities, along with sea level rises, at the forefront of the discussions on how harmful global warming will turn out to be to the global economy and the Earth's ecosystems (Adams et al. 1990; Cline 1992; Downing 1992; Rosenberg 1992; Rosenzweig and Parry 1994; Mendelsohn et al. 1994; Darwin et al. 1995; Pearce et al. 1996; Reilly et al. 1996). The focal point placed on agriculture and food security in the early days mirrored that of the Rome Club report which had questioned the sustainability of economic growth, i.e., whether the world can continue to feed its citizens, issuing a dire warning on the future of economic growth (Meadows et al. 1972).

Unlike the impact studies on sea level rises which had few disagreements among the economists, early debates on agriculture and food security have intensified over time, attracting a large number of researchers to the field. The debates, often contentious, have given rise to numerous major research initiatives around the globe which aimed at tackling varied aspects of the debates and sometimes developing new concepts and methodologies that can help resolve outstanding points of disagreement (see, for major reviews, Reilly et al. 1996; Mendelsohn and Neuman 1998; Gitay et al. 2001; Easterling et al. 2007; Hillel and Rosenzweig 2010; Dinar and Mendelsohn 2011; IPCC 2014b).

Over this time period, political, institutional, and economic environments have changed rapidly. As the first commitment period of the Kyoto Protocol signed in 1998 kicked in with binding emissions targets among the Annex 1 countries in 2008 (UNFCCC 1998), regulatory and financial implications of the research findings have become clearer. As such, recently participations of the international policy organizations have significantly increased, not to mention regional and national agencies (see, for example, recent reports from CEEPA 2006; PROCISUR 2007; FAO 2009; ADB 2009; IFPRI 2010; CGIAR 2011; World Bank 2011, 2012; White House 2013). On the horizon, policy interventions in agriculture and natural resource sectors loom large at the global policy landscape through, for just one example, the Green Climate Fund (GCF) which has been promised to be as large as 100 billion US dollars annually (UNFCCC 2011b; UN 2014).

With this background, one of the goals that the present author hopes to achieve is to provide a timely review of the literature on climate change and agriculture and food security in a pertinent manner to the on-going policy discourses. Given a large number of articles and reports written and still being written on the topic, it is a daunting task to produce a fair and illuminating review of the field. At the same time, be reminded that there is still not a comprehensive review on the topic, after more than two decades of extensive research and contentious debates. This task is vitally important and urgent.

In approaching this task, the author deviates from the most reviews available in the market such as the IPCC reports which are heavily tilted to the experimental studies and devises an innovative approach to synthesize a large variety of distinct models and often incongruous findings. To be more specific, the author classifies the past economic studies into one of the three categories based on the capacity of each model in accounting for and capturing adaptation behaviors. As such, adaptation itself will turn out to be the key economic and policy decision variable in this book, on top of numerous other secondary factors that are emphasized throughout the book for policy discourses.

The three categories of models are as follows. In the one category of modeling efforts, the author presents the Agro-Economic Models (AEMs) which are based on crop experiments in the laboratory or in the field but are known to have a limited capacity for including the effects of adaptations (Adams et al. 1990, 1999). In another category of modeling efforts, the author presents the G-MAP models (Geographically-scaled Microeconometric model of Adapting Portfolios in response to climatic changes and risk) which has the capacity to capture a full range of adaptation strategies (Seo 2006, 2010a, 2012a). The G-MAP models naturally followed from the original insights of the Ricardian model which argued in an influential manner that farmers are not dumb, therefore can substitute farming inputs in response to climatic changes efficiently in order to reduce the damages from global warming (Mendelsohn et al. 1994). In the capacity for accounting for adaptation strategies, somewhere in-between these two methodologies lies the third category of models: the econometric studies of grain yields with a focus on weather deviations. The yield studies have a partial capacity to include the effects of adaptations to climatic changes and have been popularly applied in several formats (Deschenes and Greenstone 2007; Schlenker and Roberts 2009).

Before we proceed any further, the present author wants to make it clear that the ultimate goal of this book is not to provide a comprehensive review of the field which is by itself an urgent task. The book goes beyond the task. The book presents the foundations for the micro-behavioral economics of global warming. The results from the G-MAP models which are empirical models of the micro-behavioral economics of global warming are presented in detail throughout the book. The distinguishing feature of the micro-behavioral economics and the G-MAP models is adaptation decisions made by individuals and sometimes at the community level in response to climatic conditions. The micro-behavioral economics is the central idea of the book from which all the other models and studies are strung together.

There isn't any particular personal reason that the literature should be reviewed with the framework of the three categories other than that the literature has developed "naturally" in that way. In fact, it can be a four-category classification if the author treats the ecosystem-based studies as a separate tradition. In a broad sense, a variety of methods that have been developed by economists and natural scientists to measure the impacts of climate change on agriculture and natural resources fall either into a physically-based model or into a behaviorally-based model. The physically-based studies are founded on controlled laboratory (or field) experiments on yield changes of selected crops under varied CO_2 conditions (Fisher 1935). The behaviorally-based studies are founded upon examinations of farmers' revealed preferences through changes in individuals' choices and resultant profits at the micro farm level under altered climatic regimes (Samuelson 1938).

The AEM researchers rely on the results from controlled experiments on selected major crops such as wheat, maize, rice, and soybeans and integrate the experimental results into a national Agricultural Sector Model (ASM) to simulate future impacts of climatic changes on agriculture (Adams et al. 1990, 1999, 2003; Reilly et al. 2003; Parry et al. 2004; Butt et al. 2005; Fischer et al. 2005). Controlled experiments are conducted through the crop simulation models such as the CERES (Crop Environment Resource Synthesis)-Maize/Wheat and the EPIC (Erosion Productivity Impact Calculator) or through the FACE (Free-Air CO_2 Enrichment) experiments in the natural growing environment (Jones and Kiniry 1986; Williams et al. 1989; Tubiello and Ewert 2002; Ainsworth and Long 2005).

Behavioral models are, on the other hand, built from detailed rural households' decisions faced with varied climatic conditions. These decisions are obtained from the rural household surveys collected across a large geographical area, e.g., the entire African continent or the South American continent, which is representative of a multiplicity of ecosystems in the study region (Seo 2006, 2010a, 2014a; Seo and Mendelsohn 2008). The micro-behavioral economic models can account for a full array of adaptation strategies and at the same time make them explicit through the models by making use of the revealed decisions (preferences) by the farmers themselves (Seo 2010a, 2012a, b).

While presenting the micro-behavioral models, this book sheds lights on the mutual relationship between the micro-behavioral economics and the ecosystem studies of global warming. An individual's decisions are motivated by, among other things, the changes in types and productivities of various ecosystems that are caused by shifts in the climate system. The micro-behavioral economics is a highly apt conceptual framework in which changes in individuals' decisions and changes in ecosystems can be comprehended in a coherent manner. This book provides a review of some of the ecosystem studies that have turned out to be illuminating for the micro-behavioral economic analyses in Sub-Saharan Africa and South America (Dudal 1980; Matthews 1983; Schlesinger 1991; Gitay et al. 2001; Denman et al. 2007). The present author will bring out throughout the book how ecosystem changes (and studies of ecosystem changes) are closely related with and mutually dependent upon behavioral decisions (Seo 2012b, c, 2014a). This is in turn to highlight the multidisciplinary integrated characteristics of the micro-behavioral economics framework.

In presenting the multidisciplinary framework with the G-MAPs, the present author emphasizes that ecosystem studies alone cannot be a useful tool for understanding or quantifying the impacts of climate change on agriculture (Seo 2014a). For example, the Agro-ecological Zone (AEZ) method examines the changes in the AEZs before and after assumed climate scenarios and then connects these changes in the AEZs with the changes in agricultural productions (Fischer et al. 2005). This methodology, however, cannot capture a wide variety of economic activities that are performed within and outside the AEZ classifications. Although ecosystem studies are meaningful and pertinent for understanding behavioral changes of individuals, inappropriate applications of them are also hazardous, which will be one of the key topics to be covered in Chap. 6 of the book.

The micro-behavioral economics and the G-MAP models have been developed to model adaptation behaviors to climate change in order to provide a 'guide map' of adaptation strategies under future climatic changes. One of the objectives of the book is naturally to provide detailed expositions of adaptation strategies in agricultural and natural resource enterprises. The focus is laid on Sub-Saharan Africa and South America, two continents which straddle the Equator and are most likely to suffer the brunt of climatic disruptions. In these low-latitude developing regions, adapting to climate changes is inevitable and particularly urgent for the farmers and natural resource managers (Mendelsohn 2012). This in turn implies that the applications of the micro-behavioral economics and the G-MAP models turn out to be most fruitful.

The expositions of agricultural and natural resource enterprises in Sub-Saharan Africa and South America are in itself one of the main objectives of this book. Many parts of these continents fall upon the places where high temperatures and/or arid conditions bedevil agricultural productions. As such, many researchers had associated, even before serious global warming debates began, a persistent low agricultural productivity in Sub-Sahara with adverse climate and soil conditions of the continent (Ford and Katondo 1977; FAO 1978; Dudal 1980; Driessen et al. 2001). Two thirds of the rural population in sub-Saharan Africa lives in unfavorable areas defined as arid or semi-arid zones (World Bank 2008; FAO 2012). Consequently, climate researchers believed that the impacts of climate change would be the most severe in these parts of the world (Reilly et al. 1996; Mendelsohn et al. 2006; Easterling et al. 2007). However, the micro-behavioral economic models unfolded that a great diversity of agricultural enterprises in Sub-Saharan Africa are present as the results of farmers' adaptations to climatic conditions over time (Seo and Mendelsohn 2008; Seo 2012c).

The emphasis on Sub-Saharan Africa and South America will lead the readers inescapably to the crossroads of climate change and economic development. Although agriculture accounts for less than 2 % of the Gross Domestic Product (GDP) in the United States, it provides a means of subsistence to a vast majority of rural households in the low latitude developing countries in Sub-Saharan Africa and Latin America (Byerlee and Eicher 1997; World Development Report 2008; World Bank 2009a). Agriculture employs more than 60 % of the economically active population in Sub-Saharan Africa while rural population accounts for 40–60 % of the total population in the Andean countries in South America (Baethgen 1997; FAO 2012). At the same time, about 1.8 billion people predominantly from the rural areas in these regions live under extreme poverty and with associated problems of diseases, hunger, and mal-nutrition especially of mothers and children (Sachs 2005; Black et al. 2008). Additional climate stresses may exacerbate these problems (Downing 1992; Rosenzweig and Parry 1994; Rosenzweig and Hillel 1998; UN 2000; Hertel and Rosch 2010). Another way to interpret this is that extensive development efforts in the past may have failed because of their negligence on climate and weather constraints (Byerlee and Eicher 1997; Evenson and Gollin 2003; Seo 2010a, b). The micro-behavioral economic models are good tools to highlight these development problems and draw future programs under climatic shifts which incorporate adaptive systems.

To sum it up, this book presents the foundations of the Micro-Behavioral Economics of global warming. The G-MAP models are empirical models of the micro-behavioral economics. The G-MAP models are applied to individuals' adaptation decisions in response to climatic shifts. The micro-behavioral economics and the G-MAP models are established in a multidisciplinary integrated framework in which individuals' decisions are coupled with climate science, ecosystem studies, animal science, and others. The G-MAP models are employed to model adaptation decisions in Sub-Saharan Africa and South America where vulnerabilities to global warming are high and ecosystems are most rich and complex. The micro-behavioral economics and the G-MAP models are placed and evaluated in the context of the alternative modeling efforts such as the Agro-economic Models, the econometric studies of grain yields, and the Agro-ecological Zone methods.

One final thought to which the readers will be led again at the completion of this book is that the micro-behavioral economics should be viewed at the level of the traditional economics of global warming. The latter recognizes global warming as negative externalities to the economy and proposes a carbon tax as a remedy to internalize them into economic decisions (Nordhaus 1977, 1994, 2013). The micro-behavioral economics provides an alternative way to frame the global warming problems and proposes adaptation strategies as the quintessence of the global warming solutions (Seo 2013b, 2015).

The book is composed of the following chapters. In Chap. 2, the author presents the theoretical foundations of the micro-behavioral economics of global warming as well as the specifics of the G-MAP models. In Chap. 3, major findings of the G-MAP models applied to Sub-Saharan Africa and South America are described. In Chap. 4, the author shifts the discussions to an experimentally-based approach, i.e., the AEMs and their major findings. In Chap. 5, the topic is shifted again to the econometric studies of grain yields and annual weather fluctuations. These two chapters will highlight alternative ways to look at the nature and importance of modeling adaptation behaviors in the G-MAPs. Chapter 6 is devoted to examining the interconnections between micro-behavioral changes of individuals and ecosystem changes both of which are conditioned by climatic changes. In this chapter, the author also provides a critical review of the impact studies based on the concept of the Agro-ecological Zones (AEZ) and the Length of Growing Periods (LGP). The final chapter, Chap. 7, summarizes the book briefly and provides the contexts of the book in the literature of global warming economics. The book concludes by describing policy implications of the micro-behavioral economics of global warming and the future of the field.

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Chapter 2
The Theory of the Micro-behavioral Economics of Global Warming

Abstract This chapter lays down the conceptual foundation for the micro-behavioral economics of global warming and describes its empirical model, the G-MAP (Geographically-scaled Microeconometric model of Adapting Portfolios in response to climate changes and risk) model.

Keywords Micro-behavioral economics · G-MAP · Selection · Climate risk

Micro-behavioral economics of global warming can be defined as the field of research on how individuals, individually or collectively, make decisions to cope with or adapt to changes in the climate system. It is founded on the long line of research efforts on how an individual makes economic decisions given specific circumstances and how these decisions affect markets (Samuelson 1938; von Neumann and Morgenstern 1947; Khaneman and Tversky 1979; Shiller 2003). It is the study of changes in individuals' behaviors in response to shifts in the climatic system (Seo 2006, 2010a).

Adaptation to global warming refers to changes in economic decisions by an individual or by a community of individuals in an effort to cope with changes in the climate regime (Mendelsohn 2000; Seo and Mendelsohn 2008a). An individual will adapt to climatic changes because it is economically sensible. That is, she/he will be able to avoid an otherwise large loss from global warming by adapting to it (Seo 2010a). Adaptation takes place efficiently at an individual level, barring negative or positive externalities. A public adaptation is the least cost approach if adaptation in question calls for a coordinated effort of a large number of parties (Seo 2011a). Adaptation will take place to cope with changes in climate means as well as changes in climate risk factors (Seo 2012b).

The micro-behavioral economics of global warming has taken shapes gradually in the process of quantifying the impacts of global warming on agriculture and natural resource enterprises. This is no surprise given that climate factors affect most visibly the farming and natural resource activities on the fields which are directly exposed to outdoor conditions. By contrasts, New York City is nearly fully

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air-conditioned in the summer and nearly fully heated in the winter while New Yorkers spend less than half an hour a day outdoors. That is, in agricultural and natural resource sectors changes in individuals' decisions in responding to climatic shifts are most prominent.

Even before global warming debates began at the international stage, researchers had examined how existing climate conditions have strong influences on agricultural productions especially in low-latitude developing countries (Ford and Katondo 1977; FAO 1978; Dudal 1980). In sub-Saharan Africa, agro-climatic conditions are adverse in most parts of the continent with two-thirds of the rural population residing in arid, semi-arid, and desert zones (World Development Report 2008). Annual rainfall is extremely low in many areas and only 4 % of the croplands in the continent are irrigated (Reilly et al. 1996; FAO 2012). Temperature, rainfall, and soil conditions influence agricultural activities by determining the length of crop growing periods of farming areas (Dudal 1980; FAO 2005). Climatic factors affect the outbreaks of crops and livestock diseases and their frequencies (Ford and Katondo 1977; Ziska 2003). A multi-decadal shift in rainfall in West Africa makes it difficult for farmers to grow crops successfully for a long period of time (Hulme et al. 2001; Shanahan et al. 2009).

In South America, farmers have adjusted their practices to the available pasturelands which are more than four times larger than the croplands in Brazil and even eight times larger in Argentina, which in turn depend upon climate regimes (Baethgen 1997). South American farmers earn about 35 % of their income from forest related activities as the continent has the largest forest cover in the world (defined as >50 % cover) which accounts for 44 % of the total land area in South America (WRI 2005; Vedeld et al. 2007). A highly volatile intra-annual variation in rainfall along the high Andes Mountain ranges has been considered as one of the big obstacles to farmers in Latin America who should adapt (Magrin et al. 2007).

Given these backgrounds, there is neither mystery nor surprise in that from the initial report by the Intergovernmental Panel on Climate Change, agriculture has been at the center of the debates on potential impacts of global warming, along with sea level rises. The initial report shows that the response function of plant growth rate (and net photosynthesis) to the range of temperature is a hill-shaped function with a peak (optimal) temperature beyond which it falls sharply, based on the existing plant science literature (IPCC 1990). Reflecting the steeply sloped quadratic yield response function, the first generation assessment models reported that one third of the total global warming damage in the US, including both market and non-market sector damages, will occur solely from the agricultural sector (Cline 1992; Pearce et al. 1996). The impacts on developing countries were reported to be twice as large as those expected in temperate climate region countries (IPCC 1990; Reilly et al. 1996, Rosenzweig and Hillel 1998). Further, early studies projected that people at the risk of hunger will increase by as much as 50 % (by 300 million people) under the United Kingdom Meteorology Office (UKMO) scenario by the year 2060 due to large price increases of staple crops (Rosenzweig and Parry 1994).

The early assessment models by and large had no capacities to model adaptation decisions, let alone capture them in their assessments (Mendelsohn et al. 1994). If today's agricultural decisions and productivities are so heavily dependent upon the current climate factors as these early studies were demonstrating, it is only natural to think that future decisions will also be changed if the climate factors are altered (Seo 2006; Seo and Mendelsohn 2008a). This is because agricultural and natural resource profits to a large degree arise from productivities and distributions of ecosystems which will be altered by climatic shifts (Seo et al. 2009; Seo 2014).

What changes do we expect in natural resources, ecosystems, or ecologies if the global climate system shall be shifted in the future? Experimental studies have made strides in answering this question over many decades. Climate changes would affect agriculture directly as well as indirectly (Reilly et al. 1996; Gitay et al. 2001). Increased CO_2 in the atmosphere alters the productivities of various ecosystems by affecting the photosynthetic processes (Schlesinger 1997). Elevation in carbon concentration increases crop growth in the approximate range from 17 to 35 % and net photosynthesis (Ainsworth and Long 2005; Tubiello et al. 2007). The yield increases are in general larger in C3 crops than in C4 crops.[1] Changes in climatic conditions such as temperature and precipitation patterns influence crop and plant growth, e.g., by altering growing seasons (Reilly et al. 1996; FAO 2005). An increase in climate variability also affects crop growth, which may cross a threshold for a certain crop variety (Easterling et al. 2000; Porter and Semenov 2005; Challinor et al. 2007). Temperature and precipitation changes modify the direct CO_2 elevation effects on crops (Easterling et al. 2007). The degree of vulnerability varies across the major crops such as wheat, maize, rice, soybeans, cotton, millet, cassava, sorghum, rubber, groundnuts, citrus, and cocoa among many species and varieties (Gitay et al. 2001; Ainsworth and Long 2005). Within a crop species, a more heat tolerant genotype, e.g., Indica rice, is sometimes discussed (Matsui et al. 1997). The degree of vulnerability depends on the associated limiting factors such as nutrient and water availability and plant-soil interactions in the field (Lobell and Field 2008). Changes in climate and CO_2 level also lead to the changes in growth and distributions of weeds, insects, and plant diseases that affect the conditions of agricultural lands (Patterson and Flint 1980; Porter et al. 1991; Sutherst 1991; Ziska 2003).

Over the past decade, animal systems have gained increasing attention. Animal husbandry accounts for 52 % of the agricultural value of sales in the US and 49 % of the farms in the country own livestock while the livestock sector is growing rapidly in developing countries (Delgado et al. 1999; USDA 2007; Thornton and Gerber 2010). In Africa and Latin America, more than two thirds of the farms own some livestock species (Seo and Mendelsohn 2008a, b). Farmers in sub-Saharan Africa own animals along with crops, but as much as 20 % of the South American farms specialize in animals (Seo 2010a, b). Major animals raised around the world

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[1] Most crops are C3 crops. Notable C4 crops are maize (corn), millet, sugar cane, and sorghum.

are beef cattle, dairy cattle, goats, sheep, chickens, pigs, donkeys, beehives, and horses while major animal products are beef, milk, butter, cheese, wool, and eggs, but animal portfolios differ across the continents (Nin et al. 2007; Seo and Mendelsohn 2008a; FAO 2009; Seo et al. 2010).

Changes in CO_2 concentration, temperature, and precipitation patterns all influence the productivities of animals both directly and indirectly (Johnson 1965; Baker et al. 1993; Hahn 1999; Parsons et al. 2001; Mader 2003; Mader et al. 2009). Climatic changes affect heat exchanges between animals and the environment, which then affect weight growth, milk production, wool production, egg production, and even conception rates (Amundson et al. 2006; Mader et al. 2009; Hahn et al. 2009). Heat tolerance of animals, however, may vary across animal species, i.e., some animals are more or less tolerant (Seo and Mendelsohn 2008a). A more heat tolerant breed of a species is often discussed, e.g., Brahman cattle (Bos Indicus) which are widely raised in Asia, the US, South America, and Australia or a mixed-breed (Hoffman 2010; Zhang et al. 2013). Changes in productivities of ecosystems due to global warming imply that animal husbandry can expand when grasslands increase by decreasing either forests or croplands (Viglizzo et al. 1997; Sankaran et al. 2005; Fischlin et al. 2007). Forage quantity, quality, and grazing behaviors can be altered by elevated CO_2 (Campbell et al. 2000; Shaw et al. 2002; Polley et al. 2003; Milchunas et al. 2005). Changes in precipitation patterns associated with a warming world may also alter the frequency and severity of livestock diseases such as Nagana (Trypanosomiasis) carried by Tsetse flies in Africa, cattle tick in Australia, and blue tongue that affects sheep and goats in Europe (Ford and Katondo 1977; White et al. 2003; USAHA 2008; Fox et al. 2012). An intensive livestock production system, in contrast to a pastoralist system, has more control on the exposure of animals to climate factors by utilizing barns and shelters, air conditioning, shading, and watering (Hahn 1981; Mader and Davis 2004). The former is, however, more dependent on alternative feed (e.g. grains from crop productions) availability than the latter (Adams et al. 1999).

