Yogendra Shastri · Alan Hansen
Luis Rodríguez · K.C. Ting *Editors*

Engineering and Science of Biomass Feedstock Production and Provision

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ISBN 978-1-4899-8013-7 ISBN 978-1-4899-8014-4 (eBook)
DOI 10.1007/978-1-4899-8014-4
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2014930155

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Preface

The focus on lignocellulosic biomass-based fuels, also known as second-generation biofuels, has been increasing substantially in recent years. This is evident from the number of journals dedicated to this topic, the number of research papers published, and the number of conferences organized globally. The criticality of efficient and reliable biomass feedstock production and provision (BFPP) for sustainable lignocellulosic biofuel production is also now well acknowledged. It has further been realized that a significant shift from conventional agricultural practices may be needed to achieve the proposed biomass production targets, such as the well-known billion ton target for the United States.

Our own research on this topic started in 2008 as part of a research program funded through the Energy Biosciences Institute co-located at the University of Illinois at Urbana-Champaign and the University of California, Berkeley. The field was nascent at that stage, and the fundamental understanding of various aspects of BFPP was developing through many concurrent research initiatives. Most of the relevant information pertained to agricultural residue such as corn stover. Information specific to dedicated energy crops such as perennial grasses was sporadic in the literature. Subsequently, we have seen an explosion of research output in the last few years in the form of journal papers, conference presentations, technical reports, feasibility studies, and white papers. New knowledge was being generated and novel challenges were being identified. However, the consolidation of this new knowledge in the form of a comprehensive book is still lacking. We have interacted frequently with researchers working in this and related fields as well as with students initiating research on this topic. These interactions have emphasized the need for a comprehensive book on this topic that covers all the aspects of BFPP. Moreover, the topic of bioenergy, and consequently BFPP, has been the basis of many new interdisciplinary educational degree/certificate programs. We realize that a book on the topic of BFPP will be of significant value to the students and instructors participating in these programs.

Therefore, when Springer Science approached us in January 2012 to write a book in the area of bioenergy, we were very excited to suggest biomass feedstock production and provision as a potential topic of the book. The field had matured enough to justify the publication of a compendium of recent progress and future challenges. We are very glad that Springer Science wholeheartedly supported the idea and recognized the value of a book in this field.

Finalizing the scope of the book was an important step. The topic of BFPP comprises basic sciences, engineering, economics, policy and regulation, and social sciences. Engineering plays a key role in translating the scientific understanding into practical solutions. Given the importance of engineering and our strong background in this area, we decided to focus the book primarily on the engineering aspects of BFPP. As part of our own research, we have identified various subsystems or tasks of BFPP, namely, preharvest crop monitoring, harvesting, storage, and transportation. Our research also integrates these tasks in a holistic manner through a systems informatics and analysis task. The book follows a similar philosophy and reviews the recent developments on each of these topics. Engineering properties of biomass play an important role in all tasks described above. We, therefore, included a chapter on describing these properties and their measurement methods. We further realized that the BFPP system is impacted by aspects of agronomy, including crop establishment and management, and have included a chapter that focuses on this topic. We also recognized that the topic of BFPP would be of relevance not only to engineers but also to other stakeholders, such as farmers, plant managers, investors, policy makers, and businesses. Decisions for these stakeholders must account for the long-term sustainability viewed through the policy framework. We, therefore, have included a chapter elaborating on these issues, which makes this book really unique. There was a thought of including a chapter on processing of biomass into fuels and other products. However, we believe that there are many excellent books already published on this topic to which interested readers can refer.

Individual chapters provide an overview of the challenges, review current status, identify knowledge gaps, and provide future research directions. The chapters primarily discuss the production and provision of dedicated energy crops such as switchgrass and Miscanthus. However, literature on agricultural residue, green energy crops, and short rotation woody biomass is also discussed wherever appropriate. The target audience for the book includes engineers (agricultural, chemical, mechanical, civil), agronomists, researchers, undergraduate and graduate students, policy makers, bioenergy industries/businesses, farmers, and farm consultants. We also hope that the book will be used as learning material for classroom or laboratory instructions on this topic. A few pilot-scale biomass processing facilities have recently been set up, and focus will soon shift on setting up commercial scale facilities. The material presented in this book will provide valuable guidelines for setting up such facilities. We believe that the book will serve as an authoritative treatise on BFPP with particular emphasis on the engineering aspects. While we assume that the readers will have a preliminary understanding of the bioenergy systems and agricultural operations, all the chapters would be easy to comprehend for most readers. The readers can jump to a specific chapter of interest without going through the preceding chapters.

There are several people to acknowledge for the successful completion of the book. First and foremost, we would like to thank all the authors for their contributions. They readily accepted our request for contribution and have been very cooperative during the submission, review, and revision stages. The number of researchers working in this area is small, albeit increasing, and all the authors contributing to this book are leading researchers in their respective fields. We are, therefore, really glad that we have been able to bring them together for the purpose of this book.

We would also like to thank Springer Science for their interest in publishing in this area. The publishing house and its staff have provided us with excellent support throughout the preparation of the book. Ms. Hannah Smith, Associate Editor, Plant Sciences, helped us during the initial stages of conceptualizing the book, providing feedback on the scope, and finalizing the contributors. We thank the reviewers for providing us with valuable inputs and suggestions. Ms. Diane Lamsback, Developmental Editor, has subsequently provided very good support during the preparation and editing of the individual chapters and the compilation of the book. Needless to say, the book would not have come out without their support.

Finally, we would like to acknowledge the Energy Biosciences Institute for providing the unique opportunity to many contributing authors to work together on this important topic.

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Chapter 1
Biomass Feedstock Production and Provision: Overview, Current Status, and Challenges

Yogendra Shastri and K.C. Ting

Abstract Biomass-based renewable energy will play a critical role in meeting the future global energy demands. Lignocellulosic biomass, such as agricultural residue, perennial grasses, and woody biomass, will constitute a major portion of the feedstock for these biomass-based energy systems. However, successful transition to this second-generation bioenergy system will require cost-efficient, reliable, and sustainable biomass feedstock production and provision (BFPP). The BFPP system includes the operations of agronomic production of energy crops and physical processing and handling/delivery of biomass, as well as other enabling logistics. On the technical side, biological, physical, and chemical sciences need to be integrated with engineering and technology to ensure effective and efficient production of biomass feedstock. However, low energy and bulk densities, seasonal availability, and distributed supply create unique challenges for BFPP. Lack of experience and established standards provide additional challenges for large-scale production and provision of energy crops. The aim of this book is to summarize the current state of knowledge, identify research gaps, and provide future research directions on the topic of BFPP. Towards that end, the goal of this chapter is to set the foundation for the subsequent chapters that focus on specific components within this system. This BFPP system and its components are briefly described, current status and challenges are identified, and the research needs are highlighted. A typical production system based on current understanding and technological availability is also described. The chapter, therefore, provides an introduction to the advanced chapters that appear subsequently in the book.

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Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4_1,

1.1 Introduction

Availability of energy is very critical to the survival, well-being, and development of the society. The industrial revolution spurred tremendous development during the past century and has led to unprecedented energy demands throughout the globe. The rising global population has further intensified the energy-consumption patterns. The majority of the world's energy demand is presently being met by nonrenewable fossil fuels, mainly coal, petroleum, and natural gas [1]. However, these fuel reserves are rapidly depleting [2]. Moreover, emissions resulting from fossil fuel consumption, such as CO_2, CH_4, and N_2O, are believed to be driving the global warming trends [3], as well as being the cause of acid rain and various health problems for humans and animals. There are also implications for the national economy and security of various countries. The long-term sustainability of the prevailing energy-consumption practices, therefore, is being questioned.

These concerns have been instrumental in the drive towards alternate, renewable, regional, and "clean" sources of energy, such as biomass, solar, wind, and hydro. Although the overall contribution of renewable energy is presently not significant, it is expected that with the development of more efficient technologies, these energy sources will become cost-competitive with the conventional nonrenewable sources. Among these renewable sources, biomass holds a distinct advantage for primarily two reasons. First, the biomass-based resources can be converted to liquid fuels such as ethanol and butanol, which can readily fit into the existing transportation infrastructure, thereby requiring minimal modifications. Since the transportation sector is a major consumer of fossil fuels, biomass-based fuels can make a significant impact. Second, the availability of biomass-based resources is relatively stable and predictable as compared to wind and solar [4, 5]. Biomass can also be stored for later use. In addition to this, biomass can also be converted to heat by direct combustion, power by direct combustion or co-firing with coal, and other value-added products and chemicals, such as glycerol and lactic acid [6].

There are primarily two sources of biomass: forestry and agriculture. For each of these sources, the available resources can be classified as primary, secondary, and tertiary [4]. Currently, the production of biofuels and bioproducts is being achieved mainly from the conventional agricultural food crops such as sugarcane in Brazil, corn and soybean in the United States, as well as Europe, and palm oil in Asia. The agricultural practices to produce these crops have improved substantially over centuries, and the processes to convert these sources into fuel and products are also well understood. These systems, therefore, are economically viable. However, the use of these food crops for fuel production has spurred the "food vs. fuel" debate in recent years [7]. It has been argued that use of these crops for fuel production is increasing food prices and impacting the availability of food resources. Moreover, cascading effects of increased fuel production are leading to indirect land use change in different parts of the world, thereby also mitigating the environmental and social benefits of biofuels [8]. Therefore, lignocellulosic biomass, such as dedicated perennial grasses, agricultural crop residue, forestry residue, and short rotation woody biomass, have emerged as the more sustainable biomass resources [4, 9].

The processing of lignocellulosic biomass to fuel is more challenging compared to that of carbohydrates (starch and sugars) due to biomass recalcitrance [10]. Lignocellulosic biomass can be converted to fuels and value-added products using two different routes: biochemical and thermochemical [11]. The biochemical route involves pretreatment, hydrolysis, and fermentation as the major processing steps and is mainly used to produce ethanol [12]. The thermochemical route involves gasification to produce syngas, which can then be converted to a variety of products and chemical building blocks using Fischer-Tropsch synthesis and water-gas shift reaction [13]. The thermochemical route also includes pyrolysis to produce bio-oil, which can be refined into separate fractions [13]. There have been significant research efforts to make these conversion processes more efficient and cost-competitive through development in science and technology. It has been argued that these possibilities can be used to develop a sustainable bio-based economy driven by biomass resources [14]. Such a bio-based economy can achieve its sustainability mission by reducing environmental emissions, achieving energy security, and stimulating rural economy and social well-being.

An important precursor for the success of the proposed bio-based economy is a continuous, reliable, and cost-effective supply of biomass from sources such as farms and forests to the biorefinery that is able to satisfy the expected high demand rates while maintaining the quality. This constitutes the biomass feedstock production and provision (BFPP) system, which is the focus of this book. The next section describes the BFPP system in detail.

However, the scope of the book first needs to be defined. As mentioned before, both forestry and agriculture represent important sources of lignocellulosic biomass feedstock. The supply systems for the forestry-based material are fairly well developed as part of the pulp and paper and logging industry. It is expected that many of the operations in this system will not change even if the biomass is to be used for energy production. However, this is not true for the agricultural feedstocks such as energy grasses and crop residues. The crop residues have mostly been used for very local and immediate applications, and large-scale production of dedicated energy grasses is not yet practiced. Moreover, some of the novel energy crops may require new agricultural machinery and modified management practices. The long-distance transportation of these materials is also relatively difficult as compared to forestry material, since their bulk densities are much lower. Therefore, in our opinion, the BFPP systems for the agricultural sector require much improvement. The book, therefore, focuses primarily on the agricultural sources of biomass feedstock.

1.2 Biomass Feedstock Production and Provision

BFP is a critical subsystem of the overall bio-based energy production and utilization system. It provides the necessary materials input to the conversion process of biomass into fuel, power, and value-added products. This subsystem includes the operations of agronomic production of energy crops and physical processing and handling/delivery of biomass, as well as other enabling logistics. On the technical side,

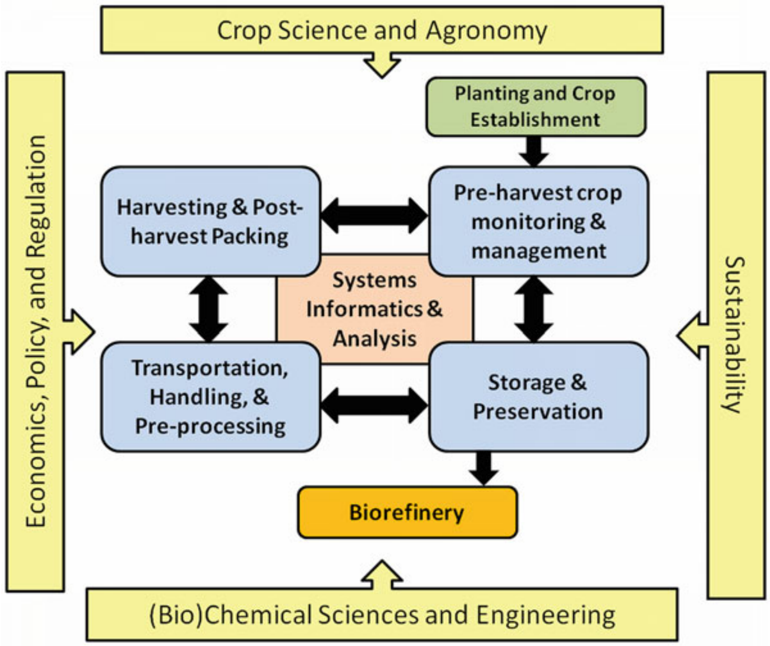

Fig. 1.1 The BFPP system consisting of four main production steps between crop production and biorefinery processing. The role of systems informatics and analysis and other extraneous factors impacting the sector are also illustrated

biological, physical, and chemical sciences need to be integrated with engineering and technology to ensure effective and efficient production of biomass feedstock. Some preliminary studies showed that feedstock supply costs including farming and delivery are up to 35–50 % of the delivered cost of bioethanol [15]. Therefore, the importance of biomass feedstock supply in the biofuels value chain is evident.

The BFPP system is shown schematically in Fig. 1.1. It can be considered as consisting of five different tasks, each representing a distinct phase in converting standing crop into biorefinery feedstock: preharvest crop management and monitoring, harvesting and handling, transportation, storage, and preprocessing. On the upstream side, the BFPP system interfaces with agronomy for crop selection, establishment, and growth. On the downstream side, the BFPP system connects with the biorefinery or bioprocessing facility that puts quantity, form, and quality constraints. These tasks are briefly summarized below:

- Agronomy: This task includes farming operations conducted prior to harvesting, including crop selection, soil preparation, planting, cultivation, fertilization, weeding, and irrigation and power. The emphasis is on developing the best management practices, which may need to be optimized for some novel energy crops.
- Preharvest crop monitoring: This task includes precision agriculture through remote sensing techniques by using tools such as cameras and sensors mounted on towers, mobile devices, or satellites. These remote sensing methods provide near-real-time

critical insights into the crop growth properties, such as salinity, nutrient status, stress levels, and yield. These insights can then be used to provide site-specific crop management strategies such as fertilization, irrigation, and weeding.

- Harvesting: Harvesting converts an energy crop in the field into feedstock material. It is considered a vital operation during the production of biomass feedstock. The efficiency of the harvester in maximizing the biomass collection is very important. A typical harvesting system can include functions such as cutting, conditioning, chopping, baling, and wrapping. Different configurations, such as self-propelled against pull type or one-pass against multiple-pass, can be used depending on the type of feedstock and equipment performance.
- Transportation: This task includes the conveyance of the biomass feedstock within the farm (short distance) as well as from farm to biorefinery or a central storage facility (long distance). Different modes of transportation include truck, rail, pipeline, barge, or a combination of these. Transportation is an unavoidable and essential task and has been identified as the major cost contributor in the overall system. The costs and energy consumption depend on crop type, bulk density, particle size, densification levels, transportation mode, and infrastructure availability. All of these must be studied to achieve maximum efficiency.
- Storage: This task aims to preserve biomass using processes that minimize total quantity and quality loss as well as biomass recalcitrance. Storage task includes on-farm open or covered storage as well as ensilage and dedicated storage such as a central/satellite storage facility that is typically covered and enclosed from all sides. Storage is important because improper storage can result in total dry matter loss, microbial deterioration, generation of chemicals inhibitory to conversion, and even combustion of the biomass. The benefits of high production yields and economical conversion to fuel will be nullified if suitable storage procedures cannot be developed to interface between the two.
- Preprocessing: Apart from the four major tasks listed above, various processing operations can be performed on the biomass as a part of these tasks. For example, drying operation is often a subtask in biomass storage [16]. Also included in this category are chemical treatments for long-term preservation of biomass or for preliminary breakdown of cellular wall structures as a precursor to biorefining, compacting or cutting of biomass for moisture removal, and biomass densification to optimize materials handling and increase vehicle transport payloads [17]. Milling has also been proposed as a potential pretreatment option.
- Biorefinery: The biorefinery utilizes the biomass feedstock made available by the preceding tasks. The feedstock may be used to produce fuel, heat, power, and/or value-added products. Each of these desired end products requires different processing routes, which may govern the optimal scale of the biorefinery. It may also impact the quantity and quality constraints of biomass that is delivered to the biorefinery.

These operations are impacted by knowledge and developments in crop sciences, chemical and biochemical sciences, chemical engineering, economics, law, regulation, policy, and sustainability. Figure 1.1 also shows these extraneous factors. In the next section, we describe a typical BFPP system that may be implemented based on the current knowledge and understanding. This description is based along the lines of different tasks described above.

1.3 Existing Biomass Feedstock Production Systems and Practices

Presently, there is very little large-scale cultivation and production of dedicated energy crops such as perennial grasses supporting lignocellulosic biorefineries. As a result, most of the lignocellulosic biorefineries are using agricultural residues such as corn stover and wheat straw as feedstock. Moreover, these biorefineries are not operating at very large scales, since many have been developed at pilot or demonstration scale to validate the conversion processes. Consequently, a commercial-scale lignocellulosic BFPP system does not exist. However, we have described here a typical production and provision system that one might expect given the currently available technologies and understanding. The system is schematically depicted in Fig. 1.2.

1.3.1 Cultivation and Crop Management

For agricultural residues as feedstocks, the agronomic practices developed primarily to optimize the yield and quality of the main crop such as corn, wheat, and rice will be used. These agronomic practices related to cultivation, irrigation, fertilization, and management have improved over the years. These are extensively covered in past literature and, therefore, are not discussed here.

The cultivation of dedicated energy crops such as Miscanthus and switchgrass (*Panicum virgatum*) has been limited and mostly on test plots with the primary purpose of conducting agronomic research. Cultivation of switchgrass is from seeds and, therefore, existing seeding equipment can be used. For Miscanthus, the practice depends on the particular hybrid being used. *Miscanthus × giganteus*, one of the hybrids that have been proposed as a potential feedstock due to its various benefits, does not produce seeds. Therefore, it is cultivated through rhizomes. The equipment for Miscanthus rhizome planting does not exist, so often potato planters are used.

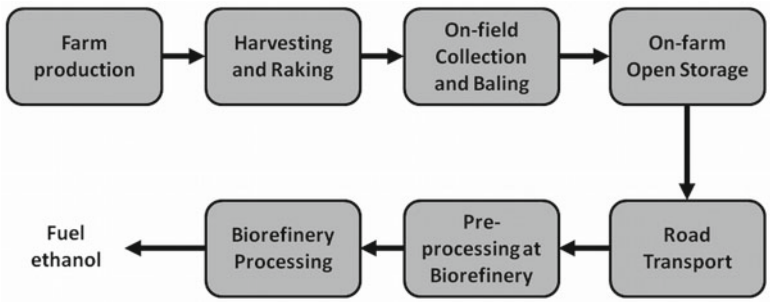

Fig. 1.2 Typical BFP system expected to be currently practiced in agriculture based on the available technology

Even for digging up the rhizomes of mature plants for propagation, a potato harvester is often used. The seeding for switchgrass and rhizome planting for Miscanthus will typically be done in late spring or early summer when possibility of frost is minimal.

The irrigation and fertilization practices for dedicated energy crops have not yet been optimized. Although these crops can produce good yields even without fertilization, some fertilization will be done, especially in the first year to improve yield. For example, the application of nitrogen fertilizer on switchgrass monoculture increased the yield significantly [18, 19]. The impact of fertilization on Miscanthus yield has been found to be less pronounced. The application of pesticides and herbicides may also be done, and the optimal application rates are being currently investigated.

A major issue for these perennial crops is survival during winter, also known as overwintering, especially in the temperate and cold regions. Excessive cold may damage the seed and rhizome, which may lead to lack of emergence during the next growing season. In the first season itself, some seeds and rhizome may fail to emerge. Consequently, some reseeding will be required at the beginning of the second and possibly third growing season.

1.3.2 Harvesting, Packing, and Handling

The crop residue is generated during the harvesting of the primary crop, such as corn and wheat. The residue left on the field after the primary harvesting operation is over will be collected and baled. The equipment and associated technology are well developed and available. Crop residue, if left on the field, enriches soil nutrients and moisture and reduces soil and water erosion. Therefore, the fraction of residue that is collected will have to be carefully decided. It has been reported in the literature that only up to 30 % of corn stover can be sustainably collected after accounting for these factors [20]. For dedicated energy grasses, the collection will depend on the type of harvesting system being employed. The two-pass collection system appears to be the one that will most often be used for energy crops. The harvester or mower will harvest the biomass crop in the first pass, while a baler will later pick it up and bale it in the second pass. The collection efficiency will be lower because all biomass cannot be picked up by the baler. Moreover, there is the possibility of soil contamination. To overcome these issues, and also to speed up the overall process, a single-pass operation is being proposed. The harvested biomass is directly sent to a baler without being dropped on the ground. This ensures that all the biomass is baled without any soil contamination. However, this technology is still at the demonstration stage. For baling, a round baler normally has a lower throughput rate and output bale density than a square baler [21]. However, it might still be used more often because it is cheaper than a square baler. Moreover, round bales shed water more readily than square bales. This means that if the bales are to be stored in the open without protection, biomass in round baled form would be better protected against rain. Another option that has been implemented, especially in Europe, is the self-propelled forage harvester (SPFH). With an SPFH, the biomass is harvested and immediately chopped into smaller particles, which are then loaded onto a wagon moving alongside the SPFH.

For the energy crops, a two-cut system has also been proposed. In this system, the crops are harvested once midway into the growing season and again at the end of the season. It has been argued that such a system will increase the total biomass output. However, studies confirming this advantage have been limited. Moreover, high moisture content of the biomass and the nutrients removed along with the biomass harvested during the first cut will be problematic. Therefore, as per the current understanding, a single-cut system will be employed.

1.3.3 Storage

The bales would normally be stored at the edge of the farm in the open. The ground may be paved or it may consist of gravel pad. It is being argued that setting up a covered storage facility on the farm may not be cost-effective given the low bulk density of the biomass. If the expected duration of the storage is long, or if the weather is not very conducive (high rainfall, stiff winds), then the bales might be covered with tarpaulin. The moisture content of the material at the time of harvesting and baling may also have an impact on the storage method. The use of an SPFH for harvesting creates problems for storage because the chopped biomass cannot be stored in the open. Closed structures, such as a shed or a silo, will be required for long-term storage of chopped biomass. An SPFH, therefore, may be preferred only in cases in which the chopped biomass is directly delivered to the conversion facility. The idea of storing of biomass at dedicated storage facilities is not widely accepted at this stage. There is, therefore, an increasing interest in incorporating some form of preprocessing along with storage at these facilities. These are often referred to as storage and preprocessing depots or centralized storage and preprocessing facilities. However, such facilities do not currently exist, even for agricultural residues.

1.3.4 Transportation and Preprocessing

The transportation of biomass would be by road using trucks and trailers. It is believed that the maximum feasible collection distance of biomass for a biorefinery would be about 150–200 km. Beyond this distance, the cost and energy consumption associated with transportation will increase substantially. Therefore, truck transportation would be most appropriate because it provides the necessary flexibility. This flexibility is essential since it allows collection of biomass from diverse locations, in relatively smaller quantities, and its delivery at the biorefinery. There is some concern about the possible traffic congestion at the biorefinery site given the number of truck deliveries required every day. This might have implications on the site selection as well as the size of the biorefinery.

1.3.5 Processing

The biomass processing and conversion facilities will typically have a buffer storage containing biomass sufficient to meet the demand for 7–10 days. The biomass received from the farms or removed from the buffer storage will first be ground to achieve the desired particle size. The optimal particle size is not yet known, and it will depend on the processing option selected. However, in general, a smaller particle size will improve the conversion efficiency by increasing the total surface area for thermal, chemical, or enzymatic reactions. The quality parameters such as moisture and ash content are not yet standardized. Hence, these parameters often differ for different pilot- and demonstration-scale biorefineries currently operational.

1.4 Challenges in Biomass Feedstock Production

Although the tasks within the feedstock production system described above are common to most agricultural products, there are challenges specific to bioenergy crops. In general, expert knowledge about the appropriate production and provision practices is not readily available, because the bioenergy feedstock sector is relatively young with very little large-scale, commercial production. Another equally important issue is the mismatch between supply and demand. Given the year-round demand for fuel, biorefineries would require an uninterrupted supply of the feedstock. Harvesting of the energy crops, though, is typically done over a period of 2–3 months. This means that the supply system must account for intermediate storage and should do so at minimum cost and quality degradation. The biomass feedstock also has very low bulk and energy densities. The bulk density of a typical baler used for agricultural residue currently is about 25 % of the bulk density of coal. Similarly, the energy density of a typical lignocellulosic material in MJ/Mg is about 30 % of that of coal. This highlights the magnitude of the challenges in handling and provisioning the feedstock for large biorefineries. The logistical complexity of biomass production systems is further characterized by a wide distribution of sources, time- and weather-sensitive crop maturity, and competition from concurrent harvest operations. In addition to these broad challenges that pervade all stages of feedstock production, each of the stages mentioned earlier also has specific challenges that need to be addressed:

- Agronomy: For many novel energy crops, such as Miscanthus and energy cane, the establishment and management techniques are not well understood and, therefore, not optimized. This includes row spacing, plantation density, fertilization and irrigation, pest control, and maturation schedules. The selection of the appropriate energy crop for each region is also a major challenge in this area. It is a function of regional attributes such as soil, weather, and rainfall in addition to the crop properties.
- Preharvest crop monitoring: As mentioned before, precision agriculture and remote sensing operations must be used to improve crop management and the

final yield through site-specific management. However, the establishment and management of energy crops may require technologies and methods different than traditional crops. The information specific to novel energy crops, such as which biophysical property to study and which sensing method is most useful, has been lacking. The functional relationships to correlate remote sensing data with physical attributes of the crops are also not established.

- Harvesting: The dedicated energy crops can be different from most forage crops and, therefore, may require new harvesting technologies to be developed. Dedicated and crop-specific machinery, therefore, needs to be developed. The design of new equipment requires fundamental understanding of the crop properties, including morphological properties such as the distribution of vascular bundles in stems, degree of lignification, and geometric size of the stem as well as biomechanical properties such as elastic modulus, tensile stress, and shear stress. The improved understanding of the engineering properties of the novel energy crops is, therefore, very important. Different cutting mechanisms and their impact on cutting speed, energy consumption, and quality of cut needs to be quantified. This information must be used to design new harvesting equipment if necessary. The performance of existing and new equipment must be systematically quantified. Different operational practices, such as one-pass and multiple-pass, also need to be systematically compared. The impact of weather on harvesting operations will also be critical.
- Transportation: The low bulk densities create enormous challenges in handling and transportation of biomass feedstock. Size reduction and densification look promising for improving the transportation efficiency. However, they need to be systematically studied. In particular, the energy consumption associated with these operations needs to be quantified. New equipment based on fundamental understanding of the cutting and compression mechanism needs to be developed. Different modes of transport must be compared. For road and rail transportations, the standardization of transportation equipment as well as policies and regulation is also needed. Software tools for optimal management and operation of the fleet are also needed.
- Storage: Maintaining the quality of biomass during storage is critical. This is especially true if the biomass is to be used for biochemical processing, because microbial degradation can lead to substantial loss of cellulose, which is critical to biochemical conversion. A fundamental understanding of the factors impacting dry matter and quality loss needs to be developed. This will help in designing optimal storage methods. The options for preparing biomass for further processing by breaking down the biomass recalcitrance during storage must also be evaluated. Evaluation of different storage methods by performing field tests using real scale facilities is also required. For building storage facilities, there exists a trade-off between costs and quality control. Accurate biomass degradation patterns as a function of regional weather and incoming biomass quality are required. The low bulk and energy densities also increase the total storage area requirement. Apart from being cost-intensive, this creates safety issues.

- Preprocessing: Appropriate preprocessing technologies need to be developed for the novel crops such as Miscanthus, switchgrass, and energy cane. This includes new size reduction as well as densification equipment based on fundamental understanding of the feedstock properties. From an operational standpoint, the optimal locations for setting up these preprocessing facilities in the supply chain must also be determined.
- Biorefinery: The biorefinery faces a number of challenges in improving the biomass conversion efficiency. However, from the BFPP system standpoint, the feedstock quality and physical form specifications need to be standardized. These will have implications on the BFPP system design and operations. Ideally, these specifications should also consider the constraints of the BFPP system in addition to processing requirement.
- Biomass feedstock properties and characterization: The biomass feedstock properties play a crucial role in the performance of the individual tasks mentioned here. For example, moisture content impacts the efficiency of harvesting, size reduction, and storage. Similarly, bulk density impacts storage and transportation efficiencies. Systematic characterization of the biomass and the quantification of its properties are, therefore, essential. However, biomass feedstock may exhibit significant variability in these properties [22]. Standardized methods to estimate these properties for different feedstock are needed but currently lacking.

In addition to addressing these task-specific challenges, the broad system-level challenges must also be addressed. These are highly interdependent tasks with implications on upstream and downstream design decisions. We must, therefore, go beyond the optimization of the individual operations and focus on the compatibility of various tasks, which will lead to the overall optimal value chain configuration. Systems-based approaches that integrate systems informatics and analysis techniques, such as database design, simulation modeling, and optimization, must be used to develop new decision-making tools. The models should account for the inherent uncertainties in the system such as weather, yield, maturity schedule, and equipment breakdown. These tools must be made widely accessible, not only to experts but also to various other stakeholders in the system. Figure 1.1, therefore, shows the role of systems informatics and analysis as central to the complete BFPP system.

Finally, sustainability considerations will be very important. Biofuels and bioenergy in general have been proposed as more sustainable alternatives to the nonrenewable fossil fuels. However, these are highly complex systems in which the economic, environmental, social, and policy issues intersect. An example of this is the issue of indirect land use change due to biofuel production that has been intensely debated in academic as well as policy forums [8, 23]. The social implications of biofuels are especially important because the feedstock providers are farmers whose livelihoods will depend on the success of this sector. The environmental and ecological issues, such as species invasiveness, fertilization and irrigation requirements, and biodiversity maintenance, must also be considered. These challenging issues must be addressed by specifically conducting sustainability-focused assessments using a holistic approach.

1.5 Objectives and Goals of This Book

Achieving a sustainable BFPP system is paramount for the success of the emerging bioenergy sector. Engineering will play a critical role in addressing these challenges and ensuring the techno-economic feasibility of this sector. It must also integrate with the biological, physical, and chemical sciences and incorporate externalities, such as social/economic considerations, environmental impact, and policy/regulatory issues, to achieve a truly sustainable system. Tremendous progress has been made in the past few years towards achieving these objectives. New challenges have simultaneously emerged that need further investigation. It is, therefore, prudent at this time to review the current status and identify future challenges, which is the objective of this book.

Each of the chapters in the book aims to discuss different issues related to feedstock production and is purposely organized based on the different challenges identified above. The chapters have been prepared such that a reader interested in a specific topic can directly go to that chapter without having to read the preceding chapters. However, given the interdependencies of these various topics in a BFPP system, the links and impacts between different stages of the system are highlighted through cross-referencing between chapters at various places.

We have identified three different agricultural biomass feedstock options that, according to our opinion, will play an important role in the near-term future of bioenergy systems. These are switchgrass (*Panicum virgatum*), Miscanthus (*Miscanthus* × *giganteus*) as dedicated energy crops, and corn stover as agricultural residue. Significantly more data are available for these feedstocks for all stages of production and provision. However, a comprehensive summary and comparison, especially for all the feedstock production and provision stages, is lacking in the literature. This is especially true for Miscanthus and switchgrass given their relatively recent emergence as potential feedstock. We have, therefore, discussed these three feedstocks in most chapters. This serves the dual purpose of providing consistency among different chapters as well as presenting a summary of crop-specific literature across all feedstock production stages. Several other feedstock options, such as energy cane, sweet sorghum, tropical maize, and short rotation coppice, are also being discussed in the literature. These have been briefly discussed in individual chapters at appropriate places and in relation to that specific topic. It must also be noted that even though many of the field studies, experiments, and case studies discussed in the book are based in the United States, the scientific concepts, engineering designs, and recommendations reported have wider applicability, making the contents of the chapters relevant for other regions around the world as well.

Our objective for this book is to serve as an authoritative treatise on the topic of BFPP based on the current literature and understanding. We hope that it will serve as a guide to various interested stakeholders in the bioenergy sector such as engineers (agricultural, chemical, mechanical, civil), agronomists, academic and industrial researchers, policy makers, bioenergy industries/businesses, farmers, and farm consultants. In addition to this, we also hope that the book will serve as a foundation for the undergraduate and graduate students interested in working in this area and as a reference guide for instructors teaching courses in this area.

1.6 Summary of Chapters

This chapter has provided a broad introduction to the topic of bioenergy and the importance of BFPP for a sustainable bioenergy system. The chapter discussed the important tasks within BFPP, reviewed the current status, and identified challenges in each of these tasks. System-level issues requiring solutions were also highlighted.

As highlighted earlier, biomass feedstock properties play an important role in all the tasks. Standardized methods to estimate these properties are being developed. Chapter 2 reviews these methods with particular focus on estimating properties relevant to engineering design of the BFPP system. The properties considered include bulk density, particle density, particle size, color, moisture content, ash content, heating value, and flowability. The chapter reviews the recent developments in the characterization techniques. These properties are referred to in all the subsequent chapters. Therefore, it is appropriate to discuss this topic before the specific tasks are covered.

Chapter 3 discusses the agronomy of Miscanthus and switchgrass, two of the most promising dedicated, perennial energy crops. Since these crops are relatively novel, knowledge on cultivation, establishment, and management of these crops is very limited. The chapter summarizes the important findings from studies published in the literature, including studies conducted by authors themselves, to provide useful recommendations and guidelines. This includes recommendations on seeding rates, preferred seasons, fertilization practices, irrigation practices, and more. Farmers and farm consultants who want to grow these grasses should find this information very useful.

Chapter 4 focuses on preharvest crop monitoring of the energy crops. The importance of monitoring is first discussed and the theory behind remote sensing tools as applied to agricultural crops is briefly presented. Since very little work has been done in this area specific to the novel energy crops, the authors summarize their own research in developing three different near-real-time remote sensing platforms for crop monitoring. The basic concepts of these three platforms are discussed and some preliminary results for Miscanthus and switchgrass are also presented.

In Chap. 5, the focus shifts to the harvesting of biomass to convert it into a feedstock for further operations. Engineering properties relevant to machinery design are discussed and different harvesting subsystems, such as cutting and conditioning, are described in detail. The chapter then reviews the harvesting technologies for four bioenergy crop options: energy grasses (Miscanthus and switchgrass), short rotation woody crops (willow, poplar), green crops (energy cane, sorghum, sugarcane), and agricultural crop residue (corn stover, orchard residue). The discussion in this chapter, aided by a number of illustrations, provides an excellent summary of the knowledge in this field.

Chapter 6 discusses the long-distance transportation of biomass feedstock to a biorefinery or storage facility. Preprocessing, such as baling or pelletization; size reduction, also known as comminution; and densification play a key role in deciding the efficiency of transportation operations. Therefore, the chapter provides a comprehensive summary of the different preprocessing options, their advantages, and their drawbacks. The different transportation modes are discussed and the challenges in optimizing the transportation logistics are also presented. Various challenges in biomass transportation that need to be addressed are also presented.

In Chap. 7, issues related to long-term storage of biomass are discussed. The different storage methods are first summarized and compared. Biomass properties that impact storage are then discussed. Total dry matter loss as well as quality degradation are the two important problems with long-term storage. Possible means to minimize these losses are discussed. Since storage can also be used for some preprocessing to prepare biomass for conversion, options to reduce biomass recalcitrance are presented. General guidelines that may be used while selecting a storage method are also presented.

Chapter 8 takes a holistic view of the BFPP system and summarizes the work done in applying systems informatics and analysis tool for BFPP system design and analysis. The literature at four different scales, namely, crop growth and management, on-farm production, local production and provision, and regional/national/global, is presented. Important modeling and informatics approaches are presented and their applications, along with key results, are summarized. The chapter also identifies several research gaps that need to be addressed in the future. The chapter should be highly relevant for farmers, managers, and biorefinery investors.

Chapter 9, a really unique component of the book, explores the sustainability aspect of BFPP. Contrary to all other chapters, it takes a legal and policy perspective to elaborate on sustainability of BFPP. Policy and regulatory initiatives existing or proposed in the USA, Europe, and Brazil to ensure sustainable production of biomass feedstock are summarized. In addition, private initiatives are also presented. Various complex issues related to these initiatives are identified. This chapter is highly relevant for businesses and potential investors who may be interested in ensuring the long-term sustainability of the bioenergy systems.

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Chapter 2
Engineering Properties of Biomass

Pak Sui Lam and Shahab Sokhansanj

Abstract Engineering properties of biomass are important for the design and operation of processing facilities for handling, storage, transportation, and conversion to fuels, heat, and power. These properties include bulk density, particle density, particle size, color, moisture content, ash content, heating value, and flowability. In this chapter, the characterization methods of these properties are reviewed. In particular, the recent development of the characterization techniques and progress in understanding these engineering properties of the biomass are discussed. The heterogeneous nature of biomass requires standardized characterization procedures and statistical models development to predict their physical properties for engineering design and operation.

2.1 Introduction

Lignocellulosic biomass sourced from plants is a renewable and sustainable natural resource that can be engineered into feedstock for producing heat, power and chemicals. Different parts of the plants have different microstructure and chemical

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Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4_2,

compositions. For example, a wood log consists of stem wood (white wood) and bark. Stem wood has a lower ash content compared to the bark by tenfold. As a result, bark may not be an excellent fuel source for combustion to produce heat and power. Therefore, biomass has to be fractionated and engineered by biomass processing in order to extract the appropriate parts for particular end-user application.

Engineering properties of biomass are those that control the way biomass is prepared for either its handling or its conversion to other forms. These properties can be divided into structural, compositional, thermal, and electromagnetic properties. Structural properties may manifest themselves in the form of mechanical and physical properties. Compositional properties are chemical constituents of the biomass. Thermal properties relate to heating and cooling rates and heat transfer between the material and its environment as well as the calorific value of biomass. Electromagnetic properties relate to the response of the material when exposed to waves from electromagnetic spectra. These four properties are highly interrelated, i.e., the change in one influences a change in the others. These material properties can be studied separately, keeping in mind that their unavoidable interactions are important.

Considerable research has been conducted on agricultural and forest material properties over the last 50 years. Much of these properties can be extended and applied to biomass. Professor Mohsenin of Penn State University was first to collect and publish the state of the art in definitions and measurements of thermal [1], electromagnetic [2], and physical properties [3] of agricultural material. Since then, numerous books and articles have been published on the properties of foods [4, 5] and woody products [6]. More recently, methods of evaluating the compositional properties of biomass were presented [7]. The ASABE Book of Standards maintains updated properties for agricultural and forest materials. Similarly, International Organization for Standardization (ISO) is in the process of establishing procedures for biomass properties characterization.

Energy providers are including bioenergy in their portfolio as the demands for energy are increasing and the known petroleum resources are dwindling. Environmental concerns with burning coal are shifting attention to biomass as an alternate solid fuel [8]. Conversion processes, whether they are simply converting biomass to heat and power or involve more complex biomass to gaseous or liquid fuels conversions, require high-quality and cost-competitive feedstock [9]. Simple combustion may utilize feedstock with a wide range of moisture contents, mixtures of species bark and stem wood, and a wide range of sizes and ash content. The more complex processes such as chemical or enzymatic hydrolysis require feedstocks with close tolerances in particle size and density [10]. Meeting tight specifications can be challenging as forest feedstocks are highly variable in many of the relevant physical and chemical compositions. The source of the feedstock will have direct impact on the available quantities of biomass and the cost of harvesting and logistics. Understanding these characteristics is an important element in ensuring that new investments in bio-industry match the available feedstock supplies.

The engineering properties of biomass highly affect the quality of feedstock for densification and eventually their use in either biorefinery or in a combustion application. These properties include density, particle size, flowability, moisture

Table 2.1 Engineering properties of biomass

Engineering properties	Engineering application	Characterization methods/standards/ reference
Density	Supply logistics, transportation, and storage of biomass in different forms: chips, logs, ground particles and pellets, etc.	[17, 18]
Particle size	Design parameter for efficient downstream conversion	[19–22, 26]
Angle of repose	Design parameter for handling and storage facilities	[27–31]
Moisture content	Design parameter for drying and thermal conversion processes	[38, 39]
Calorific value	Energy recovery efficiency	[40–45]
Ash content	Estimation of the potential risk of slagging and fouling issues during biomass combustion/gasification	[47, 48]
Color	Quality control and a quick estimation of fuel properties (e.g., heating value)	[42, 49]

content, heating value, ash content, and color, which are all important engineering properties for the design and operation of the downstream biochemical process. They also highly affect the design of handling and transportation systems, storage in hoppers and silos, and fuel conversion equipment [11, 12].

In the following sections, we discuss the typical characterization method of the physical properties of the biomass (Table 2.1) and also review recent progress in understanding their engineering properties.

2.2 Characterization Methods of Biomass Engineering Properties

2.2.1 Density

Density of a biomass is defined as the mass over its volume (kg/m^3 or lb/ft^3). In the context of bioenergy, we divide density into two groups: bulk density and particle density.

2.2.1.1 Bulk Density

Bulk density is an important characteristic of biomass that influences directly the cost of feedstock delivered to a biorefinery and storage area [13–15]. The non-uniform particle size and shape of the raw biomass including leaves and stems lead to the high cost for transportation, storage, and feeding of the particles into each unit operation. The standardization of the characterization method of the bulk density of biomass for logistic optimization is of utmost importance (Fig. 2.1).

Fig. 2.1 A container filled with 14.7-mm switchgrass particles for bulk density measurement. Reprinted with permission from Lam PS, Sokhansanj S, Bi X, Lim CJ, Naimi LJ, Hoque M, Mani S, Womac AR, Narayan S, and Ye XP. 2008. Bulk density of wet and dry wheat straw and switchgrass particles. *Applied Engineering in Agriculture* 24(3): 351–358. St. Joseph, Mich.: ASABE

Bulk density measurement of the biomass powder or large particles can be performed according to the method of ASTM D1895B [17] or ASABE S269.5 OCT2012 [18]. For the biomass ground particles (i.e., less than 2 mm in diameter), a container with a volume of 0.615 L was used, above which a funnel with the opening diameter of 1.5 cm was suspended. The funnel was then filled with the biomass grinds and they were allowed to flow freely into the circular container from a height of 20 cm. The biomass grinds were stirred continuously by a thin metal wire throughout the pouring operation to prevent clogging inside the funnel opening. The excess material on top of the container was scraped off with a straight edge. The container with sample was weighed and weight/volume (loose bulk density) was determined. For tapped density, the loosely filled container was tapped on the laboratory bench five times in a vertical direction. The weight of the filled container was recorded after five tappings.

ASABE 269.5 [18] states that for all densified products (cubes, pellets, or crumbles), use a cylindrical container with a height-diameter ratio within the range of 1.25–1.50. The diameter of the container must be at least ten times larger than the largest dimension of a single product. The container is filled by pouring from a height of 2 ft (610 mm) above the top edge of the container. The container is to be then dropped five times from a height of 150 mm onto a hard surface to allow settling. In the case of small pellets and crumbles, the material shall be struck off level with the top surface. More materials may need to be added after settling to fill the container. In the case of cubes and large pellets, remove products which have more than one-half their volume above the top edge of the container, leaving in the container those products with more than one-half of their volume below the top edge of the container. As the tendency of densified products tend to expand for some time after forming, both the time interval between forming and the moisture content during the measurement should be specified. Bulk density measurements should be repeated at least five times, and the average value and the range must be reported. Bulk density of a biomass varies with its moisture content and particle size. Therefore, the bulk density of a measured product should be specified with moisture content and particle size and shape. Information on shape and geometry of particle size is also important.