The changes in biogeochemical processes and animal systems described so far in this chapter will inevitably lead to changes in behavioral decisions of those who are working in agricultural and natural resource enterprises. A micro-behavioral model of adaptation strategies starts with an individual farm, which is in a stark contrast to either the experimental models or the agro-economic models which starts with a single crop (Seo 2006; Seo and Mendelsohn 2008a). To put it differently, the micro-behavioral models are concerned with an individual's decisions whereas the other models are concerned with the changes in crops' natural characteristics.

Sampling is conducted across the entire region of concern, e.g., South America or sub-Saharan Africa, so that the model can encompass the full variety of farm portfolios of natural resources managed in the regional economy of concern (Seo 2012a, 2014). This also ensures that the full variety of agricultural and natural resource enterprises is captured by the model.

While the agro-economic models and the econometric studies of yields which are necessarily constrained to major grains such as wheat, maize, rice, cotton, and soybeans (Adams et al. 1990; Schlenker and Roberts 2009), the micro-behavioral models include all the major and minor grains, vegetables, oil seeds, fruits, tree products, and numerous animals and animal products that are managed across the entire region of the concern (Seo 2012a, 2014). In addition, a full variety of farms including commercial farming, family farming, subsistence farming, specialized farming, and integrated (diversified) farming are all included for modeling (World Bank 2009; Seo and Mendelsohn 2008a; Seo 2010a).

Viewed from the angle of ecosystem diversity, while the agro-economic models—these models are the primary subject of Chap. 4 of this book—are based on the experiments conducted on selected sites, or laboratories, located in a certain ecosystem, a micro-behavioral modeler randomly samples rural households from a large geographical space such as the entire African continent. Therefore, one can capture the full complexity of ecosystems or ecological zones that are present in the continent of research concern (Seo 2012a, b).

In Fig. 2.1, the present author maps the locations of household surveys collected across the African continent by the World Bank Project on climate change and

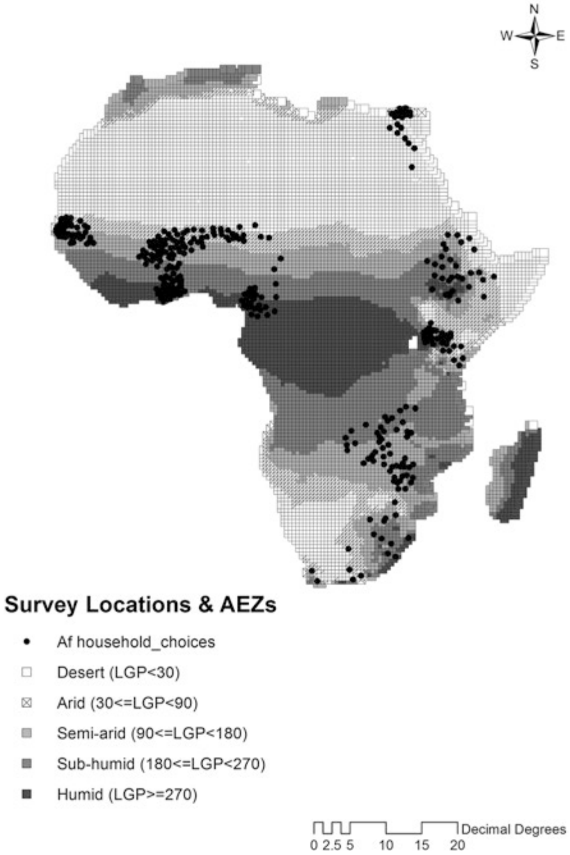

Fig. 2.1 African household surveys across agro-ecological zones

African agriculture (Dinar et al. 2008; Seo et al. 2009). Household locations are overlaid on top of the five Agro-Ecological Zones (AEZs) defined by the Food and Agriculture Organization (FAO) of the United Nations: deserts, arid, semi-arid, sub-humid, and humid zones (Dudal 1980; FAO/IIASA 2005).[2] Household surveys, as depicted by the black dots in the map, were collected from all the five AEZs which are located in eleven different countries across the five different subregions of Africa: Niger, Burkina Faso, Senegal, Ghana from West Africa; Kenya, Ethiopia from East Africa; Cameroon from Central Africa; Egypt from North Africa; Zimbabwe, Zambia, South Africa from Southern Africa. Survey locations also include high mountains such as the Kilimanjaro, lowlands in West Africa, grand rivers such as the Congo River, lake zones in East Africa, landlocked countries, and deserts such as the Sahara, the Namib, and the Kalahari (Seo 2012b).

In the micro-behavioral economics of global warming, given the external factors such as climatic and geographic conditions, a natural resource manager is assumed to maximize the long-term profit from managing agricultural and natural resources. Conditional on the external factors, she/he chooses a natural resource portfolio from the full variety of portfolios available and makes decisions on the inputs and outputs of productions in order to maximize the profit from the portfolio of choice (Seo 2006, 2010a).

If climate shall be altered from the current state to the future states owing to continued accumulation of greenhouse gases in the atmosphere resulting from ever-growing anthropogenic economic activities, the natural resource manager would adapt by adopting an agricultural portfolio as well as by altering the inputs and outputs of productions, resulting in the changes in the long-term profits earned from agricultural and natural resource enterprises.

Therefore, in the framework of micro-behavioral economics, researchers can reveal, among other things, or make explicit the following decision variables of great concern to global warming debates. First, they can show how the choices of natural resource portfolios are made currently and will be altered due to climatic shifts. Second, they can show how each of the agricultural and natural resource portfolios will suffer (or gain) from global warming in terms of the long-term profits earned over time. Third, they can show how the natural resource enterprises as a whole will fare under a variety of scenarios of global warming (Seo 2010b, 2013).

The empirical model of the micro-behavioral economics was named the G-MAP model short for the Geographically-scaled Microeconometric model of Adapting Portfolios in response to global warming) (Seo 2010a, 2011b). The rationale for the name is that the G-MAP model examines Micro behavioral adaptation decisions with econometric models, includes a full array of farm Portfolios in the analysis, quantifies explicitly Adaptation choices in the context of resultant profits, and is calibrated to integrate adaptation decisions with Geography and ecosystems. The G-MAP can further connote a guide map for adaptations to

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[2] A full description of the AEZ classification will come in Chap. 6. A more refined definition of the ecosystems of Africa is certainly possible and a number of alternative versions are already available (Seo 2013, 2014).

global warming, which was the initial motivation of the author in developing the model and its applications.

Henceforth, the present author provides a full description of the G-MAP model (Seo 2010a). A natural resource manager (n) is assumed to choose one of the agricultural and natural resource enterprises (j) to maximize the expected long-term profit (π), given exogenous factors. That is, her/his problem is written as follows:

$$ArgMax_j\{\pi_{n1}, \pi_{n2}, \ldots, \pi_{nJ}\}. \tag{2.1}$$

What are agricultural and natural resource enterprises? South America, more than anywhere else, provides an excellent case study for the diversity of rural activities and natural resource enterprises. In South America, a great large variety of crops, animals, and forest products is managed by the rural residents. A third of the total land area in South America is agricultural lands (World Resources 2005). Major crops planted are cereals such as wheat, maize, rice; oil seeds such as soybeans, peanuts, sunflowers; vegetables such as potatoes and cassavas; and various specialty crops such as cotton, tobacco, and coffee.

In addition to crop farming, animal husbandry holds much significance to South America rural areas. The continent is vastly occupied by the grasslands which differ in types and qualities. Pasturelands used for livestock are four to eight times larger than the croplands in major countries such as Argentina and Brazil (Baethgen 1997). Argentina and Brazil are the world's largest beef cattle exporters as well as the largest consumer of beef per head annually (Steiger 2006). Along with different varieties of beef cattle, most frequently raised animals are dairy cattle, chickens, pigs, goats, and sheep (Seo et al. 2010).

Besides crops and animals, forests and forest products are a vital component of the rural economy in South America. Much of the continent is covered by different types of forests (Matthews 1983). The Amazonia covers 7.5 million km^2 and is the world's largest pluvial forest (Mata and Campos 2001). Forest income may account for more than 20 % of the rural income in South America (Peters et al. 1989; Vedeld et al. 2007). People manage tree plantations for the sale of timber products, non-timber forest products, household uses, or even for carbon credits. Most common trees reported by the rural households are as numerous as mango, pineapple, cashew, citrus, cacao, banana, palm, shea nut, apple, Kola, peach, almond, prune, apricot, avocado, cherry, hickory, eucalyptus, lemon, and Brazil nut (Seo 2012a).

From the whole array of agricultural and natural resource portfolios rural households manage, we can classify the enterprises based on whether an individual household manages crops or not, whether it manages livestock or not, and whether it manages forests or not. The combinations of crops, livestock, and forests lead to the following enterprises:

Enterprise 1: Crops-only
Enterprise 2: Livestock-only
Enterprise 3: Forests-only
Enterprise 4: Crops-livestock
Enterprise 5: Crops-forests

Enterprise 6: Livestock-forests
Enterprise 7: Crops-livestock-forests

The first three enterprises are specialized in that they specialize either in crops or livestock or forestry. The latter four are diversified enterprises in that they mix at least two of the three categories. Empirically, examinations of household responses reveal that enterprise 6, a mix of livestock and forests, is very rarely found (Seo 2012a).

Let the profit of the farm (n) from agricultural and natural resource enterprises 1 and j be written as the sum of the observable component and the unobservable component while the observable component can be written as a linear function of the parameters as follows (Dubin and McFadden 1984):

$$\pi_{n1} = X_n\beta_1 + u_{n1} \tag{2.2a}$$

$$\pi^*_{nj} = Z_n\gamma_j + \eta_{nj}, \quad \mathrm{j} = 1, 2, \ldots, \mathrm{J}. \tag{2.2b}$$

The π denotes the observed profit while the π^* denotes the latent profit, i.e., the profit expected when the enterprise is chosen by the farm (n). The subscript j is a categorical variable indicating the choice amongst J enterprises.

Let's say for the purpose of the discussions to follow that $j = 1$ denotes a specialized crop system, $j = 2$ an integrated crops-livestock system, and $j = 3$ a specialized livestock system. Let's assume for the moment that the three choices are mutually exclusive and exhaustive. The vector Z represents the set of explanatory variables pertinent to all the alternatives and the vector X contains the determinants of the profit of the first alternative, the crops-only enterprise.

The vectors Z and X include as components climate variables. Climate variables encompass both climate normals and climate risk normals (Seo 2012b). Seasonal climate variables are used to capture changes in climate conditions in spring, summer, fall, and winter (Mendelsohn et al. 1994). In the Southern Hemisphere, seasons are defined using opposite seasons in the Northern Hemisphere. That is, summer season months (June, July, August) in the Northern Hemisphere correspond to winter season months. A more precise seasonal definition can be made for the region of research interests. Climate variables enter into the model in a nonlinear specification to capture nonlinear effects of climate.

The error term in the profit equation in Eq. 2.2a is assumed to be independently and identically distributed (iid) with the following mean and variance given the explanatory variables:

$$E(u_{n1}|X,Z) = 0, \quad Var(u_{n1}|X,Z) = \sigma^2. \tag{2.3}$$

The probability to choose each of the natural resource enterprises is calculated based on the profit equations, Eq. 2.2b, and the rule in Eq. 2.1. The estimation of the choice equation calls for the description of the unobservable term in Eq. 2.2b. Depending upon the assumptions, the parameters are estimated parametrically or non-parametrically (Train 2003).

Assuming $\eta'_{nj}s$ are iid Gumbel distributed (McFadden 1974; McFadden and Train 2000) and spatial neighborhood effects are controlled by re-sampling at the level of the neighborhoods in a large number of times (Anselin 1988; Case 1992; Seo 2011b), the choice probability of the farm n choosing natural resource enterprise 1 can be written as the sample average of the following Logit probabilities of the samples:

$$P_{n1} = \frac{\exp(Z_n \gamma_1)}{\sum_{k=1}^{K} \exp(Z_n \gamma_k)} \tag{2.4}$$

Having chosen enterprise 1, the farmer makes numerous decisions regarding inputs, outputs, and a variety of practices to maximize the expected profit from managing the chosen system. These decisions are variable in the short-term. They can be daily, weekly, monthly, quarterly, or yearly measures used to manage each of these chosen enterprises to cope with specific weather conditions occurring or expected with confidence in the near term.

The conditional profit of the selected enterprise can be estimated directly using Eq. 2.2a and X with the same assumption of the error terms. However, because enterprise profits are observed only for the farms that actually chose natural resource enterprise 1, the direct estimation of Eq. 2.2a will be biased because of the selection decision (Heckman 1979). Selection biases must be then corrected to obtain consistent estimates of the parameters in the profit equations.

For a multinomial choice model or in a polychotomous decision situation, there are a number of selection bias correction methods that have been proposed since Heckman. The Lee's generalized method, the Dahl's semi-parametric method, and the Dubin-Mcadden's method are most widely discussed and used (Lee 1983; Dubin and McFadden 1984; Dahl 2002). The Dubin-McFadden's method outperforms the other methods because the other methods place severe restrictions on the correlation structure among alternatives (Schmertmann 1994; Bourguignon et al. 2004). The only exception is when the choice sample is too limited, in which case the Lee's method can perform as well.

Following Dubin and McFadden (1984) for the selection bias correction for a multinomial choice situation, we assume a linearity condition, i.e., the correlation coefficients (λ_j) between enterprise 1 and enterprise j add up to one across j, allowing for a markedly more flexible correlation matrix than the other methods:

$$\sum_{j=1}^{J} \lambda_j = 1 \quad \text{where } \lambda_j = \operatorname{corr}(u_1, \eta_j) \tag{2.5}$$

The conditional land value (or profit) function for the first enterprise is then consistently estimated as follows:

$$\pi_{n1} = X_n \varphi_1 + \sigma \cdot \sum_{k \neq 1}^{J} \lambda_k \cdot \left[\frac{P_{nk} \cdot \ln P_{nk}}{1 - P_{nk}} + \ln P_{n1} \right] + \delta_{n1} \tag{2.6}$$

In the above equation, δ is a white noise error term with zero mean. That is, the parameter estimates from the above equation are unbiased and consistent. The conditional land value function for the specialized livestock system or the mixed system is estimated in the same manner through Eqs. 2.4 and 2.6.

The choice equations are identified non-parametrically. The exact identification strategy is to exclude from the outcome (land value) equations the variables that affect the choices of natural resource enterprises but not the land value functions (Fisher 1966; Johnston and DiNardo 1997).

Among the explanatory variables (X) in the G-MAP models are climate variables, primary variables of interest to climate researchers. Climatic variables can be either satellite data or ground weather station data. The satellite data are available from the late 1980s from the various instruments aboard the National Aeronautic and Space Administration (NASA) satellite programs (Basist et al. 1998; Mendelsohn et al. 2007, Seo et al. 2009). The weather station observation data are available collected historically by the national government organizations, e.g., from more than 16,000 weather stations around the world (New et al. 2002).

Besides climate variables, other control variables are soils, topology, hydrology (water flows and runoff), market access (travel hours to major markets for exports, sales, or inputs), household characteristics (gender (female), education (schooling), number of family members, etc.), policy variables (extension service), and country dummies (Seo 2011b, 2013). These data are obtained from the various geographically referenced data sources, which we will have opportunities to discuss further in the Chapters to follow.

From the estimated probabilities in Eq. 2.4 and the conditional land values (profits) for different enterprises in Eq. 2.6, the expected land value (profit) of the farm (n) is calculated as the sum across the enterprises of the probability of each natural resource enterprise to be adopted times the conditional land value of that enterprise given the external conditions. Let E be the climate factors. Then the expected land value is derived as follows, all other factors remaining unchanged:

$$W_n(E) = \sum_{j=1}^{J} P_{nj}(E) * \pi_{nj}(E) \tag{2.7}$$

Let's pick a climate scenario in which E changes from E_0 to E_1. Then, the change in welfare, ΔW, resulting from the climate change scenario can be measured as the difference in W after and before climate change as follows:

$$\begin{aligned} \Delta W_n &= W_n(E_1) - W_n(E_0) \\ &= \sum_{j=1}^{J} P_{nj}(E_1) * \pi_{nj}(E_1) - \sum_{j=1}^{J} P_{nj}(E_0) * \pi_{nj}(E_0) \end{aligned} \tag{2.8}$$

Note that the change in the expected land value (farm profit) in Eq. 2.8 captures both the changes in the probabilities that a farm will be a particular enterprise and the changes in the conditional profits that would be generated by the enterprises.

Uncertainties surrounding the estimates of the G-MAP models are provided by constructing 95 % confidence intervals. The changes in the choice probabilities (Eq. 2.4), the changes in the enterprise-specific conditional land values (Eq. 2.6), and the changes in the expected farm land value (Eq. 2.8) are calculated and bootstrapped by randomly sampling a large number of times from the original sample (Efron 1981).

The climate system, E, needs further elaborations, which is the primary variable of interests in all climate studies. The G-MAP model, like other climate economics models, is initially developed to measure the impacts of climate normals on individuals' behaviors and economic profits. That is, the purpose of the G-MAP models is not to quantify the impacts of weather in a specific year. The distinctions between weather and climate normals are essentially important in the climate science literature (Le Treut et al. 2007). Weather may be hotter this year, colder next year, and so on. However, these weather fluctuations may or may not have little to do with climate. Climate is defined to be the average of weather realizations for the long time period, e.g., 30 years. For this reason, it is called climate normals.

In the G-MAP models, temperature normals and precipitation normals are used for climate variables. Temperature normals are a 30-year average of temperature variables while precipitation normals are a 30-year average of precipitation variables. To capture different stages of crops and vegetation growth, the G-MAP models have relied on seasonal climate normals: spring, summer, fall, and winter. In the low-latitude countries where four seasons are not distinct, summer and winter seasons are used for climate normals (Seo and Mendelsohn 2008a, b).

In the G-MAP models, climate normals include both climate means and climate risk normals in the form of temperature and precipitation variabilities. Climate risks are not the same as weather risks (fluctuations) on which past studies of African agriculture have concentrated (Udry 1995; Kazianga and Udry 2006). A village may suffer from occasional weather shocks such as a drought or a flood but it can still be a low climate risk zone if such occurrences are not frequent in the long-term.

A long-term variability of rainfall can be captured by the Coefficient of Variation in Precipitation (CVP) measured from many decades of observations, i.e., for the 30-year period from 1961 to 1990. The CVP is a measure of rainfall dispersion that does not depend on the unit of measurement and can be defined as follows with R_{kj} being monthly precipitation in month j and year k (K = 30) and $\bar{R}_j$ being 30-year average rainfall for month j:

$$\mathrm{CVP_j} = {}^{\sigma_j}\!/_{\bar{R}_j} \quad \text{where } \sigma_j = \sqrt{\sum_{\mathrm{k=1}}^{\mathrm{K}} (R_{kj} - \bar{R}_j)^2 \Big/ (K-1)} \tag{2.9}$$

Another major concern with regard to climate risks is that climate change will lead to more frequent occurrences of extremely hot days and cold days and/or more variable temperature (IPCC 2001; Tebaldi et al. 2007). This implies an increase in the range between maximum temperature and minimum temperature, altering growing periods for crops (Easterling et al. 2000; FAO 2005; Schlenker and Roberts 2009). The temperature range can be measured by the Diurnal Temperature Range (DTR). Average monthly DTRs for the 30-year period mentioned above have been measured by the CRU data set (New et al. 2002). Let $T_{\max}$ be daily maximum temperature, $T_{\min}$ daily minimum temperature, j day, m month, and K year. Then, the DTR for month m is defined as follows:

$$\mathrm{DTR_m} = \frac{\sum_{k=1}^{K}\sum_{j=1}^{J}\left(T_{k,m,j}\mathrm{,max} - T_{k,m,j}\mathrm{,min}\right)}{J * K}. \tag{2.10}$$

Researchers should notice that the dependent variable in the G-MAP models too captures fully the fluctuations of farm profits year by year. That is, it is the net present value, with discount rates applied, of the stream of yearly rents (profits) expected in the future on the land, i.e., the value of the land (Fisher 1906; Seo 2013). This expectation is formed by decades of past experiences of farming on the land given climate and geographical conditions. As such, the decision to adopt a natural resource enterprise is not motivated by annual weather conditions, but rather on the long-term climate of the region, i.e., climate normals. The expected return will also include household consumption of produced goods and family labor hours used for the enterprises if rural households should exchange such goods and services at the market places otherwise (Seo 2006; Seo and Mendelsohn 2008a).

The G-MAP modeling originated from the Ricardian model which was intended to capture farmers' substitution behaviors of inputs to the full extent when climate were to be altered (Mendelsohn et al. 1994). In the Ricardian model, adaptation behaviors remained implicit, for which reason the model is sometimes referred to as a black box. The G-MAP models make these adaptation behaviors explicit (Seo 2006). That is, changes in farm choices of enterprises or species are modeled explicitly (Seo and Mendelsohn 2008a; Seo 2010a).