2.2.1.2 Particle Density

Particle density is the mass of an individual particle over its volume. For a group of particles, the particle density is the mass of all particles divided by the volume of the particles occupying excluding the pore space volume. For a particle that can be defined accurately geometrically, the mass of a single particle is measured using a digital caliper. For example, a wood pellet can be geometrically defined as a cylinder. The ends of the wood pellets are flattened with sandpaper to make them exact cylinders. The length (*L*) and diameter (*D*) of the pellets are measured with a caliper. The apparent volume is calculated by (2.1):

$$V = \frac{\pi}{4} D^2 L \tag{2.1}$$

For particles that cannot be defined geometrically, indirect methods are used. For example, wood pellet density is calculated by measuring the volume of two to three wood pellets with a Quantachrome Multipycnometer (Quantachrome, Boyton Beach, FL, USA). Nitrogen is injected into void spaces of the biomass. The pressure difference with a known quantity of pressurized nitrogen flows from a reference volume into a cell containing samples is used to determine biomass particle true volume. The volume of the particle is calculated from an ideal gas law equation (2.2). The volume measurements of particle must be repeated three times for each sample for determination of an average volume.

$$V_p = V_c - V_R \left[\frac{P_1}{P_2} - 1 \right] \tag{2.2}$$

where V_p is the volume of biomass particles (cm^3), V_C is the sample cell volume (cm^3), V_R is the reference volume (cm^3), P_1 is the pressure reading after pressurizing the reference volume (Pa), and P_2 is the pressure reading after including V_C (Pa). The density is the ratio of mass of pellets over the measured volume (2.3).

$$\rho_p = \frac{m}{V_p} \tag{2.3}$$

Interparticle porosity provides the packing information of the biomass particles inside a known container and is determined by (2.4).

$$\varepsilon = 1 - \frac{\rho_b}{\rho_p} \tag{2.4}$$

where ε is the porosity, ρ_b = bulk density of biomass grinds (kg/m^3), and ρ_p = particle density of biomass particle (kg/m^3).

For large pieces that do not fit into a pycnometer cell, the method of immersion in water is recommended [18]. A few representatives of samples are selected and their mass are weighed, W_1. The empty container is initially filled with two-thirds of water and the scale is set to zero. The container must be transparent, and its diameter must be large enough to accommodate the piece in a plastic bag. Each piece of sample is placed in a plastic bag with the breadth of 0.03 mm. A thin metal rod with a ring at the other end was used to push the piece into the water. The mass was recorded from the scale, W_2. Another check was performed by checking the sample piece absorbing through a bag with leak with W_1. The density is calculated from (2.5).

$$SW_1 = \left(\frac{W_1}{W_2 - W_3} \right) \tag{2.5}$$

where SW_1 = particle density of test piece (kg/m^3), W_1 = piece mass in air (kg), W_2 = mass of water displaced by the piece, bag, and rod (kg); and W_3 = mass of water displaced by bag and rod, without the sample piece, when they are immersed to the depth at which W_2 reading was taken (kg).

ASABE 269.5 specifies that W_3 should be further corrected by subtracting a small value, for example, 7 g, to compensate for error in the fit of the bag to the piece.

For pieces of irregular shape, the following procedure may be used: Insert a thin metal rod into the piece and immerse the piece into molten wax such that a thin film covers the surface area. Allow the wax-covered piece to cool, and then follow the procedure outlined above to determine the particle density. The particle density measured above will then be corrected to 0 % moisture content by (2.6):

$$SW_c = SW_i \frac{\%DM}{100} \tag{2.6}$$

where SW_c = particle density at 0 % moisture content (kg/m^3), SW_i = measured particle density (kg/m^3), and %DM = percent dry matter in test particle.

Particle density calculation does not make any allowance for shrinkage or expansion that may occur during a potential drying process. Measurements should be done on at least five samples and the average, range, and number of samples reported. Because of a tendency for pieces to expand for some time after forming, both the time interval between forming and the measurement and the moisture content at the time of this measurement should be specified.

2.2.2 Particle Size

Woody biomass and herbaceous crops are of irregular shapes. Some are of a needle form with high an aspect ratio (length divided by diameter) and the finely ground particles have a round shape with an aspect ratio close to one. The range of the particle size of woody biomass is huge, from spanning wood logs to ground powders after milling. For herbaceous crops, the particles include leaves and stalks which are fluffy in nature [16]. There are three dimensions for these particles, including particle length, width, and thickness. However, some of the traditional particle size measurement techniques, e.g., sieving, are limited to the measurement of one single dimension of the fibrous particles (e.g., particle width) only. In addition, a long piece may actually pass through a sieve because it is oriented perpendicular to the sieve and therefore passing through due to small width/thickness. This makes the exact dimension measurement difficult and challenging. Therefore, there is a strong need to develop accurate characterization techniques for biomass particle size and shape for designing the handling, storage, and processing units including chemical reactors for treatment. Sieve analysis and digital imaging techniques are two major characterization methods for particle size analysis.

2.2.2.1 Sieve Analysis

A particle size analysis of biomass ground particles using sieves with square holes opening was studied [19]. Prior to sieving analysis, samples were conditioned to consistent low moisture content (e.g., 10 % moisture content [w.b.]) at a drying temperature of 50 °C. This conditioning ensures that the particles do not stick to each other by capillary force of moisture during sieving process. Particle size distributions were determined according to the ASABE Standard S319.4 JUL97 [20], using a Ro-Tap sieve shaker (Tyler Industrial Products, OH, USA). A sample of approximately 20 g wheat straw, switchgrass, and corn stover grinds was placed on top of a stack of sieves, arranged from the smallest to the largest mesh number. Sieves used for 1.6-mm (1/16″) samples were 18, 25, 35, 45, 60, 80, 100, 120, 170, and 230, corresponding to nominal sieve openings of 1.00, 0.707, 0.500, 0.354, 0.250, 0.177, 0.149, 0.125, 0.088, and 0.063 mm [19]. Sieving time was 5 min for each sample. The mass retained on each sieve was weighed to obtain the particle size distribution of the biomass. The geometric mean diameter (d_{gw}) of the sample and geometric standard deviation of particle diameter (S_{gw}) were calculated accordingly.

To verify the characteristics of particles retained on each sieve, a representative sample of particles from each sieve was selected. The length and the maximum diameter of the particles belonging to each sample were measured with a caliper. It is known that the sieve opening is not a representative of particle length, but it is a representative of the particle maximum diameter. However, this relationship is weakened as particles size increases.

Different methods of size classification of wood chips were discussed by Hartmann et al. [21]. He mentioned that screens are common in wood classification.

Table 2.2 Dimensions of circular hole sieves

Screen No.	Hole diameter (mm)	Screen thickness (mm)	Open area (%)
1	48	26.0	35.98
2	32	20.0	33.00
3	16	9.53	35.65
4	8	6.35	32.45
5	4	3.00	32.77
Pan			

Because of the mentioned problem associated with long and thin particles, the application of a dynamic online image analysis can improve its effectiveness. This new classification method can sort particles based on more than one dimension, but it has the problem of particles overlapping. So, the most reliable method of characterizing the size of particles is still direct measurement of size by hand, using a digital caliper.

ASABE S424 specifies the use of a stack of thick plates with square holes to analyze the size of cut forages in the field [22]. The thickness of the plates is proportional to the dimension of the hole. Larger holes have a thicker dimension and this makes sure the long particles do not have enough space to pass through the holes during sieving. A biomass sieving system was developed at the University of British Columbia (UBC), Vancouver, based on the ASABE 424 standard. The sieving system consists of a stack of five round sieves plus pan. Each sieve has a height of 85 mm and a diameter of 305 mm except the sieve with the smallest hole that has a height of 4 mm and rests on a pan with the height of 45 mm. The dimensions of each sieve are summarized in Table 2.2.

The sieve shaker (Retsch Model AS 400, Newton, PA) applies a horizontal circular motion. The speed ranges from 50 to 300 rpm and can be electronically controlled. The actual value of the number of revolutions is digitally displayed.

2.2.2.2 Digital Imaging Technique

Digital imaging technique provides an accurate measurement of particle size by processing the particle's projected area in the image and counting the digital pixels with a preset of scanning resolution [20, 23–26]. The images can be taken either by a scanner or by a scanning electron microscope (Fig. 2.2). For the digital scanning method [26], the sample of ground fir softwood particle's images were taken by a CanoScan 4,400 F high-resolution scanner (Canon, Lake Success, NY). The resolution of the image was determined by the number of pixels per inch (DPI). The particles were scattered on a transparent plastic sheet before images were taken by the scanner. Prior to imaging, the individual particles were deliberately separated so that they did not touch or overlap with each other, which would affect the particle size analysis results. This manual separation of the particles was performed with the aid of a magnifying glass. The resulting images were analyzed with MATLAB software

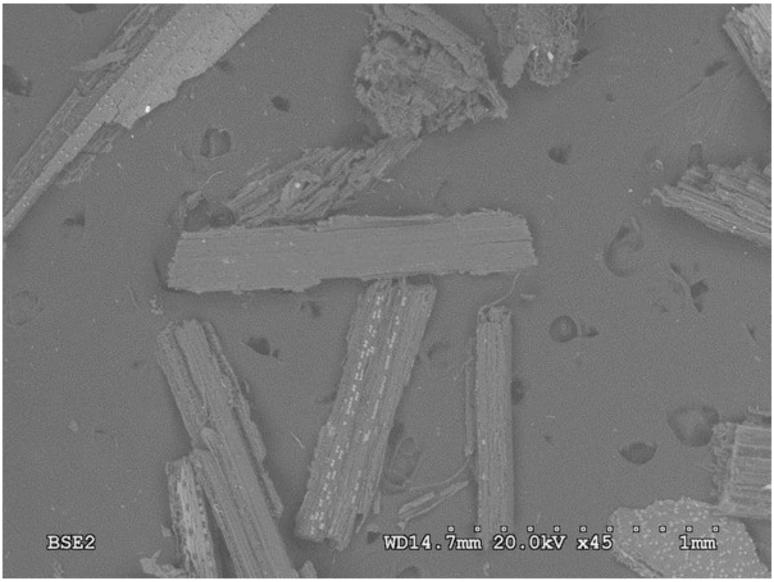

Fig. 2.2 Cross-sectional surface of switchgrass ground particles under scanning electron microscope

(The MathWorks Inc., Natick, MA) using an image processing and statistical toolbox. The particle length and particle width were defined as an ellipsoidal major axis and ellipsoidal minor axis measured by the MATLAB imaging toolbox. These two major parameters were used in the toolbox to calculate individual particle's equivalent spherical diameter and aspect ratio. The number of particles, particle length, particle width, and aspect ratio was reported. For each studied particle, three imaging replicates were measured and averages reported.

2.2.3 *Flowability*

Static angle of repose is a flowability indicator of the material, which is a function of particle shape, friction, and cohesiveness. It is defined as the angle at which a material will rest on a stationary heap. It also helps to design the loading height and the pile dimensions of the biomass particles [27–31].

Flowability of biomass grinds can be determined by the angle of repose test using a Mark 4 version tester developed by Geldart (Powder Research Ltd., UK). The sample flowability is generally classified as free flowing, fair flowing, and cohesive [32]. A flowability study of ground particles of wheat straw, switchgrass, and corn stover was studied using the Mark 4 version tester [19]. Twenty-five grams of biomass grinds collected on each mesh after sieving is slowly poured onto the uppermost stage with the vibrating chute [19]. The vibratory chute was shaken constantly in order to make sure the samples poured continuously and smoothly into the funnel. The samples will flow through the funnel and form a heap with a conical shape. Measurement of height (H) and radius (R) of the rest particles was taken five times to determine the average value of angle of repose.

The height and radius of the semi-cone were measured and the angle of repose (α) was calculated from (2.7):

$$\alpha = \tan^{-1}\left(\frac{H}{R}\right) \tag{2.7}$$

where α is the static angle of repose (degree), H is the height (cm), and R is the radius (cm).

2.2.4 Moisture Content

Moisture content of biomass is one of the important physical properties for the design of a drying process [33]. Woody biomass is usually wet when collected from the forest. It must be dried and processed to produce feedstock for heat and power and chemical production. Dried biomass is also preferred during handling and storage to minimize the mold formation [34], off-gassing [35], and self-heating issues [36, 37]. Drying kinetics of biomass for the dryer design is usually determined by the accurate measurements of the moisture content of the biomass at different intervals.

One of the standardized moisture content measurement methods for biomass is described in the ASABE Standard S358.2 [38]. The procedure involves weighing and drying about 100 g of pieces of biomass as received, in triplicate in a forced air convection oven at 103 °C for 24 h to obtain the completely dry biomass. The dried samples are cooled and weighed. A digital balance with 0.01-g precision is used for the weighing procedure. The developed ISO standards are based on European standard CEN/TS 14774-3, which specifies 105 °C for 60 min for determination of moisture content for solid biofuels [39]. The required mass of the small particles with 1-mm geometric mean diameter is a few grams, while that for the large particles (e.g., wood chips) is 500 g.

2.2.5 Calorific Value

Calorific value of biomass is crucial to determine its energy that can be recovered during thermo-conversion. From recent studies, it was found that thermally treated biomass with increased calorific value could be a suitable candidate to blend and co-fire with coal for power generation with reduced greenhouse gas emissions [40–45].

Calorific value of each biomass sample can be measured by a Parr calorimeter model 6300 (Parr Instrument Company, Moline, IL). A sample consisting of 40 g was ground in a knife mill through a 2-mm screen. Approximately 1 g of the ground particles was weighed. A pellet was made from the ground particles using the manually operated Parr Pellet Press. The weight of the pellet was entered as an input data to the calorimeter. The pellet was placed in a crucible immersed in a bucket filled with 1 L of distilled water. The bucket was placed in the calorimeter. The calorific value of the pellet was recorded as the high heat value (HHV) in MJ per kg of dry biomass.

2.2.6 Ash Content

Biomass ash causes lots of operational problems during biomass processing, combustion, and emissions. For example, silicon of biomass ash is the main contributor to wear out of the blades of the size reduction unit [46]. Potassium and calcium cause fouling of heat exchangers and slagging in the bottom of the furnace. These require shutting down the units regularly, reducing the operating time of the production units, and also increasing the maintenance cost. Therefore, the quantitative analysis of biomass's ash content is critical for process design. Sometimes, a leaching pretreatment process is required to extract the ash from the biomass before the downstream processing. This helps to facilitate an efficient and economical downstream process with a high-quality product yield.

Ash content of the oven-dried biomass was measured using the NREL/TP-510-42622 procedure [47]. A sample of softwood chips consisting of 40 g was ground in a knife mill through a 2-mm screen. Three replicates of 0.5–0.8 g of each ground sample were placed inside a muffle furnace equipped with a thermostat. The temperature control for the furnace was set at 575 °C furnace based on the suggested temperature program. At the end of the test, the ash sample was placed in a desiccator to cool. The final weight of the sample was measured and recorded. Ash content was expressed on a dry mass basis. The ash compositional analysis can be done by EDAX or ICP-MS [48].

2.2.7 Color

Color is an important attribute of the biomass. For the biomass without thermal treatment, a sample with dark color is usually correlated to high ash content. For example, the pellets made with bark are darker in color [42]. For the biomass with thermal pretreatment, the degree of the darkness of the sample can be highly correlated to their degree of thermal treatment (e.g., torrefaction and steam explosion [49]), as well as to the calorific value of the biomass.

The color of the biomass particle with different degrees of thermal pretreatment was measured using a color spectrophotometer (Konica Minolta CM-5, Osaka, Japan) [42, 49]. The black and white calibrations were performed before the reflectance measurement. All measurements were made using an observer angle of 10° and a D65 illuminant. The 0 % color was calibrated with black and 100 % with white standards. A sample of ground particle was spread out inside a Petri dish as recommended by the instrument's operator manual. The color coordinates L^*, a^*, and b^* (lightness, redness/greenness, and yellowness/blueness) were determined for each sample. Five replicates of measurement were carried out.

The variation in color coordinates was calculated as the difference between the measured values for L^*, a^*, and b^* coordinates for the untreated and treated wood. The differences were expressed in percentage of the initial value,

$$\Delta L^* = 100\frac{\left(L^*_{treated} - L^*_{untreated}\right)}{L^*_{untreated}} \tag{2.8}$$

$$\Delta a^* = 100\frac{\left(a^*_{treated} - a^*_{untreated}\right)}{a^*_{untreated}} \tag{2.9}$$

$$\Delta b^* = 100\frac{\left(b^*_{treated} - b^*_{untreated}\right)}{b^*_{untreated}} \tag{2.10}$$

2.3 Recent Progress in Analyzing Biomass Engineering Properties

2.3.1 Bulk Density, Particle Size, and Flowability

The bulk density and flowability of the biomass particles are highly influenced by the particle size and shape. In most studies, the bulk density of a mixture of ground particles from different sieves was measured [19, 50–53]. Mani et al. (2004) reported that the bulk and specific densities increase with the geometric particle diameter of the particles at the same moisture content and developed second- or third-order polynomial models relating the bulk and specific densities of agricultural biomass grinds to their respective geometric particle diameter of the biomass grinds within the range of 0.18–1.43 mm [50].

Sone's model was used to understand the compaction characteristics by tapping of different biomass [51], and it was found that the chopped wheat straw particles compacted very rapidly to reach the final tapped density as compared to the chopped switchgrass and corn stover particles [52]. This result may be due to the low value of Hausner ratio (i.e., the ratio of tapped density over the initial bulk density) of chopped wheat straw particles and also its better flowability than the chopped switchgrass and chopped corn stover. Tapping motion causes the particles to move to each other to fill up the bulk pores in between the particles and rearrange their

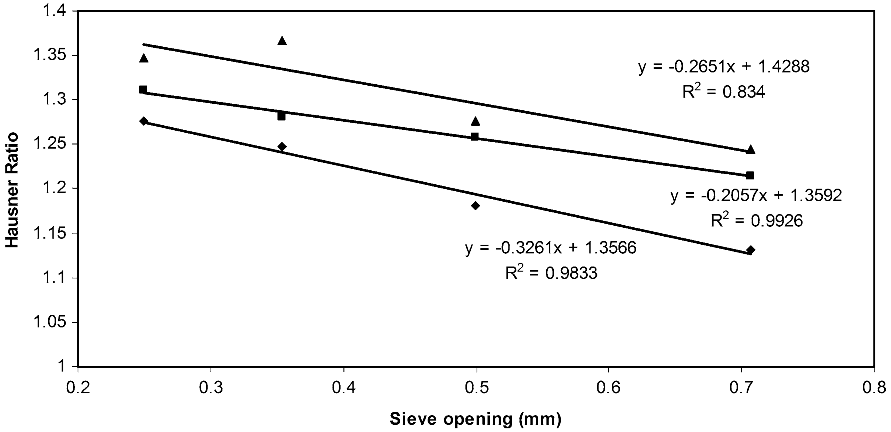

Fig. 2.3 Hausner ratio of biomass grinds at different particle sizes (*filled diamond*: switchgrass; *filled square*: corn stover; *filled triangle*: wheat straw)

packing structure to a more compacted form. Normally, a low Hausner ratio indicates that the initial bulk density of the packed particles after loading is already quite close to the tapped density. Those packed particles required fewer number of tapping to rearrange the particle packing structure in order to reach the final tapped density. The particles with poor flowability will limit the tendency of the packed particles to rearrange their pack structure to achieve a closer packing caused by tapping. For example, the particles with a rougher surface may increase the internal friction between the particles and thereby limit the particles to move to fill up the bulk pores.

When the biomass particles were further fractionated into individual particle fractions and their individual bulk density was measured [19], the bulk density of the switchgrass and wheat straw stem particles increased with decreasing particle length and the bulk density of the switchgrass and wheat straw stems increased by 10–50 % due to tapping. Switchgrass achieved lower Hausner ratio than corn stover and wheat straw for different particle sizes between 0.25 and 0.71 mm (Fig. 2.3). It was observed that the switchgrass particles flowed into the container relatively faster than wheat straw and corn stover, and hence, the initial bulk porosity was the lowest. Upon tapping, switchgrass particles had less space to fill up the interspace voids and the bulk density increased slightly to reach the final tapped density.

The flowability of the biomass grinds with the same particle sizes was different by the results of the angle of repose [19]. This difference in flowability was attributed to different particle shapes and the forces between the particles. The moisture content of wheat straw, switchgrass, and corn stover after grinding was roughly between 5.1 and 8.7 % in this study. This suggests the capillary force acting on those biomass particles is within a close range, and moisture content did not show much effect on the cohesiveness of the grinds. Nzokou et al. (2005) report that lignin and extractive content on the wood surface affects the wettability and the Van der Waal's force between the particles [54]. It may further help to explain the effect of lignin and extractives content on different biomass flowability.

Table 2.3 Flowability chart of different agricultural biomass ground particles at different particle sizes; parenthesis shows the standard deviation with $n = 5$

Species	Switchgrass		Wheat straw		Corn stover	
Sieve opening (mm)	Angle of repose	Types of powder	Angle of repose	Types of powder	Angle of repose	Types of powder
0.707	35.56 (1.21)	Free flowing	43.05 (2.00)	Fair flow	43.57 (1.23)	Fair flow
0.5	38.60 (1.15)	Free flowing	45.80 (2.60)	Cohesive	45.40 (1.37)	Cohesive
0.354	39.82 (0.48)	Fair flow	47.53 (1.87)	Cohesive	45.64 (0.73)	Cohesive
0.25	43.03 (0.23)	Fair flow	47.44 (1.61)	Cohesive	46.12 (0.55)	Cohesive

Table 2.3 shows that corn stover and wheat straw have fair flowability at the largest particle size, while switchgrass shows the best overall free-flowing characteristics for all the particle sizes. The angle of repose of wheat straw and corn stover increases from 43° to 47° with decreasing particle size. The angle of repose of switchgrass increases from 36° to 43° with decreasing particle size. The classification of the powder type for the biomass grinds is based on the measured angle of repose [32]. Wheat straw and corn stover with particle size of 0.707 mm change from fair flow to cohesive with decreasing particle size of 0.25 mm. Switchgrass particles exhibit a free-flowing behavior for the particles with sizes of 0.5–0.707 mm, and the smaller particles with particle sizes of 0.25–0.354 mm have fair flow characteristics. These results should be due to difference in forces existing on the surfaces between the inter-particles.

2.3.2 Color, Moisture Content, and Calorific Value

The color and calorific value of untreated and thermally treated biomass can be correlated. For example, it was known that the calorific value of thermally treated biomass increases with the darkness (Fig. 2.4). For industries, development of efficient characterization tools using color as a parameter would benefit them in grading different products. For example, when the power generation utilities would like to check the fuel quality of each million ton batch of delivered biomass, they may prefer to have a quick fuel properties measurement instead of sending off many small randomly selected samples to the certified laboratory for fuel properties measurement (e.g., calorific value, moisture content, and hydrophobicity). As a result, the development of new characterization protocols and standards is needed to support the growth of the use of biomass for energy production.

Our recent work reported that a simple color measurement can quickly estimate the calorific value of the thermally treated biomass using the statistical multi-linear models [49]. It showed that correlation among color coordinates and compositional properties of treated biomass is strong and could potentially lead to the development of reliable instruments (Table 2.4). The typical multi-linear regression (MLR) was used to model responses of the three color components, i.e., L^* (whiteness or

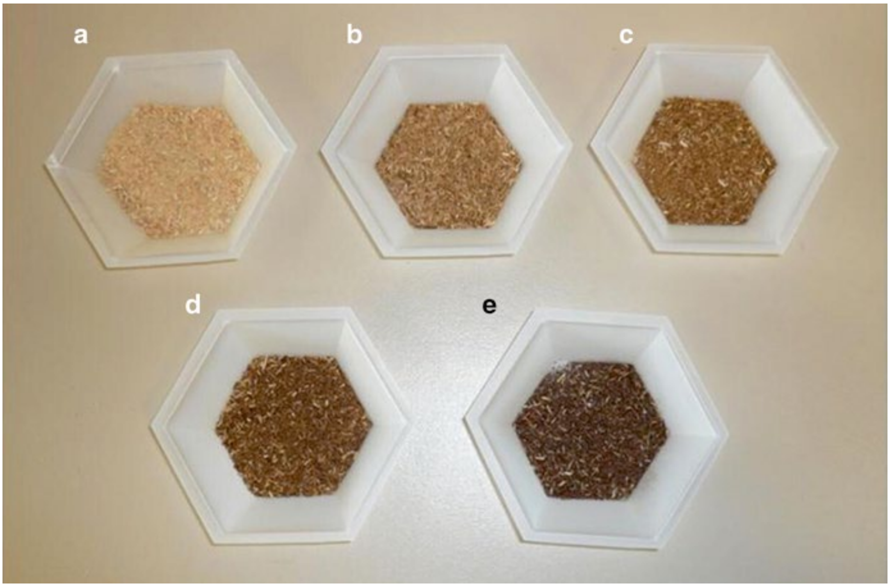

Fig. 2.4 Physical appearance of steam-exploded particles treated at different steam explosion conditions. From *left* to *right*: (**a**) untreated Douglas Fir; (**b**) 200°C, 5 min; (**c**) 200°C, 10 min; (**d**) 220°C, 5 min; (**e**) 220°C, 10 min. Reprinted with permission from Lam PS, Sokhansanj S, Bi XT, and Lim CJ.2012. Colorimetry applied to steam-treated biomass and pellets made from western Douglas fir (*Pseudotsuga menziesii* L.). *Transactions of the ASABE* 55(2): 673–678. St. Joseph, Mich.: ASABE

Table 2.4 Multi-linear regression equations (MLR) between color parameters, chemical composition, and elemental composition ($\alpha = 0.01$, number of replications = 2)[a]

	Equation parameters						
Dependent variable	Intercept	L^*	a^*	b^*	R^2	F-Value	p-Value
Elemental analysis with color parameter							
C	12.1038	1.2117	7.2308	−4.0882	0.97	261.06	<0.0001
H	0.0709	0.2654	1.602	−0.911	0.99	1093.07	<0.0001
O	−0.8498	0.0633	0.3755	−0.212	0.97	258.9	<0.0001
Chemical composition with color parameters							
Lignin	−252.71	8.5533	48.5518	−27.0467	0.97	210.67	<0.0001
Extractives	48.244	−0.6582	−3.7874	1.0474	0.99	660.38	<0.0001

[a] Reprinted with permission from Lam PS, Sokhansanj S, Bi XT, and Lim CJ.2012. Colorimetry applied to steam-treated biomass and pellets made from western Douglas fir (*Pseudotsuga menziesii* L.). *Transactions of the ASABE* 55(2): 673–678. St. Joseph, Mich.: ASABE

lightness), a^* (redness or greenness), and b^* (yellowness or blueness). MLR models were created from range-scaled factors of elemental composition, i.e., percentages of C and H of the untreated and steam-treated samples at different treatment temperature and time. By the use of range-scaled factors, differences in magnitude in

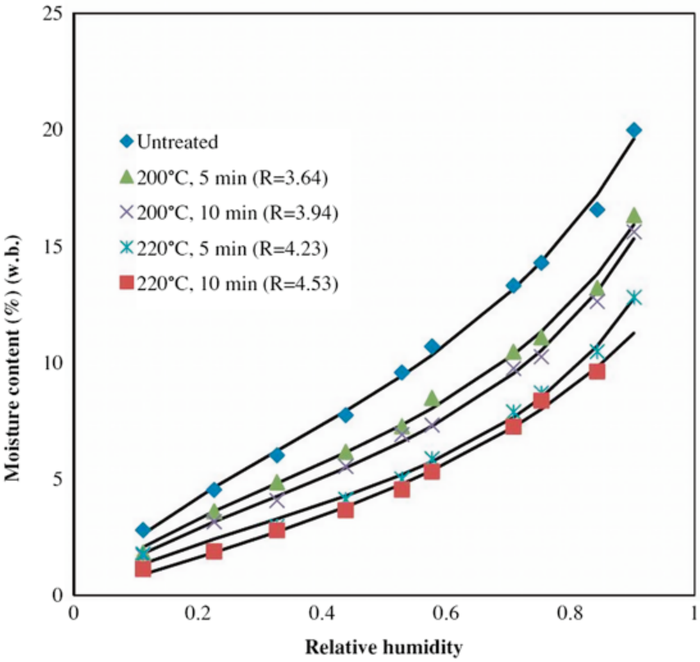

Fig. 2.5 Moisture sorption isotherms for untreated Douglas fir particles and steam-treated particles at different temperature and treatment time (solid lines show GAB model). Reprinted from Bioresource Technology, 116, Lam PS, Sokhansanj S, Bi XT, Jim Lim C, Larsson SH, Drying characteristics and equilibrium moisture content of steam-treated Douglas fir (*Pseudotsuga menziesii* L.), 7, Copyright 2012, with permission from Elsevier

the factors were extinguished when values were recalculated to range from −1 to +1. Thus, the sign of the modeled coefficients showed if the factors were negatively or positively correlated to the response. The magnitude of the modeled coefficients was equivalent to the impact that each factor had on the response. The MLR models were studied in the range between 200 °C, 5 min and 220 °C, 10 min:

$$\begin{aligned} y_i &= \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_p x_{ip} + \varepsilon_i \\ &\text{for } i = 1,2,\ldots,n \end{aligned} \tag{2.11}$$

where y_i are the measured responses, β_i are the estimated parameters of the population regression line x_i, p represents the independent variable of the ith measurement, and ε_i is the model deviation. Further research in this area will develop data on color versus material properties for a range of feedstock at varying moisture content, which appears to be a major confounding factor.

Apart from the correlation of color and calorific value, our recent research findings developed an equilibrium moisture content (EMC) database for steam-treated woody biomass both in ground particles and pellets [33]. It was found that the EMC of steam-treated samples decreased with increasing treatment temperature and time (Fig. 2.5). The Guggenheim-Anderson-de Boer (GAB) equilibrium model gave a close fit with the data with $R^2 = 0.99$. Up to now, there is a comprehensive database of moisture sorption database for woody biomass in the USDA handbook [55]. However, there is a lack of moisture sorption database for the thermally treated biomass at different severities (e.g., temperature and time) and using different thermal treatment methods. Future work should focus on the development of the moisture sorption database of thermally treated biomass to optimize the design of handling, storage, drying, grinding, pelletizing, and conversion units.

2.4 Summary

Biomass is a natural resource that exhibits heterogeneity in structure and chemical composition. A deep understanding of biomass physical properties and fast tools for characterizing these properties are required for the design and safe operation of processing facilities. Recent research on bulk density, particle size, and flowability of biomass particle showed that traditional sieve analysis cannot cover the measurement of all three dimensions of the particles and thereby could not correlate well with the packing and flowability data. Digital imaging techniques seem to be an advanced solution to capture more information from projected areas in all three dimensions. Fuel properties of lignocellulosic biomass could be quickly determined by a simple color measurement. The moisture sorption database of thermally treated lignocellulosic biomass is under development, and it will be highly useful and of interest to the power generation companies to replace coal with biomass as fuel for power generation.

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Chapter 3
Switchgrass and Giant Miscanthus Agronomy

D.K. Lee, Allen S. Parrish, and Thomas B. Voigt

Abstract Sustainable biomass feedstock production is the necessary first step for cellulosic biofuel and bioenergy production. Two species, switchgrass (*Panicum virgatum* L.) and giant miscanthus (*Miscanthus* × *giganteus*), are of interest as dedicated energy crops as both have great biomass production potential. Switchgrass, a perennial warm-season grass native to most of North America, has been evaluated for biomass feedstock production in many parts of world and shows promise as a productive feedstock with many environmental benefits. Giant miscanthus, also a perennial warm-season grass, originated in Japan and has recently been evaluated as a feedstock because of substantial biomass production. The management of these two crops is very different; switchgrass is propagated using seeds and giant miscanthus is a sterile hybrid that requires asexual propagation using either rhizomes or plugs. This chapter provides detailed practical information on establishment and post-establishment management for these two grasses as dedicated energy crops.

3.1 Introduction

According to the Billion Ton Update published in 2011, perennial grasses will provide a large portion of the biofuel used to reach the liquid transportation fuel goals in the USA because these plants meet the characteristics of ideal energy crops [1]. For example, Long [2] and Heaton et al. [3] wrote that ideal energy crops should be quick-growing; require low energy input versus energy output; use sunlight efficiently, through C4 photosynthesis; use water, nitrogen, and nutrients efficiently during growth and have low water content at harvest; require minimal cultivation

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Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4_3,

Fig. 3.1 Lowland-type switchgrass stand in August (*left*) and "Illinois"-type giant miscanthus stand (*right*) in September in Illinois

and pest-control inputs; should not be invasive; and be managed using existing agricultural equipment. Additionally, production and processing of ideal bioenergy feedstocks should generate less greenhouse gas than conventional fossil fuels and should neither compete with food production nor induce direct or indirect land-use change [4]. Finally, ideal energy crops should produce relatively large amounts of biomass on marginal lands or abandoned farms and have positive environmental effects on those settings [5, 6].

A number of perennial grasses have been identified as potential feedstocks. Switchgrass, giant miscanthus, energycane, reed canarygrass, giant reed, and US native grasses such as big bluestem, indiangrass, and prairie cordgrass are all being studied for potential use as bioenergy feedstocks. Of this group, warm-season grasses are generally desired for feedstock production in temperate, subtropical, and tropical regions. Warm-season grasses use the C4 photosynthesis mechanism which normally provides better heat and drought tolerance, as well as greater water- and nitrogen-use efficiency, compared to cool-season grasses. Two C4 grasses, switchgrass (*Panicum virgatum*) and giant miscanthus (*Miscanthus* × *giganteus*), are receiving the greatest attention in temperate areas (Fig. 3.1). In 2008 the US Department of Energy-Funded Sun Grant Regional Feedstock Partnership identified these two feedstocks, along with sorghum and energycane, for potential scale-up production [7].

In this chapter, we discuss the agronomy of switchgrass and giant miscanthus when grown for bioenergy production. Proper establishment, followed by proper management, is necessary for sustainable biomass production of perennial grasses.

Establishing both switchgrass and giant miscanthus, as well as other perennial grasses, is more challenging than establishing most annual row crops, but once established, long-term management is generally easier for the perennial crops.

3.2 Switchgrass

Switchgrass, a perennial, C4 grass, is a dominant member of North American tallgrass prairie. It has broad adaptation with great genotypic and phenotypic variation, and its range extends from Central America to southern Canada and from the eastern seaboard to Arizona and Nevada in the western USA [8–12]. It is a coarse grass, typically 0.5–3.0 m tall, with roots growing down to as deep as 3 m [8, 10]. Depending on its particular genetics, a switchgrass plant can produce short rhizomes that form tight bunches developing a plant with a bunch-type appearance or produce long, active rhizomes that form sod [13].

Switchgrass has been planted as streamside buffers, filter strips, wildlife habitats, and windbreaks for conservation. Shortly after it becomes established, the grass typically attracts wildlife, which can add recreational benefits to an area [14]. It can improve the environment and is also planted frequently in prairie restorations [11, 12, 15]. These restored sites help reduce soil erosion and remove toxins and excess nutrients that would otherwise run off into streams [14]. Switchgrass also helps rejuvenate the soil structure by adding organic matter through its extensive root system [14, 15].

Switchgrass has been used in the forage industry since the 1940s and is now a leading biofuel feedstock [16–19]. It is relatively easy to establish, is adapted to many environments, requires low-management inputs, and can be harvested with currently available equipment [20].

3.2.1 Cultivar Selection and Seed Quality

As in most plant production activities, the first step in establishing and sustainably producing switchgrass is the selection of the best cultivar for a region and climate. Switchgrass is widely distributed and well adapted to wide geographic regions in North America; its adaptation and performance are determined by the hardiness zone and latitude of its origin. Currently, many switchgrass cultivars are commercially available, and the adaptation of these cultivars covers wide geographic areas based on their origins (Fig. 3.2).

In general, moving switchgrasses that originate in the north to the south is not recommended because early floral initiation reduces biomass yields [21, 22], and in some cases, switchgrasses do not survive when moved from north to far southern locations [23]. Most of the switchgrasses that originate in the south are later-maturing cultivars that have higher yield potential than switchgrasses from northern areas

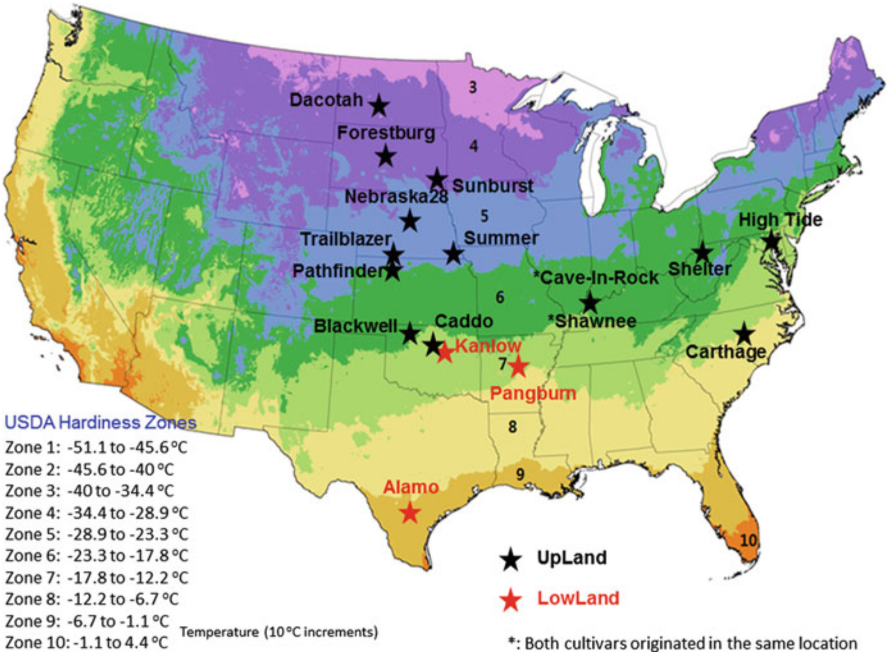

Fig. 3.2 USDA plant hardiness zones for 48 contiguous states in the USA (http://planthardiness.ars.usda.gov/PHZMWeb/Images/300DPI/SIMP_All_states_fullzones_300dpi.jpg) and the origins of commercially available switchgrass cultivars

[14, 24], but some southern cultivars are not well adapted to colder climates. In related research, several long-term studies found that switchgrass cultivars should not be moved more than one USDA hardiness zone north of their origin [11, 12, 21, 25], and Casler et al. [11, 12] also wrote that moving north or south from a switchgrass' origin (latitudinal movement) is much more critical than moving switchgrass between east and west.

When considering a cultivar for planting, producers should keep in mind the differences between lowland and upland switchgrass; upland ecotypes originate from Mexico to Canada and are more cold-tolerant and sod-forming, while lowland ecotypes originate from Mexico to Nebraska and are higher-yielding and bunch-forming grasses [25]. Lowland varieties tend to have better disease and drought resistance [22] and usually have greater yields due to tall, thick stems, two key characteristics of biomass productivity [25]. Moving a lowland cultivar that originates in southern regions to northern regions can immediately boost yields, as long as that cultivar has the winter hardiness to survive in colder climates [21].

The cultivars listed in the Fig. 3.2 are publicly available and have been developed for either forage production or conservation. With recent interest in cellulosic bioenergy, both public and private institutions are developing new cultivars that provide high biomass and energy yields such as the lowland types "EG 1102," "Performer," and "Cimarron" and "EG 2101," an upland type [26].

Fig. 3.3 Switchgrass stands during the establishment year show the importance of seed quality. The plots were planted with the same cultivar coming from different seed lots. A high-quality seed lot ensures seedling vigor and produces seedlings that outcompete annual weeds (*right side* of photo)

Switchgrass yields can vary based on the production region and ecotypes and cultivars grown. Based on a recent meta-analysis of 106 sites from 45 studies covering the eastern two-thirds of the USA and southeastern Canada, the average yield of upland and lowland switchgrasses across all regions was 6.6 ± 3 Mg ha^{-1} during the establishment year [27]. The second- and third-year biomass yields increased from 9.1 ± 5.5 to 10.9 ± 5.2 Mg ha^{-1}, respectively. During the post-establishment years, biomass yields of lowland ecotypes (11.1 ± 6.1 Mg ha^{-1}) were greater than for upland ecotypes (6.7 ± 3.2 Mg ha^{-1}). Among study sites, the highest yield (13.4 ± 4.5 Mg ha^{-1}) was observed in lower central regions (US hardiness zones 6 and 7) and the lowest yield (7.3 ± 3.1 Mg ha^{-1}) was observed in northern regions (US hardiness zones 3 and 4).

Switchgrass seed quality can be reduced by the presence of inert materials and weed and unviable seeds, which can affect seedling vigor and establishment speed. Seed quality tests that determine viability and purity should be examined before the seed is purchased to ensure the best-possible establishment (Fig. 3.3). Unlike soybean (*Glycine max* (L.) Merr.) or corn (*Zea mays* L.) seed, grass-seed quality and sales are based on percent Pure Live Seed (PLS), which is calculated by

PLS (%) = [% seed purity X % viable seed]/100; (% viable seed = % dormant seed + % germination) [28].

The laboratory-derived seed purity, viable seed, dormant seed, and germination percentages are available on the seed tag. It is important to note that the percent PLS information on seed tags can overestimate the percent of actual seed germination in the field because PLS calculations include hard, dormant seeds, which do not germinate immediately. For this reason, Mitchell and Vogel [29] suggest determining seeding rates based on the number of germinated or emerged seeds per gram of seed to reduce the risk of establishment failure.

Seed dormancy is a major factor in delayed seed germination and reduced seedling vigor and often results in poor establishment [20, 22]. Switchgrass seed dormancy is a natural mechanism for limiting the germination of late season-produced seed until the following spring, which normally improves seedling survival [30]. Postharvest ripening can naturally break seed dormancy. Vogel [31] reported that seed dormancy is greatly reduced when seed is stored for a year or more at room temperature, but viability will be decreased when seed is stored for more than 2 years at room temperature. Other methods used to break seed dormancy or increase germination, such as cold stratification or chemical treatments, are not recommended for general switchgrass production.

3.2.2 Establishment

Switchgrass can be grown in a wide variety of soil types and conditions, but performs best in well-drained soils with pH levels between 6.0 and 8.0, potassium levels of at least 200 kg ha^{-1}, and phosphorus levels of at least 22 kg ha^{-1} [14, 22]. Since switchgrass seed is small and field germination is slower than for many conventional crops, proper seeding depth, weed control, and seed-to-soil contact are all critical for successful switchgrass establishment [20]. Shallow seeding depth is critical for warm-season grass-seedling emergence [32]. To maximize seed germination, switchgrass seeds should be planted into a firm seedbed as planting in loose soil can result in seeds being planted too deeply, limit soil-to-seed contact, and ultimately result in a poor stand [14]. Switchgrass seed should be planted at depths between 5 and 20 mm in fine-textured soils and 30 mm in coarse-textured soils [14].

Proper field preparation is required to maximize seed germination and seedling growth and will vary depending on the previous crop and residue conditions. No-till planting into soybean stubble or fields with minimum residues provides the best opportunity for successful establishment, but planting into fields previously growing other crops can also be successful if the residue is incorporated and weed growth is prevented [33]. Fields with heavy surface residues, such as often occurs following maize, require tillage practices to incorporate residues. If tillage is needed to clean the soil surface, a cultipacker or roller should be used to firm the soil prior to planting. Planting switchgrass on land previously in sod or pasture requires controlling the existing vegetation and incorporating the heavy residue from aboveground vegetation and roots and rhizomes belowground. In this case, nonselective herbicides to control existing vegetation, along with tillage practices to control heavy surface and subsurface residues, are necessary.

One of the most important factors for successful switchgrass establishment is weed control. Weed competition in new switchgrass plantings can cause more establishment failures than in conventional crops. Poor establishment caused by weed pressure can delay full production of biomass for 2 or more years [34]. There are many ways to minimize weed pressure during the establishment year. Planting into a weed-free seedbed created by growing a herbicide-tolerant annual crop before planting the switchgrass will minimize the soil weed seed bank and provide an excellent seedbed. Frequently, perennial grass-seed germination is very slow, and seedling vigor is not as good as that of annual grass weeds. Therefore, planting high-quality seed in properly prepared seedbeds will produce seedlings able to compete with annual weeds (see Fig. 3.3). If a field is expected to have abundant weeds, planting should be delayed in spring until the first flush of weeds has emerged. After weed emergence, a broad-spectrum herbicide should be sprayed before planting the switchgrass.

Preemergence and postemergence herbicides are effective in controlling and reducing weed populations during the establishment year (Fig. 3.4). Broadleaf weeds are not considered a major impediment to switchgrass establishment, and several herbicides are very effective in controlling these weeds, but application should be delayed until the switchgrass seedlings have reached the four- or five-leaf stage [20]. A number of herbicides can be used to prevent and control early grassy weed growth. Many herbicides used in the forage industry will control weeds, but not all are labeled for switchgrass establishment, and consulting with local extension staff or professional advisors for additional information is recommended. In some environments, fields can be infested with weeds even though all recommended establishment practices have been followed. In these cases, mowing multiple times during the establishment year at a height slightly above the switchgrass foliage is recommended to keep the canopy open and reduce weed competition.