The Ricardian method that estimates the net revenue or land value in a reduced form as a function of climatic variables have also been applied widely across the world from the US to India, Canada, Sri Lanka, Africa, Brazil, South America, China, and Mexico (Mendelsohn et al. 1994; Maddison 2000; Kumar and Parikh 2001; Reinsborough 2003; Seo et al. 2005; Schlenker et al. 2005; Kelly et al. 2005; Kurukulasuriya et al. 2006; Timmins 2006; Kurukulasuriya and Ajwad 2007; Seo and Mendelsohn 2008b; Sanghi and Mendelsohn 2008; Wang et al. 2009). The Ricardian method is also applied to a panel random-effects model (Masseti and Mendelsohn 2011).

The paper by Mendelsohn et al. (1994) published two decades ago sowed the seed of the economic studies on the impacts of climate change conducted ever since its influential publication, including the ones cited above, by laying the conceptual foundation that farmers are not dumb, therefore will fully adapt to changes. The micro-behavioral economics studies have emerged naturally from the Ricardian models and have endeavored to unpack what is inside the Ricardian black box, i.e., adaptation strategies and consequences. One of the major goals of this book is, therefore, to present the major results on adaptation strategies from the different versions of the G-MAP model applied to sub-Saharan and South American agricultural and natural resource enterprises. This will in turn help clarify for the serious readers of the book the concepts and theories put forth in this Chapter.

Before closing this Chapter, it is pertinent at this point to mention the policy-directed nature of the micro-behavioral economics and the G-MAP models, although formal discussions will surely be followed in the ensuing Chapters.

The field and the modeling in its conception were originated from the fundamental question of "What adaptation strategies should be taken to adapt to climate changes?" The major findings from the applications of the models provide highly policy relevant research outcomes. In particular, while the world communities have recently established the Green Climate Fund (GCF), there has been no reasonable attempt to figure out how to distribute the funds into different projects of adaptation and mitigation into different countries (UNFCCC 2011). Lack of serious studies on this issue is a big hurdle for the countries which are considering pledging their contributions. Recent global warming negotiations were swamped by the disputes on the allocations and unfulfilled promises of fund contributions. The micro-behavioral economics provides a conceptual layout for answering this important policy question.

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Chapter 3
The G-MAP Models: Major Findings

Abstract This chapter describes major findings from the G-MAP models applied to agricultural and natural resource enterprises in Sub-Sahara and South America. Five versions of the G-MAP model are explained: animal species, agricultural systems, natural resource enterprises, climate risk, and public adaptations.

Keywords G-MAP · Animal species · Agricultural systems · Public adaptations · Natural resource enterprises · Climate risk

This chapter is devoted to describing major empirical findings from the applications of the G-MAP model, an empirical model of the micro-behavioral economics of global warming. The readers who have had the patience to read through Chaps. 1 and 2 will find the discussions in this chapter enlightening in the sense that the empirical results to be presented will make the theory of micro-behavioral economics clearer. At the same time, this chapter will give them an opportunity to examine the validity and usefulness of the G-MAP models.

The G-MAP model has been developed over the period of time since 2003 when the present author began working with the World Bank as a doctoral student at Yale University. Depending on the questions and the structures of natural resource enterprises the G-MAP model is calibrated to answer, there are five different versions of the G-MAP model:

1. G-MAP Animal Species: Seo (2006), Seo and Mendelsohn (2008a).
2. G-MAP Agricultural Systems: Seo (2010a, b).
3. G-MAP Public Adaptations: Seo (2011a).
4. G-MAP Natural Resource Enterprises: Seo (2012a, b).
5. G-MAP Climate Risk: Seo (2012c, 2014b).

The G-MAP model was first developed in the process of modeling the choices of animal species by African farmers (Seo 2006; Seo and Mendelsohn 2008a). The analysis showed that changes in farmers' choice probabilities of beef cattle, dairy cattle, goats, sheep, and chickens, the five most important animals in African households, occur across the ranges of temperature and precipitation observed in Africa.

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In Fig. 3.1, choice probabilities of the five animals are drawn against the annual mean temperature normals in Africa. Choices of beef cattle and dairy cattle fall sharply as temperature normals becomes hotter. On the other hand, goats and sheep are increasingly chosen more often by the farmers in the hotter zones of Africa. The choice of chickens reveal a hill-shaped probability function in which the peak in choice probabilities occurs at around the mean temperature of the continent.

This first version of the G-MAP model also clearly indentifies varied sensitivities to precipitation normals of the five major animals. Choices of cattle and sheep increase if climate normals becomes more arid while goats and chickens are chosen more often when the region becomes more humid (Seo and Mendelsohn 2008a). That sheep are favored in arid zones by the rural entrepreneurs is also found in South America (Seo et al. 2010). In Australia where climate is highly arid such that around 70 % of the country is rangelands, the number of sheep raised by a farmer increases very sharply (Seo 2015b).

The G-MAP species model is notable because it established the G-MAP model for the first time (Seo 2006). This ground-breaking work is the first behavioral economics model of adaptation to climate change in that individuals' adaptation choice behaviors are explicitly modeled. This model laid the solid foundation for the G-MAP models that have followed, thereby for the development of the micro-behavioral economics of global warming.

The G-MAP agricultural systems model was soon followed (Seo 2006, 2010a, b). This second version of the G-MAP model expands the G-MAP species model to a broader agriculture. Depending upon whether a farmer owns crops or livestock or both, a full variety of agricultural portfolios that are managed by the farmers in

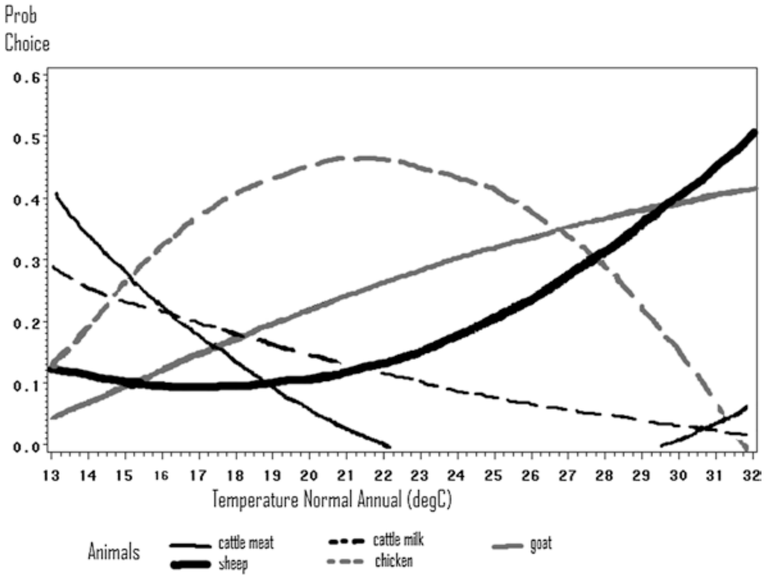

Fig. 3.1 Estimated probabilities of adopting animal species across temperature normals

Africa are classified into a specialized crop system (crops-only), a specialized livestock system (livestock-only), and an integrated system (a mixed crops-livestock) that manages both crops and livestock.

Adoption probabilities of these three agricultural systems in Sub-Saharan Africa are estimated based on a spatial Logit model (Seo 2011b, 2014a). According to the choice models, climate normals variables are a significant determinant of choices of agricultural systems by Sub-Saharan farmers. Besides climate normals, soils, topography, market access, water availability, household characteristics, policy factors, and country dummies are found to have meaningful effects on the choices of agricultural systems (FAO 2003; Strzepek and McCluskey 2006; World Bank 2009; Danielson and Gesch 2011).

The G-MAP agricultural systems model confirms that these non-climate variables that have been considered important in the literature on agriculture and development are indeed significant factors in the model. The larger the number of family members, the higher is the probability of adopting livestock systems due to additional labor for livestock herding. As the distance from a nearest port decreases, a farmer is more likely to own a crops-only system due to the possibility of exports to the other continents and the costs of storage and transport of livestock (Sachs et al. 2004). The more frequent extension service visits, the higher the probability for a crops-only system to be adopted. This is because extension services have historically been directed towards crops, especially in Africa through various international development programs (Byerlee and Eicher 1997; Evenson and Gollin 2003). In fertile organic soils such as Phaeozems, farmers are more likely to choose crops while in Luvisols and Fluvisols, frequently flooded soils, farmers avoid having animals (Driessen et al. 2001).

Adoption probabilities of the three agricultural systems in Sub-Saharan Africa are drawn in Fig. 3.2 at the level of the Agro-Ecological Zone (AEZ) (Seo 2011b, 2014a). The original classification of the African AEZs by Dudal is used for the figure while subsequent refinements of the AEZ classification by different research groups were used for different purposes (Dudal 1980; FAO/IIASA 2005; Seo 2014a). The African agro ecosystems are classified into the five AEZs: deserts, arid, semi-arid, sub-humid, and humid AEZ. The exact definitions of these AEZs will be presented in Chap. 6 when we deal with ecosystems and individuals' behaviors.

As can be seen from Fig. 3.2, a crops-only system is adopted most frequently in the humid zones and sub-humid zones of Africa around central Africa. The humid AEZ is dominant in Cameroon, Congo, and the Democratic Republic of Congo where Congo River runs through from the West to the East of Africa. As the AEZ turns into arid and semi-arid zones, adoption of this system gradually falls.

On the other hand, in the arid and semi-arid zones, an integrated crops-livestock system is most frequently adopted, indicating that farmers have switched away from a crops-only system to an integrated system as climate and ecosystems are altered due to climatic changes. Arid areas are dominant in the Sahelian region in the lowlands, but also in the southwestern deserts such as the Namib and the Kalahari deserts as well as in the Eastern highlands. The integrated system is

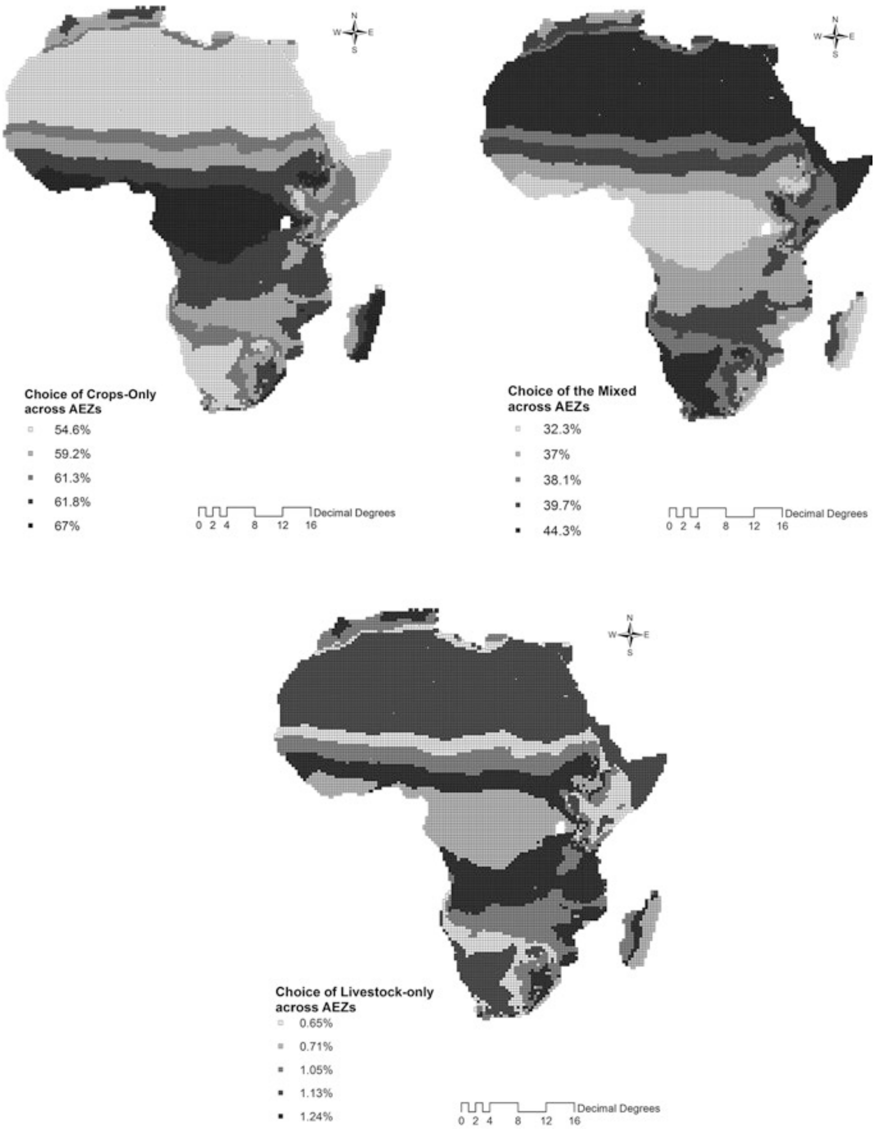

Fig. 3.2 Farmers' adoption probabilities of agricultural systems across the agro-ecological zones (from *left* Crops-only, Integrated, Livestock-only)

chosen most often in the desert AEZ. A specialized livestock system is least likely to be chosen in the humid zones.

The G-MAP agricultural systems model was subsequently developed for South America as part of the World Bank Project on climate change and rural income in Latin America (Seo and Mendelsohn 2008b; Seo 2010a). The map of Latin

Fig. 3.3 Sample clusters across South America

America is presented in Fig. 3.3 which denotes the countries where the household surveys were drawn as well as the household locations. The seven countries from which household surveys were drawn are from the Southern Cone region (Argentina, Brazil, Uruguay, and Chile) and the Andean region (Ecuador, Colombia, and Venezuela). The locations of household surveys are based on the Global Positioning System (GPS) recordings by the country researchers who conducted the surveys.

Table 3.1 G-MAP: changes in choices of agricultural systems under climate scenarios

	Crops-only	Crops and Livestock	Livestock-only
South America			
Baseline (%)	35.88	41.99	21.44
ΔCCC A1 scenario (%)	−4.14	+2.10	+2.04
ΔUKMO A2 scenario (%)	−1.59	2.13	−0.55
Sub-Saharan Africa			
Baseline (%)	40.2	53.7	6.0
ΔCCC A2 scenario (%)	−4.29	+4.05	+0.24
ΔPCM A2 scenario (%)	+0.15	−0.41	+0.25

Note The results are from Seo (2010a, 2011b)

As shown in Table 3.1, for South America, if climate is changed according to the Canadian Climatic Center (CCC) A1 scenario by 2060, adoption of the crops-only system falls by 4.1 % points. The reduction in probability is offset by the increase in the integrated system by 2.1 % points and in the livestock only system by 2 % points across South America (Seo 2010a). The CCC A1 scenario is a hotter and drier scenario where temperature increases by 2.7 °C and rainfall decreases by about 10 % by 2060 (Boer et al. 2000).[1]

With the progresses in climate science modeling, finer resolution climate models have been developed and continuously updated by climate scientists (IPCC 2014). The G-MAP models have utilized the finer resolution Atmospheric Oceanic General Circulation Models (AOGCMs) including the Goddard Institute for Space Studies (GISS) and the United Kingdom Meteorology Office (UKMO) models (Gordon et al. 2000; Schmidt et al. 2005). The G-MAP models coupled the fine resolution climate prediction models with the Global Positioning System (GPS) referenced farm data (Seo 2013a).

The United Kingdom Meteorology Office (UKMO) the Hadley Center Coupled Model version 3 (HadCM3) A2 scenario predicts an increase in seasonal temperatures by 2.5 °C and a decrease in seasonal precipitations by 5–6 mm/month for South America. Under this emissions scenario, adoption of a crops-only farm falls by 1.6 % points while adoption of an integrated farming increases by 2.1 % points (Seo 2013b).

In Sub-Saharan Africa, similar results are found under a hotter and drier CCC A2 emissions scenario. The crops-only system falls in adoption by 4.2 % points while the integrated crops-livestock system increases in adoption by 4.5 % points. Under the Parallel Climate Model (PCM) A2 emissions scenario which predicts a milder temperature increase and a rainfall increase in Africa (Washington et al. 2000), the specialized crop system is predicted to be adopted more frequently

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[1] The A1 emissions scenario is a high emissions scenario of the Special Report on Emissions Scenarios (SRES) from the United Nations in which global economy continues to grow rapidly relying on heavy uses of fossil fuels while regional economies converge over time (Nakicenovic et al. 2000).

by the farmers (Seo 2011b). As vast areas of Sub-Saharan Africa are semi-arid or arid, rainfall increase is beneficial for crops, which spurs farmers to adopt the crop system more frequently. A rearrangement of future farming activities such as adoption of an agricultural system hinges on which climate scenario comes to pass as well as the existing climate and ecosystems of the concerned region.

Given the choice of one of the agricultural systems, a farmer chooses a set of inputs, outputs, and farm practices to maximize the expected return from the chosen system. As explained in the theory chapter, we can estimate the long-term profit of the chosen system directly using the same explanatory variables as those entered in the choice model. However, such estimations are biased due to selectivity (Heckman 1979). Empirical results indicate that selection biases are large and significant and the omission of them will distort the results seriously (Seo 2010a, b).

In addition, selection terms are found to capture an important economic concept: diversification versus specialization. Selection terms mark the difference between the specialized system and the diversified system. That is, the land value of the specialized crop system is lower when the farm is observed to have chosen the mixed system, and vice versa. This implies that the correlation between the error term of the specialized (diversified) system in the choice equation and the error term of the diversified (specialized) system in the profit equation is negative. On the other hand, the correlation is positive between the two specialized systems.

After correcting for selectivity using the Dubin-McFadden method, the G-MAP agricultural systems model calculates in Table 3.2 the impacts of climate change on the land values of the three agricultural systems in South America (Seo 2010a). The conditional land values are estimated using Eq. 2.6 shown in the theory chapter. If the CCC A1 scenario comes to pass, the land value of the specialized crop system falls by 20 % and that of the specialized livestock system falls by 26 %. But, the land value of the mixed crops-livestock system falls only by 9 %.

Under the fine resolution GISS ModelE-R model's A2 emissions scenario and the GPS referenced farm data (Schmidt et al. 2005), the land value of the mixed system increases by +5.7 % while those of the other systems decline significantly (Seo 2013a). Under the same GISS ModelE-R model's A2 emissions scenario and the climate data at the district level, the land value of the mixed system falls by

Table 3.2 G-MAP: changes in the land values (per Hectare) of the agricultural systems conditional on the choices

	Crops-only	Crops and livestock	Livestock-only
South America			
ΔCCC A1 scenario	−412.3* (−20.3 %)	−190.9* (−9.4 %)	
ΔGISS ER A2 scenario (GPS data)	−653.89* (−23 %)	+105.42* (+5.7 %)	
ΔGISS ER A2 scenario (district level climate data)	−230.35* (−9.5 %)	−57.68* (−3.5 %)	629.19* (+59.5 %)

Note (1) * denotes significance at 5 % level. (2) The numbers in parenthesis are percentage changes. (3) These results are from Seo (2010a, 2013a), and the author's calculations

Table 3.3 G-MAP: the impacts of climate change on agriculture

Scenarios	Absolute changes ($)	% changes	95 % lower CL	95 % upper CL
South America with Full Adaptation: Land Value per Hectare				
ΔCCC A1 scenario	−156.5	−8.71 %	−527.8	214.9
ΔGISS A2 scenario (GPS Data)	−128.32	−6.0 %	−156.8	−99.7
ΔGISS A2 scenario (district level climate data)	−13.37	−0.72 %	−25.96	−0.79
South America without Adaptation of Agricultural Systems: Land Value per Hectare				
ΔCCC A1 scenario	−322.2	−17.9 %	−441.5	−220.8
Africa with Full Adaptation: Net Revenue per Hectare				
ΔCCC A2 scenario	−53.1	−9 %	−56.19	−50.13
ΔPCM A2 scenario	+217.4	+37 %	+200.87	+234.07

Note The results are from Seo (2010a, b), and the author's calculations

3.5 % while the land value of the specialized crop system falls by 9.5 %. The land value of the specialized livestock system, however, increases by as much as 59 % (Seo 2013a). Note that the estimates in Table 3.2 come from an array of climate data (satellite versus ground), GPS-references, climate models (CCC vs. GISS), and emissions scenarios (A1 vs. A2).

In the African agriculture, using the farm net revenue data, the G-MAP agricultural systems model indicates an even larger damage to the specialized crop system. The mixed crops-livestock system shows more resilience to climate changes. In the hot and arid CCC A2 emissions scenario, the net revenue of the mixed system falls by 9.8 % but it increases by 20 % in the milder PCM A2 emissions scenario (Seo 2010b).

What is the magnitude of the impact of climate change on agriculture considering all the systems of agriculture? The agriculture-wide impact of climate change can be calculated by combining both the changes in the choices of agricultural systems and the changes in the conditional land values of the chosen systems. Expected land values are calculated using Eq. 2.7 in Chap. 2. Table 3.3 shows that agricultural damage from the CCC scenario in South America is 8.7 % loss of the land value (Seo 2010a). Under the fine-resolution GISS ModelE-R emissions A2 scenario and the GPS-referenced farm data, the impact on agriculture is 6 % loss of the land value (Seo 2013a). Under the GISS scenario, the high resolution climatology, and the district level climate data, the impact on agriculture is only 1 % loss by the middle of this century.

In Africa, the impact of climate change on agriculture under the CCC model A2 emissions scenario is estimated to be around 9 % loss of the agricultural profit by the middle of this century when all the necessary adaptation measures are employed by the farmers. Under the milder and wetter PCM model A2 emissions scenario, African agriculture is predicted to benefit from climatic change since increased rainfall benefits African farmers on the arid zones who rely mostly on rainfed agriculture (Seo 2010b).

What would be the damage on Sub-Saharan agriculture if farmers stick to the current agricultural systems even if the climate is shifted in the future? The G-MAP model enables researchers to measure the impacts of climate change when adaptations are not taken or cannot be taken due to various constraints by farmers. This implies the G-MAP analysis can place bounds on the assumption of perfect foresight/rationality by the farmers. When farmers are irrational in responding to climate changes or face physical or psychological barriers, they may not switch farming systems timely (Kahneman and Tversky 1979).

Without adaptations of agricultural systems, the damage under the CCC model A1 emissions scenario increases to 18 % in South America. Note that under the same scenario, the damage was estimated to be only 8.7 % when full adaptations of agricultural systems are taken (the first row in Table 3.3). Depending upon whether or not farmers adjust agricultural systems sensibly in response to climate changes, the damage would more than double.

From a policy perspective at the global level or at the agricultural level, the results presented up to this point demonstrate the importance of adaptations to global warming. Any policy proposal would be distorting, instead of rectifying negative externalities, agricultural productions and resource allocations if it does not take into account the changes in enterprise behaviors due to unfolding climatic changes. At an individual level, efficient adaptations would save one or protect one from the loss of millions of dollars in the years or generations to come.

This concludes the discussions of the G-MAP agricultural systems model. The G-MAP analysis and the micro-behavioral economics have been further extended over the years into several directions. In the first direction, a rural economy model was developed to account for the full varieties of natural resource enterprises, besides crops and livestock (Seo 2012a). Using South American household data, natural resource intensive enterprises that manage a variety of crops, livestock, and forests are examined to build the G-MAP natural resource enterprises model. Six major rural enterprises which are natural resources intensive are modeled: a crops-only, a livestock-only, a forests-only, a crops-livestock, a crops-forests, and a crops-livestock-forests enterprise. The first three enterprises are specialized while the latter three are diversified enterprises, a mixed portfolio of some crops, some livestock, or some forests. The livestock-forests enterprises are found to be very rare in South America.

In another direction, concerns on increased climate risk are explicitly addressed (Easterling et al. 2000; Emanuel 2005; Hansen et al. 2012; NRC 2013). There is evidence that global warming is associated with the changes in daily maximum and daily minimum temperatures (Easterling et al. 2000). The global warming trend may also increase yearly variability of temperature and/or precipitation (Hansen et al. 2012). The warming of the oceans and the atmosphere may alter the dynamics of hurricane generation in a way that leads to more intense hurricanes (Revelle and Suess 1957; Emanuel 2005).

In the third direction, the G-MAP model was applied to model choices made collectively at the level of the concerned community (Ostrom 2009; Seo 2011a). Using the choices of public irrigation schemes against the choices of private irrigation schemes, whether from surface water or groundwater, in South American agriculture, the G-MAP public adaptation model reveals that public adaptations can lead to inefficiencies. It is found that the inefficiencies arise from two sources in the provision of public irrigation schemes. The first is that public adaptation schemes are provided mainly for rainfall scarcity ignoring temperature factors, likely due to lack of knowledge. The second is that the public adaptation is provided as a lump-sum. That is, the provision of public irrigation schemes tends to be provided too much or too less than the private irrigation schemes.

We first discuss the G-MAP natural resource enterprises model and then the G-MAP climate risk model later. As discussed before, after examining the entire portfolios of natural resources that rural households manage in South America, six enterprises are defined. The specialized enterprises are a crops-only, a livestock-only, and a forests-only enterprise. The diversified enterprises are a crops-livestock, a crops-forests, and a crops-livestock-forests enterprise. Applied for the first time to the South American rural economy, the G-MAP natural resource enterprises model finds that a crops-only enterprise accounts for 33 % of the sampled households, a crops-livestock 30 %, a crops-forests 8 %, a crops-livestock-forests 10 %, a livestock-only 19 %, and a forests-only 1 % (Seo 2012b).

An application of the G-MAP natural resource enterprises model finds that choices of the individuals of one of these natural resource intensive enterprises are highly sensitive to climate variables (Seo 2012a, b). Adaptation choices made in response to climate variables by South American farmers are summarized in Figs. 3.4 and 3.5. In Fig. 3.4, a box plot of the estimated adoption probabilities is drawn against the annual mean temperature normals for each of the six enterprises. As temperature becomes warmer across the horizontal axis, the choice of a crops-only enterprise falls rapidly after reaching a peak at around 13 °C. By contrasts, the choice of a livestock-only enterprise gradually increases as temperature normals increases, especially at higher temperatures than 24 °C. The choice of a forests-only enterprise is negligible, but visible in the high temperature zones.

Among the diversified enterprises, the choice of the most diversified portfolio, i.e., the crops-livestock-forests enterprise increases gradually as temperature normals increases. The choice of a crops-forests enterprise fluctuates across the range, but seems to be higher in temperature ranges that exceed 20 °C. The choice of a crops-livestock enterprise also falls initially, then ramps up into high temperate zones and is stabilized in hot zones.

These plots are analogous to what agronomic studies have revealed, i.e., major crops are vulnerable to climatic changes, especially to very high temperatures (IPCC 1990; Reilly et al. 1996; Gitay et al. 2001). As such, farmers are shown by the G-MAP models to switch away from crops when temperature becomes very high. From another perspective, the micro-behavioral economics analysis reveals the resilience of the other natural resource enterprises such as livestock-only, crops-livestock, and crops-livestock-forests.

In Fig. 3.5, the box plots of estimated choice probabilities of the six enterprises are drawn across the range of precipitation normals. Above all, it is quite conspicuous that adoption of the crops-only enterprise falls gradually as precipitation normals becomes higher. At a first glimpse, this result is in contrast to what agronomic

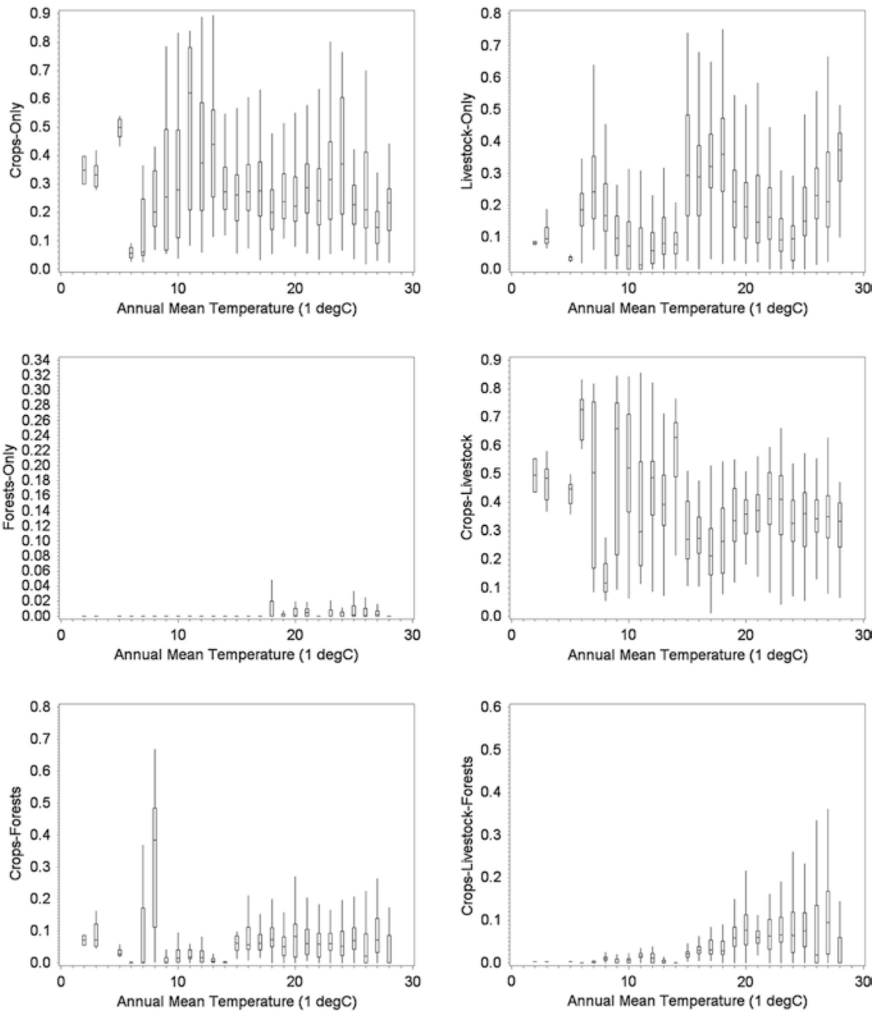

Fig. 3.4 Estimated probabilities of adopting enterprises across temperature normals in South America (from *top* Crops-only, Livestock-only, Forests-only, Crops-livestock, Crops-forests, Crops-livestock-forests)

studies have argued, i.e., rainfall increase will benefit crop growth (Reilly et al. 1996; Gitay et al. 2001). On second thoughts, the result is not contradictory. It simply shows that there are different types of crops. That is, forest-related enterprises all increase in high rainfall zones. A forests-only, a crops-forests, a crops-livestock-forests are all adopted more frequently in high precipitation zones.

Livestock enterprises are less sensitive to precipitation ranges. The probability of adopting a livestock-only enterprise does not show much sway but shows small but gradual decrease when precipitation normals exceeds 100 mm/month rainfall.

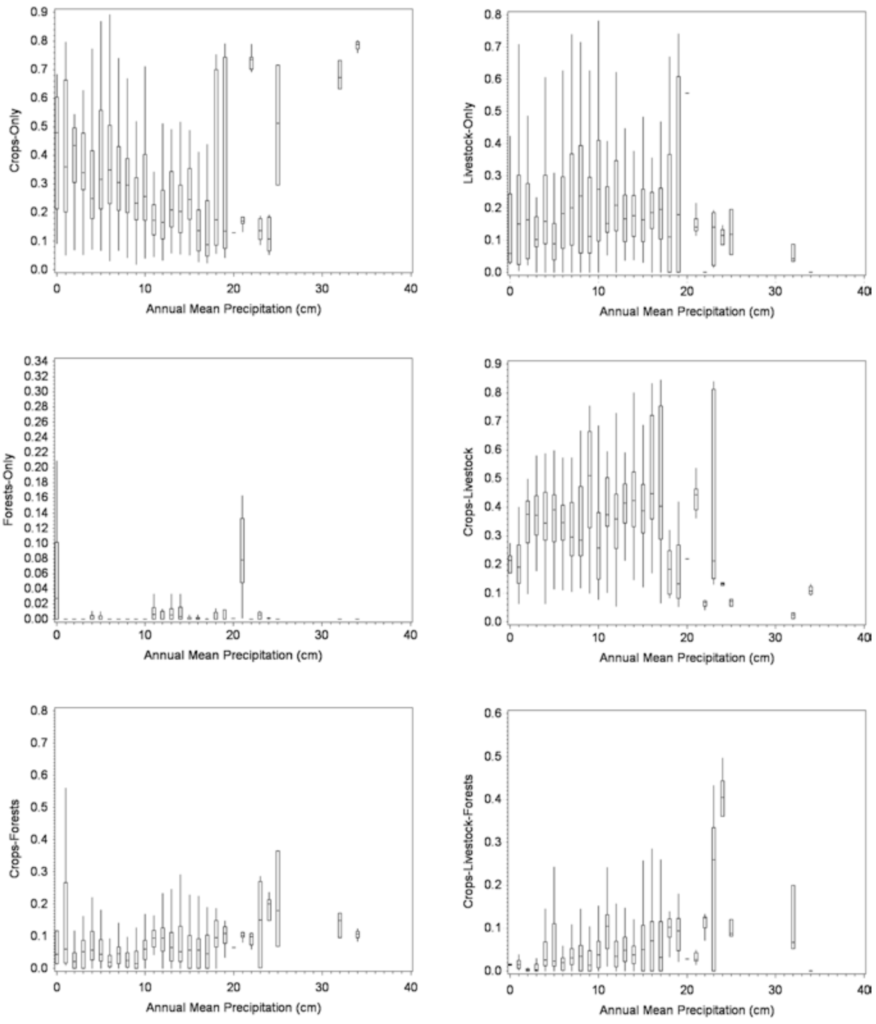

Fig. 3.5 Estimated probabilities of adopting enterprises across precipitation normals in South America (from *top* Crops-only, Livestock-only, Forests-only, Crops-livestock, Crops-forests, Crops-livestock-forests)

The choice of the crops-livestock enterprise increases incrementally but falls in very high rainfall zones, i.e., over 150 mm/month rainfall.

Based on these estimated climate-adoption relationships, the G-MAP natural resource enterprises model simulates the changes in adoption probabilities of the six enterprises assuming a set of climate scenarios for future time periods (Seo 2012b). By 2020, under a hotter and drier CCC A1 emissions scenario (Boer et al. 2000), a crops-only enterprise is projected to decrease by more than 6 % points while a livestock-only enterprise to increase by as much as 5 % points.

A crops-livestock enterprise is also expected to increase, so is a crops-livestock-forests enterprise, albeit to a lesser extent. This may be attributable to the benefits of portfolio diversification (Markowitz 1952).

These changes magnify through 2060, the middle of this century. The decrease in a crops-only enterprise reaches 13 % points while the increase in a livestock-only enterprise reaches 8 % points. The mixed crops-livestock enterprise also grows substantially by 5.4 % points by the year 2060. The CCC A1 emissions scenario is one of the most severe climate change scenarios in which temperature increase is larger and rainfall decrease is larger than most climate models.

Projections of natural resource enterprise choices turn out to be quite different under a milder but wetter PCM A1 emissions scenario (Washington et al. 2000; Seo 2012b). By 2020, a crops-only enterprise is projected to increase by 7 % points while a livestock-only enterprise to decrease by 3.9 % points. A forests-only as well as a crops-forests enterprise is also projected to increase, though by much smaller percentage points, due to rainfall increase. The choice of a crops-livestock enterprise is projected to decrease by as much as 4 % points. The most diversified crops-livestock-forests enterprise shows little changes under the PCM scenario.

In another direction of the development of the micro-behavioral economics, the G-MAP climate risk model was developed (Seo 2012c, 2014b, 2015b). Climate risk can occur in the form of either temperature risk, or precipitation risk, or some combinations of them. Precipitation risk can occur due to yearly fluctuations in rainfall which are captured by the measures such as the Coefficient of Variation in Precipitation (CVP) or due to untimely rainfall or lack of rainfall during the farming seasons. The latter is already captured by the G-MAP models through seasonal rainfalls. Temperature risk can arise due to changes in the range of temperature which can be captured by the Diurnal Temperature Range (DTR), the range between the daily maximum temperature and the daily minimum temperature.

The G-MAP climate risk model was developed in the process of quantifying choices of the agricultural systems in Sub-Saharan Africa where it has been widely known that climate risk is very high, if not the highest. The Sahelian climate is well-known to the scientists for its large multi-decadal fluctuations (Hulme et al. 2001; Seo 2012c). In South America, yearly fluctuations in weather variables occur in relation to the occurrences of the El Nino Southern Oscillation (ENSO) (Curtis et al. 2001; Seo 2014b). In both Sub-Sahara and South America, changes in ocean temperatures and/or movements are a primary factor that determines the degree of climate risk in affected regions (Ropelewski and Halpert 1987; Shanahan et al. 2009). For example, the high climate risk of the Sahelian region results from the Atlantic Multidecadal Oscillation (AMO).

Examinations of the distributions of the CVPs and the DTRs across the continent reveal that climate risks are indeed high across Sub-Saharan Africa (New et al. 2002; Seo 2012c). Especially, climate risks are much higher in the Sahel. The variation in the CVP across Africa is very large ranging from 69 to 226 %. The CVP is the largest in the lowland dry savannah and lowland semi-arid zones in the Sahel. The lowest CVP zones are humid forests and sub-humid zones regardless of

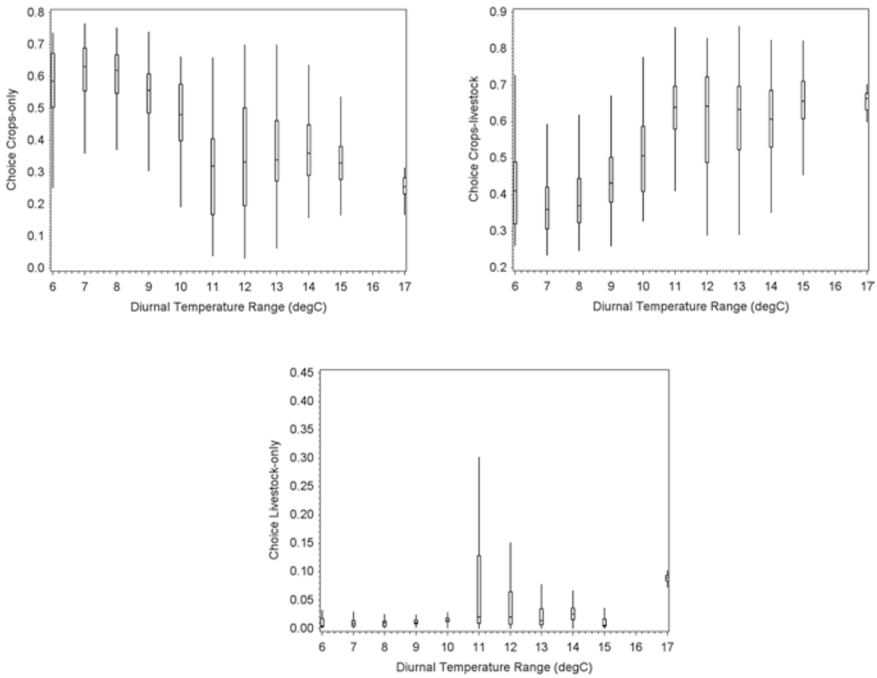

Fig. 3.6 Estimated probabilities of adopting enterprises across diurnal temperature range: Crops (*top*), Integrated (*middle*), and Livestock (*bottom*)

elevation. The DTR, on the other hand, is higher in high elevations. Also, the DTR is higher in dry zones than in wet zones. The DTR ranges from 8.6 to 14.5 °C.

Climate risks have profound effects on how farmers make decisions (Seo 2012c). From the Sub-Saharan sample, the author finds that in the high DTR zones, livestock systems are preferred, especially the specialized livestock system. Across the agricultural systems, the CVP is larger in the mixed system than the specialized systems by 16 % points. These findings indicate that livestock and integrated systems are more resilient to climate risks than the specialized crop system.

The probabilities of choosing an agricultural system are drawn across the ranges of DTR in Fig. 3.6 and of CVP in Fig. 3.7 for each of the three systems. These probabilities are calculated based on the spatial Logit model that uses the seasonal DTRs and CVPs as explanatory variables. The box plots in the figures show the means, medians, 95 % confidence intervals, and extremes of estimated probabilities across the ranges of the climate risk normals indicators.

Figure 3.6 clearly depicts varied sensitivities of adopting the three agricultural systems to the temperature range. As the DTR increases, a crops-only system falls drastically in a steady way. The choice probability is as high as 60 % in the low DTR zones, but as low as 25 % in the high DTR zones. On the other hand, the probability of adoption of an integrated crops-livestock system rises gradually until the DTR is as large as 11°, after which adoption probability stays high.

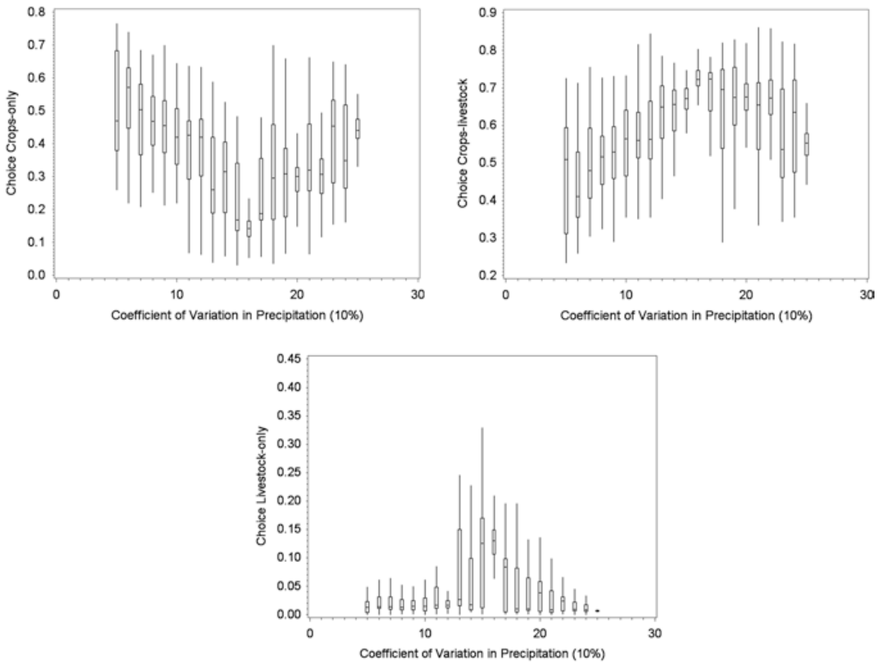

Fig. 3.7 Estimated probabilities of adopting enterprises across CV in Precipitation: Crops (*top*), Integrated (*middle*), and Livestock (*bottom*)

Adoption probability is about 35 % in the low DTR zones and is about 65 % in the high DTR zones, a very substantial shift in choices. A livestock-only system is chosen by a much smaller number of farms across the range of the DTR. Adoption probability of this system shows a fluctuating but gradual pattern across the DTR with slightly higher probabilities in the high DTR zones.