Switchgrass seed can be drilled or broadcast into prepared seedbeds. In seedbeds prepared using conventional tillage practices, either a drill or broadcast seeder with a cultipacker can be used. Many types of drills, such as grain drills with a small seedbox, native grass-seed drills, no-till drills, or conventional drills, can be used as long as the seeding rate and planting depth can be controlled. Drills should have proper closing wheels, and broadcast seedings should be followed by a cultipacker to ensure soil-to-seed contact. Broadcast seeding is not suitable in no-till seedbeds, killed pasture sod, or surfaces with heavy residues. In these cases, switchgrass seed should be drilled using a heavy no-till drill.

Optimum planting time for switchgrass is in the spring between the corn and soybean planting periods of the region [35, 36]. Switchgrass seed can germinate at soil temperature of 10 °C, but seed germination reaches a maximum between 20 and 30 °C, and seedling growth is optimal when soil temperature reaches above 20 °C [37–40]. Under optimum soil moisture and temperature conditions, switchgrass seed germination can begin 3–5 days after planting, but complete emergence can be delayed by more than a month given unfavorable soil conditions. In areas with regular spring droughts or flooding, or when being planted for conservation, dormant seeding in late fall/early winter can be used, provided soil temperatures are below typical germination temperatures and the seed can be incorporated into the seedbed.

The recommended seeding rate for switchgrass is 200–400 PLS m^{-2} [41]. The rate, however, can be reduced to 100 PLS m^{-2} depending on the seed quality and

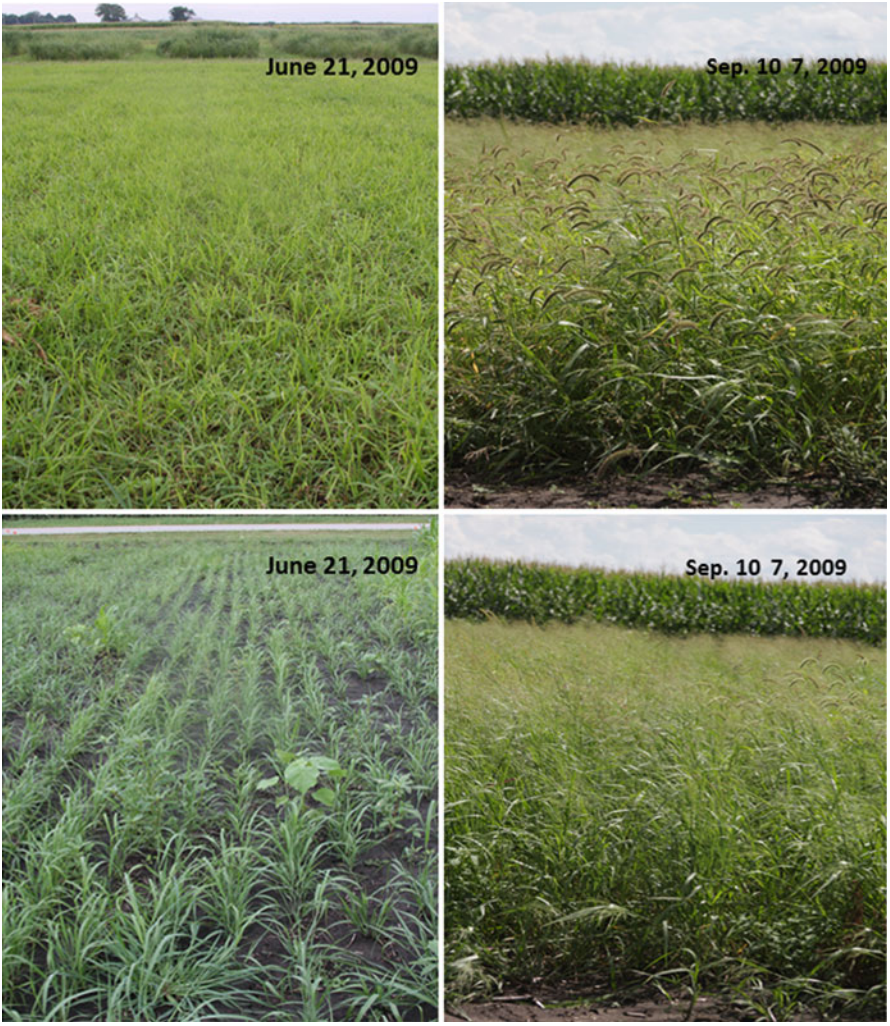

Fig. 3.4 Switchgrass stands after 2 months of planting (*left*) and at anthesis (*right*) during the establishment year, with (*bottom*) and without (*top*) preemergent herbicide

seedbed preparation [41]. Seeding rates ranging from 3 to 10 kg ha^{-1} are based on seed weight and quality [14, 15], and field seeding rates should be adjusted based on seed size and weight as well as PLS percentage, since switchgrass seed size and weight vary among ecotypes and cultivars [15]. A stand density of 20 plants m^{-2} is considered excellent, can produce harvestable biomass during the establishment year if weeds are controlled, and will typically reach full production in the second growing season. A density between 10 and 20 plants m^{-2} is considered adequate, but might require one or more seasons to reach full production. Poor stands have a density of less than 10 plants m^{-2} and should be overseeded or replanted [20].

3.2.3 Fertilization

Switchgrass can grow without fertilization in natural or conservation settings. However, the grass responds to fertilization, which can increase biomass yields [42–44]. During the establishment year, nitrogen (N) fertilization is not recommended, because switchgrass seedling growth is slow and annual weeds are better able to take advantage of the applied N [33]. Nitrogen fertilization during the seeding year may be recommended, however, if the field is relatively free of weeds and the switchgrass seedlings are not competing with weeds for N.

Post-establishment year N-management recommendations for switchgrass biomass production are determined by agronomic factors including yield goals, the production potential of the cultivars, soil conditions and fertility levels, the harvest timing and frequency, and the weather. In general, N-fertilizer application rates can be calculated based on N removal by switchgrass biomass. Nitrogen concentration in biomass harvested at flowering is approximately 1–2 %, and this concentration can be decreased by up to 0.5 % if harvest takes place after a killing frost [42, 44, 45] since a significant portion of the N is translocated into belowground biomass and recycled during the following season [13, 46]. Therefore, N applications can be made based on harvested biomass; when switchgrass is harvested for biomass after a killing frost, approximately 0.5 kg N ha^{-1} needs to be applied for each ovendry Mg ha^{-1} of harvested biomass. For example, a switchgrass biomass yield of 10 Mg ha^{-1} harvested after a killing frost removes 50 kg N ha^{-1} with a nitrogen concentration of 0.5 % in biomass. This fertilizer calculation should be adjusted based on soil test N and soil N-mineralization rates. Nitrogen fertilizers should be top-dressed in late spring when switchgrass is initiating growth.

There is limited information about switchgrass responses to phosphorus (P) and potassium (K) fertilization. Brejda [47] found that switchgrass may respond to P and K fertilization if available soil P and K are low. Continuous forage and hay production depletes soil P and K making P and K application necessary for long-term biomass production [47–51]. Additional research is needed to determine switchgrass responses to P and K application for long-term biomass production and annual removal of P and K in biomass. In general, when soil testing determines that P and K levels are low, these minerals should be applied before planting and incorporated into the soil. Following establishment, soil P and K should be continuously monitored to maintain recommended levels.

3.2.4 Harvest

Switchgrass harvest management for biofuel feedstock production is very different from that for hay and forage production where nutrient value is an important quality. Harvest timing and frequency of dedicated energy crops should be optimized for maximum sustainable biomass production and for year-round feedstock supply to conversion facilities. Switchgrass reaches a peak standing crop at flowering stage, and a single harvest at anthesis produces maximum biomass [42, 44, 52]. The quantity of switchgrass biomass continuously decreases until completion of senescence in late fall, and the yield losses range from 10 to 20 % depending on the growing regions and weather [44, 52]. Harvesting at peak standing crop unnecessarily removes nutrients and negatively impacts stand health and longevity [42]. In some cases, biomass can be harvested at peak standing crop to take advantage of high market prices or for emergency hay production. Flexible management, including extra N-fertilization or alternating harvesting timing, may be required to maintain stand health [42].

Even though delaying harvest reduces biomass yield, harvesting after a killing frost minimizes input costs, increases feedstock quality through nutrient recycling, and maximizes stand sustainability [14, 42]. Early harvesting has a negative impact on switchgrass stand and results in biomass with significantly higher N concentrations and ash content compared to biomass harvested after a killing frost. In general, the best harvest management practice for switchgrass is a single harvest following senescence, or several weeks after a killing frost, which allows N and other nutrients to translocate from the shoot into the belowground biomass for winter storage and promotion of new growth the following spring. There are several benefits of delaying biomass harvest until spring such as significant reduction of ash in biomass, improved wildlife habitats, capturing snow to add moisture to the root zone, and distribution of farm labor and storage facilities over winter. However, some biomass yield loss is expected when overwintering in the field. Moreover, the impact of weather on harvesting operations must also be considered as it may limit field accessibility due to severe weather conditions such as snow and floods.

Depending on the length of growing season and precipitation quantity and distribution, two harvests per season can be considered. However, a two-harvest system is not recommended unless two harvests produce significantly more biomass and compensate for the increased costs of two harvests.

Chapter 5 in this book discusses the harvesting operation, including the issues with machine design and operation. It is, however, important to note that many factors highlighted here will have an impact on the harvesting operations as discussed in Chap. 5.

3.3 Giant Miscanthus

The genus *Miscanthus* is comprised of 11–12 species, most of which are native to eastern and southeastern Asia [53]. Jones and Walsh [54] wrote that within the genus, *M. sinensis*, *M. sacchariflorus*, and *M.×giganteus* have the greatest potential for use as bioenergy crops. All three of these grasses have been planted as landscape ornamentals and are being considered for bioenergy production in the USA; in Asia, *M. sinensis* has been grazed in Japan [55] and *M. sacchariflorus* used by the cellulose industry in China [53]. This chapter will primarily focus on *M.×giganteus*.

Giant miscanthus (*Miscanthus* × *giganteus*) (Greef & Deuter ex Hodkinson & Renvoize) is a warm-season perennial grass originally collected in 1935 in Yokohama, Japan, that was then taken to Denmark where nurseryman Karl Foerster grew it for landscape use [56–58]. Originally, *M.* × *giganteus* was classified as a species with names such as *M. sinensis* "Giganteus," *M. giganteus*, or *M. ogiformis* Honda, or *M. sacchariflorus* var. *brevibarbis* (Honda) Adati [53]. Research subsequently conducted at the Royal Botanic Gardens in Kew, England, determined *M.* × *giganteus* to be a naturally occurring, sterile triploid hybrid of the diploid *M. sinensis* and the tetraploid *M sacchariflorus* [59].

The grass possesses several desirable traits, including high yields, drought tolerance, frost tolerance and low-temperature growth in established plants, relatively few pests and diseases along with good stress tolerance, and a positive energy input-to-output ratio [53]. Conversely, concerns with giant miscanthus include its need for asexual propagation, cold tolerance during the planting year, and variable biomass composition depending on harvest timing, growing environment, and nutrient inputs [53].

While it increases the cost of establishment, sterility in giant miscanthus is environmentally desirable because the grass has a low risk of invading and naturalizing in areas where it is unwanted. This differs from its fertile parents, *M. sinensis* and *M. sacchariflorus*. Both of these species have invaded portions of the eastern USA via seed spread, and because of its widespread horticultural landscape use, *M. sinensis* is of particular concern [60, 61].

Much of the bioenergy work in the USA employs the landscape clone of *M.* × *giganteus*, now commonly called the "Illinois" type due to the extensive research and production work conducted at the University of Illinois, Urbana-Champaign, using this grass. The original landscape-demonstration planting of *M.* × *giganteus* at the University of Illinois was made in 1988 from rhizomes obtained from the Chicago Botanic Garden (Glencoe, IL) [62]. Since the early 2000s, this planting has supplied giant miscanthus propagation material responsible for planting thousands of acres of the grass in the USA and Canada for both research and production.

Recently, there has been a great deal of interest in developing additional types of *Miscanthus* suitable for energy planting in order to increase biomass yields, reduce inputs, extend planting regions, and improve pest resistance [63]. For example, Repreve Renewables (Soperton, GA) markets a giant miscanthus, "Freedom," released by Mississippi State University researchers. Similarly, New Energy Farms (Leamington, Ontario, Canada) offers "Nagara" giant miscanthus and reports it to be extremely cold tolerant. Moreover, Mendel BioEnergy Seeds (Mendel Biotechnology, Hayward, CA) works with sterile forms of giant miscanthus and also with fertile *Miscanthus* spp. types capable of high biomass productivity. The fertile forms offer less expensive planting and establishment, but have the potential to become invasive via seed dispersal. At present, the seeded types are not commercially available. Finally, Ceres, Inc. (Thousand Oaks, CA) is working with the Institute of Biological, Environmental and Rural Sciences (IBERS) in Wales to also develop seeded *Miscanthus* spp. for bioenergy, as well as increase *Miscanthus* spp. genetic diversity and tolerance to harsh environments.

3.3.1 Giant Miscanthus Growth and Planting Sites

In central Illinois (approximately 40° N latitude), shoots typically emerge in April [62]. Giant miscanthus is able to commence growth and photosynthesize at cool temperatures; thus, it is able to take advantage of snowmelt and spring rainfall. Most years, it reaches 2 m by early June and continues to grow vegetatively through summer [62]. Peak biomass is produced in September, and the plants routinely flower in late September or early October, having grown to 3–4 m. At the onset of freezing temperatures, the plants senesce and begin dropping foliage. Harvest of the bamboo-like stems occurs in mid-December through late March following full senescence [62].

Several environmental criteria, especially water, soil, and temperature, need to be considered when selecting a site for giant miscanthus production. First, *M.* × *giganteus* responds to water. Annual precipitation and soil water retention need to be ample enough to support the growth of this large, herbaceous plant, and according to Richter et al. [64], available water may be the most limiting factor for giant miscanthus growth. In European field studies, it was shown that giant miscanthus required between 80 and 300 L of water to produce 1 kg of dry biomass. Beal et al. [65], Dressler [66], and McIsaac et al. [67] wrote that there was more soil moisture beneath switchgrass and maize-soybeans than beneath giant miscanthus, indicating a higher water-use rate. Furthermore, Beale and Long [68] and Mediavilla et al. [69] wrote that while giant miscanthus has a higher water-use efficiency than most C3 crops, the growth of giant miscanthus is often limited by water availability, even though roots can extend to approximately 2 m in the soil. This is supported in a report by Maughan et al. [71] in which the biomass yield of *M.* × *giganteus* produced in New Jersey was less in the third growing season than in the second growing season due to below-average precipitation, sandy soils, and a shallow root zone. Moreover, not all precipitation reaches the ground; Finch and Riche [72] found that approximately 20 % of the precipitation that fell between September and harvest evaporated from leaves and stems. Once established, drought can negatively impact biomass production, but the grass is normally able to survive dry periods and regrow acceptably the following season [70], as has occurred in portions of the eastern USA during portions of the 2010, 2011, and 2012 growing seasons. Without supplemental irrigation, the authors recommend planting "Illinois" type of giant miscanthus in sites that receive at least 75 cm of precipitation annually.

Miscanthus × *giganteus* is tolerant of soils ranging from organic soils to sandy soils [70]. Soils with pH ranging from 5.5 to 7.5 are recommended, and poor growth has occurred on soils having an alkaline pH of 8 and above [70]. Heaton et al. [73] recommend planting the grass on well-drained sites of medium to high fertility. Williams and Douglas [74] recommend planting giant miscanthus on USDA NRCS capability class I and II soils for best production with fewest inputs. While giant miscanthus can grow on heavy, clay soils, it is important to consider the typical soil conditions during winter harvest when wet, unfrozen sites may limit access [75]. Following planting, it commonly takes at least 3 years to reach full establishment

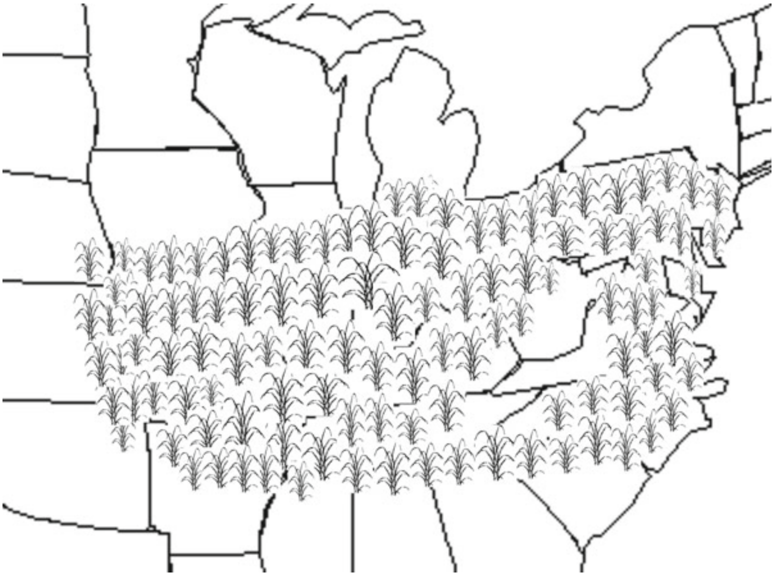

Fig. 3.5 Proposed US growing region for "Illinois" type of *Miscanthus × giganteus*. It is intended to identify areas suited to growing this grass. Additional feedstocks may also grow well and be productive in this region

and biomass production [62], but soils of low fertility can lengthen the time required to reach full establishment by several growing seasons.

For a C4 species, established *M.× giganteus* plants are extremely cold tolerant, but winterkill of first-year plantings has occurred in the Midwestern USA [71, 76]. Clifton-Brown and Lewandowski [77] reported that 50 % of newly planted rhizomes can be killed by soil temperatures of −3.4 °C at the 5-cm level. Established plants, however, have survived air temperatures lower than −20 °C in central Illinois [62]. Conversely, biomass production in subtropical settings can be limited by early flowering that restricts vegetative growth. Because it is capable of photosynthesizing optimally at cool temperatures above 12 °C [78], giant miscanthus not only begins growth in the spring earlier than many other warm-season grasses, but is also able to continue growth into the late summer and early autumn, again past the time when many other C4 grasses have ceased growth for the year [79]. The early start and late finish contribute to its annual productivity. Thus, the authors believe this crop is best planted in temperate regions.

Given the concerns about cold tolerance in first-year plantings, the water requirements for productive growth, and the productivity of other feedstocks, the authors propose that the commonly planted clonal form of giant miscanthus, the "Illinois" type, is best produced in the central region of the eastern USA (Fig. 3.5). In areas to the south of this region, feedstocks such as some lowland switchgrass varieties, energycane (*Saccharum* spp.), and napier grass (*Pennisetum purpureum*) are likely to be better suited and more productive than giant miscanthus. Areas to the west of

Fig. 3.6 A clump of freshly dug giant miscanthus rhizomes in sorting

the region lack the precipitation necessary for optimal "Illinois" giant miscanthus production, and adapted lowland and upland switchgrass varieties will probably be better producers. Finally, while giant miscanthus can survive in many areas north of this region, cold damage to first-year plantings is a potential problem. Because the crop is relatively expensive to plant and establish, stand losses are difficult to tolerate. Upland switchgrass varieties, poplar, and willow may be better choices in these environments. In the future, the region for producing *Miscanthus* spp. will probably be expanded as breeders develop improved germplasm that is capable of high biomass productivity in drier and colder regions.

3.3.2 Propagating and Establishing Giant Miscanthus

Current propagation practices in the USA employ rhizome (underground stems; Fig. 3.6) divisions for direct planting or for plug (containers of small diameter having variable depths) production. Tissue culture or micropropagation has been used to propagate giant miscanthus with some favorable results, but winter survival was better in rhizome-propagated plants than in tissue culture-produced plantlets and any growth advantages over rhizome propagation were lost as the plants matured [80]. Pyter et al. [81] found that planting rhizomes of 50–60 g at approximately 10 cm worked well. University of Illinois, Urbana-Champaign experiences have shown, however, that mechanical harvesting rarely produces rhizomes of that large size, and rhizomes of 15–25 g more often occur. The smaller-sized rhizomes can work well, provided they are fresh or have been stored properly under moist conditions at temperatures of 4 °C [81]. Plugs should be planted so that the soil level at the planting site is at approximately the same level as the soil in the container. Rhizomes have commonly been planted at densities of 1–4 m^{-1} [57]. Currently, University of Illinois, Urbana-Champaign, stands are planted at approximately 17,200 plugs or rhizomes per hectare (approximately 76 cm between rows and 76 cm between rhizomes or plugs within a row) because this density works well with existing farm equipment and surrounding plants can fill planting skips more readily than when using larger spacing. Attempts to replant skips with rhizomes or small potted plants during the second and third growing seasons have had limited success, as well as being labor intensive (authors' observations).

Planting sites are commonly rotary tilled to a depth of approximately 15 cm prior to planting rhizomes or plugs. In temperate regions, it is recommended that rhizomes and plugs be planted in early-to-mid spring. In the University of Illinois, Urbana-Champaign, research and production fields, four-row planters, similar to types used to transplant nursery or vegetable transplants, are used, which allows 2.4–3.2 ha per day to be planted and requires five or six laborers. Currently, there are several different commercial planters used in the USA and Europe that allow 12 or more hectares to be planted per day and require fewer laborers. Herbicides are necessary during the planting season and often during the second year. Harness (acetochlor) and Harness Xtra (acetochlor + atrazine), both produced by Monsanto Company (St. Louis, MO), are labeled for grass control in *M.* × *giganteus* grown for bioenergy. Broadleaf weeds are commonly controlled using 2,4-D. Additional chemical weed controls have been successfully tested [82], but have not been labeled for application to this crop.

3.3.3 Managing Established Giant Miscanthus

Managing established giant miscanthus is relatively easy due to the minimal inputs it requires—in many years, the only necessary management activity in established giant miscanthus occurs when the grass is harvested. First, while giant miscanthus responds to moisture, it is the authors' opinions that energy crops should be produced without irrigation. Irrigation adds a production expense and also uses a resource perhaps better used for human consumption or livestock and food crop production. As a C4 grass, *M.* × *giganteus* is drought tolerant once established, but production is commonly limited by water availability. Next, established giant miscanthus grows rapidly and develops a closed canopy early in the season, making it extremely competitive with weeds, which typically makes chemical weed controls unnecessary after the second growing season. In addition, while US researchers have identified several potential insect, disease, and virus problems on giant miscanthus [83–87], none of the identified pests have been shown to reduce biomass production. Moreover, there have not been reports of significant pest problems on commercially produced *M.* × *giganteus* in Europe.

Nitrogen has been the primary mineral nutrient examined in fertilization studies of *M.×giganteus* in both Europe and the USA, usually without showing a response [71, 88, 89, 90]. The lack of N response in most cases was attributed to adequate natural soil fertility. Clifton-Brown et al. [91] showed an inconsistent N response over several years and attributed this to climatic effects. In Italy, Ecroli et al. [92] reported a yield response to N in an irrigated fourth-year planting of giant miscanthus. Finally, Arundale [93] saw an N response in mature (after growing season 6) *M.×giganteus* in Illinois. It is likely that *M.×giganteus* will respond to fertilization in some locations or after a period of productive growth. In these situations, fertilizer applications will need to be adjusted based on local testing and future experiences.

3.3.4 Harvesting Giant Miscanthus

In the Midwestern USA, *M.×giganteus* is usually harvested during the winter and early spring (mid-December through late March) following full senescence and prior to the onset of spring emergence. European researchers have recommended harvesting in spring immediately prior to emergence because the biomass is drier, an advantage when it is combusted [89]. Harvest yields will typically be less in March than in December due to leaf loss and stem drying [94], and moisture in giant miscanthus biomass in Illinois dropped from approximately 50 % in October to less than 10 % in February [73]. Finally, in another Illinois study, Parrish [95] reported that over three growing seasons, harvesting established giant miscanthus before December resulted in stand decline, even when the grass was supplemented with variable rates of nitrogen fertilizer.

Giant miscanthus can be harvested using modern agricultural equipment used for harvesting hay, although the operation is usually slower due to crop density and stem toughness [63, 76]. Either a combination of mower/conditioners plus balers or forage choppers can be used [74, 76]. Both rectangular and round bales are used. Rectangular bales can be easier to stack and move, while round bales may shed moisture better. Regardless of the shape, bales should be packed tightly to reduce the number of bales transported and maximize loads, ease stacking, and reduce the storage area required [75]. If kept dry, bales of giant miscanthus can be stored for at least 3 years without deterioration (authors' observation).

A benefit of harvesting giant miscanthus with forage choppers is that for nearly all applications, the biomass will need to be chopped prior to use. Harvesting with forage choppers thus eliminates a step at the processing plant. Conversely, chopped biomass can be very expensive to transport for even relatively short distances due to a lack of density. Moisture levels for both baled and chopped giant miscanthus should be 20 % or less to avoid heating and ensure safe storage [75].

Chapters 5 and 6 discuss the harvesting and transportation issues in detail. The reader can find detailed comparisons of different harvesting options, machinery requirement, and machinery performance in those chapters.

Table 3.1 *Miscanthus × giganteus* yields (dry Mg ha^{-1}) from published and unpublished sources in the eastern USA

Site	Year	Age of stand (yr)	Yield (dry Mg ha^{-1})	Study
Dekalb, IL (north)	2004–2011	3–5	16.3	Heaton et al. [94][a]
Urbana, IL (central)	2004–2011	3–5	31.1	Heaton et al. [94][a]
Dixon Springs, IL (south)	2004–2011	3–5	30.0	Heaton et al. [94][a]
Booneville, AK	2005	2	5.9	Adapted from Burner et al. [96]
Troy, KS	2007	2	13.7	Propheter et al. [97][b]
Manhattan, KS	2007	2	11.8	Propheter et al. [97][b]
Gainesville, FL	2009	2	6.2	Sollenberger et al. [98]
Ona, FL	2009	2	4.5	Sollenberger et al. [98]
Belle Glade, FL	2009	2	10.8	Sollenberger et al. [98]
Urbana, IL	2009–2011	2–4	13.1	Maughan et al. [71][c]
Lexington, KY	2009–2011	2–4	18.4	Maughan et al. [71][c]
Mead, NE	2009–2011	2–4	24.7	Maughan et al. [71][c]
Adelphia, NJ	2009–2011	2–4	15.1	Maughan et al. [71][c]
Gretna, VA	2011	2	9.4	Maughan et al. [71][c]

[a] Yields are the average of four replicates at each site. *Miscanthus × giganteus* was not fertilized. Yield averages include unpublished 2007–2011 production

[b] Variably fertilized in both 2007 and 2008

[c] Yields are the average of plots treated with three nitrogen levels (0, 60, 120 kg N ha^{-1} year^{-1}) at each site. Yield averages include unpublished 2011 production

3.3.5 Giant Miscanthus Biomass Productivity

Whether produced for liquid transportation fuel or heat and electricity, yield is a critical consideration when selecting a biomass feedstock. The high yields of giant miscanthus, when grown in appropriate environments, make it an important energy crop, and several European studies have reported yields. Dry biomass yields ranged from 4 Mg ha^{-1} for a 3–4-year-old stand in Central Germany that was harvested in December and received 80 kg N ha^{-1} year^{-1} to 44 Mg ha^{-1} for a 2-year-old stand in Northern Greece that was harvested in September and received fertilizer and frequent irrigation in a 1990s study that reported yields from more than 15 European locations [57]. Over all locations, the sites averaged 2.8 growing seasons in age and averaged 15.3 dry Mg ha^{-1} biomass production [57]. In Rothamsted, England, Christian et al. [88] found that giant miscanthus grown for 14 seasons averaged 12.8 Mg ha^{-1} annually in a long-term study. Of interest in this study is that there were no significant yield differences among treatments when the giant miscanthus received three levels of N fertilizer (0, 60, and 120 kg ha^{-1} year^{-1}). In a final European study, Richter et al. [64] reported that harvested yields of giant miscanthus that had been established for a minimum of 3 years averaged 12.8 Mg ha^{-1} at 14 sites across the UK.

Researchers in the USA have only been studying *M. × giganteus* since the early 2000s, and results of these studies indicate that yields in the eastern USA have generally been greater than those in northern Europe (Table 3.1). This is probably due to the longer growing seasons in US areas where giant miscanthus has been produced compared to the length of the European growing seasons. Published yields of giant miscanthus ranged from 4.5 dry Mg ha^{-1} for a second-year planting in Ona, Florida, compared to an annual average yield of 31.1 dry Mg ha^{-1} over the third through tenth growing seasons in central Illinois (see Table 3.1). Several of these plantings are in long-term ongoing studies, and future productivity should be monitored. Moreover, as additional studies take place, selecting optimal growing regions for giant miscanthus should result in increased yields.

3.4 The Future

At the time of this writing, both switchgrass and giant miscanthus are being commercially produced as biomass feedstocks in the USA due to productivity and site adaptability, and the future looks even brighter for both plants. Ongoing and future research will likely make inroads into improved understanding of the biology and management of these grasses and result in improved yields, probably with reduced inputs. For example, because of its diverse genetic background and long-termed use as a pasture/forage crop, switchgrass has benefited from the availability of various commercially available pest controls and management equipment along with, most importantly, breeding improvements. Establishment efficiency and yields of modern switchgrass cultivars are significantly better than those of the best-available cultivars of only 10 years ago.

Miscanthus × *giganteus* is a more recent addition to the feedstock palette, with only a relatively small number of researchers studying the grass at a handful of US sites in 2005. As of 2013, many more researchers have contributed findings that have improved giant miscanthus agronomy, as well as our understanding of where it is best produced and of its genetic complexities. Where it is well adapted in the central USA, for example, the unimproved “Illinois” type of giant miscanthus has been quite productive and outproduced upland switchgrasses. As with switchgrass, future giant miscanthus research will focus on improving pest controls and management equipment and also on breeding for improved productivity in diverse environmental settings with limited inputs.

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Chapter 4
Preharvest Monitoring of Biomass Production

Liujun Li, Lei Tian, and Tofael Ahamed

Abstract Preharvest monitoring of biomass production is necessary to develop optimized instrumentation and data processing systems for crop growth, health, and stress monitoring and to develop algorithms for field operation scheduling. Some research questions of specific interest are as follows: (1) What are the major crop sensing needs for energy crop health monitoring and productivity improvement? (2) Which sensor/platform should be used for the field data collection? (3) What is the best process for energy crop data-to-knowledge conversion? In this chapter, we first review the basics of remote sensing and its application to energy crops. We then discuss the development of three near-real-time remote sensing systems, namely, a stand-alone tower-based remote sensing system, close proximity data collection vehicle, and an unmanned aerial vehicle-based remote sensing system to monitor crop growth. The physical status of crop growth and biomass accumulation was projected over the growing seasons. The remote sensing systems included multispectral camera, light detection and ranging (LIDAR), and a global position system sensor. The sensing systems were convenient to perform site-specific monitoring of bioenergy crops and collect data in near real time including ground reference information. These nondestructive measurements included bioenergy crop growth monitoring using typical vegetation index and estimation of biomass yield by correlating it with suitable vegetation index. The field experimental data has been presented to correlate with remote sensing data. To understand the crop growth status over the growing season, the remote sensing data could be correlated with ground truth data to develop a model for predicting dry matter biomass.

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Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4_4,

4.1 Introduction

Remote sensing technology has been recognized as the key technology to enable site-specific management of crop production. Researchers have developed precision agricultural technologies and processes that have enhanced agricultural production in traditional crops like corn and soybeans. The same methodology has been applied to the production of energy crops to maximize biomass feedstock production (BFP) throughout the world. "BFP is a critical subsystem within the overall bio-based energy production and utilization system. It provides necessary materials input to the conversion process of biomass into fuel, power, and value-added materials. This subsystem includes the operations of agronomic production of energy crops and physical handling/delivery of biomass, as well as other enabling logistics [1]." As concerns over energy security and environmental degradation have risen, ensuring sustainable biomass and biofuel production has become critical. Here, there are potentially important applications of remote sensing in ensuring that the desired objectives are met, which will ultimately lead to a sustainable bioenergy system.

The agronomic production depends on tracking the yield variability over the growing season and utilizing the optimum harvesting window to meet quantity and quality targets. The measurement of yield variability of biomass is needed for developing and evaluating site-specific crop management (SSCM) practices. In different growth stages, field spectroscopy has the fundamental importance for assessing spectral response of plant canopies and photosynthetically active radiation for biomass conversion. Therefore, multispectral imagery of preharvesting monitoring is the key point to understand crop response in remote sensing applications. Field spectroscopy involves the study of interrelationships between the spectral characteristics of objects and their biophysical attributes in the field environment. Firstly, it acts as a bridge between the laboratory measurements of spectral reflectance and the field situation and is useful in calibration of airborne and satellite sensors. Secondly, it is useful in predicting the optimum spectral bands viewing configuration and time to perform a particular remote sensing task. Thirdly, it provides a tool for the development, refinement, and testing of models relating biophysical attributes to remotely sensed data [2]. The multispectral imagery refers to images that capture data at specific wavelengths across the electromagnetic spectrum. The wavelengths may be separated by filters or by the use of instruments that are sensitive to particular wavelengths, including light from frequencies beyond the visible light range, such as infrared. Multispectral imagery can allow extraction of information from spectral response that the human eye fails to capture with its receptors for red, green, and blue. The relationships between crop reflectance in the visible and near-infrared wavelength are closely correlated with the amount of photosynthetically active tissue in the crop [3]. Currently, aerial hyperspectral and multispectral images are available for agricultural remote sensing to find nitrogen stress and mapping [4–7]. The most widely accepted method for describing vegetative growth using reflectance spectra is band ratio or vegetation indices. Vegetation indices are spectrally based values generated through the mathematical manipulation of reflectance measurements from two or more spectral wavelengths [8]. The vegetation index is used

Fig. 4.1 Miscanthus growth height variation during different growing seasons

to quantify the concentrations of green leaf vegetation [9]. Linear combination from two or more wave bands may be more sensitive and robust to assess the crop status than a single band [10]. Generally, vegetation index can be divided into broadband indices and narrowband indices according to the bandwidth of image data. The broadband indices are calculated based on broadband reflectance data, and the narrowband indices are calculated using narrow spectral bands acquired by a spectrometer or a hyperspectral image sensor [11]. There are more than 20 broadband vegetation indices that have been designed to represent different crop information from remote sensing images [12]. The Normalized Difference Vegetation Index (NDVI) is the most commonly used vegetation index, and Gitelson et al. proposed the Green Normalized Difference Vegetation Index (GNDVI), which substituted the red band in the NDVI with the green band [13]. The GNDVI proves to be more useful for assessing canopy variation in green crop biomass. The vegetation indices are the indicators from reflectance measurements and could be used to correlate with dry matter estimation for perennial grasses. One of the potential biomass crops is Miscanthus, which is a high yielding, perennial crop with good resistance against disease, cold, and drought. To ensure proper growth of Miscanthus, it is essential to know the plant stress, fertilization timing, physical parameters, and soil environment. Chapter 3 described the crop properties and also highlighted how these factors impact the successful establishment of a stable, high yielding stand. It is also important to monitor and observe these parameters over the growing season. Miscanthus grows higher and denser as the growing season progresses. As indicated in Fig. 4.1, a 2-month-old stand of Miscanthus grows faster, and the height of these plants is approximately 50 cm. The 3-year-old stand of Miscanthus grows up to 3 m high [14]. However, data acquisition is difficult due to lack of high clearance vehicle operating as on-the-go sensing system for Miscanthus and other biomass feedstock. Furthermore, the preharvest monitoring systems need to be able to fulfill data collection in different traffic conditions with high maneuverability, stability, and mobility for either high plants and short plants or different bioenergy crop plants in all growing seasons. There is a need to develop optimized instrumentations for stand-alone remote sensing applications to monitor perennial growth of biomass feedstock over the growing season as well as a specially designed close proximity data collection vehicle and an unmanned aerial vehicle (UAV)-based near-real-time remote sensing system. However, preharvest monitoring of biomass crops has not been widely done. This chapter emphasizes the description of three platforms recently developed specifically for monitoring the production of energy crops.

4.2 Remote Sensing and Its Application

Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation [15]. Herein, the art refers to technology, instruments, methods, software, skill, personal knowledge, and expertise.

There are three broad categories of applications: (1) Photogrammetric analyses use remote-sensed data to provide spatial measurements of a feature or a phenomena (e.g., distance, area, volume), (2) classification analyses identify and map areas with similar characteristics (e.g., classify land cover into categories using image analysis software tools), and (3) quantitative analyses provide estimates of earth surface properties (e.g., vegetation index to measure plant biomass). There are many ways remote sensing systems are used, some of which are mentioned here: (1) cartography and mapping; (2) natural resource management; (3) disaster management (fire, earthquakes, etc.); (3) geostationary weather monitoring; (4) sea ice, oil spill, sea surface temperature monitoring; (5) atmospheric (water vapor, ozone, etc.) monitoring; and (6) data for Geographic Information Systems (GIS) [16–18].

In precision agriculture, NDVI is widely used to predict crop leaf area index, crop growth and disease control, biomass productivity, economic yield, etc. NDVI is a very useful application of spectral ratio. This index relies on the spectral absorption and reflectance characteristics of living (i.e., green) vegetation in primarily the red and NIR wavelength bands. As illustrated in Fig. 4.2, NDVI is calculated as follows [19]:

$$NDVI = \frac{\rho(NIR) - \rho(Red)}{\rho(NIR) + \rho(Red)} \tag{4.1}$$

where ρ(NIR) = brightness values (or digital number) of near-infrared band and ρ(Red) = brightness values (or digital number) of red band in a remote sensing dataset.

The remote sensing technology has been widely used to provide image, information, as well as decision support for precision agriculture (PA) or SSCM since the first aerial photos were used as a basis for soil mapping, which began in the late 1930s with the advent of aerial photography [20–22]. SSCM is the management of

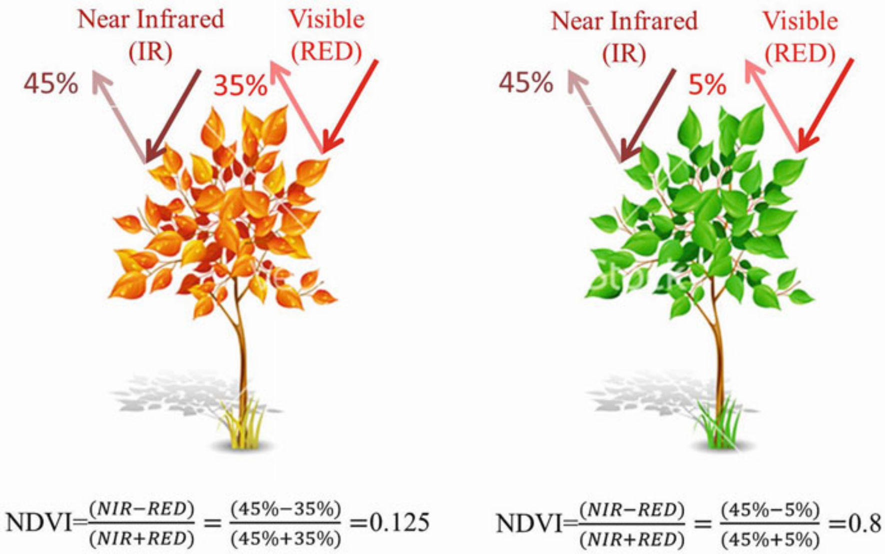

Fig. 4.2 NDVI concept for vigor variation quantification

the crop at a spatial scale less than that of the entire field. Precision agriculture is the use of information technology to achieve SSCM. Remote sensing is an efficient way of mapping and monitoring the crop and soil variability as well as the effects of any condition that affects health, yield, or quality of a crop. The imagery can be applied to monitor within/between field variability, map soil variations, investigate crop management practices, detect and map weed and pest infestations, optimize crop inputs, and pasture growth rate. As illustrated in Fig. 4.3, a typical example of remote sensing technology application is that the NDVI map was considered as the basis to generate prescription map for variable-rate fertilizer application combined with the historical yield map and then resulted in an improved yield [23].

4.3 Remote Sensing Platforms

Remote sensing data acquisition can be conducted on such platforms as aircraft, satellites, balloons, rockets, and space shuttles. Inside or onboard these platforms, we use sensors to collect data. Sensors include aerial photographic cameras and non-photographic instruments, such as radiometers, electro-optical scanners, and radar systems. There are mainly three types of platform used for remote sensing [17]:

1. Satellite remote sensing
2. Airborne remote sensing
3. Near-real-time remote sensing

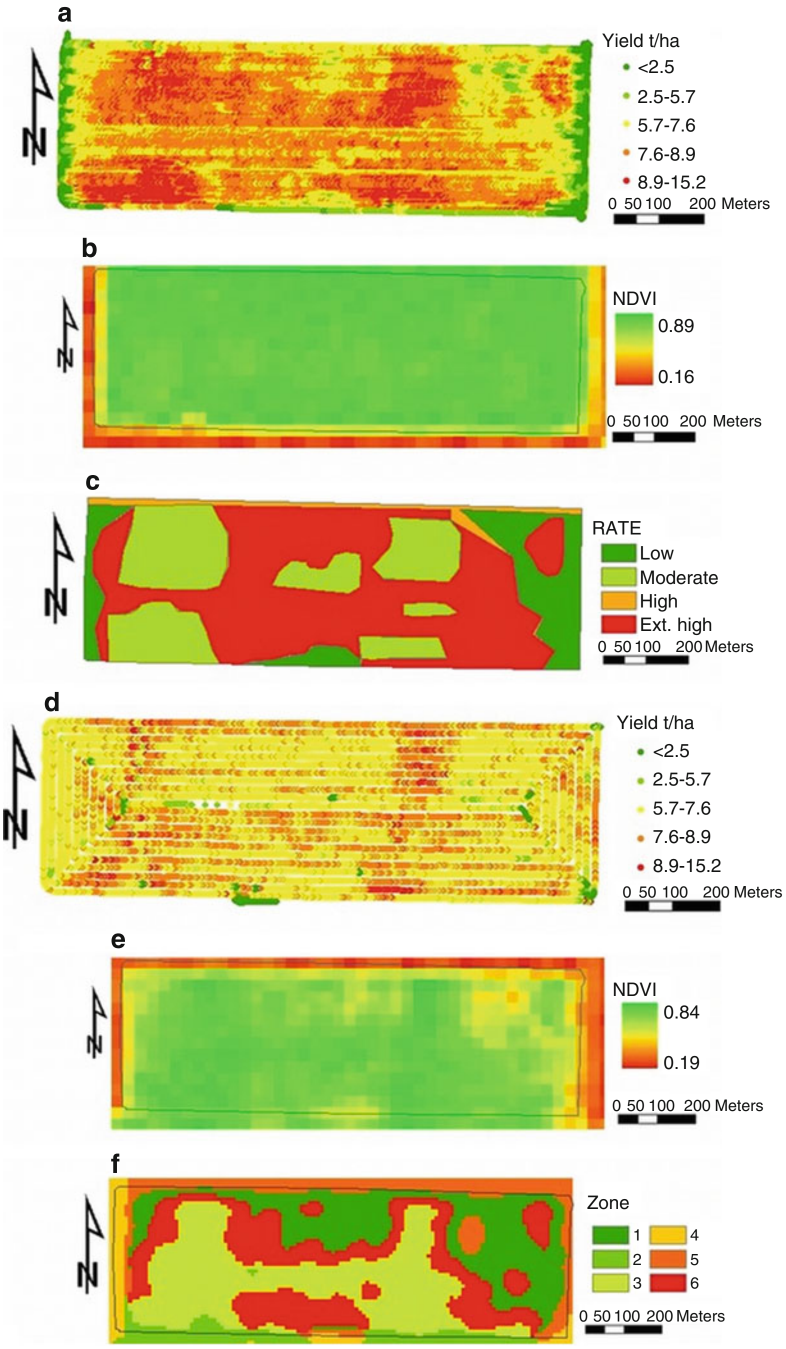

Fig. 4.3 An example of remote sensing application for precision agriculture. (**a**) Historical yield map of corn in 2003. (**b**) NDVI map by Landsat of 2004. (**c**) Zone map of variable-rate fertilizer application. (**d**) Improved resulting yield in 2005. (**e**) Corresponding NDVI map by Landsat of 2003. (**f**) Zone map when the yield data of 2003 is replaced with NDVI data of 2003. Courtesy of Xiaodong Zhang, PhD

The user needs and their required resolution are critical factors in determining the remote sensing platform and data. To decide the right platform, there are four key resolution issues involved in the decision process [23]:

1. Spatial resolution: How small an object do you need to see (pixel size) and how large an area do you need to cover (swath width)?
2. Spectral resolution: What part of the spectrum do you want to measure?
3. Radiometric resolution: How finely do you need to quantify the data?
4. Temporal resolution: How often do you need to look at it?

4.4 Satellite Remote Sensing

Satellite remote sensing is used to obtain remote sensing images with sensors on earth observation satellites looking down to the earth. They are the “eyes in the sky” constantly observing the earth as they go around in the orbits. There are various government and commercial satellites applied to generate the images of the earth by different sensors with different spectral and spatial resolutions depending on the intended use of the images the sensors generate. Again, some commercial satellites (those operated by a satellite/remote sensing company rather than a government agency) offer very high-resolution imagery (at a correspondingly very high price!) that look almost exactly the same as an aerial image—but don’t require a plane or a pilot. The company takes an order, points their sensor in the right direction, and snaps an image, but this increases the cost significantly [16, 17, 25].

The advantages of satellite remote sensing are (1) global dataset of uniform quality, (2) rapid data acquisition of large area, (3) no need to obtain permission to gather data, (4) can revisit on a regular basis for lifetime of satellite (5–10 years), and (5) spacecraft provides stable platforms. The disadvantages of satellite remote sensing are (1) high cost of satellite systems; (2) takes more than 10 years to develop, build, test, and launch; (3) possibility of single point failure; (4) relatively coarser spatial resolution; (5) longer cycle period, usually 14 days; (6) large measurement uncertainty; and (7) require extensive processing as well as storage and analysis [20].

4.5 Airborne Image-Based Remote Sensing

Airborne remote sensing is common to obtain images of the earth’s surface with downward- or sideward-looking sensors mounted on an aircraft as indicated in Fig. 4.4a [26]. The advantage of airborne remote sensing, compared to satellite remote sensing, is the capability of offering very high spatial resolution images (20 cm or less) after geo-referencing, as illustrated in Fig. 4.4b. The disadvantages are low coverage area and high cost per unit area of ground coverage. It is not cost-effective to map a large area using an airborne remote sensing system. Airborne remote sensing missions are often carried out as one-time operations, whereas earth observation satellites offer the possibility of continuous monitoring of the earth.

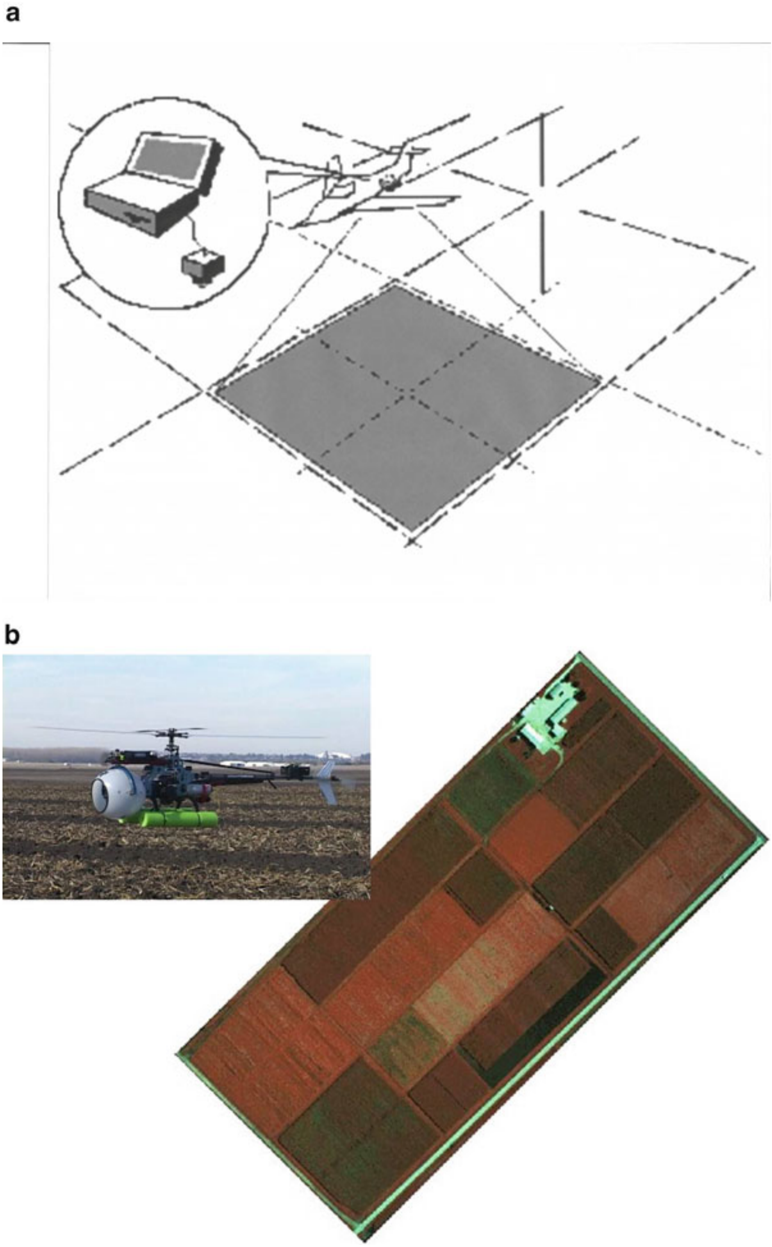

Fig. 4.4 Airborne remote sensing principle and application. (**a**) Airborne remote sensing platform. (**b**) Airborne remote sensing application in agriculture

4.6 Near-Real-Time Remote Sensing

Satellites and piloted aircraft-based remote sensing systems are the two major platforms that have been commonly used to collect remote sensing image data. Current limitations for the conventional image-based remote sensing platforms are due mainly to coarse spatial resolution, slow turnaround time, inadequate repeat coverage, and high cost [20, 21, 27]. Most importantly, since agriculture is very dynamic, remote sensing data must reach the farmer in near real time. However, this is rarely the case now [28]. Sawyer et al. also pointed out that the biggest difficulty in implementing variable-rate technology (VRT) is the lack of a reliable and consistent method of obtaining spatial and temporal variability data from a field [29]. To deal with the problems that exist in current remote sensing platforms for biomass preharvest monitoring, near-real-time remote sensing is necessary and subsequently needs to develop site-specific monitoring for biomass energy crops.

As indicated in Fig. 4.5, three near-real-time site-specific remote sensing systems for biomass preharvest monitoring are possible: (1) stand-alone tower-based

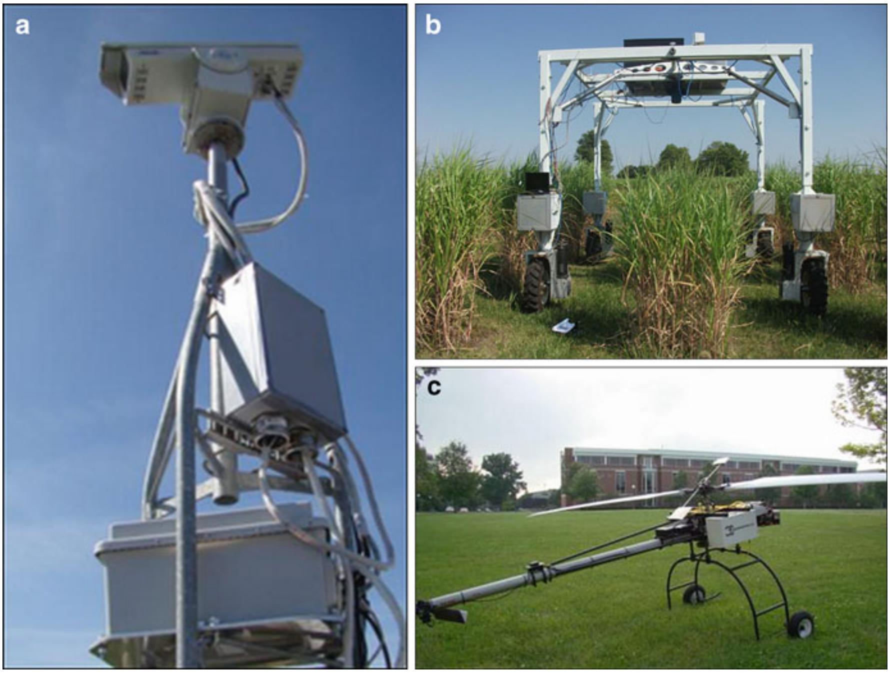

Fig. 4.5 Near-real-time remote sensing system for biomass energy crop site-specific monitoring. (**a**) Tower. (**b**) Ground reference data collection vehicle. (**c**) UAV-based remote sensing

real-time remote sensing system, (2) ground truth data collection vehicle, and (3) UAV-based remote sensing system. These three different sensing systems and their application to monitor energy crops such as switchgrass and Miscanthus are described in the rest of the chapter [30–33].

4.7 Stand-Alone Tower-Based Real-Time Remote Sensing

4.7.1 Tower Remote Sensing Principle and Instrumentations

To perform site-specific and seasonal monitoring of biomass energy crop growth conditions, a stand-alone tower-based crop sensing system as indicated in Fig. 4.6 was designed and built on the Energy Farm of the University of Illinois at Urbana-Champaign [34]. The tower is erected at the center of the field and is equipped with a motorized multispectral camera with lens controller for zoom and focus adjustment and pan-tilt device and controller for horizontal (0°–355°) and vertical (0°–90°) movement as indicated in Fig. 4.6a. The presets according to the field distribution were established using the caller identifications and automatic rotations of the pan/tilt device that had been developed. The lens motorization was developed externally and used two motors to control zoom and focus. The tower-based system captures near-real-time RGB and CIR images of four fields growing four different crops, namely, Miscanthus, switchgrass, mixed prairie, and corn. The layout of the field is depicted in Fig. 4.6b. A Labview-based real-time algorithm was developed to capture images from the field over the growing seasons. Initially, 91 preset positions were set to cover each of the fields. The 50-mm fixed focal length was chosen to capture images. The NIR, red, and green channels were averaged in the image-acquisition process. The tower coordinates and the ground reference points were surveyed using an RTK global position system (GPS) unit. The stand-alone images for the reference points present the crop response and physiological changes. Four different ground reference points for Miscanthus (M1, M2, M3, and M4) were observed during the growing season and data was collected from early spring to winter during 2009 and 2012.

The sensing system was established during August 2009, and images were ready for acquisition from September 2009. The ground reference points for mixed prairie grass (P1, P2, P3, and P4) were placed inside an 8-m by 8-m plot to track the vegetative responses. The reference points for switchgrass (S1, S2, S3, and S4) were marked inside the field. The field spectrometry was limited to three energy grasses, however, for geo-referencing the corner points for four fields (i.e., corn, Miscanthus, switchgrass, and prairie grass were surveyed).

The stand-alone camera sensor system was developed with a four-band MS4100, a multispectral charged couple device (CCD) camera (Geospatial), a pan/tilt device (PT570P medium duty) and receiver (LRD41C21/22 Legacy), and a lens controller (Fig. 4.7). The multispectral camera was a digital progressive scan camera with a high resolution of 1,920 × 1,080 pixels. In contrast to a normal CCD camera, the

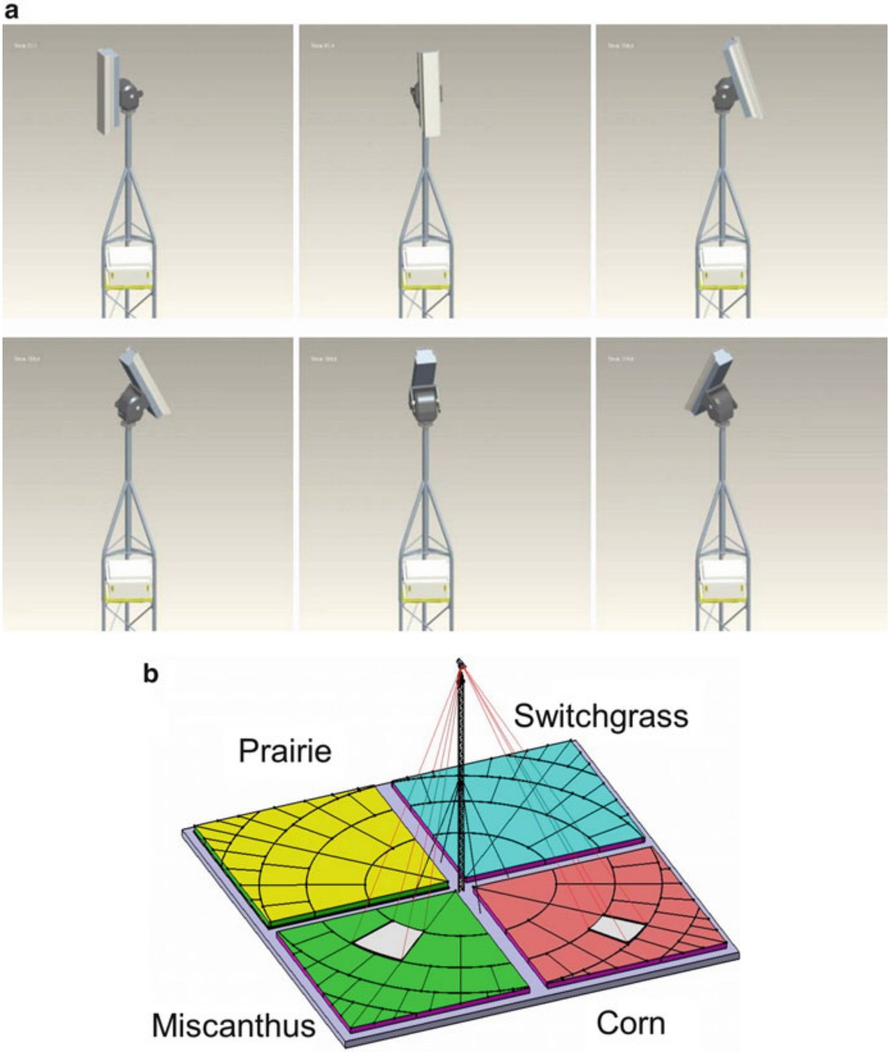

Fig. 4.6 (**a**) Image-acquisition concept using tower-based multispectral camera. (**b**) Field plots distribution and tower location at the energy farm, University of Illinois at Urbana-Champaign campus

camera was available in two spectral configurations: RGB for high-quality color imaging and color-infrared for multispectral applications. The camera had three CCD channels with center wavelengths of 500, 650, and 800 nm, respectively, and bandwidth of approximately 100 nm for each. A serial interface provided external control of gain and exposure time for each independent channel via a standard RS 232 port. The gain settings controlled the amount of the output signal amplification for each individual channel in the camera. The gain of the camera ranged from 0 to 36 dB corresponding to 95–1,023 in 16-bit digital number representation,

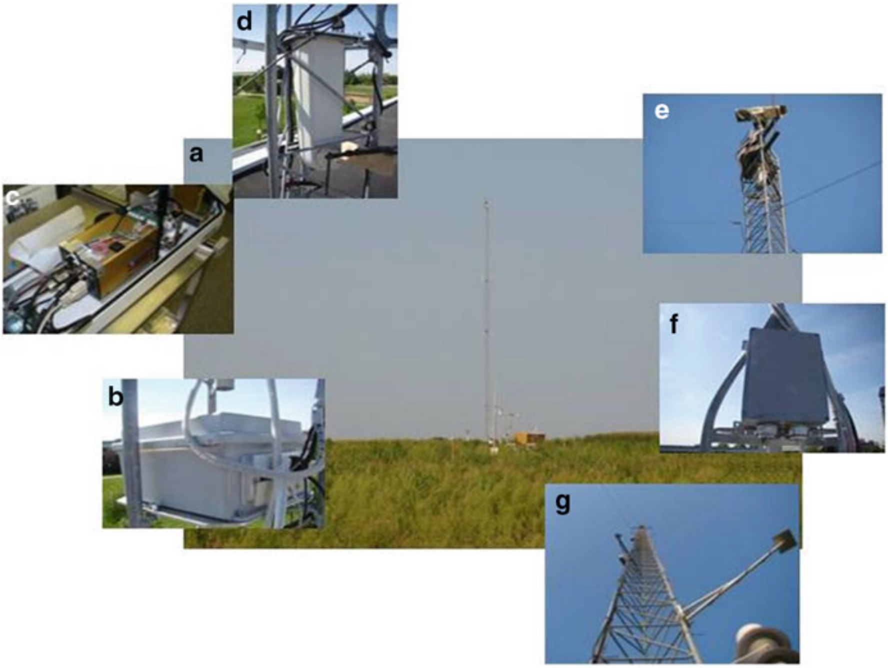

Fig. 4.7 (**a**) Stand-alone tower for remote sensing. (**b**) Computer installed at the top of the tower. (**c**) Multispectral camera with motorized zooming. (**d**) Pin-tilt controller. (**e**) Installation at the top of the tower. (**f**) Motorized lens controller. (**g**) Webcam at the halfway point of the tower

respectively, and 928 steps in total. Exposure time was the amount of time that each channel in the camera accumulated the charge before the electronic shutter was closed and the resulting value was read out. The exposure time of the camera varied from 0.1 to 108 ms that corresponded to 16-bit digital number from 1 to 1,080, respectively, with 1,079 steps in total. The maximum frame rate of the camera was 10 frames per second. The camera was able to output 8-bit and 10-bit digital image for each channel. The 8-bit mode and a digital frame grabber IMAQ PCI 1428 (National Instruments, Austin, TX) was used in the image-acquisition process. The PCI 1428 had been installed into an industrial small rugged computer with PCI expansion slot (SC241S) that could operate at extreme outdoor conditions. A serial port of the computer was connected to the external control port of the camera via a nine-pin serial cable. The pan/tilt device was rotated in horizontal and vertical directions to get the images according to the plot distributions. The Pelco D protocol was used to communicate with the pan-tilt device and receiver using RS232 serial communication. The pan-tilt rotates 0° to 355° horizontally and 0° to 90° degree vertically. The presets according to the field distribution were established using the caller identifications, and automatic rotations of the pan/tilt device had been developed. The lens motorization was developed externally and it used two motors to control zoom and focus.

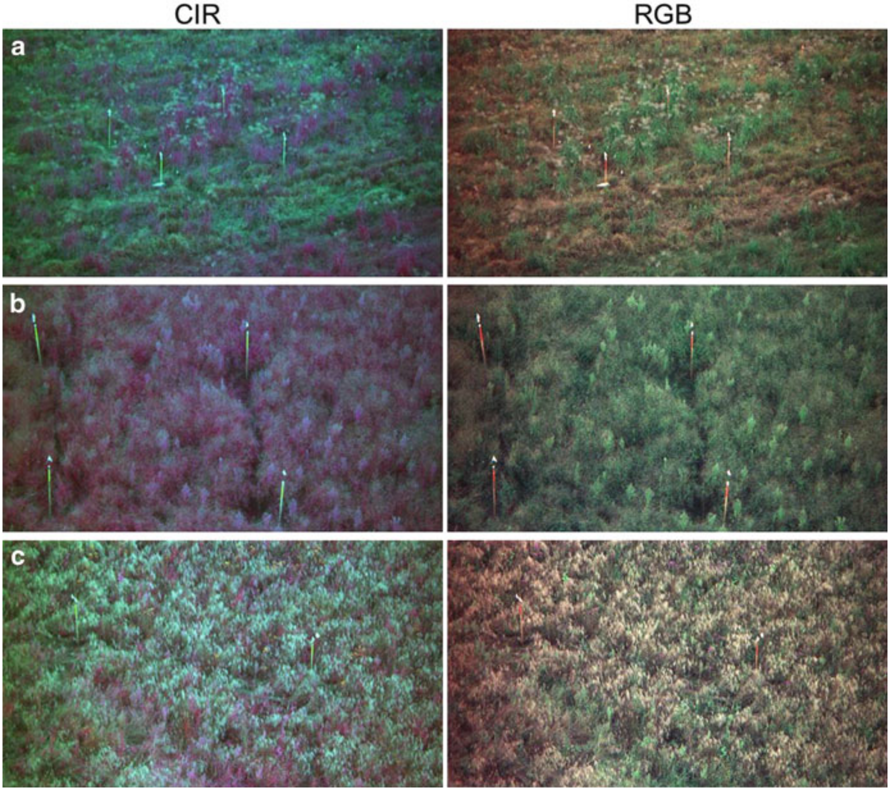

Fig. 4.8 RGB and CIR images captured on 23 September from stand-alone tower-based remote sensing system for (**a**) Miscanthus, (**b**) switchgrass, and (**c**) prairie field

The calibration was performed for zoom and focus of the lens using two potentiometers. The camera sensor system was developed to capture images from 38-m high tower for Miscanthus, switchgrass, prairie grass, and corn. The average plot size was 3.6 ha. The perennial crops were in the first year of their growth in 2009 and needed to be replanted using fresh rhizomes for uniform density of canopy. The perennial energy crop like Miscanthus requires 3–4 years to establish toward a full production potential.

4.7.2 Tower Remote Sensing Data Analysis and Result

The CIR and RGB images were captured on 23 September, 3 November, and 3 December 2009 from the stand-alone tower system for Miscanthus, switchgrass, and prairie. The first set of images was collected on 23 September as indicated in Fig. 4.8. It is visually indicated that the plant vigor and growths were good in these stages, and the switchgrass images reflected more NIR and absorbed red during September; the NIR reflectance decreased during November and December. The reference data was collected from the ground reference points during this period. The stand-alone tower images for the ground reference points present the crop response and physiological changes. In September, the crops were green, and the NIR reflectance and red band absorption were higher. The RGB images also represent the changes of canopies. The perennial crops are in the first year of their growth. The canopies would be denser as the year increases.

The images were captured from 38-m height during 12 to 3 pm daily during the growing season. The daily high temporal resolution is the major advantage of the image database. In the ground sampling, the reference points were selected to keep track of the vegetation index and intercepted solar radiation by the canopy. The spectrometer response from Miscanthus canopy was analyzed for NDVI and GNDVI (see Fig. 4.9). NDVI are related with red and NIR band and chlorophyll absorption. On the other hand, the GNDVI was related with green band. As indicated by Fig. 4.9a, the NDVI value decreased from September to November and December; that is to say, the CIR image of Miscanthus in September had more NIR information than red and gradually decreased during November and December. The GNDVI index value observed of Miscanthus was closer during the 3 months.

The NDVI and GNDVI trajectories are depicted for switchgrass during September, November, and December as indicated in Fig. 4.9b. In September, the NDVI value of switchgrass was higher than the value for November and December. On the other hand, the GNDVI was closer during September, November, and December. In the prairie field, the NDVI value for September at point 4 had noise and did not represent the regular response (Fig. 4.9c). This could have occurred due to measurement error or irregular canopy structures.

Based on the daily images from the established biomass energy crop remote sensing system, we can easily monitor the daily growth condition of biomass energy crop. The daily NDVI value, which represents the growth condition, can be calculated, and therefore, the growth pattern of different bioenergy crop in 2012 can be recognized as indicated in Fig. 4.10.

The daily NDVI value can be accumulated during the whole season for predicting the biomass accumulated in the energy crop. To verify the feasibility of biomass yield prediction based on remote sensing data, the accumulated NDVI value based on the remote sensing image of Miscanthus was correlated with the actual harvested biomass from ground truth data of year 2011 as indicated in Fig. 4.11. The results showed that the fitting accuracy (R^2) of the correlation model was 64.4 %. Therefore, there is great potential for predicting biomass yield based on the near-real-time remote sensing image after recalibration with the ground truth data.

The biomass yield of Miscanthus in 2012 was predicted based on the correlated model derived in 2011 as indicated in Fig. 4.12. Additionally, large-scale biomass yield prediction based on the near-real-time remote sensing image after recalibration with the ground truth data becomes possible and so that the decision support tool with data to knowledge can be achieved for the BFP industry.

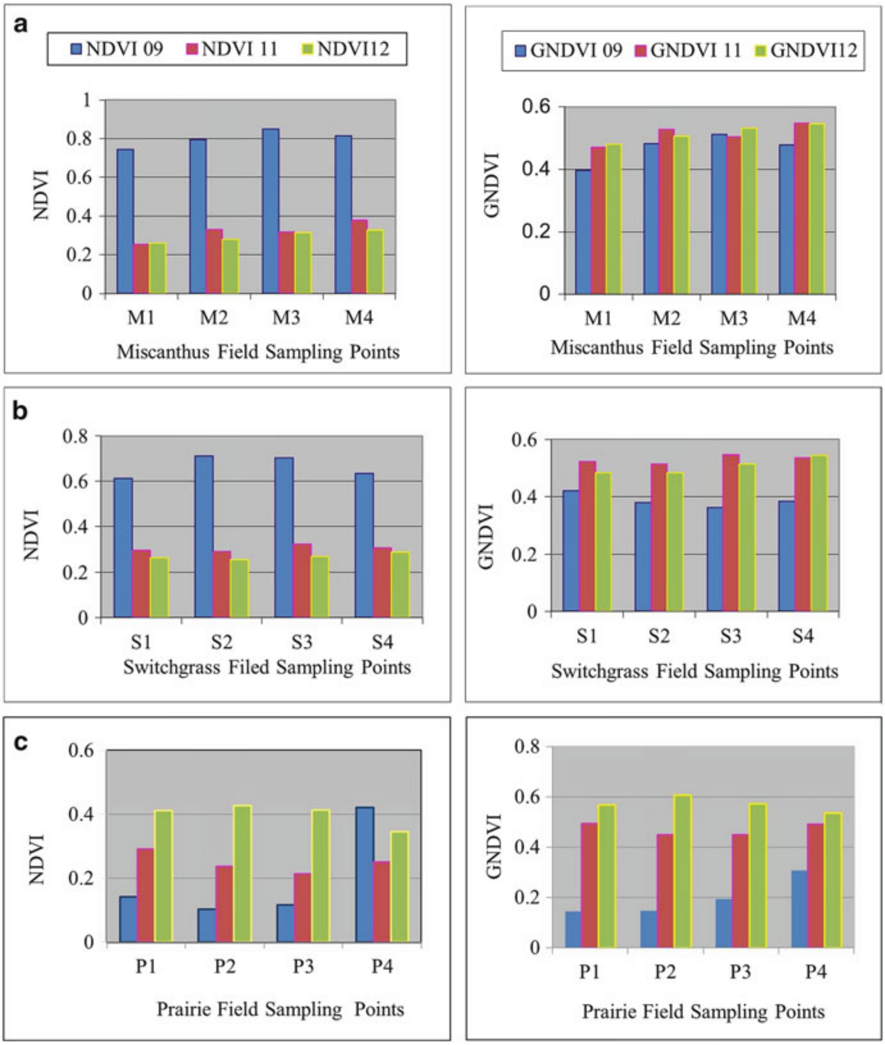

Fig. 4.9 NDVI and GNDVI trajectories at the ground reference points. (**a**) Miscanthus. (**b**) Switchgrass. (**c**) Prairie. NDVI 09, NDVI 11, and NDVI 12 indicate values calculated in the months of September, November, and December, respectively. Same convention is followed for GNDVI

4.7.3 Conclusion

The instrumentation for stand-alone tower-based remote sensing system was developed to monitor bioenergy crops. The stand-alone tower system collected images over the growing seasons to enable site-specific management. The system was independent and superior to the conventional systems that depend on weather, flying opportunity, and temporal resolutions. Especially, satellite has extensive limitations

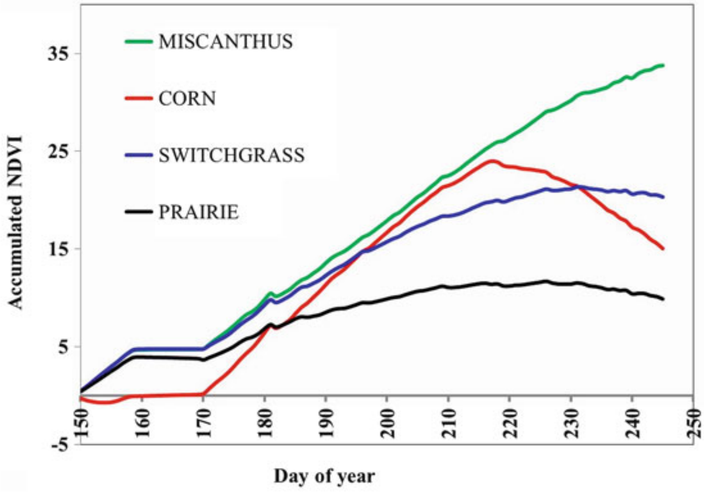

Fig. 4.10 Biomass energy crop growth pattern recognition by near-real-time remote sensing (2012)

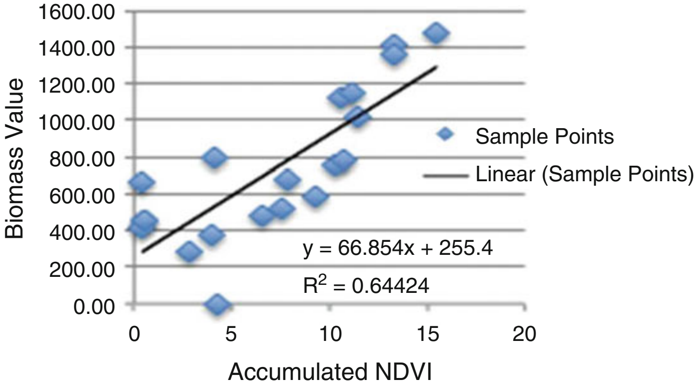

Fig. 4.11 Miscanthus biomass yield (g/m^2) correlation between the ground truth data and near-real-time remote sensing data (2011)

on revisit time to the experimental area. The ground reference sensing was done to realize the spectrometer responses for crop growth and quantum sensing to estimate biomass accumulation from intercepted solar radiation for Miscanthus, switchgrass, and prairie grass. The NDVI and GNDVI trajectories were figured out to visualize the spectral signature based on the near-infrared information. The accumulated NDVI was correlated with the ground truth data from harvested biomass yield, and a biomass yield prediction model was established. The biomass yield of Miscanthus, at other locations in the same field where the samples were collected, was predicted based on the established model. The experiments and real-time processing of images and data from spectral sensors were transmitted through wireless communication to local server for sharing with other researchers.

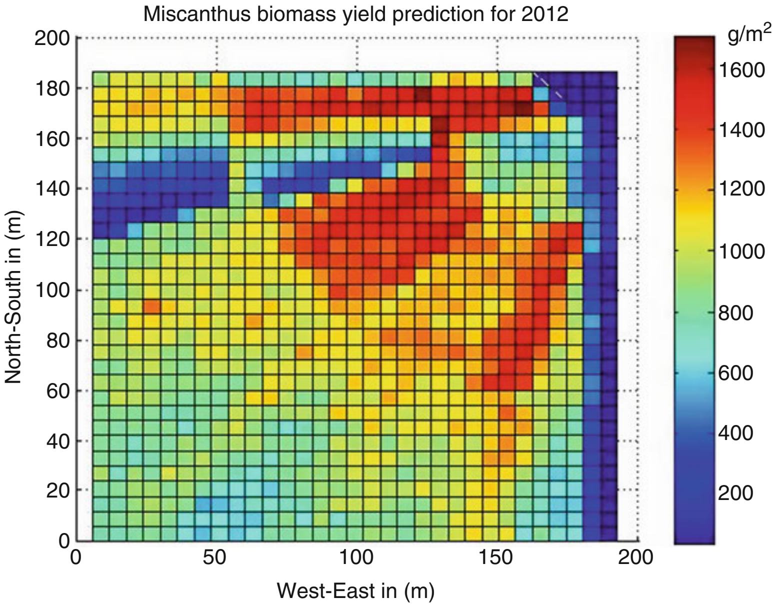

Fig. 4.12 Miscanthus biomass yield prediction

4.8 Round Reference Data Collection

4.8.1 Ground Truth Data Collection and Instrumentation

To acquire the close proximity crop data of the biomass energy crop, a ground truth data collection vehicle was built as shown in Fig. 4.13. The ground truth data collection vehicle, called a gantry, was a mobile crop monitoring and data collection platform. It was originally developed for close proximity monitoring of Miscanthus, which is a perennial energy crop that can grow up to 3–4 m high, as well as other plants. In order to fit the height of the crops, the gantry was designed as 3 m in length, 3 m in width, and 3 m in height with height adjustable to 4 m. The designs of the four independent leglike driving modules gave gantry the features of four-wheel independent drive (4WD) and four-wheel independent steering (4WS). The 4WD-4WS vehicle was more flexible to drive into the dense plant plot.

The gantry was equipped with a 6.5-kW heavy-duty gasoline generator (Champion Power), which provided 60 Hz 120 V AC, and powers the whole vehicle, including the driving system, control system, and sensors. Each of the leg was equipped with a DC motor for driving and a high torque stepper for steering. The total driving power of the vehicle was about 3 kW, and the gantry was designed to move as fast as 2 km/h in the field [32].

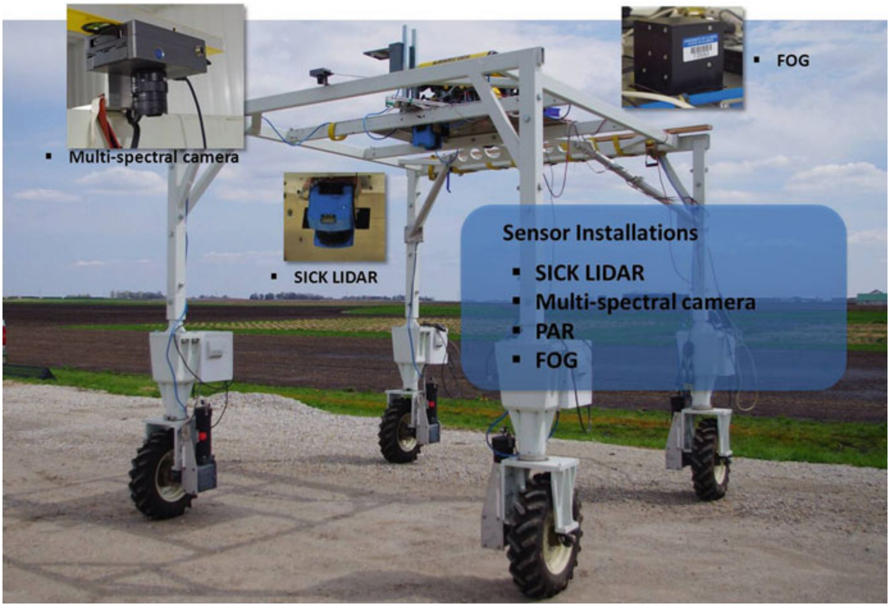

Fig. 4.13 Ground reference data collection concept scheme

To accomplish close proximity monitoring, there were a couple of sensors retrofitted and mounted on gantry for data acquisition including the Agricultural Digital Camera (ADC) for visible and near-infrared image, USB spectrometer for crop canopy reflectance measurement, and SICK LIDAR (Light Detection and Ranging) scanner for canopy 3D profile measurement, as illustrated in Fig. 4.13. A 6DOF(six-degrees-of-freedom) Inertia Measurement Unit (IMU) from Crossbow company was mounted on the vehicle where it is close to the SICK LIDAR system for scanned image corrections in order to avoid the effect of strong vibration when traveling in uneven terrain field. The red, green, and NIR bands spectral information can be used for extraction of NDVI, SAVI, and NIR/green ratio. The crop 3D information can also be correlated with the biomass yield.

4.8.2 Ground Reference Data Analysis and Results

A SICK LIDAR scanner was mounted beneath the ceiling of the vehicle for the purpose of drawing a 3D crop height map in the driving direction. The detection range of LIDAR system was up to 8 m. It only worked while the vehicle was moving with constant transit speed. Due to the vibration of the generator and the uneven off-road surface, the result from the SICK LIDAR scanner needs to be corrected based on the vehicle altitude and vibration in post data processing. The Miscanthus height distribution from the northeast to northwest of the field is shown in Fig. 4.14. The results showed that the maximum height of Miscanthus was about 2.75 m.

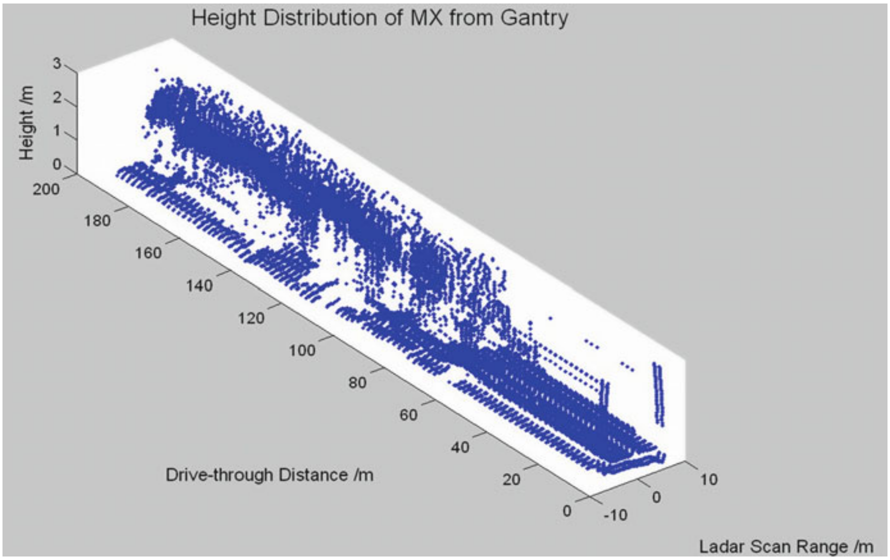

Fig. 4.14 Miscanthus crop canopy 3D profile by ground reference data collection vehicle

4.8.3 Conclusion

To get close proximity data of the biomass energy crop, the ground reference data collection vehicle was established. The gantry employed a 4WD-4WS locomotion mechanism, and the vertical clearance was adjustable from 3 to 4 m to respond to the different heights of various biomass energy crops. The gantry collected multispectral images and spectral reflectance during the crop growing season. Higher spectral, spatial, and temporal resolutions from real-time image acquisitions were achieved as compared to aerial and satellite imagery. The gantry with light detection and ranging (LIDAR) sensor provided the 3D map of the plant in the field, which is a good additive to the tower remote sensing data. The tower remote sensing data could be further validated with ground truth data for biomass preharvest monitoring and SSCM. The gantry can also drive through the field with preset position and auto navigation so that the high efficiency of crop sensing could be achieved.

4.9 Unmanned Aerial Vehicle-Based Remote Sensing

4.9.1 UAV-Based Remote Sensing and Instrumentation

An UAV-based remote sensing system is better suited and hence proposed here to fly over a large area and collect crop growth information at the right time and the right place. The autonomous UAV-based remote sensing system as shown in Fig. 4.5c was developed in Illinois Laboratory for Agricultural Remote Sensing (ILARS) at

Position
Lat 0.000000
Lon 0.000000
Alt 40.000

Attitude
Roll 0.00
Pitc 0.00
Yaw 0.00

Rate
P 0.00
Q 0.00
R 0.00

Acceleration
Ax 0.00
Ay 0.00
Az 0.00

Left: 20
Height: 40
HAOV: 81.3
VAOV: 60.4

Waypoints List

WP	Lat (deg)	Lon (deg)	Distance (m)
[1]:	40.072321	-88.211438	0.000000
[2]:	40.072321	-88.210996	37.601336
[3]:	40.072321	-88.210555	37.601336
[4]:	40.072321	-88.210113	37.601336
[5]:	40.071832	-88.210315	57.114502

Latitu: 0
Longitud: 0

☑ Show Image Box
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Fig. 4.15 UAV flyover waypoint planning with geo-reference

University of Illinois at Urbana-Champaign [35]. The system mainly consisted of a remote control (RC) helicopter, a multispectral camera, an IMU, a WAAS (Wide Area Augmentation System) differential corrected GPS sensor, a single board computer (SBC), a flight controller, a PWM (Pulse Width Modulation) switch, a wireless router, and a video transmitter. The camera, ADC, used a CMOS (Complementary Metal Oxide Semiconductor) sensor with 3.2 million (2,048 × 1,036) pixels to sense green band (520–620 nm), red band (620–750 nm), and near-infrared band (750–950 nm) images. A lens with 8-mm focal length and maximum aperture F1.6 was used on the camera. The camera can be triggered by the PWM switch at desired locations. The sensors used in the IMU were a three-axis rate gyro, a three-axis accelerometer, and a three-axis magnetometer. The SBC was used to fuse all sensors data to estimate the UAV navigation data (altitude and position) at 50 Hz [36–38].

4.9.2 *Aerial Image Acquisition and Analysis*

The UAV-based remote sensing system is able to fly over at certain intervals and get the right images of the crop over the growing season with flying path planning function, which is indicated in Fig. 4.15. The fly waypoint can be calculated based on the spatial resolution requirement and the camera parameter such as the view of angle, focal length, and resolution.

Based on the database from tower-based remote sensing system, the growth pattern of each bioenergy crop could be recognized from the daily remote sensing data as shown in Fig. 4.16. Thus, large-scale biomass yield prediction can be achieved with UAV remote sensing image or biweekly satellite images.

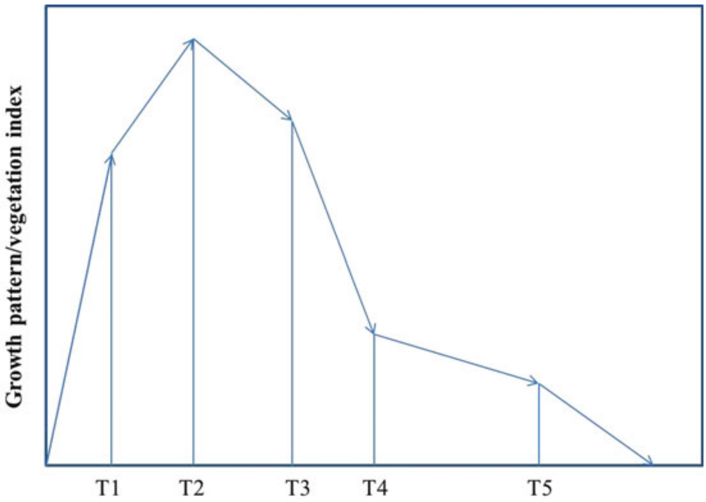

Fig. 4.16 Large-scale biomass yield prediction potential with growth pattern recognition

4.9.3 Conclusion

An automatic UAV-based remote sensing system and data collection system with flyover waypoint planning function for bioenergy crop growth condition monitoring was established. The image geo-referencing method associated with the integrated navigation system has been successfully demonstrated in this research. The resulting navigation system, using low cost inertial sensors, magnetometer, GPS, and a single board computer, has been field-tested in both ground-based and UAV platforms. This UAV-based remote sensing system was proved to be sufficient for many of the intended biomass preharvest monitoring and precision biomass production application.

4.10 Summary

Remote sensing-based preharvest crop monitoring is important to predict yield, assess stress, understand growth patterns, and achieve SSCM. Biomass preharvest monitoring is suitable for data acquisition of either high plants and short plants or different plants in all growing seasons. This is an important part of engineering solution of BFP and can provide an essential data to the tasks of harvesting, transporting, storage, and conversion through the established high-throughput phenotyping sensing and mapping system by the use of near-real-time remote sensing. However, traditional remote sensing technologies such as satellite imaginary and airborne imaginary have several critical drawbacks for biomass yield monitoring, especially for biomass feedstock quality assessment, such as low spatial and temporal resolutions, availability limited by weather conditions, and high cost. Therefore, great potential for approaching large-scale biomass yield prediction based on satellite imaginary after recalibration with the site-specific real-time remote sensing data so that the decision support tool with data to knowledge can be achieved for the BFP industry.

Acknowledgments The authors would like to thank Energy Biosciences Institute, University of Illinois at Urbana-Champaign, for supporting the program "Engineering Solutions for Biomass Feedstock Production."

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Chapter 5
Harvesting System Design and Performance

Sunil K. Mathanker and Alan C. Hansen

Abstract Bioenergy crop harvesting is a critical operation affecting bioenergy supply logistics. It includes the tasks of cutting, gathering, and conditioning of bioenergy crop so as to make it suitable for subsequent operations. Harvesting represents a significant amount of biomass cost at the farm gate. This chapter reviews and discusses harvesting technologies for four major bioenergy crop alternatives: energy grasses (Miscanthus and switchgrass), short rotation woody crops (willow, poplar), green crops (energy cane, sorghum, sugar cane), and agricultural crop residue (corn stover, orchard residue). It describes crop characteristics important for designing harvesting machinery and different machinery options used for harvesting promising bioenergy crops. It also describes the functional processes involved in a crop-specific harvesting operation and compares their operational principles. The harvesting machinery performance data are compiled to facilitate equipment selection. Finally, this chapter discusses observed limitations of the machinery evaluated and future challenges to be addressed.

5.1 Introduction

Bioenergy crop harvesting is a key operation in the supply chain that is strongly affected by technology. It also represents a substantial cost component. For example, it was about 32.5 % of overall sugar cane production cost in Louisiana, USA [1]. Equipment for harvesting conventional agricultural products such as grain and forage has evolved to high levels of productivity and efficiency as a result of decades of

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Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4_5,

research and development efforts worldwide. For bioenergy crops, the current approach is to use existing harvesting equipment, with or without modifications, rather than design a whole new machine. Field studies have demonstrated that existing harvesting machines can be used when the biomass crop characteristics are a close match with a crop already in cultivation. For example, hay and forage machinery can be used for switchgrass. However, high yield of switchgrass poses challenges to achieve a high throughput rate [2].