In Fig. 3.7, adoption probabilities are drawn against the range of the CVP. Again, an integrated crops-livestock system increases steadily across the horizontal axis as the CVP increases until the CVP approaches as large as 200 %. A crops-only system, on the other hand, falls in adoption gradually as the CVP becomes ever higher up to around 200 %. The adoption probabilities of a livestock-only system shows a hill-shaped function in which the peak is located at around 160 % of the CVP, indicating that this system is not favored in very high CVP zones.

One of the major concerns of the global climate communities, if not the major concern, is whether extreme climate events will increase under the new climate system in the future (IPCC SREX 2012). For example, many hurricane scientists agree that the most intense hurricanes will increase in a warmer world if climate system shifts as forecast by the AOGCM climate models (Emanuel 2005; Knutson et al. 2010, Seo 2015a). Similarly, severe droughts as well as extremely heavy rainfall events may occur more frequently (Tebaldi et al. 2007; Hansen et al. 2012).

Although there is no scientific consensus on which directions these extreme events will unfold (Tebaldi et al. 2007; NRC 2013), even some chances of more frequent and intense extreme events pose a significant challenge to policy-making decisions as well as to an individual's decisions (Weitzman 2009; Nordhaus 2011). The G-MAP climate risk model approaches the question from a different angle. That is, it asks directly whether extreme weather events are not adaptable. To put it differently, it examines whether individuals can adapt to such extreme events and what can be the obstacles of such adaptations, if any. Again, the results presented by the G-MAP climate risk model will profoundly affect policy as well as private decisions.

There is no scientific climate model as yet that predicts the changes in climate risk normals indicators such as the CVP and the DTR (Tebaldi et al. 2007; IPCC 2014). The G-MAP climate risk model relies on the set of assumptions about the changes in these indicators in order to simulate the changes in farmers' behaviors. In one scenario, it is assumed that the CVP would increase by 30 %. In another scenario, the DTR was assumed to increase by 3° due to global warming.

If the CVP were to increase by 30 % in a warmer world during this century, Sub-Saharan farmers would switch from the specialized crop system to the integrated crops-livestock system. The latter would increase by as much as 7 % points while the former would decrease by 5.3 % points. The specialized livestock system is also predicted to decrease (Seo 2013b).

If rainfall risk as captured by the CVP were to increase, i.e., if there were to be more frequent severe drought years and heavy rainfall years, farmers would adapt by mixing crops with livestock. Put differently, farmers should diversify their portfolios to reduce the damages incurred by precipitation risk in a similar way to a financial investor who diversifies her/his portfolio into assets which have negative correlations to economic shocks (Markowitz 1952; Tobin 1958).

If the DTR were to increase by 3 °C during this century, farmers would switch away from an integrated crops-livestock system to a livestock-only system. The integrated system is projected to fall by 1 % point while a livestock-only system is to increase by 0.8 % point. If the spatial Logit specification is used, the increase in the livestock-only system is projected to be more profound (Seo 2013b).

Finally, what do these findings portend for the Sahelian region which is faced with perhaps the highest level of climate risk in the world at present? Would a further increase in climate risk force farmers to desert the lands? The G-MAP climate risk model finds otherwise. Farmers in lowland dry savannah zones and semi-arid zones in the Sahel are projected to switch in droves to an integrated system, i.e., by almost 14 % points (Seo 2012c). The increase of an integrated system is also large in the lowland moist savannah zones in the Sahel. There is also a large increase of an integrated system in the deserts.

In these AEZ zones that lie below the Sahara desert, the G-MAP climate risk model predicts a large decrease in the specialized crop system. The crops-only system falls across all the agro-ecological zones in Sub-Saharan Africa but especially by large percentages in the Sahel. This is reminiscent of the high vulnerability of this system to climate change reported often by the past studies (Reilly et al. 1996; Easterling et al. 2007).

This concludes the presentation of the five empirical models of the G-MAP model and major findings from them. Having read this chapter, I hope the readers are now able to comprehend more clearly, and hopefully appreciate, the importance of the micro-behavioral economic perspectives and the G-MAP modeling efforts in the global warming research. The following three chapters are devoted to the explanations of the Agro-Economic Models in Chap. 4, the statistical studies of grain yields and weather fluctuations in Chap. 5, and the ecosystem-based studies in Chap. 6. These are alternative modeling approaches that have been popular among the researchers for measuring the impacts of climate change on agriculture. The purpose of presenting in detail these studies is not for the sake of these studies themselves, but for revealing further subtler meanings and implications of the micro-behavioral economics of global warming and the G-MAP models against the non-behavioral studies of agriculture and global warming. That is to say, these succeeding chapters will deepen our understanding of adaptations to global warming.

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Chapter 4
Agro-economic Models: Theory and Major Findings

Abstract This chapter describes the conceptual framework and major findings from the Agro-economic Models (AEMs). The results are compared with the G-MAP models from the perspectives of adaptations to climate changes and the AEM's capacity to model and capture them.

Keywords Agro-economic models · Crop simulation models · FACE

In this chapter, we turn our attention to the agro-economic models, an alternative modeling approach for measuring the impacts of climate change on agriculture which has been widely cited and applied among the researchers. The model is often said to have only limited capacity for modeling adaptation behaviors. A review of this approach will therefore highlight the capacity of the G-MAP models in accounting for the full array of adaptation strategies and modeling them explicitly. A review of this modeling approach will serve as an elegant way to distinguish the micro-behavioral economics studies from non-behavioral experimentally-based studies of global warming.

An agro-economic modeling approach combines agronomic crop models with a national agricultural economy model and is often called the Agro-economic Model (AEM). The AEMs begin with the experiments on the effects of elevated CO_2 on crops. Experiments are conducted on selected grains such as wheat, maize, soybeans, and rice which hold major importance to the national economy of concern. After controlling numerous factors that affect the process of crop growth, an agronomic crop model simulates the changes in the yields of the concerned crops which result from the changes in the CO_2 level (Jones and Kiniry 1986; Williams et al. 1989; Tubiello and Ewert 2002).

The experiments can be conducted in a laboratory setting or in an open field. In a laboratory setting, controlled experimental chamber, greenhouse, closed-up or open-top field chambers are utilized. An open air field experiment is more expensive but considered more realistic in the sense that it replicates the crop growing conditions in the field. After randomizing other factors of crop growth,

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climate scientists elevate CO_2 level through pipes placed around the plants in the experimental plots and record the changes in the yields (or growth rates) of the crops and plants. This type of experiment is called the Free-Air CO_2 Enrichment (FACE) experiment and has been conducted extensively in the past decades (Ainsworth and Long 2005). The experimental results differ by the climate regime in which the experiments are conducted. The experimental results can still diverge from the field observations of the changes that occurred over the past several decades (Lobell and Field 2008).

The experimental results on yield changes are inserted into a national agricultural model which is representative of the agriculture in the country of concern (Adams et al. 1990; Reilly et al. 2003; Butt et al. 2005). For example, the US researchers used the Agricultural Sector Model (ASM) which has 63 homogeneous production regions in the 48 contiguous United States (Adams et al. 1990, 1999).

The AEM descriptions henceforth will be based on the work by Adams and his coauthors in 1999 since this work contains the most detailed description of the AEMs and most sophisticated of all (Adams et al. 1999). To feed into the ASM, Richard Adams and his coauthors choose representative farms (sites) across the country which are representative of 17 major agro-climatic regions in the US. The experimental results of selected crops on the 17 selected sites are then fed into the representative enterprises to obtain the changes in crop yields for the enterprises (see also Kaiser et al. 1993 for representative enterprises). The results from the representative enterprises are then extrapolated to the national agriculture model, the ASM, to simulate the impacts of climate change at the national level after accounting for land use, water availability, and irrigation of the 63 homogenous production regions which are separately estimated.

Assuming the demand and technology for the grains remain fixed or get updated over time by an assumed formula, researchers can calculate the baseline yields, prices, consumer surplus, producer surplus, and economic welfare when there is no climate change. These measures are recalculated assuming a climate change scenario. The area between the baseline (new) demand curve and the supply curve is defined as the baseline (new) economic welfare. The impact of the climate change scenario is then calculated as the difference between the new economic welfare and the baseline economic welfare (Adams et al. 1999). These calculations are made on a crop basis in most circumstances of this modeling.

The Agro-economic Models should build upon the results from the controlled experiments conducted by agronomists and climate scientists. All the AEMs rely on a set of selected crop simulation models because they are calibrated to include all the factors that affect crop yields including CO_2 (Tubiello and Ewert 2002). On the other hand, the Free-Air CO_2 Enrichment (FACE) experiments which better replicate the field conditions have been conducting such experiments since the early 1990s when it was first conducted at the Duke Forest (Schlesinger 1997).

The results from the 15-year FACE experiments as well as from the crop simulation models are summarized in Table 4.1. The table shows average changes in the corresponding indicators of crop growth from the numerous FACE studies

Table 4.1 AEM: simulated crop yield changes under 2*CO_2

		FACE	Crop simulation models
Crops/plants	Indicators	Mean changes	Mean changes
Rice	Crop yield	Around +10 %	+10 % (AEZ) +17 % (CERES-C3) +19 % (EPIC-C3)
Wheat	Crop yield	+15 %*	+11 % (AEZ) +17 % (CERES-C3) +19 % (EPIC-C3)
Cotton	Crop yield	+42 %*	
Sorghum	Crop yield	Around +5 %	+6 % (CERES-C4)
		+40 % (under no stress)	+8 % (EPIC-C4)
Maize	Crop yield		+4 % (AEZ) +6 % (CERES-C4) +8 % (EPIC-C4)
Soybeans (Legumes)	Crop yield		+16 % (AEZ)
	Dry matter production	+24 %*	

Note *FACE* free-air CO_2 enrichment, *AEZ* agro-ecological zone, *CERES* crop environment resource synthesis, *EPIC* erosion productivity impact calculator
*denotes 95 % Confidence

when CO_2 level is elevated to 2 times the current level (Ainsworth and Long 2005). Major crops all increase in yields. On average, rice yield increases by 10 %, wheat yield by 15 %, cotton yield by 42 %, and sorghum yield by 5 % (by 40 % under no stress) under the FACE experiments. Legumes (soybeans) increase by 24 % in dry matter production.

The fourth column of Table 4.1 summarizes the results from three crop simulation models which were taken from Tubiello and his coauthors (Tubiello et al. 2007). Although the FACE experiments lead to smaller yield increases, the Agro-ecological Zone (AEZ) model results in the table are almost identical to the FACE experiment results after baseline adjustments (Long et al. 2006). The Crop Environment Resource Synthesis (CERES) and the Erosion Productivity Impact Calculator (EPIC) models predict slightly higher yield increases. For example, rice yield increases by 10 % under the FACE, but it increases by 17 % under the CERES model and by 19 % under the EPIC model. The maize yield increases by 4 % under the AEZ method, by 6 % under the CERES, and by 8 % under the EPIC. Soybean yield increases by 16 % under the AEZ method.

Using the estimated yield changes obtained from the experiments, researchers estimate the national level changes in the yields of the major crops under elevated CO_2 conditions and changed climates. For this purpose, researchers rely on the national agricultural model such as the Agricultural Sector Model (ASM) of the US agriculture or the Mali Agricultural Sector Model (MASM) (Adams et al.

Table 4.2 AEM: agricultural commodity price and quantity indices (Base = 1.0)

	Price index	Quantity index
GISS with CO_2 doubling	0.83	1.09
GFDL with CO_2 doubling	1.34	0.80

Note The results are from Adams et al. (1990)

1990, 1999; Butt et al. 2005). Assuming the demand remains unchanged from the baseline year (or gets updated over time), authors calculate the changes in agricultural prices caused by yield changes due to climate change and CO_2 elevation (Adams et al. 1990). Table 4.2 shows the changes in the Fisher price index from the baseline under the two climate scenarios. The table shows the supply increase by 9 % under the Goddard Institute for Space Studies (GISS) scenario but the decrease by 20 % under the Geophysical Fluid Dynamics Laboratory (GFDL) scenario. Accordingly, agricultural price index falls by 17 % under the GISS scenario and increases by 34 % by the GFDL scenario. These predictions hinge on the assumptions about the future such as, among other things, population growth, income growth, consumption patterns, and technological changes. Especially, substitution patterns of consumption may be decisive.

By shifting the agricultural supply caused by climatic change, authors calculate the changes in consumer surplus and producer surplus as well as total economic welfare. Table 4.3 reports the results from the two GCM scenarios assuming 1981–1983 economy (Adams et al. 1990). The total welfare increases by 11.4 % under the GISS scenario while it falls by 10.9 % under the GFDL scenario. Under the GFDL scenario where yields fall sharply and prices increase, consumers lose income substantially, but producers gain income by 20 % due to price increases. These results are predicated on the assumption that no changes in production patterns will occur even though climate system is shifted.

Adams and his coauthors have improved this AEM model over time primarily in two directions. First, they extended the analysis to non-major cereals such as cotton-sorghum, tomatoes-citrus-potatoes, and forage-livestock production (Adams et al. 1999; Reilly et al. 2003). However, experimental results from either the agronomic models or the FACE experiments are less well understood on these farm products. Forage yield changes were obtained from the EPIC crop simulation model for the Southeast US and from the CENTURY model for the western US (Parton et al. 1992). Based on the simulations on 17 sites in the Southeast and 12 sites in the Western US, the ASM yield changes were estimated. From the pasture yield changes, the number of acres required per head was estimated under the changed climate conditions. In addition, direct effects of climate on cattle production on food intake (appetite depressing) were estimated to calculate production efficiency using the NUTBAL model (Stuth et al. 1999). However, these results are preliminary and the effects of climate change on livestock are still not well understood; changes in animal numbers, weights, breeds, animal products, grasslands, land uses, and water uses are not well understood. In particular, physical adaptive capacities of livestock as well as the impacts on conception are not well understood (Amundson et al. 2006).

Table 4.3 AEM: economic consequences of climate change on the US agriculture

	Consumers	Producers	Foreign surplus	Total
Adams et al. (1990)*: assuming demand and technology remain unchanged*				
Baseline	77.32 billion$	17.8 billion$		95.2 billion$
GISS with CO_2 doubling	+12.0 %	+8.9 %		+11.4 %
GFDL with CO_2 doubling	−18.0 %	+19.9 %		−10.9 %
Adams et al. (1999)*: assuming 2060 baseline*				
GISS with CO_2 doubling	+20.6 billion$	+45.4 billion$	+50.6 billion$	+116.6 billion$ (around +7 % of total value of agriculture sector)
GFDL with CO_2 doubling	−65.7 billion$	+52.2 billion$	−3.4 billion$	−16.9 billion$ (around −1 % of total value of agriculture sector)

Putting all things together, authors estimated that the impacts of climate change on livestock are negligible. The revised model is best summarized in the bottom panels of Table 4.3 (Adams et al. 1999). Under the GFDL scenario, the impact is around 1 % loss of the total welfare in which 52 billion dollars of producer surplus is offset by the larger loss by the consumers, domestically and internationally through export price increases.

In another direction, the original model was also applied to a non-US country, e.g., Mali, an arid zone country in the Sahel (Butt et al. 2005). Relying on the Mali Agricultural Sector Model (MASM), authors find severe crop damages due to climate change as well as livestock weight losses. However, they find that the impacts on the weights of goats and sheep are not discernible while cattle weight decreases substantially due to both decrease in forage quality and appetite. In most circumstances, non-US studies rely on the controlled experimental findings conducted in the US on crops, pasture, and livestock.

The agro-economic modeling approach has been adopted widely for the past two decades. Rosenzweig and Parry relied on a similar approach to measure the impacts of climate change on global food supply (Rosenzweig and Parry 1994; Parry et al. 2004). Crop simulations from the 18 countries around the world are used for wheat, maize, soybeans, and rice. Site specific yield changes are aggregated to the national levels. Based on the results from the 18 countries and 4 major crops (wheat, rice, maize, soybeans), authors extrapolated to the yield changes in the rest of the world as well as to the all the other crops raised across the world. Using the Basic Linked System (BLS) composed of a set of linked national agricultural models, authors then simulated the world food trade. Trades of grains among the world regions and their prices were modeled (Tobey et al. 1992; Reilly et al. 1994).

However, it is likely that these models are substantially less accurate than the US model since extrapolations to the other crops, to the national agricultures, and to the other countries in the world will likely involve substantial distortions.

In addition, national level experiments are not as soundly implemented as those conducted in the US. Further, projections of national economies of the developing countries into the end of this century are extremely difficult.

This approach was further refined by incorporating varied crop potentials of different Agro-ecological Zones (AEZ) around the world using the FAO Global AEZ (GAEZ) data set (Fischer et al. 2005; FAO 2005; Hillel and Rosenzweig 2010). The full description of the AEZ methodology and the drawbacks of the AEZ impact methodology will be reserved for Chap. 6 which is devoted to the studies of ecosystems and individuals' decisions to cope with climate changes (Seo 2014).

Despite much interest among the AEM modelers, there have been few studies conducted on extreme events or catastrophic events and progresses in modeling efforts have been extremely slow over more than two decades on the topic (Easterling et al. 2000; Rosenzweigh et al. 2001; Challinor et al. 2007).

Having discussed major findings from the two modeling approaches, i.e., the G-MAPs in Chap. 3 and the AEMs in this chapter, we are well positioned to discuss how adaptation behaviors are modeled in the two methodological traditions. Indeed, one of the fundamental differences between the AEMs and the G-MAPs, the micro-behavioral economics of global warming, lies in the ways how adaptation behaviors are conceptualized and empirically modeled.

The two methods differ fundamentally in that the AEMs are well suited (intended) for understanding the changes in crop yields and their economic impacts while the G-MAPs are designed for understanding the behavioral changes that occur at the farm level and their economic consequences. That is, the base unit of analysis is a crop for the AEMs (Adams et al. 1990; Rosenzweig and Parry 1994; Antle et al. 2004) while the base unit of analysis is a farm for the G-MAPs.

The AEMs can be effectively linked to agronomy, i.e., crop experiments which are conducted locally, i.e., at a specific experimental plot (Jones and Kiniry 1986; Williams et al. 1989; Tubiello and Ewert 2002). The experiments are conducted on a selected site in a given agro-ecological zone. The AEM modelers rely on the shifts in agro-ecological zones under climatic changes to model subsequent changes in agricultural activities (Fischer et al. 2005).

The G-MAPs utilize observed choices of farmers and realized profits and land values across the range of climate conditions (Seo 2006, 2010a, 2010b). When climate is altered, resultant changes in choice decisions and land values are measured simultaneously. Changes in adaptation decisions are then associated with changes of the eco-systems at a given farm location (Seo 2012b, 2014; Matthews 1983; FAO 2005).

The G-MAP models of the micro-behavioral economics encompass a full array of farm portfolios managed by the farmers while the AEM is based on selected crops (Adams et al. 1990; Seo 2012a). As explained in the above, AEM modelers select several major grains, e.g., maize, rice, wheat, and soybeans. Therefore, there is no internal mechanism to account for choice of a specific crop, let alone choice of a crop not included in the analysis, i.e., non-major crops. The G-MAP framework can be used, conceptually, to model choice of any portfolio from the full array of available portfolios. And, it can be modeled explicitly, i.e., explained quantitatively in a consistent fashion.

One of the key findings on adaptation to climatic changes is that a farmer can turn away from a specialized portfolio to a diversified portfolio, or vice versa, in an effort to cope with changes in climate normals or climate risks (Markowitz 1952; Fabozzi et al. 2009). A farmer may diversify from a specialized crop system to an integrated crops-livestock system under a hotter climate (Seo 2010a, b). One may also diversify into activities of crops, livestock, and forests (Seo 2010c, 2012a). The opposite way is also possible. That is, one may switch from a mixed system to a specialized crop system when rainfall increase is coupled with a mild temperature increase. The AEMs, on the other hand, have limited capacity in explaining a farmer's adaptive behaviors through diversification or specialization (Adams et al. 1999; Antle et al. 2004; Easterling et al. 2007). More fundamentally, diversification strategies cannot be obtained from laboratory or field experiments.

Adaptation to increased climate risks is one of the key questions facing the agricultural sector's capacity to cope with climatic shifts (Easterling et al. 2000; Hansen et al. 2012). The G-MAPs draw on the long and rich tradition of behavioral economic studies of risks and uncertainties in financial decisions (Markowitz 1952; Tobin 1958; Arrow 1971; Arrow and Fisher 1974; Udry 1995; Zilberman 1998; Shiller 2003). The micro-behavioral economics has taken on some aspects of the behavioral economics traditions of risk and economic behaviors. The G-MAP model is a highly effective methodology to explain behavioral decisions under risk.

A G-MAP model shows that farmers in sub-Saharan Africa cope with climatic risks caused by increased variations in rainfall and temperature measured by the Coefficient of Variation in Precipitation (CVP) and the Diurnal Temperature Range (DTR) by adjusting agricultural portfolios (Seo 2012c). When the CVP becomes high, a farmer is more likely to turn to a mixed crops-livestock system. When the DTR becomes high, a farmer is more likely to resort to animals than to crops.

In the AEM models, taking into account climate risks and uncertainties has been a continuing challenge (Rosenzweig et al. 2001; Challinor et al. 2007). As our review in this chapter shows, few attempts have been made by the AEM modelers to date to model adaptation behaviors under such conditions of risk and uncertainty. The impasse, in turn, can be attributed to the intrinsic challenges of conducting an appropriate lab/field experiment on how changes in climate risk or uncertainty would alter an individual crop's yield and a specific portfolio's yield (Porter and Semenev 2005). Without such experimental results available, the AEM modelers have failed to make a progress in this important topic.