The development of special purpose machines to account for the unique crop characteristics and increased productivity and efficiency is also being explored [3]. For example, harvesting energy grasses such as Miscanthus does not require field drying so a single-pass machine would make more economic sense [4]. It could also reduce the intake of impurities such as soil and decayed litter while harvesting. Designing harvesting equipment requires careful consideration of the functional requirements, biomass quantity to be harvested, and desired biomass quality. Key processes such as cutting, conveying, conditioning, chopping, and densification are affected by the properties and condition of the biomass. The form in which the biomass is prepared for transportation impacts on transport efficiency and logistics. For example, to meet weight limits of semitrucks, the bale density should be around 225 kg m^{-3} compared to current bale density of 150–180 kg m^{-3}[5].

The goal of this chapter is to review past literature on the harvesting of dedicated energy crops, which includes the discussion of the field experiment data as well as conclusions drawn from those field studies. This chapter is accordingly arranged as follows. The next section describes crop harvesting characteristics. The third section explains the functional processes, and the fourth section focuses on harvesting machinery systems for the four main categories of bioenergy crops: energy grasses, short rotation woody crops, green energy crops, and agricultural residue. The last section describes future challenges.

5.2 Crop Harvesting Characteristics

5.2.1 Biomass Properties

Morphological properties of bioenergy crops influence the material flow and energy consumption. The properties of interest include distribution of vascular bundles in the stem, degree of lignification of vascular bundles, and geometric size and shape of the stem. Tall and sturdy Miscanthus stems can cause inconsistent crop flow in a mower-conditioner and plugging of the pickup unit in a baler if not conditioned enough [4]. Similarly, the stem moisture content affects cutting. The moisture content varies with harvest time, and higher moisture content requires more cutting energy because it provides viscous damping effect during cutting [6]. The knowledge of expected crop moisture content at harvest is necessary for designing effective and efficient harvesting machinery. The desired moisture content at harvest is often defined by the needs of the subsequent processes. For example, baling corn stover is more effective at about 15–25 % moisture content, whereas chopping can

Table 5.1 Approximate moisture content and bulk density recorded while performing a crop-specific operation[a]

Product	Moisture % wet basis	Density	
		kg WM m^{-3}	kg DM m^{-3}
Whole sugar cane	65	200	70
Bundled whole cane	65	400	140
Billeted sugar cane	65	350	120
Shredded sugar cane	65	290	100
Billeted sorghum—300 mm TLC[b]	65	215	75
Chopped sorghum—60 mm TLC	65	310	110
Chopped sorghum—6 mm TLC	65	360	125
Shredded stacks of corn stover	24	60	45
Round baled corn stover	24	135	105
Square bales corn stover	24	190	145
Chopped corn stover	47	140	75
Bagged and chopped corn stover	47	290	155
High-moisture ear corn in field	32	625	425
Dry ear corn in crib	13	450	390
High-moisture shelled corn in field	28	640	460
Dry shelled corn	12	770	675
High-moisture cobs	47	220	115
Dry corn cobs	6	165	155
Ground corn cob	9	270	245

[a] Adapted from [8]

[b] *TLC* theoretical length of cut

be done at higher moisture content. Furthermore, the moisture content often also dictates the storage method adopted. Table 5.1 provides moisture content recorded while performing various crop-specific operations.

Biomass yield and biomass quality, in addition to morphological properties, depend on harvest time. Delayed harvest results in a lower biomass yield because of the loss of leaves and tops. It also results in lower crop moisture content, which eliminates the need for field drying, especially for energy grasses. Furthermore, delayed Miscanthus harvest has been shown to improve combustion quality because of reallocation of the minerals from the stems to the rhizomes [7]. Thus, autumn Miscanthus harvest reduced yield by 35 % but also reduced ash content by 38 %, potassium content by 67%, chloride content by 75%, nitrogen content by 20%, and moisture content by 48 % [7]. The lower nutrient content in aboveground-harvested biomass also reduces nutrient demand for the subsequent cropping season.

5.2.2 Biomechanical Properties

Biomechanical properties affect many mechanical actions involved in bioenergy crop harvesting, such as bending, cutting, conveying, size reduction, and densification. Each of these actions can be performed in a variety of ways, and the selection

Table 5.2 Biomechanical properties of bioenergy crops

Mechanical properties		Switchgrass	Miscanthus	Alfalfa	Maize	Sunflower	Rice straw
UFTS (MPa)		97.8 (Alamo) 89.7 (Kanlow)		9–36	55–69	2.8–8.7	10–13.3
UFSS (MPa)		20.5 (Alamo) 17.9 (Kanlow)		0.4–18			
MOE (GPa)	Internodes		4.5		6.8–17.2		
	Nodes		5.8				
FR (Pa)	Internodes		1.0–2.6				
	Nodes		2.9–3.6				
SCE (kN m^{-1})	KBA 30°	6.3					
	KBA 45°	10.1					
Reference		[12, 13]	[11]	[14]			

UFTS, ultimate failure tensile stress; UFSS, ultimate failure shear stress; MOE, modulus of elasticity; FR, flexural rigidity; SCE, specific cutting energy; KBA, knife bevel angle

of the optimum way depends on the biomechanical properties of the crop and the cutting parameters [9, 10]. Mostly, the design of cutting devices aims to minimize energy consumption while maintaining the desired quality of cut. Table 5.2 summarizes the biomechanical properties of different crops. Tensile failure stress of the maize stem was lower than for the switchgrass. The elastic modulus of Miscanthus was lower than that of maize crop, and it varied from 2 to 8 GPa with harvest time and node number [11]. Flexural rigidity of the Miscanthus stem internodes decreased linearly with higher internode number, and for the nodes it decreased exponentially. The elasticity decreased linearly from the lower to the upper part of the Miscanthus stems, but it did not vary in a systematic pattern with respect to harvest time [11]. Figure 5.1a shows that the shearing stress (curve 1) and maximum shearing force (curve 4) required to cut Miscanthus stems were inversely proportional to the height of cut from the stem base [9].

5.2.3 Cutting Mechanics

The cutting mechanics of agricultural materials differ significantly from metals or plastics because agricultural materials are viscoelastic, meaning they do not possess a strictly defined relationship between stress and deformation. Deformation in plant materials is a function of time (creep), and their modulus of elasticity is not constant [15]. The plant materials also behave differently under tensile and compressive forces as well as static and dynamic loading. Although the cutting mechanics of plants are difficult to predict theoretically, plants are often viewed as bundles of fibers of high tensile strength bound by materials of much lower strength. The diameter of the bundle of structural fibers rather than the outside diameter of the stem determines the bending and tensile strength of the stem. Thicker stems, such as those found in Miscanthus and corn, are often composed of strong node and weak

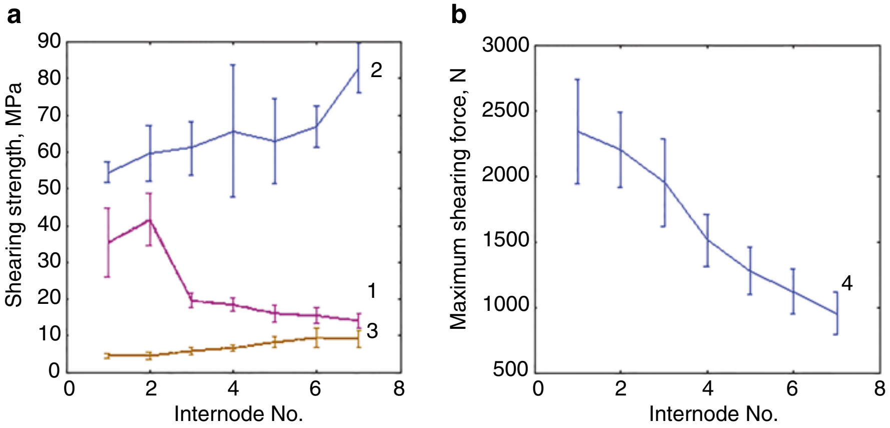


Fig. 5.1 (**a**) Shearing strength of Miscanthus stem and cortex: curve 1 = shearing strength of stem in cross-sectional direction, curve 2 = shearing strength of cortex in cross-sectional direction, curve 3 = shearing strength of cortex in longitudinal direction, and (**b**) curve 4 = maximum shearing force for stem in cross-sectional direction. Each half bar represents one standard deviation. Adapted from [9]

internode sections. Internode sections may be hollow or non-hollow and more uniform than the nodes. Moisture content affects the strength of plant stems by changing the internal turgor pressure in plant cells [16].

Cutting of plant stems occurs when the pressure exerted by the cutting blade exceeds a critical value, which ranges from 9 to 30N mm^{-2} for various plant materials. Plant cutting results in multiple modes of tissue failure. Initial knife penetration causes localized plastic deformation, followed by significant buckling and deformation as the knife advances. As the knife continues to advance, the fibers in the stem are deflected and eventually fail in tension. The plant stem is also deformed and compressed ahead of and to the sides of the knife. These compression effects alone may account for 40–60 % of total cutting energy [16].

5.2.3.1 Cutting Modes

Cutting processes in hay and forage machinery can be supported or unsupported (Fig. 5.2). Unsupported cutting is often referred as inertial or impact cutting because the cutting force is supported by the inertia of the plant. The impact cutting occurs at high blade speeds (60–80 m s^{-1}) [16]. Supported cutting occurs at lower speeds (3 m s^{-1}) in a scissorlike action as the crop is sheared between the blade and ledger plate [17]. Commercial rotary mowers employ an unsupported cutting mode, whereas reciprocating mowers employ a supported cutting mode. However, in practice both types of mowers may employ a combination of both cutting types as neighboring plants can immobilize their neighbors, and some cutting in reciprocating mowers occurs before the knife reaches the ledger plate. Cutting throughout the stroke of the reciprocating mower results in uniform stubble height and reduces

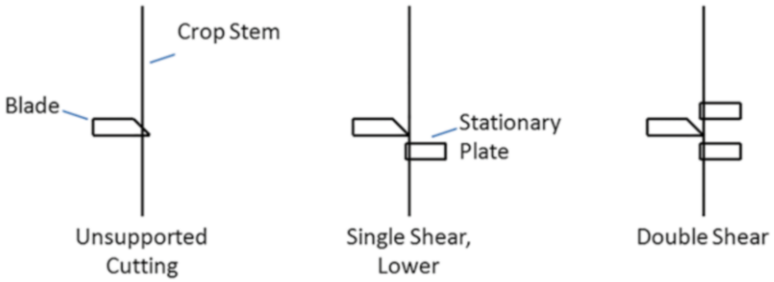


Fig. 5.2 Crop stem cutting mode: unsupported, single shear, and double shear. Adapted from [19]

peak cutting forces. Stems can be supported in three different ways while cutting: upper shear, lower shear, and double shear (see Fig. 5.2). Impact cutting typically requires more energy but does not require sharp blades or ideal crop conditions [17]. For example, shear cutting of grass stems (about 2.5 mm diameter) required 30 mJ per stem, whereas impact cutting energy required 100–1,000 mJ per stem [18]. Higher energy in impact cutting is attributed to increased blade-stem friction and increased acceleration of the plant stem. High speed unsupported cutting may result in greater plant compression and deformation leading to elevated power usage [15].

5.2.3.2 Cutting Energy

Cutting standing crop is the most important functional operation performed by a harvesting machine. A cutting system should be able to maintain a uniform height of cut, harvest lodged crop, leave minimum stubble, promote regrowth or emergence of the subsequent crop, and consume minimum cutting energy. For a specific crop, the cutting energy depends on stem diameter, cutting speed, blade type, blade geometry, and height of cut. For example, Fig. 5.3a shows that energy required to cut sugar cane stems was proportional to the stem diameter [20]. Figure 5.3b shows that the cutting force for the flat blade was higher than the serrated blade for cutting Miscanthus stems [9].

5.2.3.3 Critical Cutting Speed

Unsupported and partially supported cutting requires that the cutting force is supported by the plant's structural rigidity or inertia [15]. Hence, cutting can only occur when the resistive forces of the plant exceed the required cutting force. Since cutting forces generally decrease with decreasing cutting speed in grasslike stems, it is possible to define a critical cutting speed in which cutting forces exactly equal the reactive forces of the plant. A clean cut requires the stem to be severed above the critical speed. It also ensures significantly less stem deflection, which results into lower and

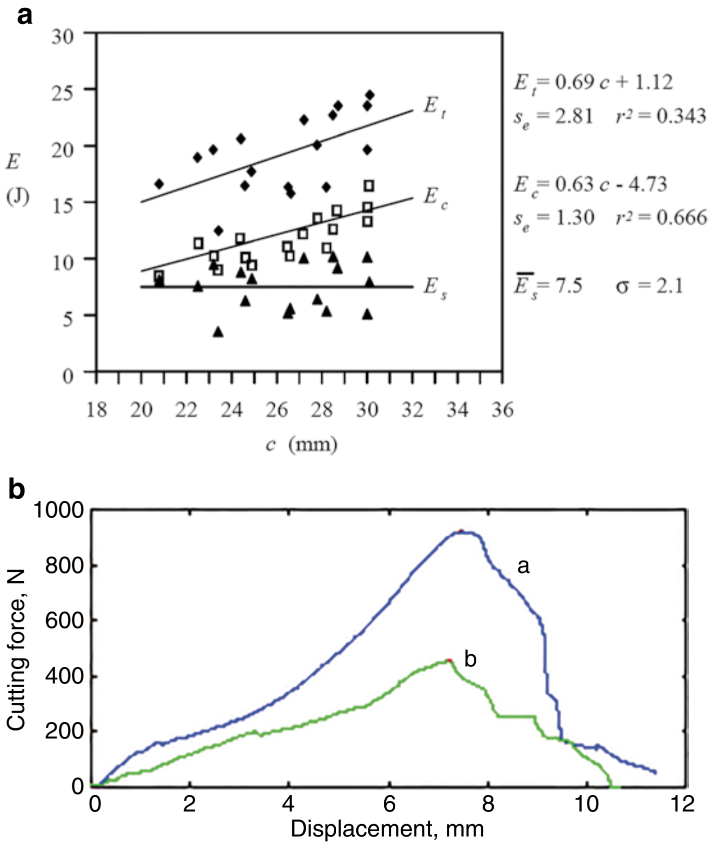


Fig. 5.3 (**a**) Total (E_t), cutting (E_c), and stalk (E_s) energy required for impact cut of sugar cane stalks of different diameters. Adapted from [20]. (**b**) Cutting force required to cut a Miscanthus stem across its diameter. a, flat cutting blade; b, serrated cutting blade. Adapted from [9]

uniform stubble height. By equating cutting forces with the expected rigidity of the plant, Persson and ASAE [15] provides an equation for this critical speed

$$v_k = \sqrt{d_s \frac{F_x - F_b}{m_p} \left(1 + \frac{z_{cg}}{r_g^2}\right)} \tag{5.1}$$

where v_k=critical knife velocity, m s^{-1}, d_s=stalk diameter, mm, F_x=cutting force, N, F_b=bending resistance of stump, N, m_p=mass of cut portion of plant, kg, z_{cg}=height of center of gravity of cut plant, m, r_g=radius of gyration of cut portion of plant, m.

A simple approximation to this equation can be obtained by assuming that $r_g = z_{cg}$ [16]. Critical cutting speeds in grass are typically about 25 m s^{-1}, but commercial impact cutting machinery operates at 60 m s^{-1} or higher cutting speeds.

5.3 Harvesting Subsystems

A typical biomass harvesting machine consists of one or more of following subsystems: cutting, conveying, conditioning, collecting, baling, and chopping. If two machines are involved in harvesting a crop, then it is called a two-pass system, such as mowing and baling. If only one machine is involved, then it is called a single-pass system, such as a sugar cane chopper-harvester. A single-pass system is preferred when the crop needs to be harvested green such as sugar cane or there is no need for field drying such as corn silage. A two-pass system is preferred when the crop needs to be field dried to the desired moisture content before baling such as sorghum.

A bioenergy crop harvesting system consists of cutting plants and transforming the cut plants to a transportable form. The common transportable forms are bale, chopped biomass, wood chips, and billets. The main functional processes in forming a bale are cutting, material conveying, conditioning, windrowing, picking up windrows, compaction, knotting, and bale release. The functional processes in chopped biomass or wood chips are cutting, material conveying, chopping, and blowing chopped biomass into a wagon. Similarly, the functional processes in forming sugar cane billets are base cutting, cutting stems into billets, cleaning trash, and conveying billets into a wagon. The following sections describe each of the main processes in detail.

5.3.1 Mowing

Cutting devices are classified based on the cutting mode for which they are designed. Impact cutting and shear cutting are the commonly used cutting modes in bioenergy harvesting machinery.

5.3.1.1 Reciprocating Sickle Bar Mowers

Sickle bar mowers cut the crop by slicing it between a moving knife section and a stationary ledge plate (Fig. 5.4a). The construction of a typical cutter bar section is shown in Fig. 5.4b. Knife section edges can be smooth or serrated and can be re-sharpened or replaced. Ledger plate edges are usually serrated on the underside and are not re-sharpened. The correct clearance between a knife section and ledger plate is maintained by a knife clip. The guards protect the knives from being damaged by rocks and also help to deflect stems at the end of a sickle stroke.

The cutter bar mowers are of two types: (1) single oscillating element with a fixed finger bar or (2) dual oscillating elements. The single oscillating element mowers consist of a fixed part (bar with guards, fingers, or teeth) and a moving part (the cutter blade which is composed of many knives) (Fig. 5.5a). The ground speed for the single oscillating element (see Fig. 5.5a) is about 5–7 km h^{-1} (Table 5.3), whereas the dual oscillating elements (see Fig. 5.5b) have relatively higher ground

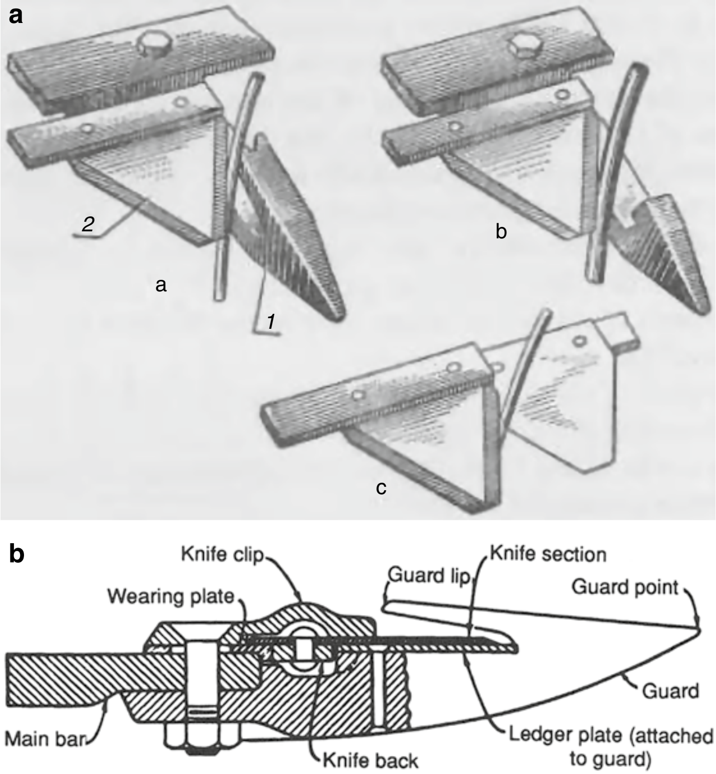


Fig. 5.4 (**a**) Types of sickle bar cutters: (a) finger bar with lip, (b) finger bar without lip, and (c) dual-action cutter bar. Adapted from [19]. (**b**) Constructional details of a typical cutter bar section. Adapted from [16]

speeds (8–9 km h^{-1}). The dual oscillating elements either have dual oscillating knives (see Fig. 5.5B_1) or an oscillating knife and an oscillating finger bar (see Fig. 5.5B_2). The oscillating knife and oscillating finger bar type (see Fig. 5.5B_2) are more robust and better suited for cutting crops close to the ground, whereas the dual oscillating knives type (see Fig. 5.5B_1) is vulnerable to soil and rocks because it is not protected by the guards.

5.3.1.2 Vertical Axis Rotary Mowers

Vertical axis mowers avoid many of the complications of reciprocating mowers. They cut the crop with freely pivoting blades attached to the rotating disks (see Fig. 5.5c, d). The pivoting action of the blades allows them to freely swing away from rocks and other obstacles. In all rotary mowers, the crop is unsupported during cutting. For a clean cut, the cutting force must be absorbed by the rigidity of the

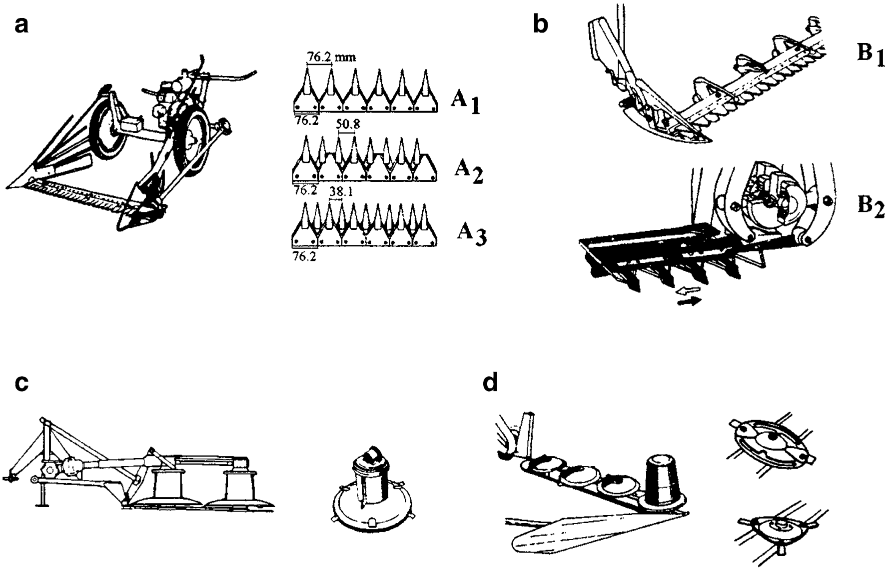


Fig. 5.5 Different mower solutions: (**a**, **b**) cutter bars and (**c**, **d**) rotary mowers. (**a**) Single cutter bars with different finger intervals (A_1, A_2, A_3); (**b**) double oscillating cutter bars: double knife bars without fingers (B_1) or one cutter bar and one finger bar moving in opposition (B_2); (**c**) two drum mower with top drive; (**d**) disk mower can have several disks with two or three knives. Adapted from [21]

plant's stem and its neighbors. There are two types of vertical axis rotary mowers: disk and drum. Drive mechanisms in disk mowers are located beneath the cutting blades to facilitate the cut crop flow through the machine. It also reduces energy required in crop conveyance. Blades may be counter rotating to leave the cut material in distinct bands or corotating for uniform distribution across the cutting width. Drum mowers have their drive mechanism above the cutting blades. The cut crop passes through the narrower spaces between or under the drums, which increases energy required in crop conveyance.

5.3.1.3 Horizontal Axis Rotary Mowers or Flail Mowers

Flail mowers are used in "direct-cut" harvest operations to cut and condition forage. Cutting is accomplished by freely pivoting blades attached to a horizontal rotating drum (Fig. 5.6). Flail mowers employ impact cutting mode. The cut crop is conditioned and conveyed as it passes over the high velocity cutting blades. Forage can be collected directly behind the mower or allowed to drop into the field for wilting. In general, flail mowers tend to be less precise than the sickle or disk mowers. The crop losses are about 10–15% higher than other mowers for standing crops [16]. Conversely, flail mowers perform better than sickle and disk mowers in highly lodged crops. Because of this, they are ideal for harvesting energy grasses after overwintering.

Table 5.3 Machine performance parameters in forage harvesting[a]

Operation, machine	Speed (km h^{-1})	Average working width (m) or volume (m^3)[b]	Capacity (ha h^{-1}) (t h^{-1})[b]	Minimum power (kW)	Energy consumption (kWh ha^{-1})	Time (man-h ha^{-1})
Mowing						
Walking mower (finger bar)	2–3	1.2–1.4	0.2–0.25	8	18–20	4–5
Finger bar mower	5–7	1.5–2.5	0.4–0.5	15	18–20	0.8–1.6
Double knife cutter bar	6–9	1.5–2.5	0.5–0.7	15	18–20	0.6–1.2
Rotary disk mower driven from below	9–10	1.5–3.0	0.7–0.8	25	20–25	0.5–1.0
Rotary drum mower driven from the top	10–12	1.5–2–0	0.8–0.9	30	20–25	0.6–0.9
Mowing + windrowing						
Rotary drum mower driven from the top	10–12	1.5–2.0	0.8–0.9	30	20–25	0.6–0.9
Windrowing						
Rotary rake	7–9	3–6	0.3–0.4	25–30	18–20	0.6–1.5
Parallel bar rake	6–7	2–3	0.25–0.35	15–20	15–18	1.0–2.0
Finger wheel rake	6–8	2–5	0.25–0.35	15–20	15–18	0.7–2.0
Loading						
Forage self-loading wagon	4–6	1.2–2.0	0.6–1.2			
		15–30[b]	15–20[b]	30	15–20	0.8–1.5
Mowing + loading						
Self-propelled forage wagon equipped with mowing system	4–7	2–2.5 15–30[b]	0.6–1.0 10–15[b]	30	5–20	1–1.5
Flail forage harvester + forage wagon		1.5–2.0	0.6–0.8			
	4–7	15–30	10–12[b]	40	30–50	1.2–1.6

[a] Adapted from [21]

[b] Capacity is presented in t h^{-1} when the volume of biomass was measured instead of working width of the machine

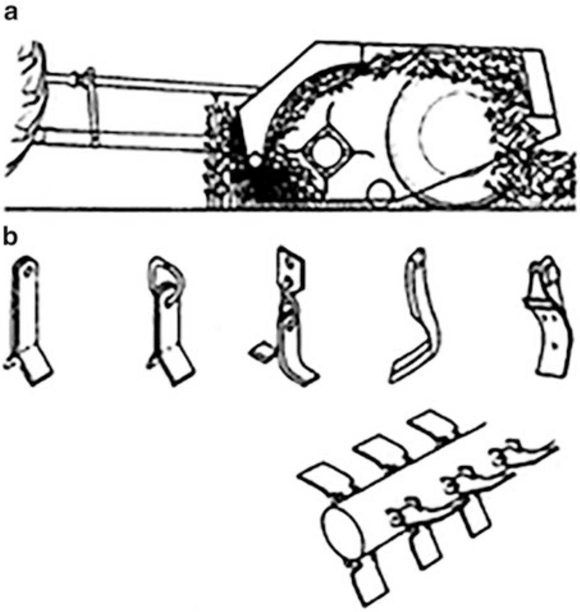


Fig. 5.6 A flail mower, showing (**a**) side view and (**b**) types of flails commonly used and their arrangement. Adapted from [15]

The main sources of losses in flail mowers are uneven stubble heights and recutting of the crop. The recutting of plant makes it difficult to be picked up. A push bar in front of the mower reduces the losses by bending the crop away from the machines. This action pushes the upper portion of plant stems out of the path of the blade and thereby reducing the losses by eliminating recutting. The push bar also puts pressure on the stems, which immobilizes them and allows cutting at a lower velocity. The higher power requirements are due to friction of rotating parts, impact cutting, and air pumping as crop is conveyed [16]. Horizontal axis mowers are now falling into disuse due to poor cut quality. However, vertical axis mowers are becoming popular due to their higher ground speed (see Table 5.3), robust construction, and low maintenance requirements.

5.3.2 Conditioning

Conditioning is an operation designed to field dry high-moisture crops. Various conditioning methods, such as mechanical, chemical, and thermal, have been evaluated for forage crops [22]. In mechanical conditioning, impellers or rollers are used to crimp (Fig. 5.7a) or crush the cut plants (see Fig. 5.7b). The plant crushing or crimping facilitates the moisture evaporation. Impeller or flail conditioners and roller conditioners are the two main kinds of mechanical conditioners. Impeller conditioners are used to condition whole stalks of a crop whereas rollers are used to condition both whole stalks and chopped biomass. Impeller conditioners use

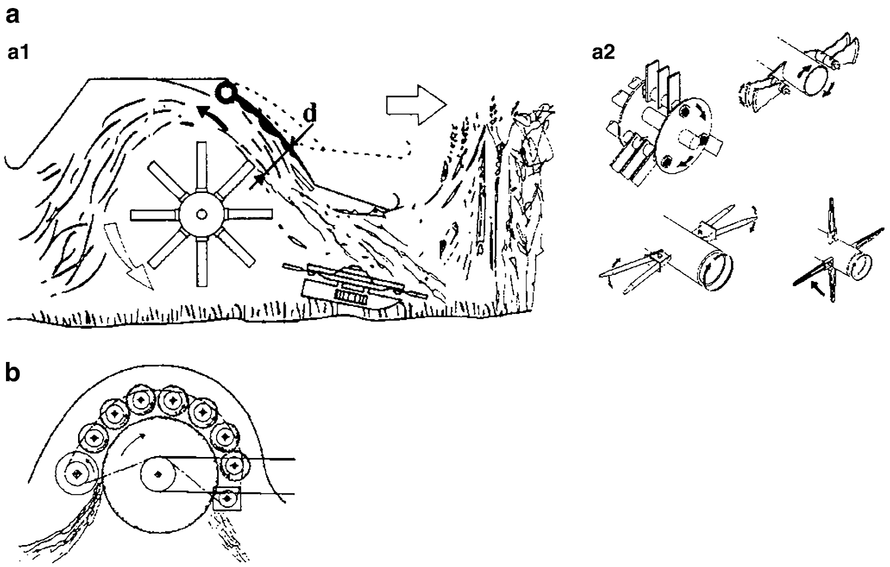


Fig. 5.7 (**a**) Flail conditioner can vary performance by changing the distance (*d*) between the flails and peripheral housing (A_1) or using different flails (A_2). (**b**) Mat conditioning system: forage is treated more rigorously due to differences in the peripheral speed of the central big drum and the peripheral small drums. Adapted from [21]

rotating tines or brushes to scratch the plant cuticle. A curtain is used to guide the cut crop to the impeller conditioner.

Roller conditioners pass the crop between rollers to crimp or crush the crop. The rollers are mounted parallel to the cutter bar. Roller conditioners are used to condition both chopped stalks and whole stalks. The intensity of conditioning depends on the construction of the two rollers, which can be metal, rubber coated, smooth, corrugated, or grooved (Fig. 5.8). Conditioning effectiveness can be improved by operating the rollers at slightly different peripheral speeds (0.5–10 %). The lower clearance between two rollers also increases effectiveness of conditioning. For uniform and effective conditioning, the width of the conditioners should be comparable to the cutting implement. The diameter of conditioning rollers generally ranges from 170 to 220 mm, while the speed ranges from 700 to 1,200 rpm.

Energy grasses like Miscanthus and switchgrass are harvested when the crop moisture content is typically 10–15 %, thus eliminating the need for field drying. However, conditioning is done to facilitate pickup by the baler. The rubber rollers are more suitable for thin-stemmed crops like switchgrass, while steel rollers are more suitable for thick-stemmed crops such as Miscanthus. The amount of conditioning depends on moisture content of crops, subsequent equipment needs, and crop being harvested. For example, heavy conditioning of Miscanthus stems is necessary to break the stems into smaller pieces to avoid choking the baler because of an uneven feed of material.

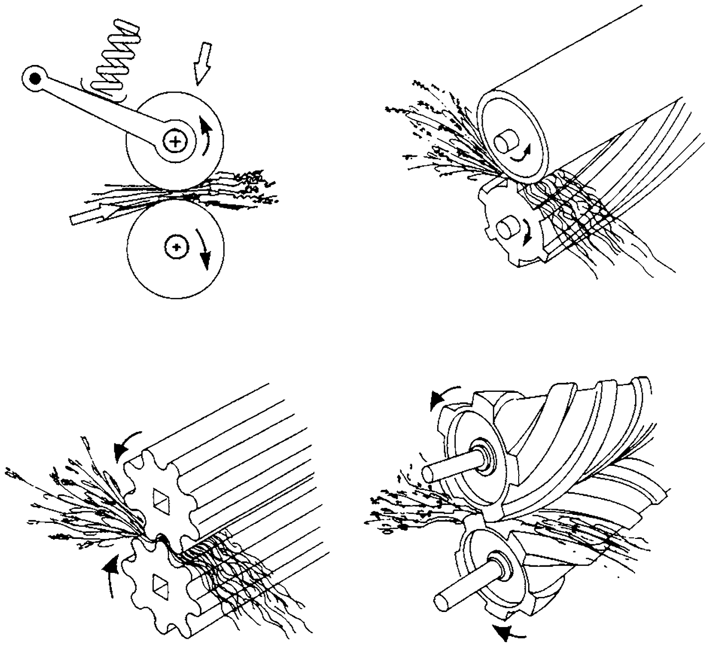


Fig. 5.8 Different types of conditioning rollers. Adapted from [21]

5.3.3 *Chopping*

Chopping is a process in which the cut plants are reduced into small pieces. Chopping is one of the basic operations needed for ensiling moist crops or for preparing biomass for combustion in power plants. Chopping also facilitates material handling operations during transport and storage. There are two basic types of forage chopping: precision cut and non-precision cut. Precision-cut chopping relies on a cylindrical cutter head and a stationary counter shear. Non-precision cut forage chopping uses a flail cutter for cutting and chopping the standing crop [16]. The most important parameters in the chopping operation are mean cutting length and energy consumption. The mean cutting length depends on rotational speed of the cutting drum, number of knives on the chopping drum, and incoming biomass feed rate.

5.3.3.1 Forage Harvesters

A forage harvester typically consists of a base machine and harvest head (see Fig. 5.11). The forage head either cuts a standing crop or picks up the windrowed biomass. The biomass is then conveyed to a chopper after which the biomass, having been chopped into short pieces is conveyed to an accompanying wagon or a trailed wagon. Forage harvesters may be tractor operated or self-propelled. Self-propelled forage harvesters offer better maneuverability, operator conveniences, and high capacity.

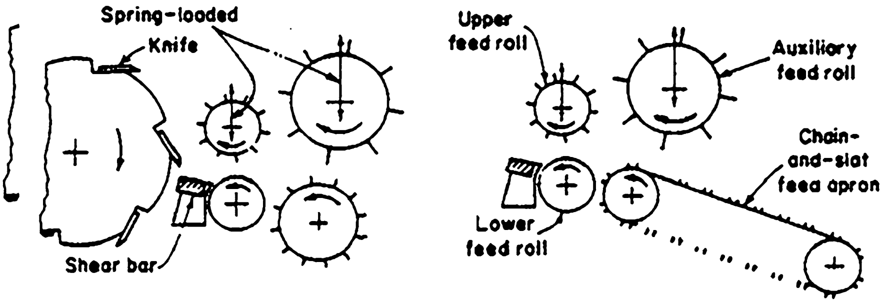


Fig. 5.9 Two types of feed mechanisms for a forage harvester. Adapted from [16]

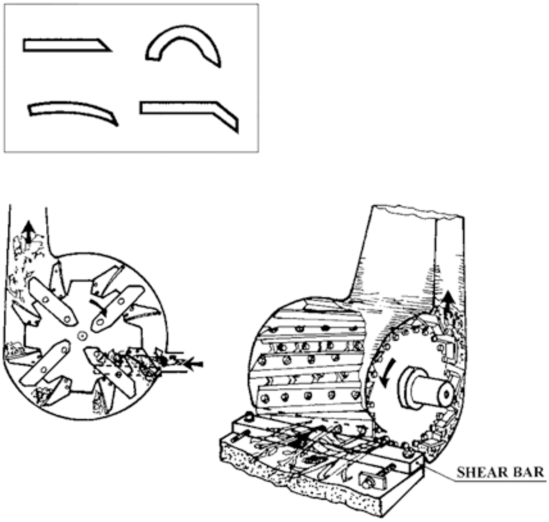


Fig. 5.10 Flywheel (*left*) and cylinder (*right*) type cutterhead. Also shown are the main knife shapes (*top*) employed in the cylinder cutterheads. Adapted from [21]

The base machine consists of a feeding mechanism (Fig. 5.9) and cut-and-throw cutterhead (Fig. 5.10). The cut crop passes through the feed rolls, which consist of four to five rollers mounted on top of each other. The upper rolls are spring loaded to adjust the gap depending on the incoming biomass feed rate whereas the lower rolls are generally fixed. The lower front and upper feed rolls generally have deep flutes to firmly grip the biomass mat at all times. On the other hand, the lower rear roll is generally smooth to avoid biomass being caught and dropped on the ground. To clear jamming, provision to reverse the direction of rotation of feed rolls is often provided. The biomass feed rate is varied by changing the roller speed. The feeding mechanism may also incorporate metal-detection systems.

The cutterhead is the most significant component of a forage harvester. It determines the capacity, efficiency, and quality of cutting. These interlinked parameters depend on the shape and condition of the knives and the stationary knife or shear bar. The cutterhead consists of a rotor, along the periphery of which are mounted a set of

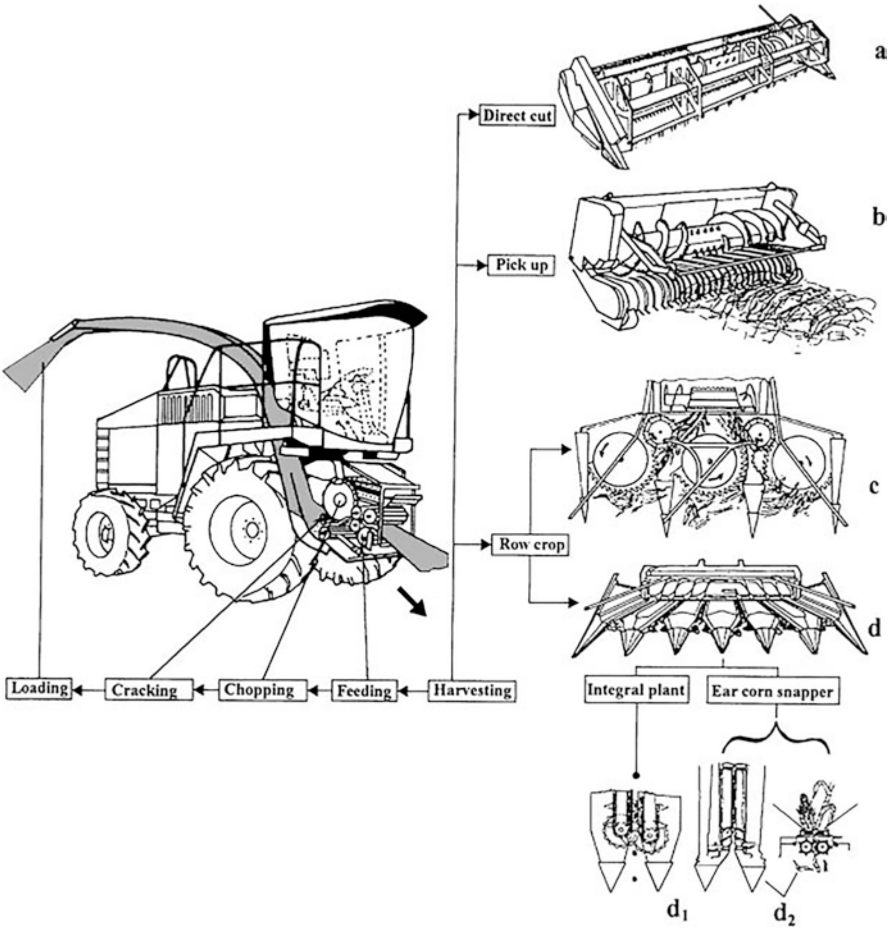


Fig. 5.11 Self-propelled forage harvester and different heads: a, mower bar; b, pickup; and c and d, row crop, ear-corn snapper (d_2). Adapted from [21]

knives (see Fig. 5.10). The rotor diameter ranges from 500 to 800 mm. The rotor width varies from 250 mm for one-row side-mounted machines to 800 mm for self-propelled forage harvesters. The peripheral speed of the rotor ranges from 15 to 20 m s^{-1}. Higher capacity machines use spiral knives, and smaller machines generally use straight knives. A cylindrical rotor offers better performance, higher reliability, lower energy costs, and greater simplicity of construction than flywheel-type rotors.

The forage heads (Fig. 5.11) are classified into the following main categories:

- Direct cut or mower bar: Mower bar heads are suitable for direct cutting of energy grasses. Direct-cutter heads are equipped with a reel to gather crop material into an auger which feeds material into the feed rolls.
- Windrow pickup: Windrow-pickup heads are generally used to pick up a windrow formed earlier by a mower-conditioner. Retractable fingers and auger-flight extensions feed the pickup biomass into the feed rolls.

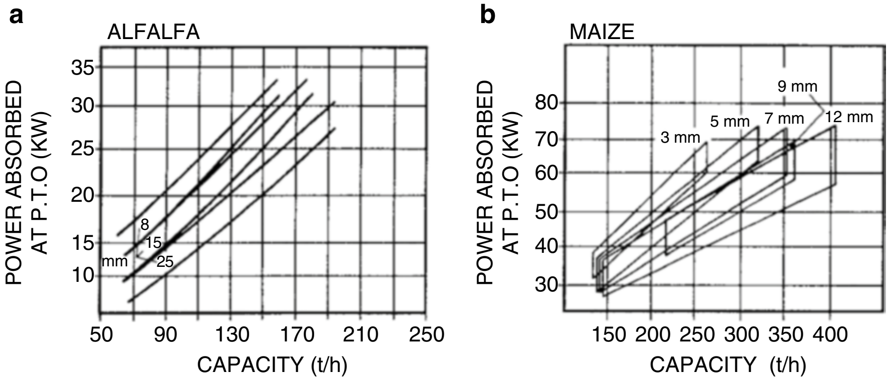


Fig. 5.12 Power required at PTO and capacity as affected by cutting length for alfalfa (**a**) and maize (**b**). Adapted from [21]

- Row crop: Row-crop heads are usually used to harvest corn or sorghum and are generally available in one to six row sizes and with different row widths. The gathering chains or belts grab the cut stalks and feed them into the feed rolls. The belts are more efficient in the lodged crops. Some row-independent heads are also available, which permit harvesting independent of row width and they are also effective for the lodged crop.
- Ear-corn snapper: Ear-corn snapper heads are similar to corn heads for combines and are equipped with two counter rotating rolls which pull stalks through snapping bars under the gathering chains to snap off the ears. Gathering chains carry the ears back to a cross auger which conveys corn to the cutterhead for chopping.

The energy consumption is dependent on the crop and its dry matter content, length of cutting, sharpness of the knives, and distance between the knives and fixed shear bar. Typical energy requirement varies from 2 to 3.0kWh t^{-1}. The PTO power requirement as affected by the cutting length is shown in Fig. 5.12.

5.3.4 Collection and Densification

After biomass is cut or chopped, an important process that follows is collection and densification. For dry energy crops, baling is the most common method of densification. For chopped biomass, processes of either cut-and-throw or cut-and-blow are typically employed.

5.3.4.1 Baling

Balers are designed to produce either round bales or rectangular bales. The size of rectangular bales falls into small and large categories. For bioenergy crops, large rectangular balers or large round balers are most commonly used. Round bales are more resistant to water penetration, and rectangular bales are better suited for handling and shipping. Bale dimensions and bale density are the two important parameters, and Fig. 5.13 shows different types of bales and their properties.

During the 1950s and 1960s, small rectangular bales weighing 20–30 kg were popular. However, by the late 1960s, bale handling became the major bottleneck and could not be solved by the simple bale accumulators and sophisticated bale wagons. The first solution suggested was the densification of the forage into bite-size packages with characteristics approaching those of a fluid, so that they could be conveyed using augers or conveyor belts. The second solution suggested was to make the bales large enough to justify their individual manipulation with dedicated lifting equipment. The first concept led to the development of hay cubers, which was abandoned due to high energy costs and limited applications. The second concept led to the development of big balers generating both round and rectangular bales and making use of stack wagons.