One of the questions that climate researchers have attempted to address is whether adaptation is costly (Kelly et al. 2005). In the G-MAP models, adaptation costs are internalized in the farmer's decisions. That is, a farmer would make adaptation decisions based on both the revenue and the cost of adopting or deserting a system. Transition costs, in the Bayesian sense, could incur additionally, but only when the farmer is not informed of, i.e., ignorant of which strategy to take under a changed climate condition in order to adapt.

In the AEM modeling tradition, a researcher can calculate an estimate of financial costs of adaptations to climate change, e.g., financial needs for expanded research, extension, and capital expenditures under changed climates, and add them to the total cost of climate change (McCarl 2007; Parry et al. 2009). But, up until now such financial costs of adaptations are not linked to desired adaptation projects and are treated exogenously of adaptation behaviors, and eventually of the impact estimates from the AEMs.

Besides adaptation strategies that may be adopted by an individual natural resource manager, some strategies are cost effective at a community level, which evokes the lessons of managing community resources (Ostrom 2009). For example, an irrigation system established by the community as a whole may reduce the total cost of irrigation (Seo 2011a). The G-MAP models have the capacity to examine adaptation strategies at both an individual level and a community level. This distinction poses a further challenge to the AEM models due to the focus on a crop-by-crop approach.

This concludes the presentation of the AEM modeling approach. It is worth emphasizing one more time that this chapter on the AEMs is intended to unpack what the micro-behavioral economics and the G-MAP models contain and achieve, which becomes clearer when they are put together and compared with an alternative modeling approach, the AEMs in this chapter.

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Chapter 5
Econometric Models of Yield Changes with Weather Shocks

Abstract This chapter describes the methods and major findings from the econometric models of grain yield changes and/or weather fluctuations. The results from the econometric models are reconciled with those from the G-MAP models using the modeling capacities of the two methodologies to capture adaptation strategies.

Keywords Econometric studies · Yield changes · Weather shocks

In this chapter, the present author discusses another major research methodology which is distinct from either the AEMs or the G-MAPs. The goal of this methodology is to measure the impacts of climate change on yields of major grains such as maize, wheat, rice, and soybeans. A researcher estimates a yield function of a selected grain using either a parametric method or a non-parametric method. S/he examines changes in the yield of the grain when weather variables are altered year by year (Deschenes and Greenstone 2007; Schlenker and Roberts 2009; Lobell et al. 2011; Fisher et al. 2012).

The author's intention in writing this chapter is again not to describe this methodology per se which has been wildly popular among the researchers of climate change and/or agriculture. Rather, the present author is interested in unpacking the micro-behavioral economics of global warming and the G-MAP models through an alternative modeling approach which differs in major ways. The presentation of this chapter is rooted on the paper published recently at Climatic Change journal on the same topic (Seo 2013b).

This research deviates sharply from the two modeling approaches surveyed in the previous chapters in that it does not address the total profit from farming either at the farm level or at the national level. That is, this research tradition is concerned about a single crop or several crops. Although the focus on a single grain is not necessarily desirable from the economics point of view, this line of research has reflected the widely-held concern that a certain grain's yield may be severely damaged under changed climates or the early presumption in the

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literature that the most important grains such as rice and maize will be severely harmed due to global warming (Reilly et al. 1996).

Let me state more formally some of the reasons why the present author provides a review of this literature. First, this research field has attracted much attention from the researchers due to the large catastrophic impacts of climate change on agriculture predicted by these studies. Second, the econometric models used for this type of research have the capacity to capture adaptations, but only in a limited way. Therefore, the review of this methodology gives us another opportunity to evaluate the importance of adaptation modeling in the literature. Third, the review of this research tradition provides us with an opportunity to visit the topic of climate normals versus weather fluctuations, a fundamental concept in climate science.

Statistical methods that focus on estimating a yield function of a selected grain using weather variables had been widely used by the researchers, formally or informally, even before the subject of global warming became a major policy and research field. This is no surprise given that crop yields are heavily swayed year by year due to weather fluctuations. However, it is only recently that this tradition has entered into the discussions of global warming and agriculture (Deschenes and Greenstone 2007; Schlenker and Roberts 2009).

Over the years, different econometric models were presented, which I will summarize here. These models belong to the same framework in that they estimate a yield function of a selected grain using weather variables. First, a panel data analysis for the US agriculture was developed to explain the changes in net revenues and grain yields in response to yearly weather fluctuations using the US county data (Deschenes and Greenstone 2007, 2012; Fisher et al. 2012). Second, researchers estimated non-parametrically yield functions of selected crops across weather variables in the US using the aggregated (at the US county level) yield data compiled by the USDA (Schlenker and Roberts 2009). Using the time series data of grain yields from 1980 collected globally, researchers examined the changes in the yields of major crops and associated them with historical weather changes identified as the number of standard deviations from climate means in the given year (Lobell et al. 2011). Yield changes in Africa were also associated with the changes in ENSO (El Nino Southern Oscillation) and NAO (North Atlantic Oscillation) indices over time (Stige et al. 2006). The combined impact of Asian Brown Clouds and greenhouse gases was examined in Indian rice production using aggregated (at the state level) harvest data over time since 1960–2000 and subsequently in the selected rice producing regions of South Asia (Auffhammer et al. 2006; Welch et al. 2010). Using the state level panel data of yields of major grains in the US, variances in the yield functions were explained using climate variables (McCarl et al. 2008).

The basic conceptual setup of these models is the same, so we do not need to explain all of them. Of these, the Schlenker and Roberts's study has attracted much attention for several reasons. The authors reported that cereal yields in the US would decline, when accounting for nonlinear yield responses, by as much as 30–46 % by around the century's end under the mild climate change scenario (B1) and 63–82 % under the severe warming scenario (A1F1) (Schlenker and Roberts 2009).

Table 5.1 Yield studies: impacts from the non-parametric yield functions in the US

	Corn (maize)	Soybeans	Cotton
2070–2099, *piecewise linear*			
Hadley B1 scenario (%)	−43	−35	−38
Hadley A1F1 scenario (%)	−82	−72	−72

Note The results are mean changes approximately taken from the impact figure from Schlenker and Roberts (2009)

Table 5.1 summarizes mean yield impacts for corn, soybeans, and cotton under the Hadley climate model predictions by 2070–2099 as reported by the authors.

The authors argued that the large yield losses are expected due to a nonlinear (non-symmetric, more appropriately) yield response to temperature. They argued that the decline after the peak is much steeper than the incline before the peak if a crop yield response is estimated non-parametrically. That is, there is a precipitous fall in the grain yield in high temperatures. In addition, although corn would suffer the most, the other grains such as soybeans and cotton which have been known to be more resilient to high temperatures would suffer similarly (Table 5.1).

These predictions are largely at odds with the experimentally-based crop yield studies (Ainsworth and Long 2005; Tubiello et al. 2007; Adams et al. 1990) and by and large with the crop yield response functions known to agronomists (IPCC 1990; Jones and Kiniry 1986). Although puzzling at first, these dire predictions can be understood comfortably from the purview of the micro-behavioral economics. That is, people can adapt by moving away from these crops.

The Schlenker and Roberts's paper and their African yield paper (Schlenker and Roberts 2009; Schlenker and Lobell 2010) do not address a farmer's selection decisions and consequently suffer from selection bias (Heckman 1979; Seo 2010a, b). For example, farmers have shifted from these major crops to animals or forest products or a mixed portfolio of them (Seo 2012a, 2014). Therefore, the bias comes from two types of behaviors: adoption and diversification.

From this perspective, it is also not difficult to see that the application of the non-parametric methods exacerbates the problem of selection bias. With its inability to account for switching and mixing behaviors of individuals, the magnitude of selection bias will be even larger in a non-parametrically estimated yield function than in a parametrically estimated yield function with the same statistical specification and explanatory variables. This is because the non-parametric methods "trace" the observed yields.

An even more illuminating case with regard to yield changes due to weather fluctuations is a panel data analysis of the US agriculture (Deschenes and Greenstone 2007, 2012). This method was developed to explain the changes in net revenues as well as grain yields in response to yearly weather fluctuations (Deschenes and Greenstone 2007, 2012). Although the original intention of the Deschenes and Greenstone was to show the changes in net revenues, the focus was shifted by Fisher and his coauthors to grain yields (Fisher et al. 2012).

The Deschenes and Greenstone's approach is noteworthy for several reasons. The authors constructed the panel data of net revenues and yields of the major crops obtained from the USDA Census of Agriculture in 1978, 1982, 1987, 1992, 1997, and 2002 (Deschenes and Greenstone 2007). After constructing the panel data at the US county level, authors measured the changes in net revenues and grain yields in response to deviations of temperature and rainfall conditions in a given year from the long-term average weather.

Authors found that the US agriculture sector copes well with the yearly fluctuations of weather, predicting only minor changes in agricultural profits and yields due to climate changes in the future. As shown in Table 5.2, the authors find that agricultural profits, corn yield, and soybean yield increase insignificantly by the end of this century under the Hadley scenario mentioned above.

The results imply that yearly weather impacts on agriculture are modest in the US owing to various technological options and financial systems available in the advanced economy as well as the post-harvest physical storage capacity (Udry 1995; Wright 2011). These results contain, by and large, similar implications to the past studies on African farmers who are found to cope with weather shocks through saving and storage of grains (Udry 1995; Kazianga and Udry 2006). However, the original Deschenes and Greenstone paper did not address the storage effects explicitly.

A recent comment by Fisher, Hanemann, Roberts, and Schlenker (FHRS hereafter) points out that the impacts of weather fluctuations on grain yields are likely severe once several mistakes are corrected and more recent climate scenarios are applied to the Deschenes and Greenstone model (Fisher et al. 2012). However, both teams of researchers find that the impacts are likely much muted once the capacity of storage is fully considered as far as agricultural profit (net revenue) is concerned (Fisher et al. 2012; Deschenes and Greenstone 2012).

Table 5.2 Weather studies: panel fixed effects estimates of profit and yield changes in the US

	Agricultural profits ($)	Corn (yield)	Soybeans (yield)
DG 2007 (*state-year fixed effects*)			
Baseline (2002)	32 billion dollars	8.67 billion bushels	2.38 billion bushels
Hadley 2 (2070–2099)	+1.29 billion dollars	+0.01 billion bushels	+0.02 billion bushels
DG 2012 (*state-year fixed effects*)			
Hadley 2 (2070–2099)	−1.7 billion dollars		
Hadley 2 (2070–2099) with distributed lag	−3.7 billion dollars		
CCSM 3 A2 scenario with distributed lag	−8.6 billion dollars		
FHRS 2012 (*soils*, *county fixed effects*, *year fixed effects*)			
Hadley 3 B2 (2070–2099) (%)	−55.99	−42.01	−51.59

Note The results are from Deschenes and Greenstone (2007, 2012) and (Fisher et al. 2012)

The panel fixed effects models used by the both teams of researchers examine the relationship between the deviations of a grain yield in a given year from the average yield and the temperature (and rainfall) deviations in a given year from the average weather, after controlling county fixed effects. A variety of the panel fixed effects models can be summarized succinctly as follows (Deschenes and Greenstone 2007; Lobell et al. 2011; Fisher et al. 2012):

$$(y_{it} - \bar{y}_{\Lambda T}) = \alpha + \binom{x_{it} - \bar{x}_{\Lambda T}}{z_{it} - \bar{z}_{\Lambda T}}' \binom{\beta}{\gamma} + \varepsilon_{it}, \quad \forall i, t. \tag{5.1}$$

where y,x,z are respectively grain yield, weather, and covariates; t, T, i, Λ are respectively a year, all years in the sample, a county, and a State to which the county belongs; ε_{it} is a white noise error. Note that Eq. 5.1 controls both year fixed effects and county fixed effects. Both teams used growing degree days for temperature along with precipitation as weather variables (Masseti et al. 2014). Note also that some covariates can disappear from the model if these variables are constant across time periods. For example, soils may have remained constant over this time period.

As is evident from Eq. 5.1, the panel fixed effects models, however, can only capture the impacts of weather deviations on the deviations of grain yields through the estimated parameters β. Note that climate normals in the US remained constant for the time periods of the panel data. That is to say, one cannot account for the impacts of a shift in the climate system through Eq. 5.1 and consequently the effects of a variety of adaptation behaviors to a climatic shift. Numerous adaptation strategies to climatic changes that were described in detail in Chaps. 2 and 3 and those that will be further elaborated in Chap. 6 cannot be captured in these studies (Seo and Mendelsohn 2008, Seo 2013a). Neither the panel fixed effects model can reveal such adaptations.

This is a serious drawback, both conceptually and empirically, given that whether farmers and entrepreneurs adapt to long-term climatic shifts or not will by and large determine the magnitude of the impact of climate change on agriculture, as has been demonstrated in the previous chapters. The impacts of climate change on grains are especially heavily dependent upon the farmer's ability to adapt in the long-term since farmers at present are highly selective when making decisions to grow grains.

Therefore, the large damages on agriculture and crops predicted by the panel fixed effects models, especially by Fisher and his coauthors (2012), are attributed largely to random weather fluctuations, not climatic shifts. Another way to verify this is through actual historical data in the US agriculture. A large damage that a severe weather event causes is well documented in the agricultural economics literature. In Fig. 5.1, I draw the historical corn (maize) yields in Des Moines, Iowa, along with the growing season precipitations in the region, over the time period from 1971 to 1990. This figure was presented by Cynthia Rosenzweig and her coauthors in their paper appropriately titled 'Climate Change and Extreme Weather Events—Implications for Food Production, Plant Diseases, and Pests' (Rosenzweig et al. 2001). Des Moines, Iowa is one of the major crop growing regions in the US.

The growing season precipitation is a weather variable in this figure which is shown to fluctuate largely year by year. The figure clearly depicts the effects of

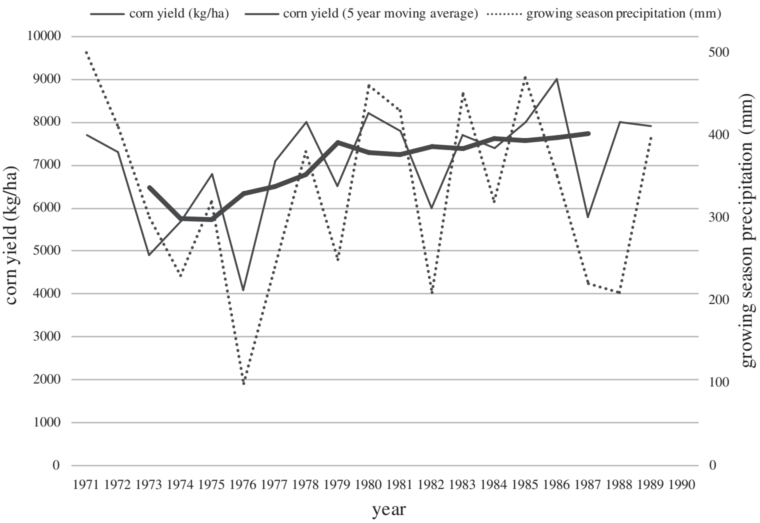

Fig. 5.1 Yearly precipitation deviations and corn yields in Des Moines, Iowa

random weather fluctuations, i.e., yearly precipitations, on the yearly corn yields of the region. As can be seen, a very low rainfall in a given year results in a large reduction in the corn yield of that year, often more than 20 % from the average year, while a high rainfall year also leads to a high corn yield. A high rainfall year would offset the loss in a low rainfall year to some degree. In either case of rainfall, the maize yield deviates from the average 'normal' yield, probably by a similar percentage size.

It is, however, not correct to conclude from this figure that climate change (e.g. a reduction in rainfall normals) will lead to a similarly large reduction in corn yields. This figure only captures the variations observed in corn yields in response to random weather fluctuations. What the panel fixed effects models described above have estimated is the impacts of weather fluctuations on the yield fluctuations clearly depicted in this figure. Note that in the figure a severe drought year often leads to a more than 50 % loss in the corn yield from the maximum yield reported in the region.

It is also not hard to see from this figure that climate change will not have the same impacts on grain yields as weather fluctuations have. On top of the figure presented by Rosenzweig and her coauthors, I overlaid the five-year moving averages of the corn yields as a thick black line. It shows the five-year moving average corn yields have been little affected by weather fluctuations during this time period. Indeed, the corn yields were slightly increasing over this time period. The upward-sloping thick black line emphatically tells that the impacts of climate change on agriculture will be different from the impacts of random weather (Seo 2012b).

The author will conclude this chapter with a couple of summary comments on the capacity of the econometric models of yields to capture adaptation behaviors.

In the overall structure of this book, the econometric models fall into the middle ground between the AEMs and the G-MAPs with regard to the modeling capacity of adaptations. The econometric models of yields can include some adaptations taken by the farmers in the short-term but cannot account for adaptation strategies that would be adopted in response to the shifts in the climate system (Deschenes and Greenstone 2007; Seo 2013a). How short is a short-term here? Given that farming seasons last less than 6 months, the short-term means several months, i.e., not a full year. When the weather in a specific year is observed by a farmer to deviate noticeably from that of the 'normal' year, s/he would take necessary measures to cope with that year's weather. For example, s/he may plant earlier/later or plant certain crops.

From a slightly different angle, the econometric models of grain yields capture by and large ex-post adaptations to weather changes. That is, a farmer adapts grain productions after seeing weather realizations during the farming season. For example, a rice farmer, having observed the weather realizations, may plant earlier than normal years due to a warmer weather in that year or irrigate her/his farmland using water from a nearby reservoir or river in a drier-than-normal year.

Lastly, the fact that these econometric models can capture some adaptation activities, short-term measures as well as ex-post measures, does not mean that these models are capable of modeling them. These models treat adaptations implicitly while the micro-behavioral economics and the G-MAP models model them explicitly. That is, there is a black box of adaptations.

The arguments that I have presented so far in this chapter by and large underlie the new efforts by Deschenes and Greenstone (2012) to capture lagged effects of weather variables into subsequent years. I should also emphasize that the panel fixed effects model by the above authors was developed to explain total net revenues, not individual grain yields. That is to say, the authors were in some sense aware of these problems outlined in this chapter.

This concludes the chapter on econometric models of grain yields with weather deviations. Again, the author's purpose of presenting this chapter is only to explain what subtleties are embedded in the micro-behavioral economics and the G-MAP models especially with regard to capturing adaptation strategies.

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Chapter 6
Micro-behavioral Decisions and Ecosystem Changes: A Multidisciplinary Integrated Framework

Abstract This chapter presents the multidisciplinary characteristics of the micro-behavioral economics of global warming by coupling individuals' decisions with ecosystem changes. In the second part of the chapter, the author provides a review of the AEZ-based (Agro-Ecological Zone) impact methodology and its limitations.

Keywords Micro-behavioral models · Agro-ecological zones · Ecosystems

Having discussed the two alternative modeling approaches in detail in the previous two chapters, we redirect our attention to the micro-behavioral economics and the G-MAP models in this chapter. The topic of this chapter is ecosystem changes and how these interact with behavioral changes of individuals. Through this chapter, the present author highlights a multidisciplinary and integrated framework of the G-MAP models.

A great diversity of ecosystems exists in the world and one of the key factors that determines the types and productivities of ecosystems is climate (Schlesinger 1991; Denman et al. 2007). It has long been recognized by the researchers that agriculture and natural resource enterprises are intertwined with ecosystems and ecological zones (Global Biodiversity Outlook 2010). Changes in ecosystems that are expected to unravel as a result of climatic shifts in this century will therefore have profound consequences on the behaviors of individuals who manage agricultural and natural resources (Seo 2012b, c).

The G-MAP models have been developed in a way to couple changes in individual behaviors with changes in ecosystems caused by climatic changes (Seo 2014a, b). For this reason, the G-MAP was named "Geographically-scaled" meaning that individual behaviors are scaled to geographical components, the most prominent of which is ecosystems (Seo 2011). The first half of this chapter is devoted to explaining the interconnections between individuals' decisions and ecosystem changes as reported by the G-MAP models applied to Sub-Saharan Africa and South America.

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In another line of inquiry pursued in the latter half of this chapter, the present author evaluates in detail another major methodological approach which has been popular among the agricultural researchers, called the Agro-Ecological Zone (AEZ) method (Fischer et al. 2005). This method is based on the concept and classifications of the AEZs, i.e., agro-ecosystems. This chapter will introduce the AEZ concept as it was historically developed. The present author will then evaluate the application of the AEZ concepts to measuring the impacts of climate change on agriculture from the perspectives of both observed micro behaviors and future adaptation possibilities to climatic change scenarios (Seo 2014a).

Let's start with the existing ecosystems in the two low-latitude developing continents that we have been investigating throughout this book, South America and Sub-Saharan Africa. Ecosystems, or equivalently ecological zones, are highly diverse and complex across South America. An early study by Matthews classifies them into major land covers—or vegetations—based on the collection of existing studies on land uses and the National Aeronautic and Space Administration (NASA) satellite imageries at the resolution of a degree cell which is the size of 1° latitude by 1° longitude (Matthews 1983). Major land covers across South America are extracted from the NASA Goddard Institute of Space Studies (GISS) data set by the present author and redrawn in Fig. 6.1.

Tropical rainforests are expansive across northern Brazil and the Andean countries including the Amazon Basin and the Ecuadorian Yasuni. In the high lands of Colombia and Venezuela, there exist grasslands with <10 % woody cover, called the Llanos, and tropical/subtropical drought deciduous forests. Eastern parts of Brazil are grasslands with smaller (<10 %) or larger (>10 and <40 %) woody covers and xeromorphic forests.[1] Western and Southern parts of Brazil, including the Cerrado, are various types of forests such as xeromorphic forests, tropical/subtropical drought deciduous forests, seasonal forests, and evergreen forests. Uruguay is dominantly grasslands with shrub cover. The northern part of Argentina is tall grasslands. The large areas of Argentina are covered by drought deciduous shrublands. There exist meadows and deserts in the southern parts of Argentina. Southern parts of Peru are dominantly meadow with no woody cover. Northern parts of Chile, including the Atacama Desert, are meadows with no woody cover and xeromorphic shrublands. The middle parts of Chile are xeromorphic forests and subtropical and temperate evergreen rainforests. Southern parts of Chile are temperate evergreen rainforests and cold deciduous forests. Major land covers in Paraguay and Bolivia, two landlocked countries, are xeromorphic forests, tropical/subtropical seasonal forests, subtropical evergreen forests, and evergreen needle-leaved woodlands. Along the coastal areas, water ecosystems, e.g., oceans, rivers, or lakes, are dominant. The Andes Mountains provide the highland mountain ecosystems that are distinct from the lowlands' including the glaciers such as the Zongo glacier in Bolivia and the Antisana glacier in Ecuador (Rabatel et al. 2013).

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[1] Xerophyte is any plant adapted to life in a dry habitat by means of mechanisms to prevent water loss or store available water, e.g., Joshua tree.

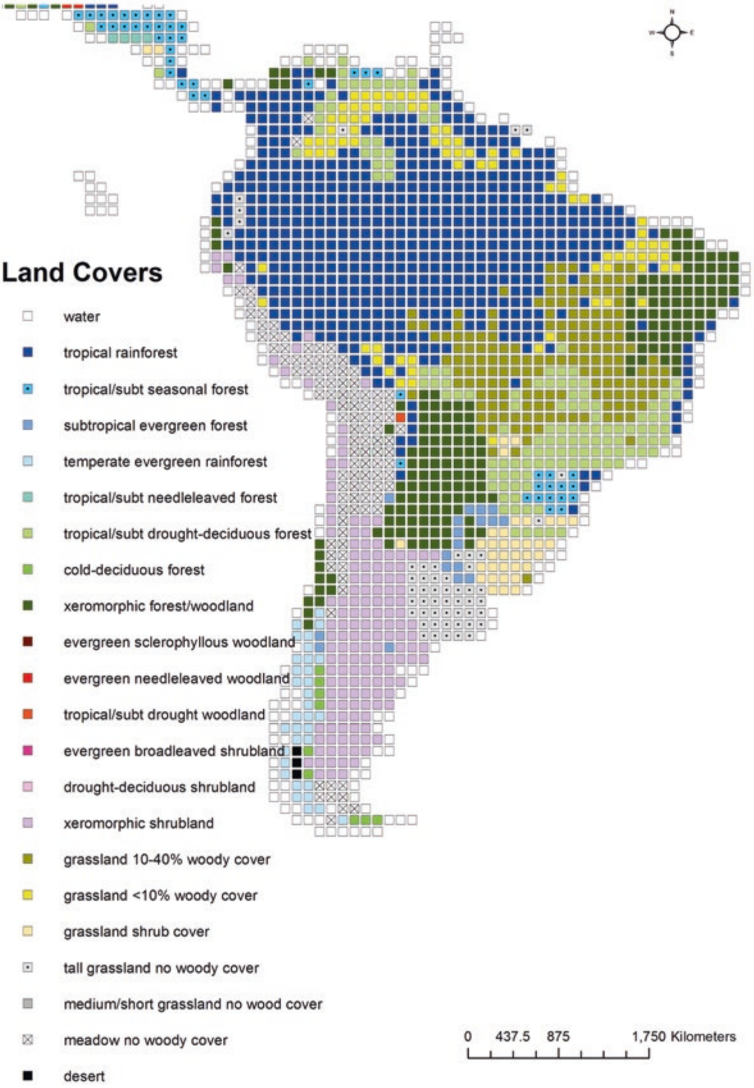

Fig. 6.1 Major land covers in South America

Across the multitude of ecosystems, agriculture and natural resource enterprises are managed in varied ways. At present, about a third of the total land area in South America is utilized for agricultural lands (World Resources 2005). Different types of crops are planted across the continent: Major cereals planted are wheat, maize, rice; Major oil seeds planted are soybeans, peanuts, sunflowers; Major vegetables are potatoes and cassavas; Specialty crops include cotton, tobacco, and coffee.

As can be seen in Fig. 6.1, the continent is vastly covered by different types of grasslands. As such, pasturelands used for livestock are eight times larger than the croplands in Argentina and four times larger in Brazil and elsewhere (Baethgen 1997). Consequently, animal husbandry is a critical part of agriculture in South America. A specialized livestock system accounts for about 20 % of all farming households in the continent while it accounts for only 5 % in sub-Saharan Africa (Seo 2010b, 2011). As mentioned before, Argentina and Brazil are one of the world's largest beef cattle exporters and consumers of beef per head annually (Steiger 2006). Major animals raised by farmers are beef cattle, dairy cattle, chickens, pigs, goats, and sheep across varied land covers (Seo et al. 2010).

Forest ecosystems are dominant in South America, especially near the Equator. As shown in Fig. 6.1, the Amazon rainforests cover 7.5 million km^2 of land area and is the world's largest pluvial forest (Mata and Campos 2001). The income earned from forests may account for more than 20 % of the rural income in South and Central America (Vedeld et al. 2007). People manage tree plantations either for the sale of timber products or non-timber products, or even for various government subsidies and international aids (Peters et al. 1989). Most common trees reported by the households who responded to the household surveys are as numerous as palm, cashew, cacao, mango, pineapple, citrus, banana, shea nut, apple, Kola, peach, almond, prune, apricot, avocado, cherry, hickory, eucalyptus, lemon, and Brazil nuts (Seo 2012a). On the other hand, Latin America accounts for around 70 % of the total world emissions of carbon dioxide due to land use changes, mainly from deforestation (Houghton 2008).

How are these natural resource enterprises distributed across the ecosystems in South America? To put it differently, how have farmers adopted natural resource enterprises given the ecosystems? Based on the portfolios of the natural resource products such as crops, animals, and forests that rural households reported to manage, the present author defined the six major natural resource intensive enterprises, as already introduced in Chap. 2. Three specialized enterprises are a crops-only, a livestock-only, and a forests-only enterprise. Mixed enterprises are a crops-livestock, a crops-forests, and a crops-livestock-forests enterprise. Where in each of the ecosystems is each of these natural resource enterprises favored by rural households? The micro-behavioral economics and the G-MAP models have paid a great deal of attention on this linkage and how it would be shifted when a global climate shift occurs.

The choices of rural enterprises across the land covers in South America are summarized in Table 6.1 (Seo 2012b). First, a livestock-only enterprise accounts for 49 % of the total households in the tall/medium/short grasslands with shrub cover, a dominant land cover around Uruguay, while only 24 % of the households choose a crops-only enterprise there. A large portion of the Pampas Plain has this type of ecosystem. Similarly, in the tall/medium/short grasslands with <10 % wood cover, a livestock-only enterprise is chosen by 41 % of the households. This ecosystem is dominant in the highland grasslands, the Llanos in Colombia and Venezuela.

Table 6.1 G-MAP: observed adoptions of rural enterprises by major land cover (% of total farms in each land cover)

	Grasslands				Shrublands	Meadow	Woodlands
	Tall/medium/short grassland, <10 % woody cover (%)	Tall/medium/short grassland, shrub cover (%)	Tall/medium/ short grassland, 10–40 % woody cover (%)	Tall grassland, no woody cover (%)	Xeromorphic shrubland/dwarf shrubland (%)	Meadow, short grassland, no woody cover (%)	Xeromorphic forest/woodland (%)
C+L	8.7	15.4	23.1	24.0	19.8	42.5	35.1
C+F	19.6	7.0	7.5	5.5	10.7	5.0	4.2
C+L+F	4.3	4.2	29.4	1.6	1.5	3.8	10.6
L	41.3	49.0	21.9	12.2	30.5	13.8	19.0
F	4.3	0.7	0.6	0.0	0.8	0.0	0.5
C	21.7	23.8	17.5	56.7	36.6	35.0	30.6
	Forests						Coasts, rivers, lakes
	Tropical/sub-tropical evergreen seasonal broad-leaved forest (%)	Cold-deciduous forest, with evergreens (%)	Subtropical evergreen rainforest (%)	Temperate/ subpolar evergreen rainforest (%)	Tropical evergreen rainforest (%)	Tropical/ subtropical drought-deciduous forest (%)	Water (%)
C+L	23.1	0.0	19.5	87.5	25.9	35.1	24.6
C+F	3.8	69.2	9.8	0.0	8.8	3.8	20.3
C+L+F	57.7	7.7	2.4	0.0	12.2	7.5	17.8
L	0.0	0.0	19.5	9.4	15.5	12.1	17.8
F	11.5	0.0	0.0	0.0	0.4	0.4	3.4
C	3.8	23.1	48.8	3.1	37.2	41.0	16.1

Note C crops, *L* livestock, *F* forests

For a crops-only enterprise, tall grasslands with no woody cover, subtropical evergreen forests, tropical/subtropical drought-deciduous forests are favored zones where this type of enterprise is chosen by 57, 49, 41 % respectively of the rural households in each of these ecosystems.

The crops-livestock enterprise is most often adopted in temperate rainforests, meadow/short grasslands with no woody cover, xeromorphic forests, and temperate drought-deciduous forests. In xeromorphic forests/woodlands, a crops-livestock enterprise is preferred to a crops-only enterprise by 35–31 % while a livestock-only is chosen by 19 % of farms.

A crops-forests enterprise is adopted most often in the tropical rainforests, the coastal/lake/river ecosystems, and cold-deciduous evergreen forests. A forests-only enterprise is most frequent, in the number of households that adopted, near the water body such as oceans, rivers, and lakes.

A crops-livestock-forests enterprise is most favored in order by tropical/subtropical seasonal forests, tall/medium/short grasslands with substantial (10–40 %) woody cover, and tropical rainforests.

The distributions of agricultural and natural resource enterprises across major land covers at the present time are conditioned on climate variables, therefore future changes in the climate system will lead to the changes in the present distributions of these enterprises. In Chap. 3, we already saw how changes in choices of enterprises would unfold in the next half century assuming a set of climate scenarios, so we do not need to go through them again here. The upshot is that climatic shifts lead to changes in ecosystems, which then lead to changes in enterprise decisions by individuals. With these links disjointed, impact studies that purport to quantify the damage from climatic changes on agriculture will end up with a great bias.

Now, the present author would like to turn the readers' attention to Sub-Saharan Africa. For one, this would give me the chance to introduce another scientific tradition for classifying ecosystems or ecological zones, i.e., the Agro-Ecological Zones (AEZs) (FAO 1978; Dudal 1980). For another, this would allow me to lead the readers to an impact analysis methodology which predominately relies on the concepts of the AEZ classification, that is, with little micro-behavioral aspects. The present author will make it a point to elaborate on why the AEZ impact methodology can be greatly off the target in measuring the magnitude of the damage from climatic change (Seo 2014a).

In Fig. 2.1, we already discussed the Agro-Ecological Zones of Africa in order to show that household surveys were collected from all the AEZs. The continent is divided into deserts, arid, semi-arid, sub-humid, and humid AEZ. The concept of AEZs was originally developed by the researchers who studied African agriculture in an attempt to indentify the suitability of the African lands for crop production (FAO 1978; Dudal 1980). They classified African lands into the five AEZs, as mentioned above.

The classification of the AEZs is made based on the concept of the Length of Growing Period (LGP) for crops (FAO 1978; Dudal 1980). The LGP is defined as the period during the year when climate and soil conditions are conducive to crop growth. The LGP is a similar concept to the growing degree days used by the econometric models of yields surveyed in the previous chapter, but not the same (Schlenker et al. 2006; Deschenes and Greenstone 2007).

Formally, the LGP refers to the number of days within the period of temperatures above 5 °C when moisture conditions are considered adequate. Under rain-fed conditions, the beginning of the LGP is linked to the start of the rainy season. For crops, soil moisture that is 0.4–0.5 times the level of reference evapotranspiration is considered sufficient to meet water requirements of dryland crops, depending on soil types and structures. Soil moisture storage capacity of soils depends on soil physical and chemical characteristics, but above all on effective soil depth or volume (FAO/IIASA 2005, 2012).

The distributions of LGP bands across Africa are shown in the recent article by the present author, so interested readers can refer to the article (Seo 2014a). The baseline geographical unit of measurements of the LGPs—and the AEZs—is a cell which has the resolution of 0.5° latitude by 0.5° longitude. Across Africa, the LGP zones are divided into 16 categories.

The AEZ classification based on the concept of the LGP was proposed originally by Dudal (FAO 1978; Dudal 1980) and the basic conceptual framework remained unchanged although several refinements have been made over time (IITA 2000; FAO/IIASA 2012). According to Dudal, the five AEZs are classified as follows:

$$AEZ = \begin{cases} \textit{deserts} & \text{if LGP} < 30 \\ \textit{arid} & \text{if } 30 \le \text{LGP} < 90 \\ \textit{semi-arid} & \text{if } 90 \le \text{LGP} < 180 \\ \textit{sub-humid} & \text{if } 180 \le \text{LGP} < 270 \\ \textit{humid} & \text{if } 270 \le \text{LGP} \end{cases} \tag{6.1}$$

Given the agro-ecological conditions of her/his lands, an individual manager will choose a natural resource portfolio composed of crops, animals, and forests for sale, trade, storage, and/or family consumption. As we did for the South American land cover analysis above, we can ask the same question: Do individuals alter their portfolios when the AEZ is altered due to climatic shifts? The answer is ‘yes’ and the readers who are interested in this question—or many aspects of this question—can refer to the articles that are available (Seo 2010b, 2011, 2012c). To avoid repetitions, we skip this now and move on to another intriguing inquiry with regard to ecosystem studies.

That is, the present author asks whether the AEZ classification is a good indicator of what farmers actually do presently on the fields. Since the AEZ concept is concerned with crops as a whole, a crops-only enterprise should be more frequently adopted in the zones in which the LGP is sufficient for crops if it is any useful classification system. Further, it is expected that yields of crops are higher in the AEZs where the LGP is greater.

From the World Bank household surveys collected across 9 Sub-Saharan countries, the present author calculated the observed percentage of the total households in each of the five AEZs that chose each of the three agricultural systems: a crops-only, a crops-livestock, and a livestock-only system (Seo 2014a). The results show that in the humid AEZ where the number of growing days is the largest, a crops-only system is indeed more likely to be adopted. In the humid AEZ, 53 % of the enterprises chose the crops-only system. On the other hand, 36 % of the enterprises in sub-humid zones and 27 % of the farms in semi-arid zones chose the crops-only system. Arid zones and deserts have respectively 43 and 33 % of the farms who chose the crops-only system. These results tell us that the AEZ classification does indeed provide some valuable information on farmers' preferences for crop production.

To look deeper into farmers' enterprise choices, a spatial Logit model of adoption of one of the three agricultural systems is estimated, based upon which adoption probabilities of the three systems are calculated (Seo 2014a). The procedure is the same as the other G-MAP procedures. For explanatory variables, climate, soils, topography, water availability, market access, household characteristics, and country dummies are entered into the model. Adoption probabilities of the agricultural systems are then calculated using the estimated parameters for each of the rural households surveyed. The probabilities calculated at the level of rural households are then averaged at the AEZ level and mapped across Africa using the AEZ definition. The adoption probability distribution maps for the three agricultural systems were shown before in Fig. 3.2. The first map (left) is for the crops-only system. The second map (middle) is for the mixed crops-livestock system. The third map (right) is for the livestock-only system.

From these choice maps, let's first compare visually the AEZ map in Fig. 2.1 with the adoption probability map for the crops-only system drawn in Fig. 3.2. We find that it is quite noticeable that the probability to choose a specialized crop system is higher in the humid AEZ where the length of growing days is larger than in the other AEZs. In the sub-humid AEZ in West Africa, the length of growing periods becomes shorter, wherein adoption probability of a specialized crop system is also reduced. In the semi-arid AEZ which has an even shorter LGP, the probability of choosing a crops-only system is further reduced. The visual correspondence between the AEZs and the choice probabilities again demonstrates the usefulness of the AEZ concept.[2]

By contrasts, the probability distribution of a mixed crops-livestock system across the AEZs shown in the middle in Fig. 3.2 tells a contrary story. Adoption probability of a mixed system is the lowest in the humid AEZ where the length of growing days is the longest. As the LGP falls in the sub-humid AEZ, the probability of choosing a mixed system increases, i.e., it does not decline. As the LGP gets even shorter in the semi-arid and arid AEZs, adoption probability of a mixed enterprise further climbs up. Rural managers in these arid zones have adopted this system more frequently than anywhere else.

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[2] Note, on the other hand, that adoption probability is higher in the desert AEZ than in the arid and semi-arid AEZs. This is probably because desert zones are cooler in climate than these arid areas because of the distance from the Equator.

The AEZ-level choice probabilities of the livestock-only system are shown at the right panel of Fig. 3.2. They are low across the AEZs, but this system is shown to be most frequently adopted in the sub-humid and the desert AEZs.

What the two livestock—mixed or specialized—adoption maps in Fig. 2 enlighten us is that the AEZ/LGP classifications are not a good predictor of non-cropping systems of agriculture. Livestock systems are adopted more frequently where growing crops falls out of favor. The more unfavorable climate becomes, the finer the mixing strategy of portfolios becomes.

Evidence at an even finer level can be presented through the distributions of individual species of animals owned by rural households across the AEZ zones (Seo 2014a). A rural household in the humid AEZ owns, on average, 3 sheep, but 39 sheep in the arid AEZ and 450 sheep in the desert AEZ. For goats, a rural household in the humid AEZ owns 3.7 goats, in the sub-humid AEZ 4.8 goats, in the semi-arid AEZ 7.6 goats, in the arid AEZ 26.1 goats, and in the desert AEZ 59 goats. For beef cattle and dairy cattle, similar distributions across the AEZs are found, although not as dramatic are the changes in the numbers from one AEZ to another. The distribution of chickens is rather different: the wetter the AEZ zone, the larger the number of chickens owned.

From another viewpoint, Figs. 2.1 and 3.2 together confirm the conventional wisdom in finance that an investor should diversify her portfolio into negatively correlated assets to reduce the risk in the portfolio return (Markowitz 1952; Tobin 1958). Although the micro-behavioral economics and the G-MAP models are ideally built to incorporate such behavioral decisions, there is no conceptual mechanism in the AEZ/LGP classifications which permits such diversification benefits.

That is, it is quite possible that a rural farm remains profitable by keeping a diversified portfolio of selected crops and livestock even if the neighborhood farms that specialize in crops were to suffer substantially from the high risk in crops that occur more often than not due to changes in climatic conditions. As Fig. 3.2 reveals, even though the length of growing days for crops is short in the arid and the semi-arid AEZs, Sub-Saharan farmers have continued to manage a variety of crops along with a variety of animals even in the highly arid zones of Sub-Sahara. Diversification is a key strategy of rural areas' risk managements in coping with climate normals and risks in Sub-Sahara (Seo 2011, 2012c).

All the discussions up to this point in this chapter lead us seamlessly to another major inquiry of this chapter. That is, to what extent can climate researchers utilize the AEZ/LGP classifications for measuring the impacts of climate change on agriculture? In particular, a group of researchers developed the AEZ impact methodology relying on the concepts of the AEZs to quantify the impacts of climate change on agriculture (Fischer et al. 2005). This method has been cited frequently and influential in the literature [see, for example, the IPCC report (Easterling et al. 2007)]. However, a critical examination of this methodology has never been conducted. The discussions so far in this chapter set us up well to be in a position to tackle this issue.

Let us start with a brief summary of this methodology as described in the Fischer and his coauthors' work (Fischer et al. 2005). In the first stage, the

AEZ methodology determines the impacts of climate change on crop growth determinants of yields, e.g., length of growing periods, at the resolution of 5 arc-minute grid cell with the AEZ (Dudal 1980). In the second stage, changes in crop production potential under changed climates are calculated across all the cells based on the information in the first stage (Tubeillo et al. 2007). That is, for each AEZ the change in crop production potential is calculated. In the third stage, production changes are then fed into an economic model called the Basic Linked System (BLS) to assess how different climate (and socio-economic) scenarios affect variables of concern such as productions, demands, prices, mal-nutrition, poverty, and hunger (Rosenzweig and Parry 1994).

Note that the AEZ impact methodology is not drastically different from the AEMs reviewed in Chap. 4. The third stage of the AEZ methodology differs from the AEMs only in that it is cast into the global context. The AEZ methodology is less sophisticated than the AEMs in acquiring changes in crop yields in that the latter is based on a large number of laboratory and field experiments.

Applying this methodology, the researchers reported that cereal production in Sub-Saharan Africa will fall by 1.9 % under the HadCM3 scenario and fall by 11.7 % under the Commonwealth Scientific and Industrial Research Organization (CSIRO) scenario from the baseline in which agricultural growth is incorporated. The cereals are major grains such as maize, millet, sorghum, rice. The paper is less clear about the baseline which of course is first very hard to project into the century's end and second will confound the impact estimates. The number of people at risk of hunger is projected to increase by about 70 million people due to the above climate change scenarios from the baseline with no global warming (Fischer et al. 2005).

For the AEZ impact methodology to be meaningful, however, it should have the capacity to indentify agricultural activities that are performed in each of the AEZs. As discussed in detail so far in this chapter, there are major identification problems with the AEZ/LGP concepts. That is, the AEZ/LGP classification fails to identify livestock systems from crop systems. Neither does it identify non-grain crops such as forest-related products from a grain system of crop agriculture. The consequence is that the AEZ impact methodology will get the baseline portfolios wrong that vary across the AEZs, let alone the future portfolios under changed climate regimes. Nor is there any mechanism in the AEZ impact methodology to predict the productivities of unidentified systems of agriculture.