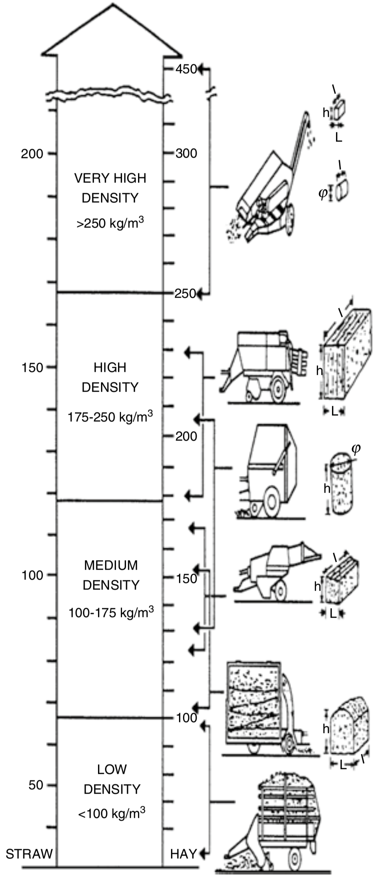
Small Square Balers

A trailed and PTO-powered baler lifts forage from the windrow through a pickup unit and conveys it to an auger or feed fork mechanism. The forage is then forced into a compression chamber (Fig. 5.14) where a plunger, driven by a crank arm and pitman, moves at about 80–100 strokes per minute. The section of the compression chamber is generally 36×46 cm with adjustable bale length from 0.60 to 1.2m. The small bales weigh about 20–30 kg with a corresponding bulk density of 120–170 kg m^{-3}. These balers achieve high-quality levels and work rates that can exceed 10 t h^{-1} of hay.

Round Baler

Round balers are of two types, namely, core compacted balers and loose core balers. The compression chamber has a variable section for the core compacted balers and a fixed section for the loose core balers. The variable compression chamber guarantees uniform compression of the whole biomass, from core to periphery. The fixed compression chamber produces bales that are less dense in the center but increasingly dense towards the periphery. The loose core balers facilitate greater air circulation in the central area of the bale facilitating drying and forage fermentation. The compression chamber in round balers can be constructed in different ways (Fig. 5.15) with a variable chamber using belt, bar, and chain components or fixed chamber relying on belt, roll, bar, and chain components.

Since 1980, large round baling systems offer the main advantage of producing weather-resistant bales because the bales can be wrapped with a plastic film (Fig. 5.16). The main components of these large round balers are a fixed-section compression chamber, presence of a chopper (based on rotor and knives or flails), and feeding of the chamber from the top (see Fig. 5.16). Typical dimensions of the large round bales are 1.2×1.5 m.



biomass format	Dimensions	Energy requirement (hay) [kW-h t^{-1}]	Capacity (hay) [Mg h-1]	Minimum tractor power [kW]
cubes	Length (l) = 20-60 mm Height (h)= 20-40 mm Width (L) = 20-40 mm weight = 2-20 g	20-28	4-6	150
rolls	Diameter (ϕ) =100-300 mm l = 50-300 mm weight = 0.1 -0.2 kg	5-8	5-10	80
large square bales	l = 1-2.4 m h = 0.8-1.2 m L = 0.5-1 m weight = 0.2-0.7 t	2-2.5	10-20	100
large round bales	ϕ = 1-1.8 m h = 1-1.8 m weight= 0.2 -0.7 t	2-2.3 (compact core) 2.2-2.5 (loose core)	4-12	50
small square bales	l = 0.7-1.2 m L = 0.4-0.5 m h = 0.35-0.45 m weight = 15-30 kg	1.5-2.5	4-8	30
compressed stacks	l = 2-5 m L = 2-3 m h = 2.5-1.5 m weight = 1-6 t	1.5-1.8	10-15	60
wagon	volume = 10-20m^3 weight = 1.3 t	1-1.2	4-6 (transport included)	30

Fig. 5.13 Bale density, power requirement, and capacity for different baling and packing systems for hay equipment. Adapted from [21]

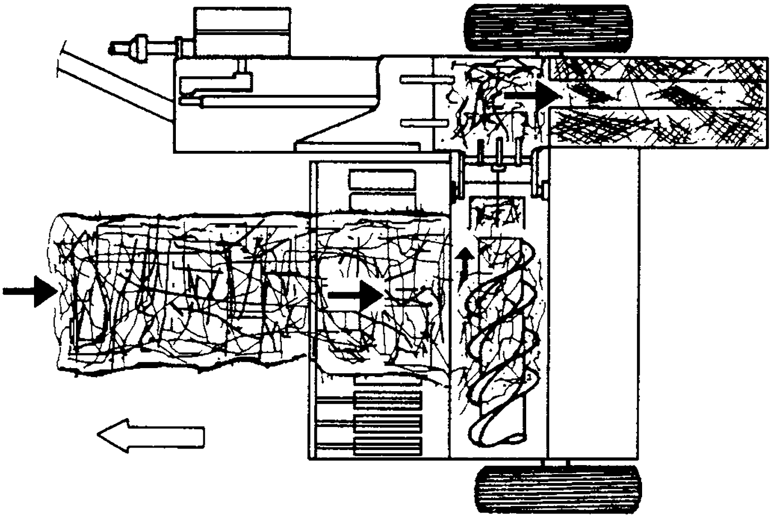


Fig. 5.14 The forage flow through a small square baler. Adapted from [21]

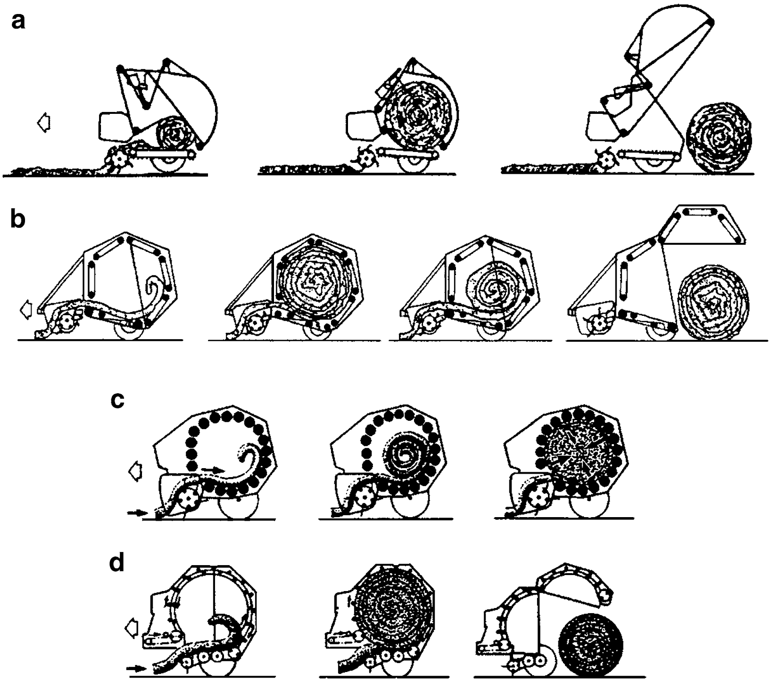


Fig. 5.15 Different round baler solutions: (**a**) variable chamber, core compacted; (**b**–**d**) fixed chamber, loose core. Adapted from [21]

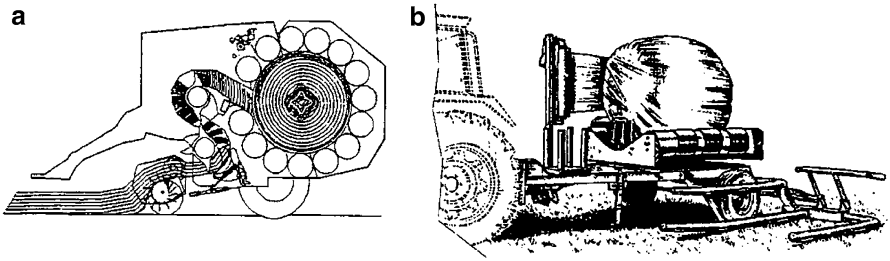


Fig. 5.16 (**a**) Round baler specifically designed for bales to be wrapped; (**b**) a wrapping machine in operation. (**a**) Shows presence of a dual chopper and feeding of the chamber from the top. Adapted from [21]

Large Square Baler

Rectangular balers offer better performance than round balers because they can continue to operate when releasing a bale compared to the round balers which stop when releasing the bale. In addition, square bales are convenient to stack and transport. The large square bale size and density (see Fig. 5.13) are optimized for transport. Typical bale size is about 0.9×1.2×2.4 m, and bulk density is 150–230 kg m^{-3}. Like round balers, rectangular balers are also towed by the tractor. A pickup head gathers windrowed biomass and feeds it to a chopper unit. Well-conditioned windrows are smaller and easier to pick up [2]. Figure 5.17 shows a well-conditioned and a poorly conditioned windrow. The poorly conditioned windrow on the left was difficult to pick up compared to the well-conditioned windrow on the right [19]. The chopper unit is equipped with crop processing knives to reduce the size of the material being baled. In modern large square balers, biomass from the pickup is first gathered in a pre-compression chamber. It accumulates to a designated pressure before being pushed into the bale chamber by an electronically triggered stuffer fork (Fig. 5.18). Optimal baler throughput is obtained when enough hay is entering the chamber to produce around one stuffer stroke for each stroke of the main plunger. The baler's monitor indicates the ratio of stuffer to plunger strokes so that the operator can maintain optimal performance. The re-expansion of hay in the bale chamber is prevented by fixed wedges and spring-loaded dogs. Square balers maintain the structure of each bale by wrapping it with twine which must be cut and knotted in each bale.

5.3.4.2 Stack Wagons

Stack wagons consist of a rectangular compression chamber, with vertical sheet metal side walls, and a mobile canopy on top which acts as a compression element. Typically, a flail-type pickup harvests the crop which is conveyed into the chamber by pneumatic means. The stacks are very large (1–6 t), and the work rates vary up to 10–15 t h^{-1}. Figure 5.19 shows a self-loading wagon.

Fig. 5.17 Effect of conditioning roll pressure on windrow characteristics. The windrow on the left is unconditioned and difficult to pick up because stems are lying flat. The properly conditioned windrow on the right stands up taller and is easier to bale. Adapted from [19]

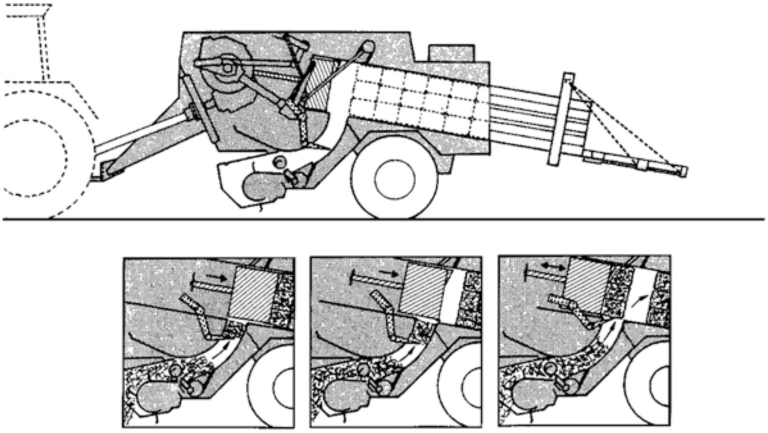


Fig. 5.18 A large rectangular hay baler illustrating the windrow pickup, pre-compression chamber, plunger, and bale chamber. Adapted from [21]

5.3.4.3 Hay Cubers

Hay cubers were developed to facilitate handling, transport, and storage operations but could not be adopted because of their high energy costs. Field cubers consist of a pickup, sprayers, feeding rolls, a chopper, and a cubing apparatus (Fig. 5.20a).

Fig. 5.19 Self-loading wagon (Pöttinger Jumbo 8000). Adapted from [23]

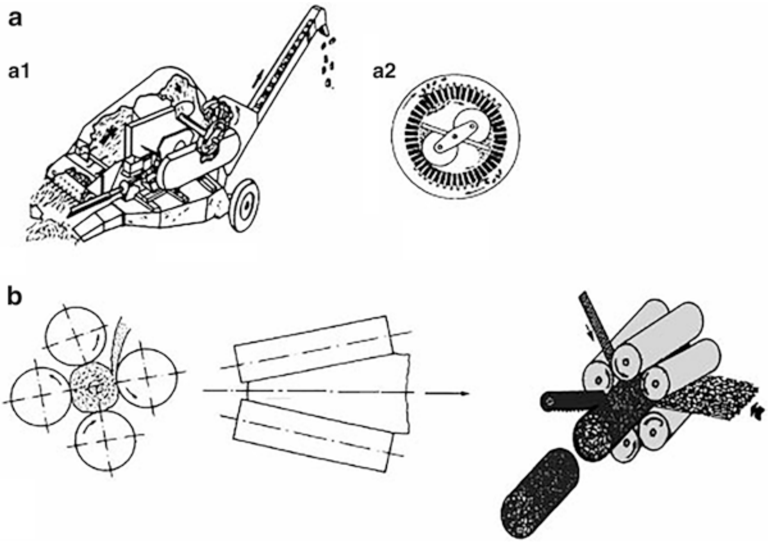


Fig. 5.20 (**a**) A trailed field cuber (a_1) and its cube-forming wheel (a_2) based on the extrusion principle; (**b**) roller wafer system. Adapted from [21]

The cubing apparatus is composed of a rotary auger and a heavy press wheel, which forces biomass into and through die openings in a ring. The 4- to 8-cm cubes have a square section of 2 to 4 × 2 to 4 cm, and their bulk density is 350–400 kg m^{-3}. The extrusion process based on sliding friction consumes about 25–30 kWh t^{-1} energy. Another alternative which compressed the biomass into small cylinders (see Fig. 5.20b) having a diameter of 10–20 cm, random length (5–20 cm), and high density (300–350 kg m^{-3}) was also studied. The energy consumption was about 8–10 kWh t^{-1}.

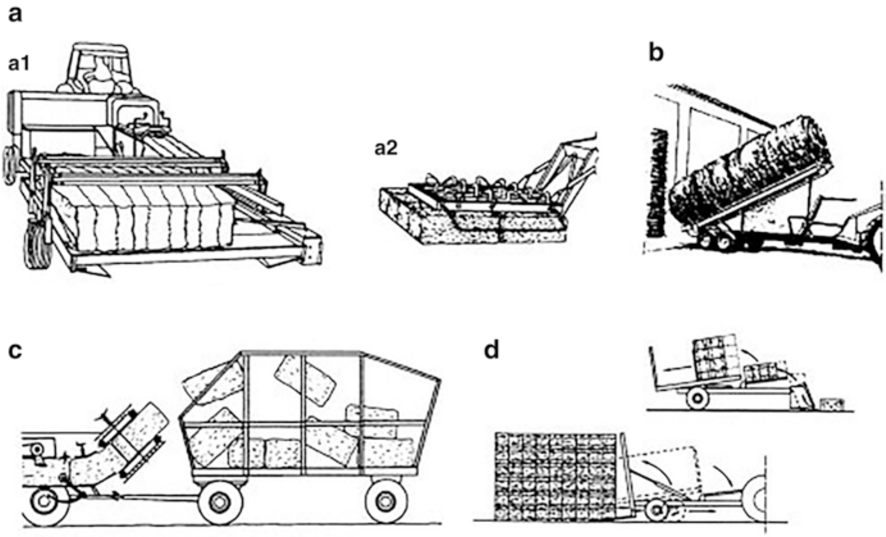


Fig. 5.21 Some special means for conventional bale handling: (**a**) bale accumulator (a_1) and its specific fork lift (a_2); (**b**) round bale trailer capable to perform both bale loading and unloading; (**c**) bale ejector; and (**d**) automatic bale wagons load the bales orderly and store a group of 60–100 bales in a stack. Adapted from [21]

For conventional small two-twine bales, specialized handling equipment has been developed. The bale accumulator is a frame attached to the baler into which the formed bales accumulate and are later deposited at the headlands in the form of a stack (Fig. 5.21a). A bale ejector tosses the bale into a trailer (see Fig. 5.21c). The ejector consists of two rubber belts moving at high speed and capable of throwing the bale a distance of 4–5 m. An automatic bale wagon consists of a trailer equipped with a mechanical device to pick up the bales and arrange them on the loading bed (see Fig. 5.21d). However, the big bales are handled by front-mounted tractor loaders (Fig. 5.22a), although dedicated self-propelled industrial loading vehicles (see Fig. 5.22b) are also available.

5.4 Harvesting Systems for Bioenergy Crops

5.4.1 Energy Grasses

Switchgrass and Miscanthus are the dedicated bioenergy grasses that are most frequently proposed as those having high potential. These crops are perennial, and once established they can be harvested for 10–15 years. Another advantage is that energy grasses are harvested when the plants have senesced, i.e., nutrients have

Fig. 5.22 (**a**) Tractor-mounted front loader to pick up and transport large square bales. (**b**) A self-propelled automatic bale loading machine

been translocated into the roots/rhizomes. After senescence, the moisture content typically drops to 15–20 % thereby eliminating the need to field dry them. A schematic of different harvest and transport options for energy grasses is shown in Fig. 5.23. Miscanthus is the most challenging crop because of thickness and toughness of its stems. However, it can be harvested after minor modifications and adjustments in hay and forage machinery. Typically, two-pass harvesting consisting of mower-conditioning and baling is practiced (Fig. 5.24). Single-pass harvesting is

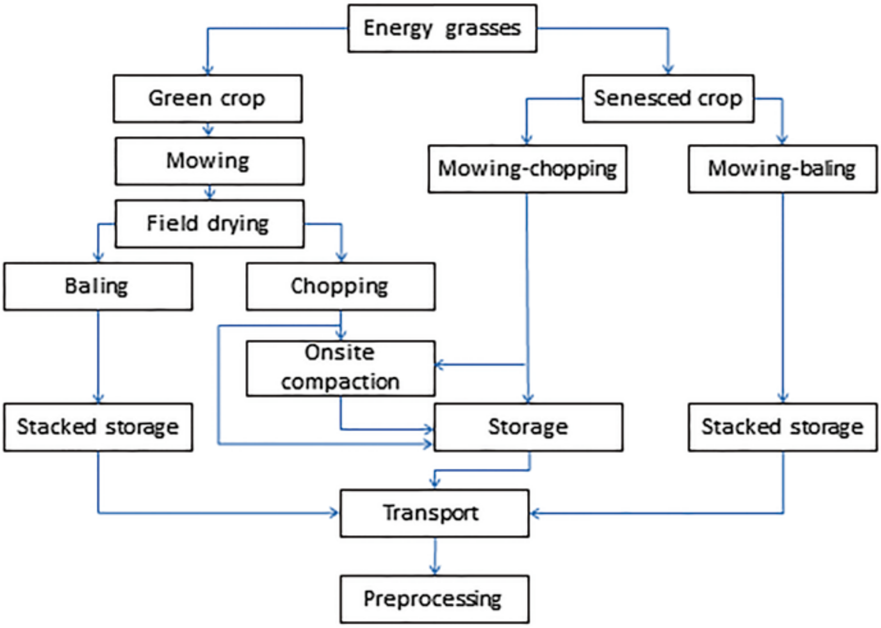


Fig. 5.23 Schematic of functional processes in harvest and transport of energy grasses

carried out using forage harvesters that cut, chop, and then blow the biomass into an accompanying wagon (Fig. 5.25a). There have been some attempts to develop a single-pass machine which can mow and bale the crops in one pass (see Fig. 5.25b).

5.4.1.1 Two-Pass Harvesting of Energy Grasses

In the first pass, grasses are cut and windrowed. A sickle bar head or a rotary disk head is most commonly used. A sickle head works well for thinner grasses such as switchgrass (see Fig. 5.24a), but it experiences difficulty in cutting Miscanthus crop because of the thickness and sturdiness of Miscanthus stems. A rotary disk head works well for Miscanthus (see Fig. 5.24b) though material conveying and conditioning need to be improved. Overall, a disk head can more easily harvest Miscanthus, switchgrass, and other energy grasses compared to a sickle head. A mower-conditioner forms a windrow in the field which is later picked up by a baler in the second pass. Typically, large round balers (see Fig. 5.24c) or square balers (see Fig. 5.24d) are used. Large square balers are preferred because squares bales are easier to stack for storage and transport. Both round and square balers work well for thin energy grass, but they experience difficulty in baling Miscanthus crop if it is not well conditioned. Presence of long straight stems often results in plugging of a baler. Because of higher yield of Miscanthus and switchgrass, the baler ground speed is lower compared to traditional hay grasses such as prairie grass.

Fig. 5.24 Harvesting machinery for energy grasses: (**a**) a sickle head mower-conditioner mowing switchgrass, (**b**) a rotary disk head mower-conditioner mowing Miscanthus, (**c**) a large round baler baling switchgrass, and (**d**) a large square baler baling Miscanthus

Fig. 5.25 (**a**) Self-propelled forage harvester chopping Miscanthus. (**b**) A single-pass machine that can mow and bale in a single pass

Compared to other energy grasses, Miscanthus presents the greatest challenge to traditional hay and forage harvesting machinery because of its higher yield and high stalk rigidity. The thickness and sturdiness of Miscanthus stems make them difficult to cut and convey. Heavy conditioning after mowing helps to break stems and improve crop flow into a baler. Metal crimping rollers perform better than the rubber rollers. Poor conditioning causes plugging of baler and frequent field stops.

5.4.1.2 Single-Pass Harvesting of Energy Grasses

A single-pass machine has advantages such as eliminating one pass and reducing ash content and biomass losses. A forage harvester is a good example of a single-pass harvesting machine. A forage harvester cuts and conveys the chopped biomass into an accompanying wagon (see Fig. 5.25a). The chopped biomass has a typical density of 100 kg m^{-3} compared to 150 kg m^{-3} for a square baler. There have been attempts to develop a single-pass machine that would cut energy grasses and then bale the harvested biomass, thus eliminating the need for a second pass (see Fig. 5.25b).

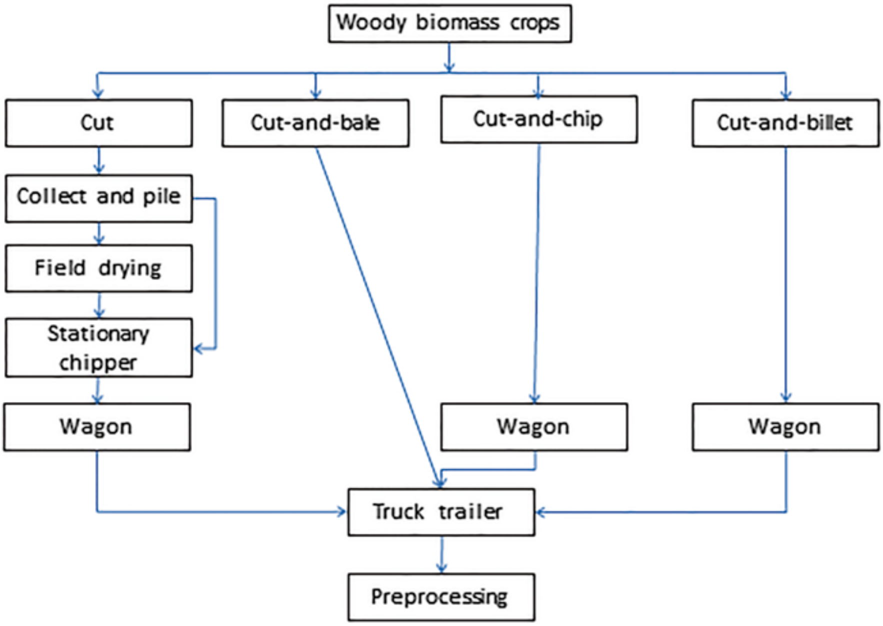


Fig. 5.26 Functional processes in harvest and transport of short rotation woody crops

5.4.2 *Short Rotation Woody Biomass Crops*

Woody crops with stem diameter less than 80mm are typically classified as short rotation wood crops that are grown on agricultural lands. Willow and poplar are the two candidate crops worldwide, and the machinery used to harvest them is similar. Willow harvesting is carried out when leaves have fallen from the willow stems. In North America, the harvesting period varies from the end of November until April. The moisture content is about 55–60 % when the willow is harvested. Since willow stools are more aggressive and can puncture tires, forest-based machinery tires that have tougher side walls are often used. The cutting devices may be redesigned so that they do not leave stubble which can puncture the tires of machines following the harvest. Figure 5.26 shows functional processes in harvest and transport of woody biomass.

5.4.2.1 Two-Pass Harvesting of Short Rotation Crops

The first option in two-pass harvesting is whole stalk harvesting and chipping. Whole stems are cut (Fig. 5.27a) and chipped wet or after natural drying (see Fig. 5.27b). Chipping of dried whole shoots is difficult because drying makes the shoots brittle. Also, small side twigs break off easily during handling, and a large

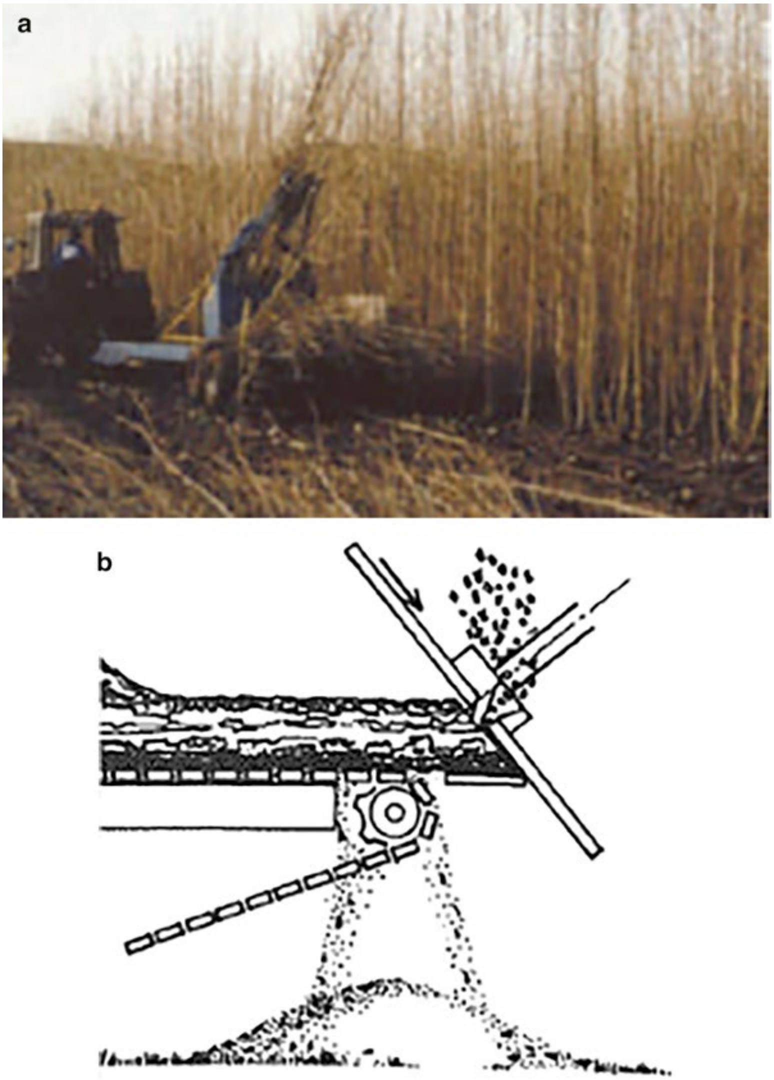


Fig. 5.27 (**a**) Whole stalk harvesting of willow stems. Adapted from [24]. (**b**) Tree chip cutter. Adapted from [15]

pile of debris can be left behind after chipping. The second option in two-pass harvesting is to cut and shred the crop with a mulcher (Fig. 5.28a) and bale the shredded windrow using a baler (see Fig. 5.28b). The bales are dropped in the field and later collected and transported.

Fig. 5.28 (**a**) BH-120 Fecon head mulcher. (**b**) Claas Rollant 250 round baler used to harvest forest understory bushes. Adapted from [25]

5.4.2.2 Single-Pass Harvesting of Short Rotation Crops

Willows can be harvested using cut-and-chip, cut-and-billet, and cut-and-bale methods. The cut-and-chip method involves use of a cutting mechanism and chipping mechanism designed for tougher woody material like willow (Fig. 5.29a). The cut-and-billet method is employed by typical sugar cane chopper-harvesters (see Fig. 5.29b). The chipped or billeted material is received in a trailer. Self-propelled machines pose soil compaction problems because of their weight. The use of track-type machine reduces compaction, but the track-type machine needs to be transported on a low loader from site to site. Further, the trailer used for receiving chips

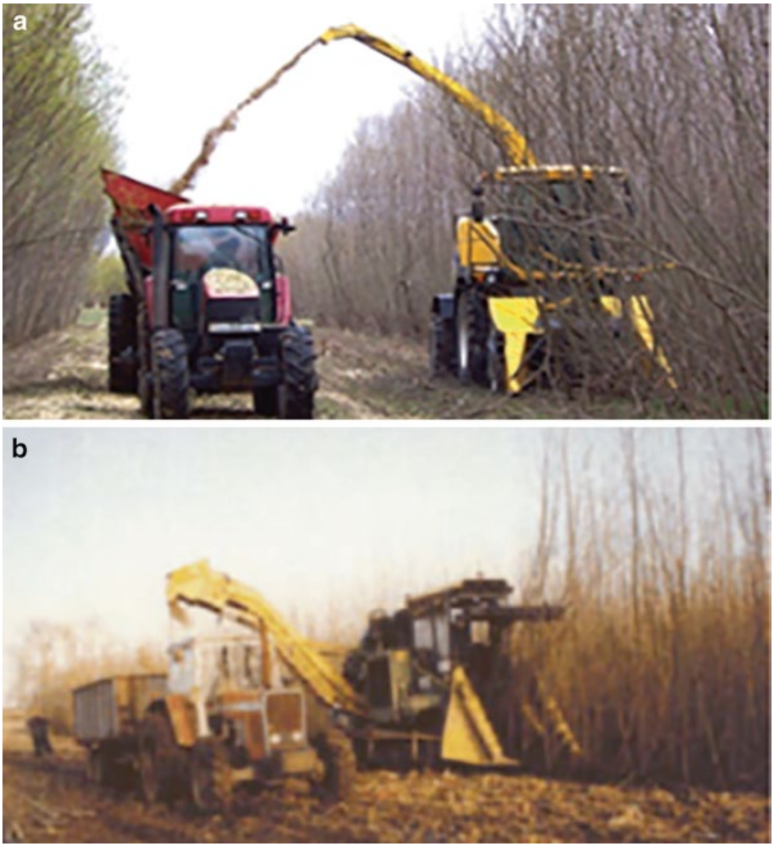


Fig. 5.29 Harvesting machinery for short rotation woody crops: (**a**) Case New Holland coppice harvester and chipper blowing chips into a tractor-pulled transfer bin. Adapted from [3]. (**b**) An Austoft cut-and-chip harvester chopping poplar. Adapted from [24]

or billets also needs to be fitted with tracks. The chip or billet size can be adjusted to meet specific needs. The cut-and-bale method for willow is a developing concept. It involves cutting and shredding the stalks (Fig. 5.30a) and baling them in a single pass (see Fig. 5.30b). The bales can be picked up by a loader and transported to the edge of the field.

5.4.3 Green Energy Crops

Important green energy crops are sugar cane, energy cane, and sorghum. Sugar cane chopper-harvesters or forage choppers can be used to harvest these crops. Typically, sugar cane has higher sugar content but lower fiber content than energy cane.

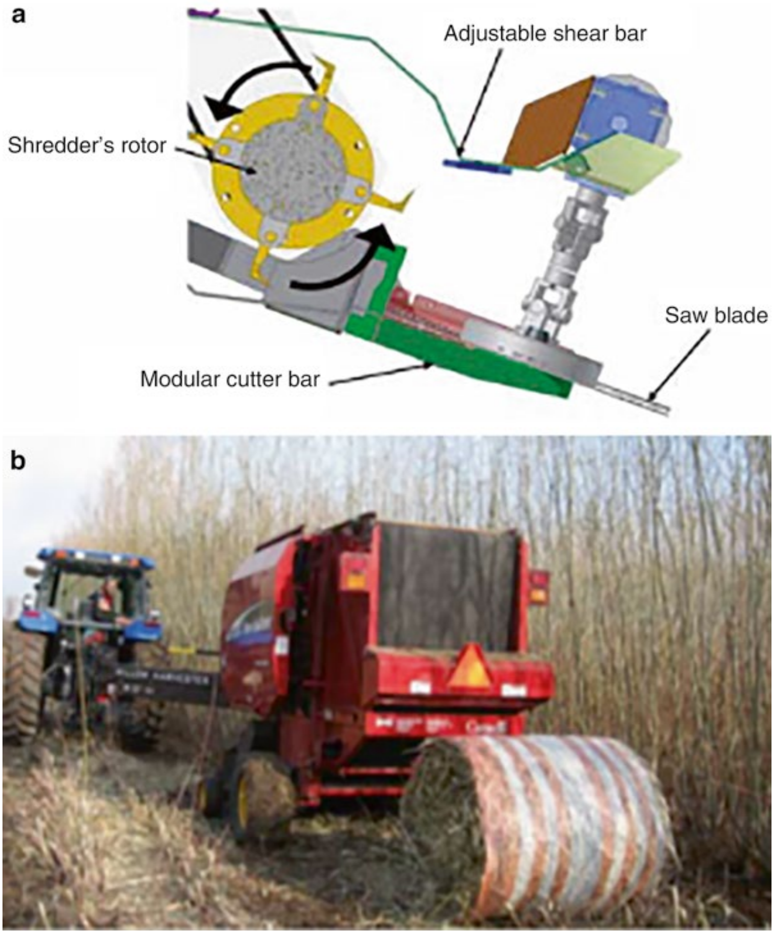


Fig. 5.30 (**a**) Cross-section of the cutting and shredding mechanisms for willow stems. (**b**) Cutter-shredder baler cutting and baling willow stems. Adapted from [26]

The energy cane stems are thinner and taller compared to sugar cane, but they possess higher lodging resistance. It is widely believed that sugar cane harvesting machinery can be adapted for energy cane harvesting with some modifications. There are several sugar cane harvesting methods, each having their own set of advantages and disadvantages (Table 5.4). Some developing countries still practice manual harvesting of sugar cane in varying proportion, whereas most of the developed nations practice mechanical harvesting of sugar cane. Mechanical harvesting increases soil compaction and also ash content as the harvested produce can be contaminated with soil dirt picked up through the harvesting process. A schematic of different harvest and transport options for green energy crops is shown in Fig. 5.31.

Table 5.4 Comparative features of sugar cane harvesting technologies used in Brazil[a]

	Type of harvesting		
Parameter	Semi-mechanized	Mechanized—chopped cane	Mechanized—whole cane
System features	Hand cutting with mechanical grab loading	Stalk and top cutting with simultaneous cleaning and loading	Stalk and top cutting with cane bundling
Fraction of today's harvest	About 80 % (decreasing)	<20 % (increasing)	<2 %
Harvesting capacity	Cutting: 4–7 t man^{-1} day^{-1}	400 t machine^{-1} day^{-1} (may achieve 600)	600 t machine^{-1} day^{-1} (may achieve 700)
	Loading: 400 t machine^{-1} day^{-1}		
Cost (US$ t^{-1})	3–4 (cutting and loading)	2	1.5
Main restrictions	Lack of labor obliging import of labor from other states in the country	Loss of raw material from base cutter, conveyor rollers, chopper, and extractors	Losses of raw material originate from base cutting and elevating rollers
	Interruption of production because of regional strikes	Intense traffic between lines, two transits by the harvester, and the transport vehicle	Traffic between lines; two transits by the harvesters
	Need for training to maintain quality and productivity	Overload of decanters at the factory	Damaged stalks by the base cutter and transporting rollers
	Makes green cane harvesting more costly		
Advantages	Better quality (e.g., lower soil content)	Reduced labor compared with manual cutting	Minimum incidence of labor (only in operation and maintenance)
	Lower raw material losses	Reduced harvesting costs	Independence of cutting and transporting operations which eases the operation management
	Avoids the setup of operation and maintenance infrastructure of harvesters and specialized operation teams	Easy harvesting operations	Increases productivity of cutting and transporting operations
		Makes green cane harvesting feasible	

Operating principle	Cutting: the cane stalks are cut at the base and deposited on five-row windrows oriented towards the planting lines	Cutting and loading: double horizontal rotating disks for cutting helped by helicoidal rotating cones feeders (helpful for non-erect cane harvesting)	Cutting and feeding: double horizontal disks for base cutting helped by a pair of rotating cones with helicoidal edges for separating, elevating, and feeding the non-erect cane with intercrossed stalks between the lines
	Loading: grab loaders with hydraulic handlers mounted on tractors remove 600–1,200 kg bunch that are transferred to the transporting vehicle (cost of loading: US$ 0.5–0.6 per ton)	Tops cutting: cutting by inertial blades fed by two converging counter-wise rotors (mainly for erect cane)	Tops cutting: inertial cutting through a disk with peripheral trapezoidal knives fed by two converging counter wise rotors
		Elevation and dirt separation: cascade of paired-mounted rolls, rotating in opposite directions with increasing tangential speed to the chopper	Elevation and dirt separation: cascade of paired-mounted rolls, rotating in opposite directions with increasing tangential speed to the discharge
		Chopping and ventilation: two rotating axial knives with contrary and synchronized rotation, chop and upload the material in a pneumatic cleaning chamber to separate the leaves by terminal velocity	Mowing and discharge: the whole stalks are launched to the interior of a bin where they are accumulated to form a bunch to be discharged in regular intervals forming rows perpendicular to the planting lines. The traffic during the loading operation should be perpendicular to the furrows which has been a rejecting factor by the harvester's users because of trucks and loaders overloading

[a] Adapted from [28]

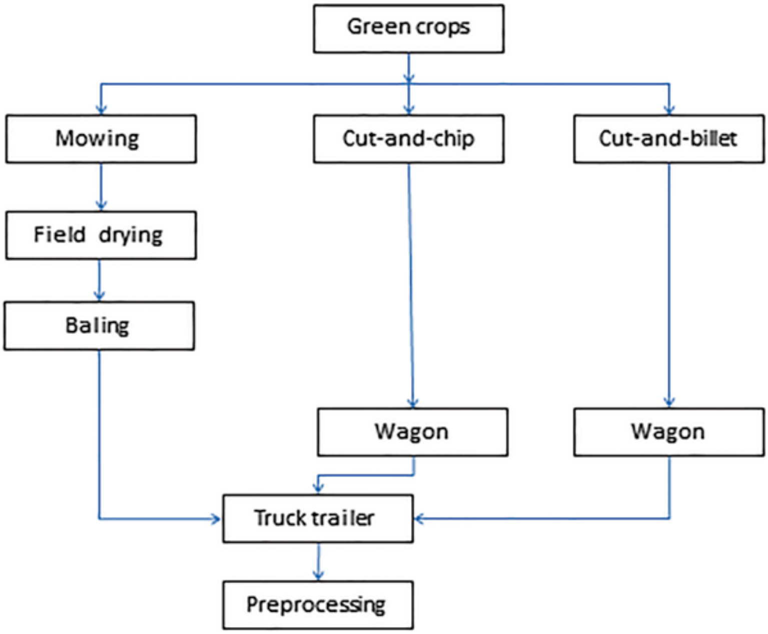


Fig. 5.31 Functional processes in harvest and transport of green crops

5.4.3.1 Whole-Stick Harvesting

Whole-stick cutting consists of cutting the cane at the base, removing the leafy green top and sometimes the trash or leaves, and placing the cane in swaths or heaps. These operations are facilitated by burning the crop in the field. However, burning is considered an environmentally unacceptable practice and is increasingly discouraged. The equipment available for whole-stick harvesting and transport are discussed below:

- Cutter windrowers: Cutter-windrower operations consist of straightening the cane, cutting the green top, cutting at the base, and conveying the cane and windrowing (Fig. 5.32a). The machines are available in one- or two-row form and can achieve average throughput of 60 t h^{-1}. The windrows are picked up by the loaders. These machines were designed for Louisiana conditions in which the cane is planted on ridges 1.7 m apart. They are not suitable for cane yielding more than 100–120 t ha^{-1} or for lodged cane.
- Cutter stackers: Cutter stackers are designed for a single row. The cane is straightened up, topped, cut at the base, and conveyed to a hopper to form bundles of 500 to 1,500 kg (see Fig. 5.32b). The bundles are expelled in the field for later picking up by a loader. These machines can achieve 50 t h^{-1} throughput rates. These machines can be used for high yielding cane, such as 150 t ha^{-1} and above and for less erect crops.

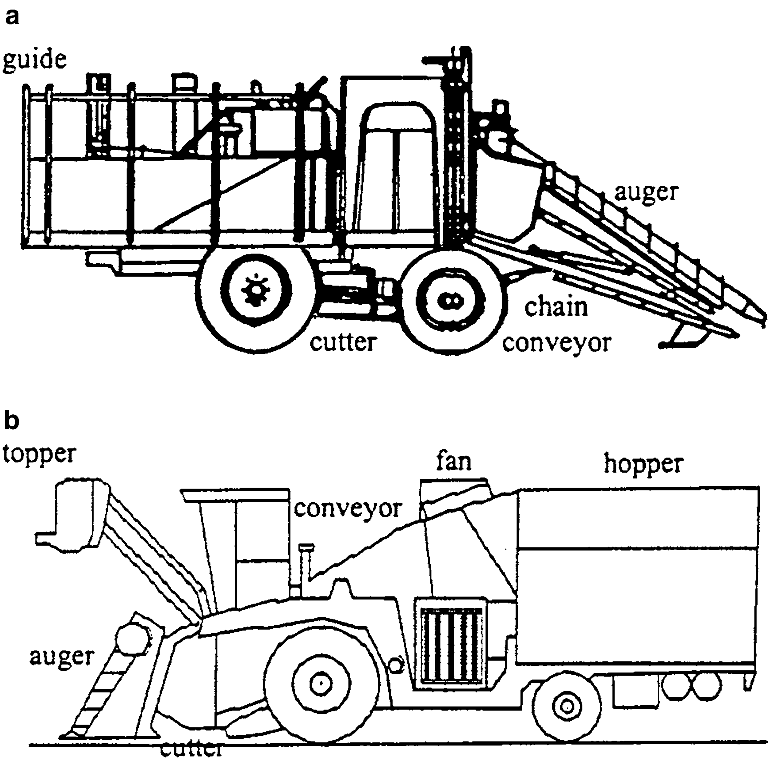


Fig. 5.32 (**a**) Cutter-windrower and (**b**) cutter-stackers used in whole-stick harvesting of sugar cane. Adapted from [21]

5.4.3.2 Loading Whole Cane

Discontinuous and continuous loading are the two basic ways of loading whole cane. Windrows could be picked up by a continuous loader whereas heaped cane and windrows could be picked up by a discontinuous loader. Continuous loading can result in a large amount of rocks and soil being incorporated in the load.

Discontinuous Loaders

Front-Mounted Tractor Loader. The loader is mounted on an agricultural tractor through a frame adapted for the type of tractor hitch. The grab or drag is controlled through hydraulic cylinders. It is a suitable attachment for small farms with a throughput capacity of 15 t h^{-1}. Its operation can cause damage to cane stumps although this attachment is suitable for both loading and transporting (Fig. 5.33a).

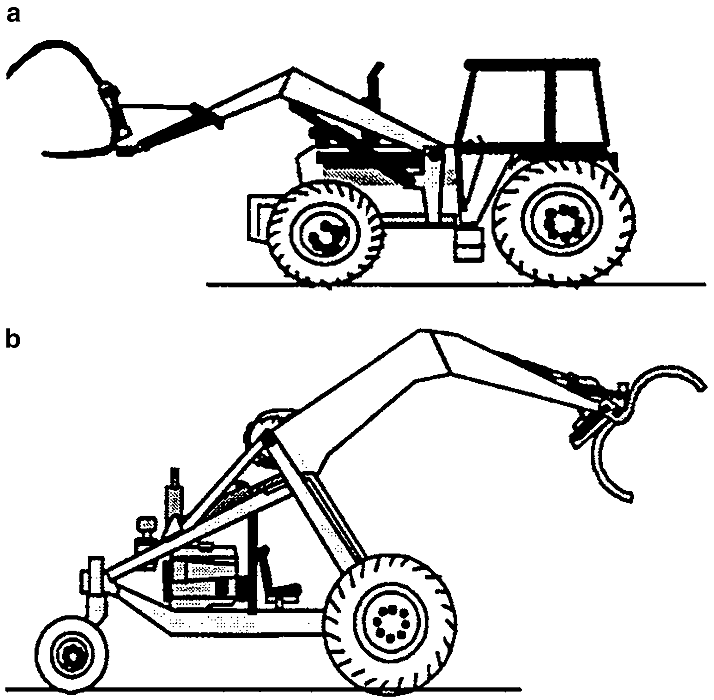


Fig. 5.33 (**a**) Front-mounted tractor loader and (**b**) self-propelled front-end loader used in whole-stick harvesting of sugar cane. Adapted from [21]

Self-Propelled Front-End Loader. The bell loader, a three-wheeled fixed-arm loader, is equipment designed for sugar cane which has exceptional maneuverability. It can handle both heaped and windrowed cane with a throughput rate of 30–40 t h^{-1} (see Fig. 5.33b).

Swivel Loader. This type of loader is mainly used for loading cane stacked beside roads. Loading capacity in the field is about 40–45 t h^{-1} while its capacity is about 60–65 t h^{-1} when loading from the headland.

Power-Loading Trailer. This machine is typically designed to lift and transport the cane bundles over the side (side loader) or back of the trailer using a winch.