At an even subtler level, the effects of behavioral responses to climatic shifts cannot be explained by the AEZ impact methodology. One such behavioral response is diversification. As a concrete example, let's have a closer look at the consequences of portfolio diversification by a Sub-Saharan farmer using the observed household data (Seo 2014a). For the mixed crops-livestock system and the crops-only system, the distributions of net revenue from crop production show distinct patterns in the two systems. In the same humid AEZ, the net revenues earned from crop production are different in the two production systems. In the specialized crop system, a rural household earns on average 718$ per hectare of cropland. But, in the diversified crops-livestock system, a rural household earns on average 605$ from crops per hectare of cropland (excluding livestock revenue). This means that, although faced with the same humid AEZ, some farmers have reduced crop production (profit) to diversify into farm animals.

In the arid AEZ, however, this relationship is reversed. That is, a mixed crops-livestock farm earns more profit from crops than a specialized crop farm in the arid AEZ. A mixed crops-livestock farm earns on average 223$ per ha of cropland from growing crops while a specialized crop farm earns 158$ per ha of cropland from growing crops. In the arid AEZ where the climate is unfavorable for crop growth, adapting to climatic conditions by a diversified portfolio of crops and livestock leads to an increased profit even from crops (from 158 to 223$/ha), i.e., excluding the net revenue generated from livestock management.

What these profit data tell us is that the effects of diversification are likely to be substantial. The distribution of crop net revenue will differ in the two systems of agriculture as well as in different Agro-Ecological Zones because of portfolio diversification. A behavioral strategy of diversification will play a profound role in the decisions of farmers who attempt to cope with climatic changes (Seo 2010a, 2012a, 2013). Without knowing the full array of portfolios that agricultural and natural resource enterprises hold, the AEZ impact methodology will have no feasible way to correctly estimate the impacts of climate change on agriculture. The complete array of farm portfolios reflects micro-behavioral aspects of climate change decisions. Only one of such aspects is diversification.

Turing our attention now from the present to the future, we ask “Can the AEZ impact methodology model adaptive changes of farmers in response to climatic changes in the future?” As shown throughout this Book, the G-MAP models make known adaptive changes in behaviors across the AEZs and the effects of such changes are fully integrated into the models. In the G-MAP agricultural systems models, for example, under a hotter and drier Canadian Center for Climate Modeling and Analysis (CCCma) A1 scenario by mid-century (Boer et al. 2000; Seo 2011), a crops-only system of agriculture falls across Sub-Saharan Africa, but the decrease is much larger in the currently most favored zones for crops, i.e., in the humid and sub-humid AEZs. On the other hand, a mixed crops-livestock system of agriculture increases across Sub-Saharan Africa, but the increase is larger in arid, semi-arid, and desert AEZs.

In the AEZ impact methodology, such shifts in agricultural systems are not modeled. In other words, it assumes no changes in agricultural systems even if the climate system were to be shifted seriously. In fact, the AEZ methodology assumes no behavioral changes at all. The bias that results from assuming no behavioral adaptations is likely to be very large because behavioral changes under varied climate regimes are shown to be numerous and effective (Seo 2014a).

In closing this chapter, I am reminded that individuals’ behaviors, ecosystem changes, and climatic changes are mutually dependent in an intricate way. The micro-behavioral economics of global warming and the G-MAP models are developed in a manner to bring this interdependence to light in a rather superb way. This achievement may not have been realized if the G-MAP models had been applied to the other geographical areas or to the other economic sectors. That is to say, the applications of the G-MAP models to agricultural and natural resource enterprises in Sub-Sahara and South America have inevitably, in the author's retrospect, led to the enlightening analyses and findings on individuals' decisions and ecosystem changes in the time of climatic shifts. In the natural resource enterprises as well as in the two low-latitude continents of Sub-Sahara and South America, these intricate relationships are economically meaningful and therefore prominent. The study of these relationships turns out to be also instructive to climate researchers and those who care for the on-going changes in the Earth's climate.

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Chapter 7
Wading into the Century of Global Warming and Adaptation Strategies

Abstract The final chapter looks ahead into the upcoming century of global warming and discusses the roles of the micro-behavioral economics in the humanity's enduring struggles against the threats of global warming. The micro-behavioral studies of adaptation strategies and the G-MAP models will provide a guide map in the perilous journey ahead.

Keywords Micro-behavioral economics · Adaptation strategies · Carbon tax · Financial markets · Technology

Throughout this book, the present author presented the framework of the micro-behavioral economics of global warming from a variety of angles. The empirical models of the micro-behavioral economics—the G-MAP model (Geographically-scaled Microeconometric model of Adapting Portfolios in response to climate change and risks)—have been developed to quantify micro-behavioral decisions of individuals faced with climatic shifts and the consequences of such decisions.

The five G-MAP models are elaborated in the book: the G-MAP animal species, the G-MAP agricultural systems, the G-MAP natural resource enterprises, the G-MAP public adaptations, and the G-MAP climate risk model. The five G-MAP models are applied to individuals' agricultural and natural resource enterprise decisions in Sub-Saharan Africa and South America. Micro-behavioral decisions and the resultant profits and land values are matched with the multiplicity of ecosystems in Sub-Saharan Africa and South America. The distinct ecosystems in the two low-latitude continents are the results of the climatic system but at the same time have caused individual natural resource managers to make distinct decisions.

The micro-behavioral economics of global warming and the G-MAP models are about the future changes as much as they are about the present. Assuming that individuals will adapt to future changes in climate, future agricultural and natural resource enterprises are simulated based on a family of climate models and

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scenarios that have been made available by climate scientists. The G-MAP models provide a guide map of adaptations to climatic changes that would unfold in the centuries to come.

The micro-behavioral economics is a new tradition in the global warming economics that has been developed over the past decade (Seo 2006, 2010, 2012a, b, 2013b, 2014a; Seo and Mendelsohn 2008a). The field itself can be best understood in contrast to the traditional global warming economics which has delved into devising a globally optimal carbon policy (Nordhaus 1977, 1994, 2013). The level of analysis as well as the level of policy interventions is the globe in the traditional climate economics. In the micro-behavioral economics, it is an individual that is the basis of economic analyses and policy proposals. At the individual level, adaptation strategies are particularly prominent as a climate policy tool. In the traditional economics of global warming, mitigation through putting a price on carbon globally has been the dominant climate policy mechanism (Nordhaus 1994). Having read through this book, I hope the readers have come to the conclusion that adaptation strategies form the essential aspects of the human responses to global warming challenges.

The G-MAP models are developed in the process of research endeavors to measure the potential effects of climate change on agriculture and natural resource sectors (Mendelsohn et al. 1994; Seo and Mendelsohn 2008a; Seo 2010). Adaptation behaviors particularly stand out in these sectors where economic activities are mostly exposed to natural variations of weather and climate. This means many things. This means that adaptation is a key factor that determines how vulnerable these sectors are to climatic changes (Seo 2013b); This means that adaptation behaviors can be studied at the individual level using the past decisions on farming activities; This means that adaptation is a key policy variable in these sectors in coping with climate changes.

In the simplest definition, the micro-behavioral economics of global warming refers to the study of an individual's adaptation decisions in the face of global warming. An individual is here broadly defined to capture both a person and a closely-knit community of individuals. It differs from the traditional global warming economics of carbon tax for it is based on individuals (Nordhaus 1994, 2013). It has not a few similarities to behavioral finance and economics in that it is concerned about how individuals' decisions are made faced with market and risky conditions (Kahneman and Tversky 1979; Shiller 2003, 2005).

In retrospect, the success of the micro-behavioral economics in the literature of global warming was guaranteed from the very beginning because of the hidden troves of adaptation behaviors so rich in natural resource enterprises that were waiting there to be uncovered. Or, is it just a sort of serendipity?

The treasure trove has turned out to be immensely rich in agriculture and natural resource enterprises in the low-latitude developing countries of Sub-Saharan Africa and South America. As noted before in this book, agriculture employs a vast majority of total population in Sub-Saharan Africa and provides a primary source of subsistence, income and livelihoods. The same is more or less true in South America (WDR 2008; FAO 2012).

In addition, these two continents are known for a great diversity in ecosystems and biodiversity (Matthews 1983; FAO/IIASA 2012; Global Biodiversity Outlook 3 2010). As the ecosystems are sources as well as sinks of greenhouse gases, the science of climate change cannot be sound without the full-fledged research on how diverse ecosystems react to the changes in climatic components and are managed (Schlesinger 1991; Denman et al. 2007; Strickland et al. 2013). Climate scientists have devoted a majority of its efforts to quantifying the impacts of climate change on a variety of ecosystems through, e.g., the FACE (Free-Air CO_2 Enrichment) experiments (Ainsworth and Long 2005; Tubiello et al. 2007; Fischlin et al. 2007).

It is no surprise then that decisions of individuals who manage or deal with these natural systems are deeply climate dependent and we expect them to be altered when the climate system is shifted in the future. The micro-behavioral economics of global warming, as established throughout this book, is the study of the crossroads between economic decisions and ecosystem changes. This is then an ideal meeting place between economists and scientists of climate change.

Throughout the developments of the G-MAP models, farmer decisions in Sub-Sahara and South America have served as the platform for analytical and conceptual developments. It should be emphasized, however, that regional vulnerabilities and risk factors for agriculture and natural resource enterprises in the world are not homogeneous (Reilly et al. 1996; Gitay et al. 2001). Therefore, unique characteristics of the world regions should be taken into considerations in planning the future. Sub-Saharan African countries are highly vulnerable to climatic risks because the region is already hot and highly variable in climate; large areas are in deserts, arid, and semi-arid zones; many areas have poor access to markets due to poor road and transportation systems; weak market economies arising from lack of property rights and political instabilities (Downing 1992; Butt et al. 2005; UNECA 2005; Kurukulasuriya et al. 2006; Seo et al. 2009; Hassan 2010; World Bank 2009a, b). In South America, increases (or decreases) of the grasslands, including the Pampas, the Brazilian Cerrado and the Sertao, and the Venezuelan/Colombian Llanos, and the vast areas of forest ecosystems including the Amazon rainforests are at the center of the regional vulnerabilities as well as the impacts on the vast high-altitude ranges of the Andes mountains where most smallholder farms are located and sometimes major glaciers are located (Viglizzo et al. 1997; Baethgen 1997; Magrin et al. 1997, 2007; Rosenzweig and Hillel 1998; Seo and Mendelsohn 2008b; World Bank 2009a; Rabatel et al. 2013).

In South and Southeast Asia, regional vulnerability hinges, among other things, on the impacts of climate change on rice production which is a primary staple crop in the region, abilities of farmers to diversify into specialty crops and forest products, and the melting of the Himalayan glaciers in the long-term which provide water resources to many countries (Kumar and Parikh 2001; Aggarwal and Mall 2002; Seo et al. 2005; Auffhammer et al. 2006; Challinor et al. 2007; Sanghi and Mendelsohn 2008; ADB 2009; Welch et al. 2010; Jacob et al. 2012). In Central Asia and continental North America, regional vulnerabilities depend, among other things, on the impacts of climate change on the steppes and the prairies (Baker et al. 1993; Milchunas et al. 2005; Batimaa et al. 2008; Olmstead and Rhode 2011). In Oceania, rangelands which account for about 70 % of the Australian lands are key vulnerability zones to climate change, given the backdrop of prolonged droughts and heavy rainfall that alternate caused by the ENSO events (Campbell et al. 2000; White et al. 2003; Seo 2014b, 2015a). New opportunities and associated risks are expected to arise as the formerly frozen lands become suitable for agriculture in the high latitude countries including Canada, Russia, and Northern Europe (Easterling et al. 2007).

Besides climate factors, future impacts of climatic shifts on agricultural and natural resource enterprises depend on economic, institutional, social, and political changes that will unfold in the future which are often uncertain and sometimes unpredictable (Downing 1992; Ruttan 2002; Darwin et al. 2004; UN 2004; FAO 2006). Above all, the establishments of secure property rights, democracy, and law and order in the African countries will help improve food and agricultural security in the continent even with increased stresses from global warming (UN ECA 2005; Rotberg and Gisselquist 2007; Goldstein and Udry 2008). An increase in international trade and removal of distortive agricultural subsidies can significantly alter agricultural landscapes around the world but may also help ameliorate the severe impact from climate change on a specific crop in a specific region (Tobey et al. 1992; Reilly et al. 1994; Darwin et al. 1995; Anderson and Masters 2009; Sumner and Zulauf 2012). Future demand for food is dependent upon population growth, consumption changes, and changes of diet to meat or non-meat, especially in developing countries (Delgado et al. 1999; UN 2004; FAO 2006, 2009). In the G-MAP models, these variables are treated as control variables using property ownership, access to output and export markets, agricultural subsidies, and country policies in order to single out the effects of climate factors on adaptation decisions and changes in natural resource enterprise profits (Seo 2011a, 2011b, 2012a). It goes without saying that the external effects of these non-climate factors can be singled out, measured, and projected for the future in the G-MAP model framework.

Advances in technology and engineering that have underpinned the past growth in agricultural productions and the declines of crop prices through crop variety improvements are likely to continue but face increasing resource constraints such as available lands and marginal agro-climatic conditions (Ruttan 2002; Evenson and Gollin 2003; World Bank 2009a; Brisson et al. 2010; James 2012). Breakthroughs in genetic science and technology may make it possible to reduce the outbreaks of deadly livestock diseases and carriers, e.g., sleeping sickness (Trypanosomiasis) caused by Tsetse flies that have plagued the African livestock industry for a long time (Ford and Katondo 1977; Aksoy and Attardo et al. 2014). The G-MAP models, however, show that past extension efforts were most often directed towards crops while neglecting animal farms in Sub-Saharan Africa even though animal husbandry is more profitable (Byerlee and Eicher 1997; Seo 2011a). The critical lesson here is that technology alone cannot solve the problems in the natural resource enterprises caused by global warming.

What are the policy outlooks looming on the horizon and beyond? As many modeling efforts in the book have indicated, climatic changes in the next century and beyond will impose significant stresses on agriculture and natural resource enterprises and adaptation challenges will be high. Adaptations will be a key part of the global policy negotiations. A Green Climate Fund (GCF) established from the recent United Nations conferences in Copenhagen, Durban, and Warsaw has the goal of generating more than one billion US dollars annually by 2020 which will be used in large parts to support adaptation programs in the most vulnerable populations, sectors, and regions (UNFCCC 2011b). A large fraction of the fund is expected to flow into agricultural and natural resource enterprises in low-latitude developing countries to support 'climate smart' agriculture (World Bank 2011). Although the pledges of funds are at the moment slow and insufficient against the initial enthusiasm expressed by the parties of conferences, institutional structure is already established. The city of Songdo in South Korea is chosen to be the host of the United Nations GCF secretariat and the World Bank as the trustee of the funds.

Notwithstanding, there is little knowledge base developed to guide the distributions of many trillions of dollars over the many decades to come. The G-MAP models and the micro-behavioral economics can provide sound guidance in the future adaptation efforts especially in the low-latitude countries. The establishment of guidelines and principles are especially urgent as is demonstrated by recurring conflicts between the developed world and the developing world with regard to the lack of financial pledges and actual funding raised from the developed countries. Moving forward, the bigger question will likely be who should or shouldn't get a bigger slice of the pie.

In addition, policy experiences in the past decades indicate that agriculture will be a part of the larger discussions on mitigating the effects of greenhouse gases by, *inter alia*, adopting carbon conserving techniques, reducing methane emissions from livestock management, managing grasslands, preserving and replanting forests, and productions of bio fuels (Antle and McCarl 2002; US EPA 2006; Rajagopal et al. 2007; Rosenzweig and Tubiello 2007; Smith et al. 2008; Houghton 2008; Avetisyan et al. 2011; UNFCCC 2011a). Adaptation options presented throughout this book bear strong implications on abating and/or sinking greenhouse gas emissions (Seo 2013c, 2015b). Adaptation strategies presented by the G-MAP models can be guided to reduce carbon emissions, e.g., by reducing methane emissions from cattle and other animals through dietary changes and feed additives (US EPA 2006). Adaptation through increased forests and grasslands has the additional benefits of carbon sinks (Seo 2012a). On the other hand, mitigation efforts through government regulations and supports such as biofuel subsidies are destined to fail to achieve the goal if farmers' reactions are not thoughtfully incorporated into such programs.

What prospects does the research field of climate change and agriculture and natural resources hold? What are the prospects of adaptation research in the coming decades? Given the large uncertainty on the degree of climatic changes particularly at the local level, researchers must keep track of the realized changes in climate factors through time and help plan adaptation strategies that are efficient at the local level. Adaptation modeling efforts presented in this book can provide a yardstick for adaptation studies in the future as today's climate predictions would become realized or not realized in the future.

As a new climate system gradually unfolds in the near future, adaptation measures taken by the farmers can be directly learned from the field observations and farm surveys. Changes in crop yields and farming practices in response to changing climates will become observed and measured by the researchers. These new data can provide valuable resources for adaptation research. However, researchers should pay great attention to distinguish the response to climatic changes from the responses to yearly weather fluctuations (Seo 2013b).

Ideally, adaptation measures should be taken by the affected individual who actually cultivates in the fields and manages natural resources. But, a public adaptation support and coordination is needed at times at varied levels of government or at the community level if efficient adaptation calls for a large number of affected individuals/groups to be involved. Such a government support should be carefully planned in a way not to interfere with privately efficient adaptations. It should be designed in a way not to provide too much of adaptation nor induce mal-adaptations (Seo 2011b). From another perspective, privately-owned resources can be best managed and adapted in response to climatic changes by the individuals themselves while open-access resources should be attended at the community level (Ostrom 2009).

A particularly interesting area of research in this regard is examinations of efficiency effects of the United Nations' adaptation programs, i.e., the Green Climate Fund (GCF) (UNFCCC 2011a, b). As adaptation funds are distributed to specific sources and programs in the coming years and decades, it would be worthwhile for the researchers to examine whether such programs have led to best adaptation practices or, on the contrary, caused distortions in efficient resource allocations, i.e., adaptation efforts.

Researchers must heed not only to the vulnerabilities but also adaptation possibilities to extreme weather events, increased climate risks, and climate thresholds which may (or may not) increase in frequency and strength in the future in some, albeit not all, of the world regions (Easterling et al. 2000; Rosenzweig et al. 2001; Tebaldi et al. 2007; Lenton et al. 2008; Schlenker and Roberts 2009; Hansen et al. 2012). In many aspects of climate science on extremes and risk, more precise projections will likely become possible in the future while scientific insights and oversights on climate change will improve over time (Emanuel 2005, 2013; Le Treut et al. 2007; NRC 2013). Studies on risks and extremes must not ignore the lessons from the micro-behavioral economics that farmers are already faced with climate risks and have employed coping strategies to deal with them (Seo 2012b, 2014b, 2015c). Future will surely not be any different: They will adopt measures to cope with climate risks and extremes.

Research on genetics and biology may hold lasting promises in global warming roundtables. Among many other things, new varieties of crops that are more resilient to varied climatic conditions, if developed in the near future, are certain to improve by a great deal food productions and the ways how agricultural and natural resources are managed (Evenson and Gollin 2003; World Bank 2009a).

Research and field experiences on genetic engineering which have concentrated on crop varieties up until recently may make inroads into livestock breeding (Hoffmann 2010; James 2012). Genetic sciences signal the possibility of reducing, if not eliminating, the vulnerabilities of livestock to some pests and diseases which have been so common and prevalent in some parts of the world, e.g., sleeping sickness of African cattle carried by Tsetse flies (Aksoy and Attardo et al. 2014).

Financial innovations will hold as much promise as biological and genetic innovations will have on addressing global warming problems. Forward, futures, and options markets have contributed greatly to smooth price volatilities of major agricultural products due to weather fluctuations and other external shocks (Fabozzi et al. 2009; Wright 2011). Hurricane and/or flood insurance provide the buffer against an unpredictable event, so does fire insurance. These events may or may not increase with global warming, but these insurances provide additional options regardless of which directions these changes occur (US GAO 2003). Catastrophe bonds can help spread the financial risk of those affected by unpredictable and catastrophic events (Shiller 2004). Much needs to be and can be done in this area so that these financial instruments can be directly tied to address climate risks specifically.

Looking far ahead beyond this century into the distant future by which time climatic changes and global warming will have unfolded substantially, the present author foresees that agricultural and natural resource enterprises will have continued to capture the hearts and minds of climate researchers and concerned citizens. Climatic changes will unravel expectedly as well as unexpectedly. The impacts of such changes will be felt personally and increasingly more severely by the individuals as well as by the affected communities. Adaptation strategies will be planned ahead and rolled out timely, which will significantly alter the landscape of natural resource communities as well as the society in general. Local municipalities will be compelled to address the increasing impacts of global warming so long as competitivenesses of the local enterprises are altered over time. Policy designs, negotiations, and implementations for the agricultural and natural resource sectors at a global, a national, and a local level will turn out to be a complex as well as an enduring process.

If we were to look back three hundred years later from toady having battled through all sorts of climatic changes in all variations and surprises, would we be able to say that the humankind has successfully fended off grave global warming challenges posed back then? The present author believes that the answer will certainly hinge to a very large degree on how wisely the world communities will have adapted to ever-changing climatic shifts and surprises. The micro-behavioral economics of global warming presented in this book lays down the foundation for the humanity's adaptations to global warming. The G-MAP models will—it is hoped—provide a guide map of adaptation strategies for this enduring journey through this century of global warming.

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