Continuous Loaders

Pushloader. This tractor-mounted machine consists of forks designed to push the windrows to form a heap in front of the tractor. A claw gathers the heap formed by the fork and picks it up to load into a truck. These machines can typically handle 60–80 t h^{-1}.

Continuous Loader. This machine has wide chain elevators that pick up the windrow and convey the canes to a chopping device which cuts the cane into 40–50 cm billets. The billets are loaded into a following trailer. The capacity is about 200 $\mathrm{t\ h^{-1}}$ but losses are high.

5.4.3.3 Transport and Delivery of Whole Cane

Cane is transported by agricultural tractors and trailers over short distances (up to 10 km) and by high-capacity (70 $\mathrm{m^3}$) road trailers or articulated lorries (trailer trucks) for long distances. Some sugar factories transport cane by rail, with sidings where cane is picked up from collection points on the edge of the fields. Cane weighing and sampling at the receiving stations is an integral part of the system. Chained bundles are unloaded by a suitable crane on a traveling gantry. Whole cane can be tipped from the side or rear of the trucks. In addition, agricultural trailers (wagons) can be elevated and then emptied into a bigger trailer. The cane is picked up at the factory again by a loader or a stacker and thrown on to the feed table, which conveys the cane to the crusher.

5.4.3.4 Harvest of Chopped Cane

A chopper-harvester cuts the cane at the base, chops the cane into billets of 20–40 cm size, and loads the billets into a following wagon. Figure5.34 shows a schematic of functional components of a chopper-harvester. A topper removes the green cane tops, and extractor fans remove the trash. Feed rolls convey the cut cane to the chopping unit, and billets are conveyed by an elevator. A chopper-harvester is distinguished by the location of where it chops the cane. It is called a bottom chopping type when it chops the cane immediately after base cutting. This type consumes less power, but the chopping blades are exposed to rocks. A second type chops the cane after conveying it through the machine and is called a top chopping type. It consumes more power but eliminates potential damage by rocks.

The wagons typically transfer the chopped billets into a truck trailer with crates fabricated with plain or steel-mesh walls (Fig. 5.35). The capacity of trailers varies from 6 to 14 tons of chopped cane. Higher tonnage is possible in flat terrains, similar to "cane trains" in Australia that carry over 100 tons. At the factory, the trailers tip their load into the receiving hoppers. An elevator empties the billets on to the main conveyor table for feeding to the crusher.

5.4.3.5 Sorghum Harvesting

Sorghum can be harvested green similar to corn silage using forage choppers or harvested dry similar to hay by mowing-conditioning, field drying, and baling. Mower-conditioner capacity is affected by harvest time (Table 5.5) and also lodging direction

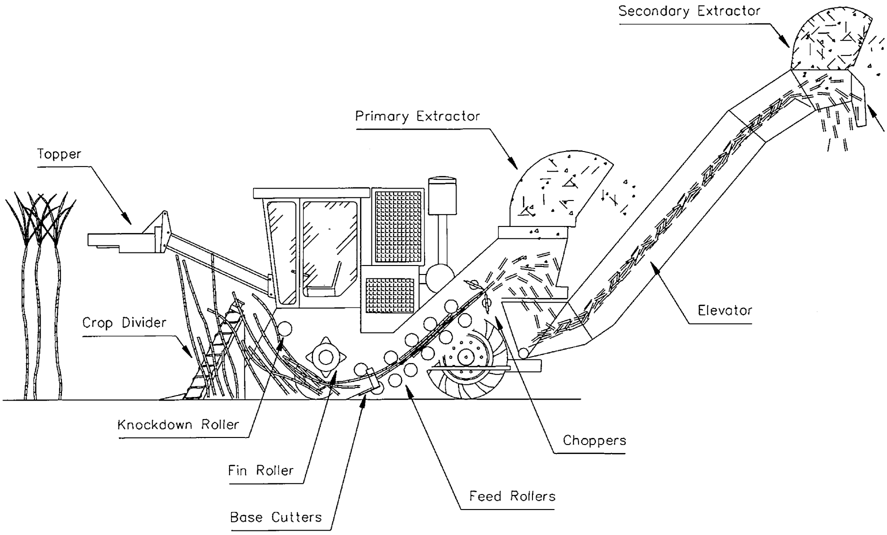


Fig. 5.34 Functional components of a sugar cane chopper-harvester. Adapted from [27]

Table 5.5 Field capacities (ha h^{-1}) and throughput rates (Mg h^{-1}, wet basis) for different mower-conditioners for sorghum as affected by the harvest time[a]

	Early August		Late August		October		November		January	
Harvest	ha h^{-1}	Mg h^{-1}	ha h^{-1}	Mg h^{-1}	ha h^{-1}	Mg h^{-1}	ha h^{-1}	Mg h^{-1}	ha h^{-1}	Mg h^{-1}
MacDon Auger	1.78	76.9	1.55	83.7	0.88	56.8	0.99	59.6	1.88	58.7
MacDon Disk	2.03	90.2	1.72	88.0	1.01	62.1	0.67	48.2	2.57	73.4
Deere Tri-Lobe	1.85	77.3	1.32	64.7	1.41	87.1	NA	NA	0.63	21.5
Deere Flail	1.92	74.8	1.20	60.2	1.10	65.2	NA	NA	0.91	NA

[a] Adapted from [29]

[29]. The field efficiencies for the mower-conditioners can be reduced due to machine plugging and crop build-up in front of the header. Poor windrowing (presence of longer stems) also reduces baling capacity. The baler field capacity is much lower compared to the mower-conditioner (Table 5.6). The theoretical cut length and moisture content also affects the self-propelled forage harvester performance (Table 5.7).

5.4.3.6 Energy Cane Harvesting

Energy cane can be harvested green similar to sugar cane or harvested dry similar to hay. Typically, green energy cane harvesting is similar to sugar cane harvesting along with other field operations. The other alternative is to harvest energy cane similar to hay. It consists of mowing green crop with rotary mowers capable of cutting 5- to 6-m tall plants with 2- to 4-cm diameter and conditioning. A throughput

Table 5.6 Field capacities (ha h^{-1}) and throughput rates (Mg h^{-1}, wet basis) for a baler and a self-propelled forage harvester (SPFH) for sorghum as affected by the harvest time[a]

	LB 433 Baler		FR 9080 SPFH	
Harvest	ha h^{-1}	Mg h^{-1}	ha h^{-1}	Mg h^{-1}
Early August	1.0	26.8	2.1	53.6
Late August	Na	na	3.0	51.3
September	1.0	54.2	2.8	53.4
October	1.0	44.1	na	na
November	0.8	37.3	1.4	52.1

[a]Adapted from [29]

Table 5.7 Ground speed (km h^{-1}) and throughput rate (Mg h^{-1}) for a forage harvester chopping sorghum as affected by theoretical length of cut (TLC) and harvest time[a]

Harvest	Theoretical cut length (mm)	Ground speed (km h^{-1})	Throughput rate (Mg h^{-1})	Moisture content (w.b.) %
Early August	6.3	2.91	43.8	40
	6.3	4.41	33.5	19
	15.9	4.17	23.3	40
	22.9	4.42	48.7	17
Late August	6.3	3.13	12.9	27
	14.7	4.57	34.4	29
	23.4	5.84	47.4	45
	31.8	8.77	55.3	25
September	6.35	3.30	54.1	22
	31.8	3.44	65.0	27
November	31.8	1.42	25.8	34

[a]Adapted from [29]

rate of about 18–20 Mg D ha^{-1} has been achieved [30]. About 5–7 days are needed, in Florida, to dry the conditioned crop to about 15–20% moisture, which is safe for storage [30]. One fluffing operation is needed to expose the wet crop in contact with the soil. Additionally, fluffing may be needed if rain occurs. In a 5-year study in Florida, it was found that for about 65 % of the time the conditioned crop would be exposed to the rain [30]. It was possible to bale the crop when moisture content was 35 % or lower. Most of the equipment tested had challenges in handling high quantities of biomass. Table 5.8 shows the cost of harvesting operations for energy cane and elephant grass.

5.4.4 Harvesting Agricultural Residue

Most of the agricultural and horticultural crops produce a substantial amount of residue, which is left in the field. Harvesting agricultural residue looks promising because it could provide additional income to farmers in addition to income from the main produce. A schematic of different harvest and transport options for agricultural residue is shown in Fig. 5.36.

Table 5.8 Cost of harvesting operations for energy cane and elephant grass[a]

Operation	Grass	\$ ha^{-1}	\$ Mg^{-1} (dry basis)
Cutting	Energy cane	117	5.8
	Elephant grass	114	4.7
Fluffing	Energy cane	30	1.5
	Elephant grass	21	0.9
Baling	Energy cane	89	4.4
	Elephant grass	101	4.1
Totals	Energy cane	236	11.8
	Elephant grass	236	9.6

[a] Adapted from [30]

Fig. 5.35 (**a**) Sugar cane chopper-harvester in operation and (**b**) a truck trailer ready for long-distance travel. Adapted from [27]

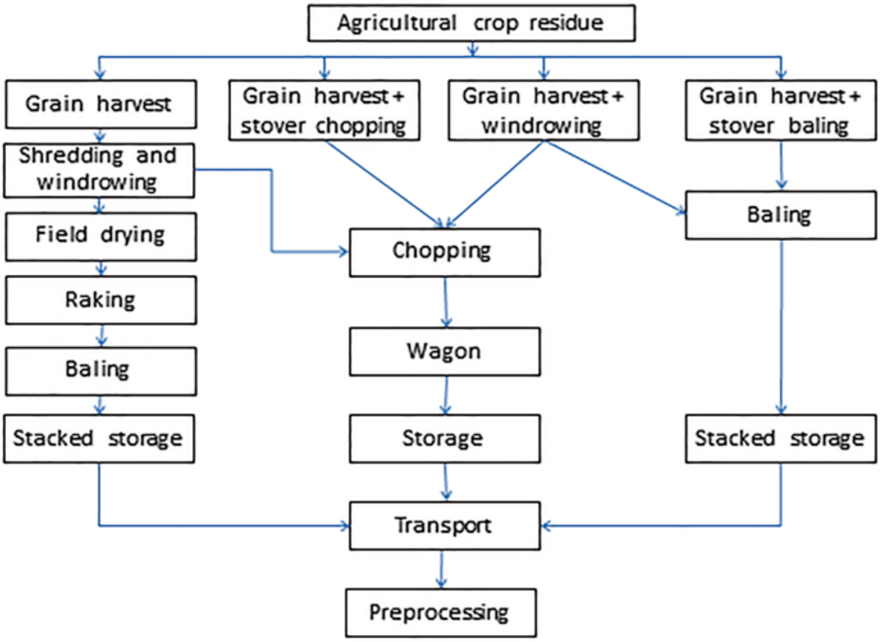


Fig. 5.36 Functional processes in harvest and transport of agricultural residue

5.4.4.1 Corn Stover

Corn stover consists of the stalk, leaf, cob, and husk of the corn plant and excludes the grain. The estimated corn stover yield in North America is about 130 Tg, which can produce 38.4 GL of ethanol [31]. Corn stover has a considerable advantage compared to switchgrass and small-grain straw because of its current availability as a by-product of corn grown as a food and fuel source. However, corn stover removal results into loss of soil cover and nutrients, which could potentially increase soil erosion and water pollution.

Typically, dried corn stover is baled. Traditionally, after grain harvesting, a flail shredder shreds the stalks, the sunlight dries the spread stover, a rake forms windrows, and a round baler bales the windrows at about 20–25 % moisture. In North America, it takes several days to weeks before the stover reaches baling moisture because of low ambient temperature and rains. Sometimes stover is harvested wet (>45 % moisture) and preserved by ensiling [32]. Wet harvesting eliminates field drying and improves timeliness. After a combine has harvested the grain, a shredder shreds and windrows the stover in a single pass. A forage harvester with a windrow pickup head gathers and chops the stover. Table 5.9 shows the results of a study in North America on the performance of a precision-cut forage harvester for corn stover harvesting. The wet throughput rate varied from 40 to 55 Mg ha^{-1} and dry

Table 5.9 Productivity and physical properties of corn stover harvested as chopped material using precision-cut forage harvester[a]

		Harvester mass flow		Density in truck		Density in silo bag		Final
Length of cut	Moisture (%, w.b.)	Wet (Mg h^{-1})	Dry (Mg h^{-1})	Wet (kg m^{-3})	Dry (kg m^{-3})	Wet (kg m^{-3})	Dry (kg m^{-3})	particle size (mm)
2002								
6.4 mm	48.4	49.1	25.9	158^{b}	82^{b}	288	150	17.8
12.7 mm	47.9	53.7	28.0	134^{c}	69^{c}	301	157	25.4
19.1 mm	45.8	55.5	30.1	126^{c}	67^{c}	286	150	27.9
LSD[d] ($P=0.05$)	4.1	14.3	9.1	18	5	91	43	NA
2003								
6.4 mm	49.6	40.8	20.2^{c}	136	67	261	130	20.3^{c}
12.7 mm	48.0	51.3	26.0^{b}	131	69	251	128	22.9^{b}
19.1 mm	45.8	51.3	26.8^{b}	128	69	240	122	27.9^{b}
LSD[d] ($P=0.05$)	6.5	11.1	4.2	24	13	75	37	2.5

[a] Adapted from [32]

[b] In 2003, particle size of stover before shredding and chopping was 610 mm and after shredding but before chopping was 172 mm. Stover yield was 10.5 Mg DM ha^{-1} just preceding grain harvest. Average harvested stover yield after shredding, windrowing, and chopping was 5.8 Mg DM ha^{-1}

[c] In 2002, particle size of stover before shredding and chopping was 690 mm and after shredding but before chopping was 290 mm. Stover yield was 9.2 Mg DM ha^{-1} just preceding grain harvest. Average harvested yield after shredding, windrowing, and chopping was 4.9 Mg DM ha^{-1}

[d] Averages with different subscripts in the same column are significantly different at 95 % confidence

Table 5.10 Productivity and physical properties of wet corn stover harvested as baled material using large round or large square balers[a]

		Baler mass flow		Bale density		Harvested yield[b]	
	Moisture (% w.b.)	Wet (Mg h^{-1})	Dry (Mg h^{-1})	Wet (kg m^{-3})	Dry (kg m^{-3})	Wet (Mg ha^{-1})	Dry (Mg ha^{-1})
2002							
LRB[c]—Twine	37.9	18.0^{b}	11.2^{b}	176^{b}	109^{b}	6.7^{b}	4.3^{b}
LSB[c]	39.9	34.7^{c}	20.9^{c}	248^{c}	149^{c}	9.0^{c}	5.4^{c}
LSD[d] ($P=0.05$)	2.9	2.5	1.6	13	6	0.9	0.5
2003							
LRB[c]—Net	36.8	21.9^{c}	13.6^{c}	186	117	9.0	5.7
LRB[c]—Twine	36.8	16.1^{b}	10.2^{b}	190	118	8.5	5.4
LSD[d] ($P=0.05$)	6.3	2.4	1.2	16	10	1.8	0.7

[a] Adapted from [32]

[b] Stover yield of standing plant material was 8.6 Mg DM ha^{-1} just preceding grain harvest in 2002 and 11.3 Mg DM ha^{-1} in 2003

[c] *LRB* large round bales, *LSB* large square bales

[d] Averages with different subscripts in the same column are significantly different at 95 % confidence. LSD (least significant difference)

throughput rate from 20 to 30 Mg ha^{-1} as the theoretical cut length varied from 6.4 to 19.6 mm [32].

In the same study [32], the round bale density was found to be lower than the square bale density for both wet and dry harvest (Tables 5.10 and 5.11). The throughput rate was higher for the square baler than the round baler. Low ambient

Table 5.11 Productivity and physical properties of dry corn stover harvested as baled material using large round or large square balers[a]

	Moisture (% w.b.)	Baler mass flow Wet (Mg h^{-1})	Dry (Mg h^{-1})	Bale density Wet (kg m^{-3})	Dry (kg m^{-3})	Harvested yield[b] Wet (Mg ha^{-1})	Dry (Mg ha^{-1})
2002							
LRB[c]-Twine	23.0	6.8^{b}	5.2^{b}	123^{b}	94^{b}	4.7^{c}	3.6^{c}
LRB[c]—Net	23.5	7.3^{b}	5.5^{b}	138^{c}	106^{c}	2.9^{b}	2.2^{b}
LSB[c]	24.0	17.2^{c}	13.1^{c}	178^{d}	134^{d}	4.3^{c}	3.1^{c}
LSD[d] ($P=0.05$)	3.5	2.4	1.8	8	6	0.7	0.5
2003							
LRB[c]-Twine	$15.7^{b,c}$	11.2^{b}	9.5^{b}	139^{b}	118^{b}	5.4	4.7
LRB[c]—Net	17.0^{c}	16.5^{c}	13.7^{c}	138^{b}	114^{b}	5.6	4.7
LSB[c]	14.6^{b}	16.3^{c}	14.0^{c}	150^{c}	128^{c}	5.4	4.7
LSD[d] ($P=0.05$)	1.3	0.9	0.8	8	6	0.4	0.4

[a] Adapted from [32]

[b] In 2002, stover was harvested about 1 month after grain harvest, and stover yield was 8.9 Mg DM ha^{-1} just preceding grain harvest. In 2003, stover was harvested within 1 week of grain harvest, and stover yield was 11.6 Mg DM ha^{-1} just preceding grain harvest

[c] *LRB* large round bales, *LSB* large square bales

[d] Averages with different subscripts in the same column are significantly different at 95 % confidence. LSD (least significant difference)

temperatures and frequent precipitation posed challenges in field drying, and in only one out of four trials, the stover moisture decreased to about 20 % within 4 days of grain harvest [32]. For chopping, wet baling, and dry baling, the collection efficiency averaged 55 %, 50 %, and 37 %, respectively. The throughput rate of a forage harvester, large square baler, and large round baler was 26.2, 16.0, and 9.8 Mg DM h^{-1}, respectively, when harvesting shredded stover. Gathering shredded stover with the pickup mechanisms was a common challenge experienced by the equipment tested.

5.4.4.2 Single-Pass Harvesting of Corn Stover

A single-pass harvester to harvest both corn stover and grain simultaneously has been developed [33]. The harvester was a modified combine with three heads to separately collect stover and grain (Fig. 5.37). The collected stover from the ear-snapper head consisted of cob and husk, whereas from the stalk-gathering head, it consisted of stalk and leaves, and from the whole-plant head, it included stalks, leaves, husk, and cob. Area productivity with the ear-snapper, whole-plant, or stalk-gathering head was 3.4, 1.5, and 1.9 ha h^{-1}, respectively (Table 5.12).

One way of achieving single-pass harvesting is to blow the residue coming out of the combine into a trailed wagon. Another way is to feed the residue into a baler. Figure 5.38 shows single-pass machines developed for corn stover baling and grain harvesting in a single pass [34, 35].

Fig. 5.37 Single-pass corn stover and grain harvester. (**a**) Grain combine modified with a stalk-gathering head (*front*) and cob-gathering head (*back*). (**b**) A grain combine modified with a whole-plant head and gathering cobs and husk. Adapted from [33]

Table 5.12 Stover and grain mass flow rates for different head types[a]

Year	Head type	Ratio of head to ear height	Area productivity (ha h^{-1})	Mass flow (Mg h^{-1})			
				Wet stover	Dry stover	Dry grain	Wet grain
2006	Ear snapper	0.57	2.9^{d}	8.4^{c}	5.3^{c}	37.6^{d}	29.2^{d}
	Whole plant	0.50	1.4^{b}	14.3^{e}	8.8^{d}	18.7^{b}	14.6^{b}
	Stalk gathering	0.43	1.8^{c}	14.8^{e}	8.8^{d}	23.2^{c}	18.1^{c}
	Front wagon			9.9^{d}	5.7^{c}		
	Rear wagon			4.9^{b}	3.1^{b}		
	LSD ($P = 0.05$)		0.1	0.8	0.5	3.0	2.4
2005	Ear snapper	0.45	3.4^{d}	12.0^{c}	7.3^{c}	50.4^{c}	38.1^{c}
	Whole plant	0.22	1.5^{b}	24.9^{e}	12.2^{e}	24.2^{b}	18.4^{b}
	Stalk gathering	0.22	1.9^{c}	18.4^{b}	9.5^{d}	25.0^{b}	18.9^{b}
	Front wagon			13.6^{c}	6.5^{c}		
	Rear wagon			4.8^{d}	3.0^{b}		
	LSD ($P = 0.05$)		0.3	2.3	1.2	3.7	2.2

[a] Adapted from [33]

[b, c, d, e] Different subscripts in the same column are significantly different at 95 % confidence. LSD (least significant difference)

Fig. 5.38 Combine-baler systems. (**a**) AGCO-developed combine-baler baling corn stover. Photo courtesy of AGCO Corporation [34]. (**b**) Single-pass machine showing grain harvest and corn stover baling. Photo courtesy of Dr. Matthew Darr, Iowa State University [35]

5.4.4.3 Two-Pass Harvest of Corn Stover

A two-pass system to harvest grain and stover was developed (Fig. 5.39b) and compared with a single-pass harvester [36]. The first pass of the two-pass system consisted of grain harvest, stover gathering, and windrow formation. The second pass involved picking up the windrow with a self-propelled forage harvester fitted with a windrow pickup head. The performance data are shown in Table 5.13. The two-pass grain harvest system reduced area productivity by 9 % compared to the conventional grain harvest system.

Fig. 5.39 (**a**) Combine harvester configured to harvest corn stover in a single pass using a precision-cut stover processor. (**b**) Combine harvester configured to harvest stover in two passes by forming stover windrows during grain harvest. Adapted from [36]

5.4.4.4 Orchard Residue

Orchard residue collection consists of pruning the trees and then harvesting the pruned branches. Figure 5.40a shows the pruned branches being harvested using a machine consisting of a pickup head and chipper. The current orchard residue collection requires two passes, one to prune the orchard trees and the second to windrow the pruned branches and chip them. A single-pass harvester (speedy cut,

Table 5.13 Stover and grain mass flow rates, area productivity for the different combine harvester configurations, and stover harvesting methods[a]

Harvester configuration	Header type		Ratio of harvest to ear height	Mass flow rate[b] (Mg DM h^{-1})		Area productivity (ha h^{-1})	
				Stover	Grain	Combine	SPFH
Single pass[c]	Ear snapper	With recutter	0.40	6.1[b]	34.5[c]	3.5[c, e]	–
		Without recutter	0.39	6.3[b]	34.4[c]	3.7[e]	–
	Whole plant	High cut	0.47	14.0[c]	23.7[b]	2.5[b, c]	–
		Low cut	0.40	15.2[c]	22.7[b]	2.3[b]	–
Two pass[d]	Stalk gathering		0.31	15.4[c, d]	32.8[c]	3.3[c]	3.8[b]
	Whole plant		0.24	18.7[c]	26.9[b]	2.7[c]	3.9[b]
Multi-pass[e]	Ear snapper		0.33	18.8[c]	35.7[c]	3.6[c, e]	4.2[b]
LSD[f] ($P=0.05$)				3.4	3.2	0.3	0.5

[a] Adapted from [36]

[b] Stover mass flow through the combine for single-pass treatments and through the self-propelled forage harvester (SPFH) for two-pass treatments

[c] Single-pass harvesting involved simultaneous harvest of grain and stover with the modified combine harvester. Theoretical length of cut of the stover processor was 19 mm, and recutter screen openings were 76 mm

[d] Two-pass harvesting involved a first pass to harvest grain with a combine harvester and a second pass to harvest stover with SPFH. Theoretical length of cut of the SPFH was 6 mm

[e] The multi-pass control configuration involved a first pass using an ear-snapper header to harvest grain, followed by stover harvest using flail shredding, raking, and chopping with SPFH

[f] Within each column, means followed by the same letter are not significantly different at the 5 % level. LSD (least significant difference)

Fig. 5.40b) capable of performing both pruning and residue harvesting in a single pass for olive orchards has been developed [37]. Table 5.14 compares self-propelled and tractor-mounted residue harvesting machinery [38]. The average cost of collecting olive pruning residue was 28 Euros per ton.

5.5 Rotary Power Requirement

Most of the machinery used for bioenergy harvesting, except the self-propelled units, are driven by the power-takeoff drive. Rotary power required for most of the machines can be calculated as power take-off power [39]:

$$P_r = C_1 + C_2 W + C_3 F \tag{5.2}$$

where P_r = rotary power required, kW; W = working width of machine, m; F = material throughput, t h^{-1} wet basis; C_1, C_2, C_3 = machine specific parameters given in Table 5.15.

Power required to overcome the implement and power unit rolling resistance is not included in the above equation and Table 5.15.

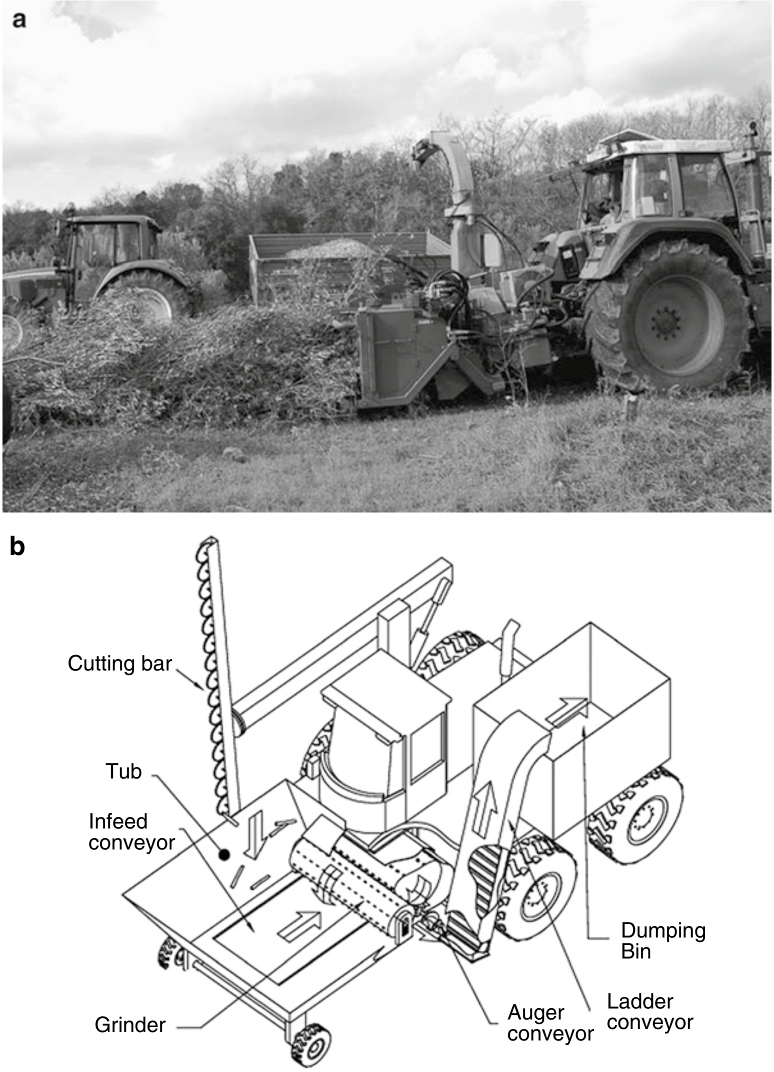


Fig. 5.40 (**a**) Tractor-mounted machine harvesting olive pruning residues. Adapted from [38]. (**b**) Single-pass orchard residue machine. Adapted from [37]

Table 5.14 Harvesting cost and productivity of two orchard pruning and chipping systems[a]

Machine	Self-propelled							Tractor mounted		
Field	1	2	3	4	5	6	7	8	9	10
Collecting comminuting (s)	3,233	1,496	10,302	3,858	3,992	2,564	7,112	1,606	7,052	8,920
Turning (s)	892	326	618	595	643	469	680	516	1,005	619
Forwarding (s)	1,028	664	6,060	1,452	1,466	598	3,589	0	0	0
Unloading (s)	494	368	3,359	1,159	1,481	755	2,773	226	1,106	1,602
Mechanical delays (s)	1,930	76	4,680	457	228	0	1,073	76	811	1,103
Other delays (s)	1,107	886	1,500	328	945	2,219	3,405	206	1,049	889
Total time consumption (s)	8,686	3,816	26,519	7,849	8,755	6,606	18,631	2,630	11,023	13,132
Mass harvested (t)	10.6	3.2	49.5	17.8	22.8	11.0	22.8	4.1	20.2	29.2
Area	6.57	1.61	7.04	8.61	12.90	10.20	18.44	0.59	1.74	1.58
Mass productivity (t)	4.4	3.0	6.7	8.2	9.4	6.0	4.4	5.7	6.6	8.0
Area productivity (ha h^{-1})	2.7	1.5	1.0	3.9	5.3	5.6	3.6	0.8	0.6	0.4
Hourly cost (Euro h^{-1})	158	158	158	158	158	158	158	149	149	149
Unit cost (Euro t^{-1})	36.1	51.9	23.5	19.3	16.9	26.3	35.9	26.4	22.6	18.6
Incidence of delays (%)	35	25	23	10	13	34	24	11	17	15
Mechanical availability (%)	78	98	82	94	97	100	94	97	93	92

[a] Adapted from [38]

Table 5.15 Parameters for determining rotary power requirements of agricultural equipment with an expected range in average power requirement due to differences in machine design, machine adjustment, and crop conditions[a]

	Parameter			
	C_1	C_2	C_3	Range
Machine Type	kW	kW m^{-1}	kWh t^{-1}	±%
Baler (small rectangular bales)	2.0	0	1.0[b]	35
Baler (large rectangular bales)	4.0	0	1.3	35
Baler large round (variable chamber)	4.0	0	1.1	50
Baler large round (fixed chamber)	2.5	0	1.8	50
Beet harvester[c]	0	4.2	0	50
Beet topper	0	73	0	30
Combine (small grain)	20.0	0	3.6[d]	50
Combine (corn)	35.0	0	1.6[d]	30
Cotton picker	0	9.3	0	20
Cotton stripper	0	1.9	0	20
Feed mixer	0	0	2.3	50
Forage blower	0	0	0.9	20
Flail harvester (direct cut)	10.0	0	1.1	40
Forage harvester (corn silage)	6.0	0	3.3[e]	40
Forage harvester (wilted alfalfa)	6.0	0	4.0[e]	40
Forage harvester (direct cut)	6.0	0	5.7[e]	40
Forage wagon	0	0	0.3	40
Grinder mixer	0	0	4.0	50
Manure spreader	0	0	0.2	50
Mower (cutter bar)	0	1.2	0	25
Mower (disk)	0	5.0	0	30
Mower (flail)	0	10.0	0	40
Mower- conditioner (cutter bar)	0	45	0	30
Mower-conditioner (disk)	0	8.0	0	30
Potato harvester	0	10.7	0	30
Potato windrower	0	5.1	0	30
Rake (side delivery)	0	0.4	0	50
Rake (rotary)	0	2.0	0	50
Tedder	0	1.5	0	50
Tub grinder (straw)	5.0	0	8.4	50
Tub grinder (alfalfa hay)	5.0	0	38	50
Windrower/swather (small grain)	0	1.3	0	40

[a] Adapted from [39]

[b] Increase by 20 % for straw

[c] Total power requirement must include a draft of 11.6 kN m^{-1} (±40 %) for potato harvesters and 5.6 kN m^{-1} (±40 %) for beet harvesters. A row spacing of 0.86m for potatoes and 0.71 m for beets is assumed

[d] Based upon material-other-than-grain (MOG) throughput for small grains and grain throughput for com. For a PTO-driven machine, reduce parameter **a** by 10 kW

[e] Throughput is units of dry matter per hour with a 9-mm (0.35 in.) length of cut. At a specific throughput, a 50 % reduction in the length of cut setting or the use of a recutter screen increases power 25 %

5.6 Summary, Future Challenges, and Recommendations

Worldwide research and development efforts to adopt existing harvesting equipment for bioenergy crops have achieved reasonable success. With current technology, it is possible to harvest most of the bioenergy crops with reasonable efficiency. However, biomass harvesting still constitutes a significant portion, for example, about 32.5 % for sugar cane, of crop production cost, and many technological challenges still need to be addressed. To address these technological challenges, collaboration between the manufacturing industry and research universities is highly desirable. Limited acreage under bioenergy crops due to lack of market for biomass is a major constraint in the development of machinery dedicated to bioenergy production.

Design modification to meet crop-specific needs is one of the ways to reduce the biomass harvesting cost. The model of having a crop-specific head with a common power unit looks promising. Proper matching of the machine capacities, involved in multiple passes, is critical in optimizing the delivered biomass cost. Similarly, operator education and operational management decisions are also critical. Furthermore, number of machines involved in harvesting and transport of the bioenergy crops need to be reduced to minimize the cost and to increase system reliability. Single-pass machines might help to bring down the harvest cost. Similarly, the critical submachine systems need to be identified and redesigned to increase the throughput rate of harvesting machinery. Documentation of bioenergy machinery evaluation should also be encouraged to avoid duplication of work and to promote efficient utilization of resources made available for bioenergy research.

Yield variability, within a plot and between plots, is another critical factor affecting harvesting cost. If equipment is operated at almost constant field speed in the low yielding as well as in the high yielding areas, then the harvest cost for the low yielding areas would be higher compared to the high yielding areas. Although a highly skilled operator can adjust the field speed of a machine according to yield levels, use of an onboard biomass yield sensor can play a critical role in automatically adjusting the field speed [40, 41]. In addition to biomass yield sensing, there is a need to develop methods for infield sensing of biomass quality such as ash content, sugar content, and cellulose content. If biomass from a bale or a wagon has higher ash content, then this specific biomass may be diverted to nonfuel purposes such as livestock bedding.

Overall, machinery to harvest bioenergy crops is available though there is need to improve their performance. Sensing methods can help in reducing variability in harvesting cost by variable speed control and determining the biomass quality while harvesting.

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Chapter 6
Transportation

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Abstract Transportation of lignocellulosic biomass feedstock is an important task within a biomass-based energy provision system. The distributed availability of low-density feedstock makes this operation highly challenging. The proposed aim to replace a large percentage of fossil fuels with renewable lignocellulosic bioenergy sources by the year 2030 [1, 2] will require adaptation and possibly renovation of the existing transportation infrastructure. The complexity of the biomass provision system will be further increased as compared to the current system since the biomass feedstock portfolio will consist of a range of energy crops, grown in various locations with unique climates and transportation infrastructures.

Ideally, biomass would be preprocessed into a gravity-flowable particulate bulk form that allows utilization of and expanding upon the existing transportation infrastructure of agricultural bulk products such as corn and soybean. Such a form would require size reduction of feedstock, which is energetically expensive, followed by compression. To optimize long-distance transport, the bulk density of this feedstock would ideally be as high as that of coal in railcars. This would require very high "in-mold" particulate densities of the feedstock generated by machines with very high throughput. Even if this goal could be achieved, it is currently not clear what the effect of such a highly densified material form on the conversion efficiency would be.

Finally, apart from technical challenges in producing the ideal form of biomass from a provision and conversion perspective, there is a huge challenge in the mere scale of the proposition: If the goal set by the US government of replacing 30 % of

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Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4_6,

current fossil fuels by 2030 is to be reached, the annual transported volume of biomass would be three times that of the 2011 US corn yield.

This chapter reviews the literature on research that addresses biomass feedstock provision including transportation and identifies challenges that must be addressed in the near future.

6.1 Introduction

The US Biomass R&D Technical Advisory Committee has recommended a 30 % replacement of the current US oil consumption with biofuels by 2030 [1, 3]. This is motivated by the desire to move towards sustainable sources of energy to address looming problems such as climate change and energy security. The sources of biomass feedstock are highly distributed because high biomass yielding energy crops are limited to specific growth regions characterized by land use policy, water availability, soil type, climate, and latitude.

In first-generation biofuels, corn starch and sugar cane are converted into ethanol, while vegetable oil, soybean oil, palm oil, and similar sources are converted into biodiesel. Since these sources are conventional agricultural products, the transportation of first-generation biofuel feedstock can employ the infrastructure built for corn, soybean, and other field crops. A drawback of first-generation biofuels is that the crops used as feedstock compete with food production. In contrast, second-generation (advanced) biofuels are produced from lignocellulosic nonfood sources, such as agricultural residues, energy grasses, forest residues, and woody plants. With the emergence of second-generation biofuels, new challenges have arisen, since crops such as Miscanthus, switchgrass, and energy cane need to be efficiently harvested, preprocessed, stored, and transported. Since these are not conventional agricultural products, the existing infrastructure is not optimized for their transport. Firstly, size reduction (comminution) is required, because no conversion process can process uncut material directly. Secondly, the energy density of the crop in the field is very low, and compression beyond baling is needed for long-distance transportation [4]. Thirdly, the scale of feedstock provision is huge: The goal of a 30 % replacement of the current US oil consumption by 2030 will increase the annual demand for feedstock to one billion dry tons of cellulosic feedstock, which is more than threefold the 2011 US corn production [1, 2, 5]. Biomass can be combusted directly (either for domestic heating or commercial power generation) or in combination with fossil fuels such as coal, but even here challenges arise, mainly because of the biomass' high ash content. The logistics of direct combustion are relatively straightforward. For domestic heating, the biomass is preprocessed into pellets, briquettes, woody chips, or bundled firewood logs, which are also produced from prairie grass feedstock, sugar cane bagasse (a by-product of sugar cane ethanol production), or agricultural residues (e.g., corn stover). For commercial power generation, biomass can be co-combusted through blending with coal, converted into a gas, or fed directly into a furnace.

The production of liquid fuels is achieved through thermochemical/hydrothermal, biochemical, and/or chemical processes, with or without pretreatment. These processes typically produce ethanol or bio-oil as the fuel. The liquid biofuel production chain consists of three sequential parts: (1) feedstock provision, (2) pretreatment, and (3) conversion. If the complete liquid biofuel production chain is to be optimized, the biomass material must be preprocessed into a form that optimizes each of the three parts, but unfortunately they are not necessarily in agreement: The optimal form of the material during the feedstock provision phase is dominated by handling and transportation requirements. For instance, to optimize the provision phase, the material should ideally be preprocessed into a form that minimizes losses (e.g., by limiting dust), flows under gravity to allow the use of traditional conveying equipment such as augers, chutes, and conveyor belts, and have a sufficiently high bulk density to ensure that the transportation equipment reaches its weight and volume limits simultaneously. From this viewpoint, stable biomass consisting of flowable particulates of consistent size and shape with a high material density would be ideal. This concept has been captured in the Uniform Format as defined by Idaho National Laboratory [6]. The aim here is to gradually transition from "Conventional Bale" systems through a "Pioneer Uniform" system, which uses mainly existing equipment, to the futuristic "Advanced Uniform" system, which provides stable solid biomass in a blendable, tradable commodity form. The target is to reduce the cost of delivered biomass from US\$100 ton^{-1} in 2007 to US\$30 ton^{-1}, in 2017 [6].

To optimize the complete biofuel production chain, the provision phase must produce materials in a form that are well suited for pretreatment, which must transform them into a form that allows for optimization of conversion. Pretreatment is a process in which the structure of the lignin, cellulose, and hemicellulose matrix is broken down to enable enzymatic activity during hydrolysis. This can be achieved by chemical methods using acids and ionic liquids, using enzymes, using physical methods (such as the classical steam explosion process used in corn ethanol production), or by using a combination of chemical and physical methods, such as the ammonia fiber explosion (AFEX) method [7, 8]. The extent to which the pretreatment method is robust with respect to the biomass form is not known for most bioenergy crops. Although AFEX employs a physical explosion process, it is sensitive to particle size in the case of corn stover [9]. In general, for pretreatment methods that do not incorporate physical separation processes, the ideal particle size may be as small as 80 μm. This is achievable by ball milling the material for a rather long time. However, research on *Miscanthus giganteus* has shown that size reduction to such a small size requires 100 % of the inherent heating value (PIHV) of the material. Therefore, the optimal particle form for conversion is to a large extent determined by the trade-off between the energy requirement for comminution and the increased conversion efficiency for smaller particle sizes. As a general rule, the feedstock must be comminuted into particle sizes ranging from 9.35 to 25.4 mm with pretreatment and smaller than 1 mm without pretreatment. Table 6.1 shows an overview of typical particles sizes as a function of conversion technologies and feedstock.

The chapter is arranged as follows: Firstly, various types of feedstock currently either employed or under investigation are addressed. Secondly, preprocessing

Table 6.1 Biomass feedstock type and forms matrix for four categories of conversion technology[a]

Biomass conversion technology	Major outputs and products	Preferred feedstock types	Feedstock form requirements
Gasification	Electricity, thermal energy, hydrogen, bio-oils, charcoal	Dry feedstock	Coal size particle distribution
Pyrolysis	Bio-oil, charcoal, electricity, thermal energy	Any feedstock (<10 % moisture content preferred to assure high heat transfer rate)	<6-mm particle (1–2 mm preferred)
Biochemical ethanol production	Ethanol, lignin, electricity, and heat	Cellulosic/woody biomass	<9.35- to 25.4-mm particle with pretreatment, <1 mm without pretreatment
Chemical biodiesel production	Biodiesel, soaps, and glycerin	Bio-oil from feedstock gasification or pyrolysis	The same as gasification and pyrolysis

[a]Adapted from [48] and [11]

operations are discussed with an emphasis on energy requirement. Thirdly, transportation of biomass using truck, rail, water, and pipeline are addressed. Fourthly, a section is devoted to future directions, which discusses challenges and potential areas of research. A summary concludes the chapter.

6.2 Types of Feedstock

In a first-generation feedstock such as corn for ethanol production, the form of the material is essentially unchanged from harvest until milling takes place in the biorefinery. The reason is that corn kernels in bulk form comprise a near-ideal granular material that is gravity flowable with a relatively high bulk density of 720 kg m^{-3}. In addition, an expansive transportation system that includes elevators with drying facilities, roads, railroads, and waterways has been built over the past century. Sugar cane is mostly harvested in billet form and directly delivered to the sugar mills or the biorefinery using truck transport without intermediate storage because of the perishable nature of sucrose. In the processing plant, the material is separated into juice with a high sugar concentration and a cellulosic bagasse sidestream.

The logistics associated with second-generation biomass feedstock are more challenging than those of first-generation feedstock. As an example, harvesting of the high-yielding energy grass *Miscanthus giganteus* takes place in winter, at which time the crop consists of bundles of tall thin stems that can be cut and baled using adapted hay baling equipment (Fig. 6.1). Second-generation biomass bales typically have a density ranging from 105 to 150 kg m^{-3}, although modern high-compression balers can achieve a density of up to 230 kg m^{-3} [10, 11]. To put the densities of

Fig. 6.1 A stand of *Miscanthus giganteus* ready for harvest. At harvest time in winter, no leaves are present, and nutrients have been recycled to the root system

crops in perspective, Table 6.2 shows the mass density in kg m^{-3}, the specific energy in MJ kg^{-1}, and the energy density in MJ m^{-3} of corn, *Miscanthus giganteus*, sugar cane bagasse and switchgrass, and, as a comparison, coal.

An advantage of second-generation biomass feedstock over, for instance, sugar cane is that it can be stored for longer periods, albeit at the cost of a gradual quantitative and qualitative loss of biomass. However, at some point along the provision chain, the form of the material needs to be changed because the conversion plant cannot process baled material directly. Therefore, comminution (size reduction) must take place to allow for optimal pretreatment and conversion. The determination of the optimal location for comminution along the provision chain now becomes important. For smaller biorefineries, bales could be directly delivered using truck transport, and comminution could take place at the biorefinery itself. For larger biorefineries, the transportation distances are much larger, which makes road transport expensive and rail and water transport more attractive. In rail and water transport, there is potential for creating a large number of regional depots, sometimes termed centralized storage and preprocessing centers (CSPs), which are connected to the biorefinery using rail or water transport. However, bales do not possess sufficient density to optimize long-distance transportation in railcars. To optimize rail transport, compression of the material is needed before transportation either in bale form or in post-comminution (powdered) form. Railcars could be developed with an integral loading/compression mechanism that ensures an optimal material density for transportation. One of the drawbacks of early stage comminution is that the powdered material needs to be stored in containers. Bales, on the other hand, can employ

Table 6.2 Energy content of biomass feedstock in various forms

			Mass density (kg/m^3)		Specific energy (MJ/m^3)	Energy density (MJ/m^3)		
Feedstock	Form		Min	Max		Min	Max	Reference
Coal	Lignite			600	28.47		17,082	a
	Anthracite			850	35.30		30,005	a
Corn				720	15.28		11,002	b
Miscanthus giganteus	Loose		70	100	17.10	1,197	1,710	c
	Milli	1 mm		265	17.10		4,532	d
		2 mm		235	17.10		4,019	d
	Compacted	Baled	130	150	17.10	2,223	2,565	c
		Pelletized		620	17.10		10,602	e
Sugarcane baggase	Loose		50	75	18.10	905	1,358	c
Switch grass	Loose			108	19.06		2,058	c
	Milli	1 mm		260	19.06		4,954	d
		2 mm		220	19.06		4,193	d
	Compacted	Baled	105	133	19.06	2,001	2,534	c
		Pelletized		620	19.06		11,814	e

(a) Coal. (n.d.). In Wikipedia. Retrieved June 27, 2013 from http://en.wikipedia.org/wiki/Coal
(b) Maize. (n.d.). In Wikipedia. Retrieved June 27, 2013 from http://en.wikipedia.org/wiki/Maize
(c) Scurlock, J. (n.d.). Biomass Feedstock Characteristics. Retrieved June 27, 20913 from https://bioenergy.ornl.gov/papers/misc/biochar_factsheet.html
(d) Miao Z., Grift T.E., Hansen A.C., Ting K.C. Energy requirement for comminution of biomass in relation to particle physical properties. Industrial Crops and Products 2011;33: 504–513
(e) Miao Z., Grift T.E., Hansen A.C., Ting K.C. Energy requirement for lignocellulosic feedstock densifications in relation to particle physical properties, pre-heating and binding agents. Energy & Fuels 2013;27: 588–595

inexpensive twine since the longer biomass strands gives some rudimentary rigidity. A commonly applied option is to compress powdered material into self-contained pellets or briquettes. If biomass pellets could be produced with a bulk density of coal in a pile, the existing coal infrastructure could be expanded, enabling transportation of the massive amounts of biomass needed to reach the stated goal of a 30 % replacement of the current US oil consumption by 2030. In addition, having materials with the same density makes blending easier since the gravitational segregation effect is eliminated, although segregation caused by varying particle size remains.

The feasibility of potential preprocessing methods, including methods for comminution, depends on the feedstock origin, physical properties of the material, and the biorefinery input requirements. In contrast to green energy crops, dry herbaceous energy crops and agricultural residues are characterized by low moisture content and a low bulk density at the senescence stage. The harvest window of prairie grasses is about 2–3 months long, during which the moisture content falls below 20 %. Windrowing and field drying after cutting and conditioning can reduce the "baling moisture" content to approximately 15 %. Since the moisture content is inversely proportional to leaf loss, timely harvest, baling, and preprocessing are of the essence, especially for round bales [12]. At harvest time, green energy crops have a high moisture content of up to 50 %, which makes preprocessing and storage more challenging than in the case of dry biomass. For instance, the majority of the existing milling machines, such as knife and hammer mills are incapable of fine size reduction of wet lignocellulosic feedstock. The same problem is present in sugar cane mills, where roller mills produce bagasse particles that are usually larger than 25.4 mm. Because of the high moisture content of green energy crops, typical road transportation vehicles reach their weight limit before their volume limit, which is suboptimal. Green energy crops also exhibit high fiber content, resulting in higher preprocessing energy consumption compared to dry biomass crops. Preprocessing of green energy crops such as short-rotation coppiced willow and poplar can utilize chippers and shredders for size reduction. Energy cane and energy sorghum are currently using sugar cane technology to extract juice with high sugar content. Forest-based biomass, including lumber wood logs, branches, and foliage, possess high moisture content, high fiber content, and a high bulk density. Similar to green energy crops, forest biomass preprocessing is challenging. Forest-based biomass often grows on hill slopes and marginal lands with limited accessibility; therefore, harvest and transportation of forest biomass is more difficult than that of dedicated energy crops and agricultural residues, which grow in farm fields and plantations. River transportation has been used to transport wood logs in some areas. Transpiration methods have been proposed to dry forest-based biomass, but the method is dependent upon many uncertain factors, such as weather and soil moisture. Since forest biomass does not have a distinct harvest window, to circumvent storage, just-in-time (JIT) harvest and transportation approaches are suitable.

6.3 Feedstock Preprocessing

The three main preprocessing methods consist of baling, size reduction, and pelletization. Common biomass forms include rectangular and round bales, pellets, and briquettes generated by extrusion, chopped forms such as generated by a self-propelled forage harvester (SPFH), and milled forms after size reduction by various types of milling machines.

6.3.1 Baling and/or Bundling

Bales comprise the most common biomass feedstock form used for on-road transportation. Baling is one of the elementary steps of one- or two-pass biomass harvest and collection systems as discussed in Chap. 5. For prairie grasses, the two-pass harvest system includes cutting, conditioning, infield windrowing, and baling. For agricultural residues such as corn stover, the two-pass harvest system includes one

Fig. 6.2 *Miscanthus giganteus* in a square bale form

pass for grain collection and another where cutting, chopping, and/or baling takes place. Single-pass whole-crop harvest systems are sometimes used for prairie energy crops and agricultural residues. For short-rotation woody coppice, the single-pass harvest system comprises cutting and baling. The efficiency of two wood harvesters, a single-pass Biobaler and a two-pass Fecon mulcher cutting head combined with a Claas baling system, were compared in earlier research [13].

Round and square baling equipment is common in North America. Baling machinery designed for energy crops can produce square bales with a dimension of 122 × 122 × 244 cm, weighing as much has 454 kg (Fig. 6.2). The bale density of herbaceous grasses and agricultural residues typically ranges from 150 to 200 kg DM m^{-3}, although balers designed for bioenergy feedstock can reach 230 kg m^{-3}. Specialized stationary round baling machines, such as the BaleTech3, can reach values ranging from 360 to 400 kg m^{-3}. Round baling equipment has been widely adopted for forage hay, agricultural residues, forest residues, and short-rotation woody coppice. Figure 6.3 shows a set of round switchgrass bales on a flatbed trailer. The capacity of large round balers varies from 227 to 1,134 kg, and bale sizes range from 1.2 m diameter × 1.2 m wide to 1.8 m diameter × 2.4 m wide. The bulk density of round bales ranges from 100 to 170 kg m^{-3} for herbaceous biomass and from 321 to 373 kg m^{-3} for short-rotation wood coppice or forest residues [13]. Round bales are more difficult to load and stack compared to square bales, and consequently have higher storage and transportation costs, especially for long-distance transportation and large-scale stacked storage [6]. Although theoretically the porosity among round bales stacked in a triangular configuration as present in Fig. 6.3 amounts to 9.3 %, in practice, the top bales settle into the void spaces, reducing the porosity. The possibility and merit of filling a standard-sized ISO

Fig. 6.3 Tractor trailer carrying round switchgrass bales

container with 32 round bales was investigated, and the conclusion was that the packing time required to load the container presented the limiting factor [14]. Round bales have higher biomass losses than rectangular bales during storage, but they are preferred for completely open storage since they shed rain water more effectively.

A developing trend for harvesting and collecting dedicated energy crops and agriculture residues is the single-pass harvest-chopping-baling combine. This machine has the advantage of reducing soil contamination and biomass loss by circumventing infield windrowing, at the cost of requiring lower biomass moisture content at harvest time. The single-pass system can also be applied to stover harvesting, where a combine separates grain and agricultural residue simultaneously [15]. The development of the single-pass machine started over a decade ago, when the Haimer company produced the Biotruck 2000, which combined a SPFH with a drying system (elegantly using the engine's waste heat) and a pelletization unit. The material density of the pellets ranged from 850 to 1,000 kg m^{-3}, and the bulk density of the pellets, from 300 to 500 kg m^{-3} [16].

6.3.2 Size Reduction

As shown in Table 6.1, comminution of biomass is imperative, since the conversion processes cannot directly process crops as they grow in the field. Size reduction can take place during harvesting, such as in the SPFH, which contains a chopping mechanism and a chute that pneumatically conveys the low-density chopped material into a wagon. Balers typically also have a cutting mechanism, but the size of the material strands is kept sufficiently long to allow baling using either string material in the case of square bales or netting or other forms of wrapping in the case of round bales. Further size reduction can take place at local depots or CSPs using wood chippers, such as those employed for tree harvesting, hammer mills, knife mills, and tub grinders that are often used to comminute bales for animal feed. Disk and attrition mills produce biomass particles of more uniform shape and finer size at a cost of higher energy consumption compared to hammer and knife mills [17–20]. The vibratory ball mill was found to be more effective than the rotary ball or rod mill in reducing cellulose crystallinity of spruce and aspen chips, generating fine particles and improving their digestibility [21, 22]. Polynomial relationships between bulk density and particle size of switchgrass, corn stover, wheat, and barley straw grindings were found [22] as

$$\rho_b = ax^3 + bx^2 + cx + d \tag{6.1}$$

Here, ρ_b is the dry bulk density in kg m^{-3}, x is the geometric mean diameter of particles in mm, and a, b, c, and d are regression coefficients. The relationship between the dry bulk density and particle size of wheat straw and switchgrass (for particles larger than 8 mm) can be described by a power law equation [10] in the form

$$\rho_b = ax^{-b} \tag{6.2}$$

where ρ_b is the dry bulk density in kg m^{-3}, x is the nominal particle size in mm, and a and b are regression coefficients. The functions as shown are specific to crop species, initial biomass properties, milling machine type, and machine parameters.

Size reduction can also increase the bulk density of the biomass and, therefore, can be regarded as a form of densification. The bulk density of chopped biomass (greater than 25.4 mm) before finer size reduction is typically less than 80–100 kg m^{-3}. For Miscanthus, it has been shown that the bulk density of the ground biomass through a screen with an aperture size of 4 mm can reach values of 150 kg m^{-3}, which are well in the range of typical field-produced bales [20]. By grinding biomass through a 1-mm screen and therefore performing further size reduction, a density of 250 kg m^{-3}, equal to that of bales produced by high-pressure balers, can be reached [20]. Although size reduction is an operation that requires ample energy, it could also be used as an alternative to chemical pretreatment [23, 24].

6.3.2.1 Energy Requirement of Size Reduction

Since size reduction is a key operation within the biomass provision chain, it is imperative to assess the energy consumption of the machinery. This can be achieved by monitoring the net input power that the machine requires for comminution and integrating this power over time. In general, the energy requirement of comminution is a function of the cutting mechanism (knife, hammer, ball), motor speed, feed rate, material feeding mechanism, strength of the milled material, and degree of size reduction [20, 25–31]. The specific energy consumption of biomass comminution is given as

$$E = f\left(r,\ sc,\ c,\ x,\ mc,\ p\right) \tag{6.3}$$

Here, E is the specific energy consumption, r is motor speed of the milling machine, sc is the milling or chopping machine scale, c is the material composition, fiber angle and/or structure, x is the ratio of initial and output particle sizes, mc is the moisture content in % w/w, and p is the applied axial pressure [10, 20, 22, 32]. Independent of the machine scale, a power (or exponential) law was found appropriate to describe the relationship between energy consumption and resulting particle sizes.

Experiments have shown that the energy consumption of size reduction is high: For instance, to grind air-dried (8 % moisture) Miscanthus through a screen with an aperture size of 1 mm, 5 PIHV was required. Willow ground through the same screen required up to 12 PIHV. By extrapolating these results, a particle size representing 100 PIHV, at which the energy required for comminution is equal to the inherent heating value of the material, was 80 μm for Miscanthus and 50 μm for switchgrass.

The biomass moisture content also has a significant impact on the energy requirement for comminution: The energy requirement for comminution of Miscanthus and switchgrass with a moisture content of 15 % was roughly 1.5 times higher than that of the same crops with a moisture content of 8 % (air-dried) [21].

6.3.3 Biomass Compression

Table 6.2 shows the energy densities of *Miscanthus giganteus*, switch grass, sugar cane bagasse, corn, and coal. When Miscanthus is baled, its energy density ranges from 2,223 to 2,565 MJ m^{-3}. Corn in bulk form on the other hand has an energy density of 11,002 MJ m^{-3}, over four times higher. Anthracite coal in comparison has an energy density of 30,005 MJ m^{-3}, which is 11.7 times higher than that of baled Miscanthus. It is clear that mechanical compression of biomass is essential to optimize the transportation efficiency, since at low material bulk densities the transportation medium reaches its volume limit far before its weight limit [33].

On-road flatbed and box trailer vehicles in the United States are limited to carrying materials with a density of 231 kg m^{-3}; thus, the achievable infield density of bales is well matched to on-road vehicles. This is, however, not the case for long-distance rail transport. Typical “gondola-type” railcars for coal are designed such that they reach their weight and volume limits simultaneously [34]. If biomass could be transformed into particulates with a bulk density equal to that of coal (850 kg m^{-3}), the existing coal transportation infrastructure could be expanded upon to accommodate the huge feedstock transportation task in the future.

Mechanical compression of biomass is a poorly understood process since the biomass’ mechanical properties in general and rheological properties in particular are rather elusive. The compression process can be divided into three distinct phases: (1) removal of air, (2) compression of biomass under material reorganization, and (3) compression of material in a settled matrix. In the first process, little pressure is needed, since merely the material porosity is reduced. In the second process, during which particulates move and fill the pores, exponential or power law functions seem to adequately describe the relationship between the applied force and biomass volume [4]. The third phase, where the biomass essentially behaves like a solid and Hooke’s law may apply, is only reached at extremely high pressures. During a high-pressure experiment using Miscanthus as a test medium, this behavior was observed at applied pressures of more than 350 MPa [35].

Fig. 6.4 *Left*: sample of Miscanthus ground to 12.7-mm particle size at a density of 350 kg m^{-3}. *Right*: sample after being exposed to a pressure of over 750 MPa at a density of approximately 1,470 kg m^{-3}

6.3.3.1 Energy Requirement for Biomass Compression

The energy requirement for compression of biomass can be calculated by monitoring the force applied onto the biomass by a piston and integrating this force across the distance through which the piston travels during the compression. As in the case of comminution machines, for extruders, the net input power the machine required for compression can be monitored and integrated over time. In both cases, the energy requirement pertains to the net energy needed for compression, without taking into account energy required to run ancillary equipment. To determine the pressure needed to compress biomass to a desired value, a sample of biomass was compressed with a universal testing machine, capable of producing a force of 13 MN [35]. Figure 6.4 shows the sample before the test, pre-compressed to a density of 350 kg m^{-3}, and after the test at a density of approximately 1,470 kg m^{-3}. Figure 6.5 shows the energy requirement for compression of the same pre-compressed sample in PIHV. It is clear that the energy requirement is proportional to the density and that a power law seems adequate to capture this relationship. Note that compression to 1,000 kg m^{-3} required only 0.035 PIHV and that compression up to a density of 1,321 kg m^{-3} required only 0.1 PIHV: Even compression to a very high density of 1,767 kg m^{-3} required merely 0.315 PIHV. The conclusion of this research was that energy consumption for compression is not an inhibiting factor. However, the machinery required to produce particulates of this density level at a large throughput would most likely be expensive.

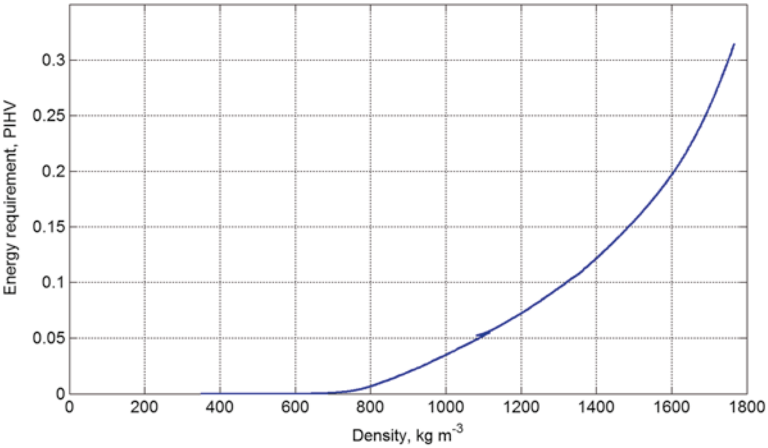

Fig. 6.5 Energy requirement in PIHV for compression of the sample shown in Fig. 6.4, versus the “in-mold” density

Finally, there is a common misconception that compressing biomass may diminish its inherent energy-producing potential. No evidence has been shown in the literature that this is the case. Further research is needed to determine the effect of compression on the biomass conversion efficiency.

6.3.4 *Pelletization*

Pellets, briquettes, and cubes made from biomass have the advantage of yielding a flowable material form, which is suitable for long-distance rail transportation [4, 11]. To produce pellets, biomass feedstock needs to be ground to a particle size of approximately 2–8 mm and compressed while potentially applying increased temperatures and binding agents. The energy requirement for pelletization is a function of the particle size, the required pellet material density, and the required pellet quality which includes durability, a function of the pellet hardness [4, 36]. Typical biomass pellets have a diameter ranging from 12 to 15 mm [32].

One of the drawbacks of pelletized material in bulk form is that it exhibits porosity due to air pockets among the pellets. Various mathematical models predict the porosity of randomly packed cylindrical particles in a bulk material as a function of the pellets’ aspect ratio, which, for typical biomass pellets, ranges from 1.5 to 2.5. In this range, the so-called Z-Y model predicts a porosity of approximately 0.32 [37]. To reduce the porosity, secondary compression of bulk pellets may be feasible; however, this method may compromise the integrity of the pellets.

A second limiting factor is long-term post-compression rebound, which is defined as the increase in volume of the pellet after the pressure applied during pelletization has been removed. This effect can amount to over 30 %. Taking both post-compression rebound and porosity into account, to achieve a desired bulk density of pelletized material, the “in-mold” density of the material must be over twice as high. In addition, when biomass material flows through channels at extreme pressure levels, the material can potentially self-combust [35]: The compressed sample shown on the right side of Fig. 6.4 exhibits areas where the biomass was charred due to excessive heat during compression. This heat caused localized pyrolysis in which volatile gases are produced. These gases subsequently ignited, which led to an explosion.

6.3.5 Storage

Lignocellulosic biomass is typically harvested in a short-time window of about 2–3 months. Since the aim of the conversion plant is to produce fuel year round, storage of biomass is needed. The issues of the location of the storage operation within the provision chain, the conditions of storage, and the infrastructure required are still being addressed in research. Due to the low energy density and monetary value of the material, uncovered outdoor stacking of bales may be most economical, but long-term uncovered storage will incur quantity losses and possibly the emergence of fungi and molds that are detrimental in the conversion process. Bales, either round or square, may be a viable option before comminution, since inexpensive twine is sufficient for containment. Wrapping bales in plastic for long-term storage may prevent biomass loss, while allowing a high bale density and stacking on unprepared grounds, but it requires low moisture content and is expensive. If storage is to take place after comminution, the biomass must be preprocessed into a self-contained compressed form such as pellets or briquettes, since storage of powdered low-density biomass would be very inefficient. This is the idea behind the Advanced Uniform Format as proposed by the Idaho National Laboratory [6].

6.4 Transportation

The success and sustainability of the biofuel industry depend largely upon an efficient feedstock provision system, in which transportation plays a key role [6]. While it will provide a huge economic opportunity for communities across the United States, harvest, preprocessing, storage, and transportation of massive amounts of biomass will be challenging [38]. Dependent upon the biomass densification level and transportation mode, transportation represents between 13 and 28 % of the feedstock provision costs, which limits the collection area. Taking into account the US Department of Transportation’s legal load limit of 21.8 tons for on-road transportation, at least 150,000 road trips will be required per day by 2030 to transport three million tons of biomass feedstock from farms to biorefineries.

With a throughput rate of 15–20 ton h^{-1} attainable by tub grinder hammer mills, over 6,250 such machines would be required to comminute the three-million tons of biomass feedstock to an average particle size of 25.4 mm. For a medium-sized biofuel plant with a daily demand of 2,000 dry tons of feedstock, more than 100 trips would be required per day [11].

In a typical bioenergy feedstock production process, the crop is collected and cut using a harvester, conveyed into wagons that transport materials in fields, and trans-loaded into trucks that transport the material either directly to a conversion plant or to a CSP. To illustrate the logistics involved in the production of fuels from bioenergy feedstock, a conceptual biomass provision system that includes a CSP is shown in Fig. 6.6. The sequence of events as illustrated is as follows:

1. Farmers deliver the biomass in bale form to the CSP using trucks, since the distances from the field to the CSP are relatively short. The advantage of using balers is that they are readily available, farmers are familiar with their workings, can maintain them, and can capitalize on the advantage that the containment of the biomass can be accomplished using inexpensive strings or netting and relatively low-tech machinery. The density that is achievable using modern balers allows flatbed trucks to reach their volume and weight limits simultaneously.
2. At the CSP, bales are stored and possibly dried using waste heat from the engine that powers the comminution and pelletization operations. The road traffic from farms to the CSP is seasonal and intermittent, similar to that occurring during the harvest season of corn and soybean.
3. The task of the CSP is to preprocess the biomass feedstock through comminution. This operation runs continuously and is directly followed by a pelletization operation; in fact, ideally the two operations are combined in a single large machine, which allows containment of dust while preventing "dust explosions." Before pelletizing, the biomass could be treated with bonding agents and potentially pretreatment agents. In addition, the CSP provides storage, loading, and blending facilities for the pelletized material.
4. An elegant method of conserving energy is to use the biomass itself as the energy source for the CSP. This would require direct combustion of the pelletized biomass and employing energy conversion such as through a Stirling engine. This is a constant-power machine, which runs on a temperature differential, where the "hot" end is created by burning an arbitrary fuel (in this case biomass pellets) and the "cold" end consists of a heat sink connected to the outside ambient temperature. This is an advantage in colder climates, because the temperature differential is naturally higher, compared to more temperate climates. The Stirling engine also produces "waste heat," which can be used for biomass drying. After milling, the pelletized biomass is stored in large bins, similar to current storage of corn and soybean.
5. The loading of the gravity-flowable pelletized biomass can take place using classical handling equipment such as augers, chutes, and conveyor belts. In addition, the CSP can operate bins containing various biomass types and blend them

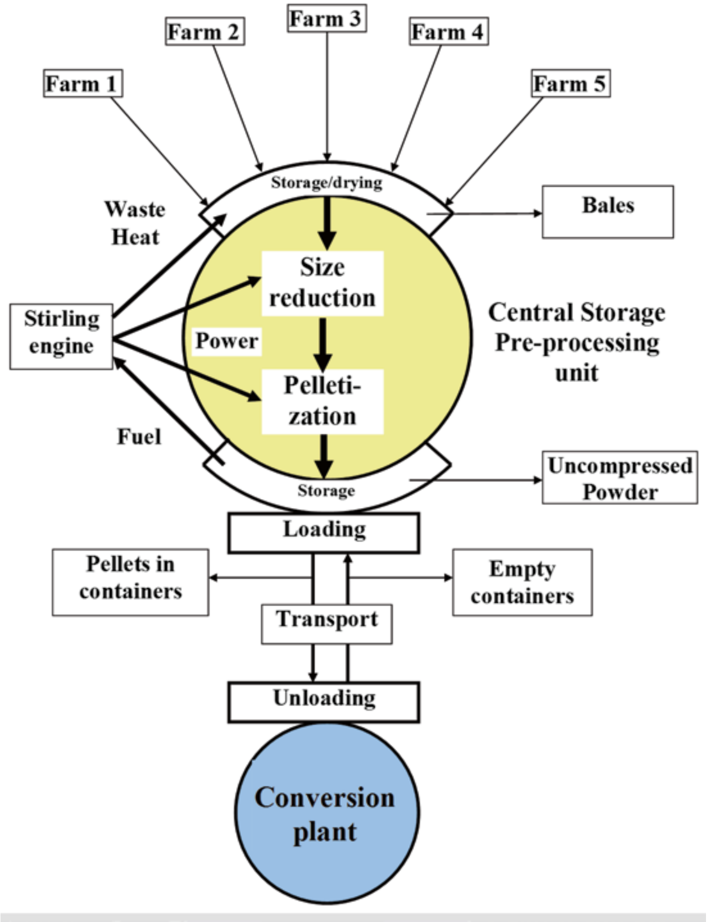

Fig. 6.6 Concept of a field-to-refinery feedstock provision system

according to the needs of the conversion plant. Secondary compression of the pelletized biomass may be an option to reduce the porosity and increase the bulk density.

6. The transportation between the CSP and the conversion plant takes place in railcar containers for bulk goods. The traffic flow between the CSP and the conversion plant is continuous, similar to current processing plants where a fixed number of railcars arrive daily, eliminating the need for long-term storage at the conversion plant. At the conversion plant, the pelletized biomass is dumped in a large collection bin, after which the pellets can be either mechanically crushed or dropped into a liquid for pretreatment.

6.4.1 Truck Transport

Green biomass such as sugar cane is perishable and needs to be processed ideally within a few hours after harvest. Therefore, in this case, short-distance truck transport is effective but not necessarily efficient. Since green biomass can have a moisture content of over 50 %, the weight limit is typically reached before the volume limit.

Flatbed trailers are often used for bale transport, and by taking into account volume and weight limits, the maximum density of the bales is 223.5 kg m^{-3} [35]. This value is achievable using modern baling technology.

Transloading is defined as the operation that moves goods from one form of transportation to another such as from a truck to a railcar or barge or vice versa. Each transloading operation can incur losses and damage, therefore the logistics system needs to be designed to minimize the number of transloading operations. Transloading of biomass in bale or containerized form can be achieved using traditional equipment such as cranes, forklifts, stackers, and bulldozers. Pelletized material can be conveyed using belts, augers, and chutes, while powdered material can be conveyed pneumatically.

Specialty trucks such as concrete carriers and dump trucks have an exempt status in terms of weight limit, but biomass is not likely to reach densities that warrant the use of such equipment.

6.4.2 Rail Transport

Short-distance transport of biomass using trucks is well suited to the achievable density of bales. However, the rail to truck fuel efficiency ratio of gondola-type railcars (such as those used for coal transport) ranges from 2.3 to 4 [39], making rail transport more efficient than truck transport. This is especially valid for long-distance transportation for which rail transport has lower operating (variable) costs than truck transport; this reduction offsets the higher capital (fixed) cost associated with rail transport. For straw and corn stover, in North America, the minimum economic rail shipping distance (MERSD), the point where rail transport becomes more economical than truck transport, is 170 km. The value for boreal forest harvest residue wood chips is 145 km due to its higher density [40].

6.4.3 Water Transport

The same issues associated with rail transport are present in water transport using barges and even ocean-going vessels. Any material in bulk form can be transported using railcars or ships, but only efficiently if the bulk density of the material is such that the volume and weight limits can be reached simultaneously. The main difference between ships and trains is that for a given loading volume, trains, supported by rail, can, in principle, accommodate densities much higher than the density of water, and ships cannot, since sufficient residual buoyancy must be maintained.

6.4.4 Pipeline Transport

Pipeline transport of biomass in a slurry form is an attractive idea, since the pipeline itself is stationary and the material is inherently contained. In the paper industry, slurries are used to convey pulp, but only for relatively short distances. High-concentration slurry disposal (HCSD) is a modern approach to remove fly ash from power plants over distances up to 10 km with a solids fraction of 70 %. For biomass to follow a similar strategy, the biomass density should ideally be similar to that of the carrying fluid (typically water), which is not the case.

The economics of pipeline biomass transport have been studied, leading to the conclusion that for flows over two million dry ton yr^{-1} and distances ranging from 100 to 500 km, pipeline transport is less expensive than truck transport [41]. However, technical limitations render the concept unfeasible since research has shown that the biomass will readily absorb the carrier fluid: woodchips absorb water from an initial water content of 45 % to over 60 % in a matter of hours. This reduces the lower heating value of the material to virtually nil. The same material in oil reached an oil content from initially zero to over 30 % after 120 h [42]. This leaves the possibility of adding biomass such as woodchips to an oil flow in existing pipelines, but the oil-pumping infrastructure, including pumps and valves, is dependent upon the fluidic behavior of oil, and adding biomass would require major engineering adaptations. The consensus found in the literature is that pipeline transport is not a feasible option for biomass transportation.

6.4.5 Biomass Transportation Logistics

Supply and biorefinery logistics represent critical barriers in energy generation from biomass [3, 6, 11, 43, 44]. Biomass supply logistics are dependent upon the conversion technology utilized, production capacity (i.e., feedstock demand), feedstock type, yield (i.e., feedstock supply) as well as pathways and technologies that make feedstock supply meet demand. In general, the components of biomass feedstock supply chain mainly include biomass harvest/collection, baling, loading, transport in the field and/or long-distance, transloading, storage, mechanical comminution and feedstock transformation (e.g., pelletization and torrefaction). At tactical and operational levels, feedstock transportation logistics are dictated by farm and biorefinery location, daily or hourly biomass quantities to be transported, handled and mechanically processed, numbers and time schedule of harvest machines, transportation vehicles, processing and handling equipment, labor requirements and personnel costs, route selection, as well contingency scenarios. In the sugar industry, various analysis tools for harvest, transportation and processing have been developed [45].

6.5 Future Directions

This section addresses some concepts that may hold promise in the future, but are currently under research.

6.5.1 Modeling

Systems analysis involving techniques of modeling, simulation and optimization can be used to study the complete feedstock provision chain, while circumventing experimentation. There are multiple levels to perform such analyses. Modeling can be used for strategic optimization, such as to determine the optimal locations to produce a bioenergy crop in relation to agronomic and environmental parameters, and social and economic driving forces, as well as to determine the optimal placement of CSPs and conversion plants related to land use policy and infrastructure availability. At a tactical level, models can be used to predict the utilization of the storage and transportation infrastructure over time. At an operational level, models can be used for real-time logistics, transportation fleet tracking, and to manage uncertainties such as adverse traffic and weather events. The main bottleneck is not the modeling effort itself, but rather the lack of pertinent data needed to drive the models, in addition to the potential unwarranted use of outputs of models that have not been properly validated [46].

6.5.2 Standardization

For a medium or large commercial biofuel plant, biomass forms and equipment performance could be standardized to streamline supply logistics and improve efficiency of biomass supply systems [11, 47]. For small-scale pilot biofuel plants, existing agricultural equipment and facilities for biomass feedstock preprocessing, storage, and transportation may be feasible. However, for medium or large commercial biofuel plants, standardized harvest, preprocessing, and supply equipment need to be developed. An example of this is the development of self-propelled bale loading/unloading equipment by the US Department of Energy's Biomass program [2].

The quality of feedstock is currently poorly defined, and a standard is needed here as well. This quality parameter should include not only feedstock composition and energy density, but also grindability, flowability, storability and, most importantly, convertibility potential.

In research, there is a need for reporting results in a consistent standardized manner. Apart from the fact that, to date, ample literature in the United States still uses the archaic English Unit system, there are other areas where inconsistencies arise. For instance, for size reduction, the specific energy consumption per unit of resulting particle area (MJ m^{-2} particle area) should be used for efficiency evaluation rather than the specific energy consumption per unit of mass (MJ kg^{-1}). For energy requirement, it is logical and intuitive to express energy usage of machinery in the PIHV, rather than Joule/tonne or worse, in BTU/lb. In economic studies, the use of purchase power parity is more sensible than using currencies such as US$ or Euro.

6.5.3 Interface Between Feedstock Provision and Conversion

Research to date has either focused on the biomass provision chain or bio-conversion aspects. The schism between the provision and conversion research is understandable, since they have traditionally been disconnected by pretreatment. There is an urgent need for a concerted effort to observe the bioenergy provision and conversion process in a holistic manner, rather than as individual entities.

6.5.4 Biomass Pretreatment During Storage

Storage of biomass is a liability, but it can also be an asset. The duration of storage can be long, and during this time, there is an opportunity to expose the biomass to chemicals for slow pretreatment. The most accessible form of biomass is directly after size reduction, but this form has a very low density requiring large volumes of storage. A superior option may be to treat the biomass with a pretreatment agent between the size reduction and pelletization operations. This concept of pretreatment during storage has had little attention in the literature.

6.5.5 Feedstock Preprocessing

Among the three main operations during biomass provision—harvesting, size reduction, and compression—size reduction is by far the most energy-intensive. For instance, size reduction of Miscanthus through a screen with an aperture size of 1 mm requires up to 5 PIHV, whereas woody biomass such as willow [20] required 12 PIHV. To reduce the energy requirement of size reduction, dedicated milling machines that employ knives with optimal cutting angles and serrations, potentially fitted with long-lasting ceramic coatings, operating at a cutting speed that minimizes energy use within an acceptable throughput window, are essential.

The energy use for compression is much lower than that of size reduction, but the machinery needs to be designed such that it can exert extremely high pressures onto the material, at a very high throughput rate, without excessive cost in machine investment. Explosions due to localized pyrolysis must be prevented.

Ideally, machines that combine the size reduction and compression (pelletization) operations could be developed that give the advantage of limiting dust generation. Within the machine, between the size reduction and pelletization actions, additives could be applied that aid in the bonding/durability of the pellets. The machine should be controlled such that machine operates at an optimal temperature for pelletization and additive efficacy.

6.5.6 Sensing Technology and Automation

Sensing technology is needed in various steps of the feedstock provision and conversion process. In comminution, sensors are needed to control feeding rates and cutting speeds, allowing the machines to operate most efficiently. At the gates of CSPs and conversion plants, real-time sensors are needed to measure, for instance, the moisture content of the biomass, which can be accomplished using classical indicators such as capacitance. However, to determine the "quality" of feedstock, sensors are needed for rapid assessment of conversion efficiency (RACE).

6.6 Summary

The main task of the feedstock provision system is to deliver biomass to a pretreatment and conversion system in sufficient quantities and in a form that allows these systems to be optimized while simultaneously optimizing its own processes.

Transportation is a key step in the provision system. Apart from transportation mode and logistics management, the provision system also includes aspects of preprocessing such as size reduction and compression that affect the transportation efficiency. Harvesting, which is energetically inexpensive, can take place using either adapted grass/forage cutting and baling equipment, or chopping machines such as the self-propelled forage harvester (SPFH).

Size reduction (comminution) is a key operation in the provision chain because pretreatment/conversion process cannot deal with uncut material directly. Apart from comminution being an energetically expensive operation, the optimal location of comminution in the provision chain is not clear. For smaller conversion plants that utilize short-distance truck transport, bales may be delivered to the conversion plant where comminution takes place. In this case, storage could take place either in field or at the conversion plant. The density of bales produced with modern equipment is such that trucks (typically flatbed types) are reaching their volume and weight limits simultaneously, allowing optimal transportation efficiency. For larger conversion plants, however, the transportation distances are much larger, and rail transport becomes more efficient and economical. In this case, centralized storage and preprocessing centers (CSPs) are needed that store bales and transform the feedstock into a stable, storable, blendable, and gravity-flowable form, such that the feedstock becomes a marketable commodity. The bulk density of the particulates in the flowable form must allow railcars to reach their volume and weight limits simultaneously. For instance, gondola-type coal railcars can accommodate the density of coal in a pile, which is 850 kg m^{-3}, rendering the production of biomass with a similar bulk density attractive. However, to produce such a bulk density, the "in-mold" density of the particulates comprising the bulk material needs to be over twice as high as the bulk density, to compensate for post-compression rebound and porosity. Overall, compression of biomass is energetically inexpensive, but the machinery that can deliver massive amounts of highly compressed biomass is arguably expensive. The same bulk form must also allow the conversion plant to efficiently pretreat and convert the feedstock into liquid fuels.

Water transport using barges is another option for long-distance biomass transportation, although the dispersion of waterways limits its application domain and the bulk density of the material being transported must be significantly lower than that of water. Pipeline transport, where biomass in particulate form is suspended in a carrier fluid, has been shown unfeasible for transportation of biomass.

In the near future, several technologies must be developed/optimized to make bioenergy a realistic alternative to fossil fuels. To integrate ongoing and future developments, the generation of comprehensive models on strategic, tactical, and operational levels must be pursued. These models must include the latest research data and technologies, and be properly validated before any conclusions can be gleaned from them.

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Chapter 7
Biomass Feedstock Storage for Quantity and Quality Preservation

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Abstract Biomass feedstock must be stored between the time of harvest and its conversion to bioenergy products such as ethanol to ensure year-round, continuous supply of quality feedstock to conversion plants. Storage of biomass entails conserving both its dry matter content and its carbohydrate content which may be converted to ethanol. Moreover, it also entails preparing the biomass in terms of its composition, particle size, and pH for the pretreatment stage where cellulose is hydrolyzed into C6 sugars and later fermented into alcohol. The goal of this chapter is to provide an overview of these aspects related to biomass feedstock storage. Various storage options, ranging from open storage without any protection to highly sophisticated controlled environment, are first reviewed to highlight their advantages and limitations. The feedstock properties important from a storage perspective are then discussed. Potential alternatives to reduce dry matter losses during storage are discussed. Mathematical relationships correlating dry matter loss with its various causes are reported. These include drying, compaction, sealing, and freezing. The factors affecting the reduction in biomass recalcitrance are then presented, and their impact on quality parameters relevant to processing is discussed. The reduction of dry matter recalcitrance to prepare biomass for further processing is discussed with the options of incorporating those in storage facilities. Guidelines to select a storage method that may be used by design engineers or managers are also presented. The review showed that the importance of storage in the value chain is being realized, leading to greater interest on developing alternatives to improve storage efficiency.

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Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4_7,

7.1 Introduction

Biomass storage occurs after harvest and before delivery to the conversion plant. Biomass is harvested during a very short window and the harvested biomass must support biorefinery operations year round. Storage can provide the necessary buffer to ensure continuous provision of biomass; therefore, it is a necessary component of the biomass feedstock production and provision system. Storage of biomass, however, presents a number of challenges that must be addressed as part of an efficient storage solution. These challenges are:

- Volume: Lignocellulosic biomass is a low-value, high-volume product. The typical density of a bale from commercially available balers is about 150–200 kg m^{-3}. The low density leads to a substantial storage volume requirement for a biorefinery of reasonable size. For example, model-based analysis by Shastri et al. [1] showed that a Miscanthus-based biorefinery processing about 2,800 Mg d^{-1} producing about 350 million liters of ethanol per year would require a covered storage area of more than 800,000 m^2 with a height of 4.88 m and an open storage area of almost 20,000 m^2 with a height of 2.44 m.
- Dry matter loss: Storage of biomass for longer durations can result in significant dry matter loss depending on the storage method. Losses as high as 25–30 % have been reported for open storage without any protection. Such high losses negatively impact the cost-competitiveness. As elaborated later in the chapter, the loss of carbohydrates as part of the dry matter loss may be even more important from the ethanol production standpoint. Moreover, Emery and Mosier [2] showed that dry matter losses during storage reduced the net greenhouse gas benefit of ethanol over gasoline by 10.9 %.
- Safety: Long-term storage of high-moisture biomass may lead to safety hazards. Microbial activity in stored biomass increases the biomass temperature and may lead to self-ignition. The emissions from storage piles can also create health hazards.

Minimizing the total dry matter loss is the primary objective of efficient storage. The dry matter loss is often caused by wind and rain erosion, leaching, high temperatures, and handling activities such as loading and unloading. Biochemical activity also causes losses in cellulose-containing dry matter [3]. It is important to understand the various factors affecting the dry matter loss and also the potential solutions to minimize those losses.

The purpose of storage is to also deliver biomass feedstock that has lost the least amount of cellulose and hemicellulose. The environmental conditions to which the feedstock is exposed after its harvest determine its quality and suitability for a particular end use [4]. Biomass quality relevant to its conversion to ethanol is defined primarily by its total dry matter content relative to when it was harvested, pH, enzyme and yeast-relevant nutrient content, and its resistance to cutting and crushing due to lignin and moisture content. Various biochemical and chemical reactions occur during storage, which influence these biomass properties.

Microbial oxidation of C6 sugars in anaerobic conditions causes losses in water-soluble carbohydrates and hydrolyzed cellulose. Sugars are fermented by bacteria in anaerobic conditions as well to produce lactic acid (ensilage). Oxidation due to air infiltration also increases cellulose loss. These causes are discussed in detail and effective storage options to minimize them, such as drying, compacting, sealing, temperature control, and freezing or cooling, are also presented.

Storage can also be used to prepare biomass for processing into ethanol by reducing the recalcitrance [5]. Other undesirable properties such as high moisture content may also be addressed during storage to improve subsequent handling and conversion. Shredding and compaction are pretreatments that typically take place before storage and affect particle size. Particle size and pH can be optimized for the pretreatment stage in the biorefinery. Lignin content can be manipulated through the plant age at harvest. Lignin is broken down through acid hydrolysis, enzymes, ultrasound treatment, and drying. The design of a storage structure also needs to take into account biomass coefficient of friction and angle of repose.

The goal of this chapter is to discuss these aspects in detail and provide a comprehensive review of the existing literature. The information presented here can ultimately be used to create a storage design model for a storage system, optimized to preserve biomass quality and quantity for ethanol production.

The chapter is arranged as follows. The next section summarizes the important storage methods that can be employed for biomass feedstock storage. Section 7.3 discusses the important properties of biomass feedstock that play a key role in storage. Section 7.4 briefly summarizes the causes for dry matter loss and then presents the alternatives to minimize the loss. Section 7.5 discusses the alternatives to reduce the biomass recalcitrance during storage so as to prepare the biomass for pretreatment and further processing. Section 7.6 presents general guidelines for selecting a storage method, and the chapter ends with a summary and future research directions in Sect. 7.7.

7.2 Storage Methods

The storage methods can broadly be classified as dry or wet methods [6]. Table 7.1 summarizes the methods that have been considered in the literature as potential alternatives. Apart from ensilage, which is a method for wet storage, all others are dry methods for biomass storage.

For dry storage, biomass needs to be harvested at moisture content less than 20–25 %. If high-moisture biomass is harvested, it must be dried on-field using windrows. Sufficiently dry biomass is then prepared for storage by further operations such as baling or grinding. For wet storage, high-moisture biomass, typically greater than 45 %, is harvested and shredded and ground immediately. The ground biomass is sent to silage pits or packed in air tight bags for long-term storage.

Most of the methods mentioned in Table 7.1 are currently used for storage of agricultural residue for various end uses. The table also provides a qualitative,

Table 7.1 Summary of various biomass feedstock storage methods and their comparison in terms of cost, dry matter loss, quality degradation, and ease of handling

Storage methods and subcategories		Cost	Dry matter and quality loss	Ease of handling (loading and unloading)	Form of biomass most suitable
Open air	On land	Very low (almost no cost)	Very high	Very easy	Round bales; square bales with tarpaulin cover
	On gravel pad	Very low	Very high	Very easy	Round bales; square bales with tarpaulin cover
	On paved pad	Low	High to very high	Very easy	Round bales; square bales with tarpaulin cover
Covered without climate control	Shed with no walls	Low to medium	High	Easy	Round and square bales
	Shed with three walls	Medium	Medium to low	Somewhat difficult	Round and square bales; chopped biomass
	Enclosed without ventilation	High	Medium to low	Difficult, especially for large square and round bales	Bales, chopped and ground biomass, pellets
Covered with climate control	With ventilation, temperature, and/or climate control	High to very high	Low to very low	Very difficult	Bales, chopped and ground biomass, pellets
Steel bin or concrete bin		High to very high	Very low	Easy for free-flowing material such as ground and chopped biomass and pellets	Chopped and ground biomass, pellets
Silage pit		Function of moisture content and storage conditions	Medium to low; leads to quality changes through lactic acid formation	Difficult	Chopped biomass

The suitability of a particular feedstock form is also mentioned. The comparisons are relative and qualitative in nature

Fig. 7.1 On-farm open-air storage on natural soil without any protection

relative comparison of these storage methods in terms of cost, dry matter loss, quality degradation, and ease of handling when loading and unloading.

On-farm open storage is by far the most common approach to store agricultural residue such as corn stover. The open storage could be on regular soil (Fig. 7.1), gravel pads (Fig. 7.2), or paved surfaces. Moreover, the material, typically in baled form, might be covered with a tarpaulin for additional protection (Fig. 7.3). Due to the low-value, high-volume nature of biomass feedstock, this method of storage is often proposed in literature as well as used for various analyses for cost calculations. Open storage is acceptable for agricultural residues since those are viewed as by-products of grain production, and the quality specifications are not that stringent for their final use. Thus, the quality degradation and high dry matter loss for open storage are not of major concern. However, if the feedstock is to be used for ethanol production, this may become a critical issue, as highlighted in the subsequent sections. Rigdon et al. [7] showed that uncovered storage for sorghum led to a reduction in dry matter content from 88 to 59.9 %, cellulose content from 35.3 to 25 %, and final ethanol yield from 0.2 to 0.02 g L^{-1}. This strongly suggests that some form of covering is desirable.

On-farm covered storage will address these problems to a certain extent (Fig. 7.4). The feedstock would be protected from rain and snow. However, wind and other factors may still lead to significant dry matter losses, especially if the moisture content is high. Covered storage with walls will provide adequate protection against severe weather conditions. However, such facilities require additional capital investment, thereby making them cost-effective at a larger scale. Recently, there has been substantial interest is setting up regional preprocessing depots, also known as

Fig. 7.2 On-farm open-air storage on gravel pad without any protection

Fig. 7.3 On-farm open-air storage on gravel pad with tarpaulin on the *top* for protection from rain and snow

centralized storage and preprocessing centers, as an option to improve supply chain efficiencies [8]. Therefore, it is expected that the covered facilities with walls, and with as well as without climate control, will only be set up as part of these depots.

Fig. 7.4 On-farm covered storage of round bales in a shed without walls and any climate control mechanism

Fig. 7.5 Ensilage of biomass in bags. Ensiling can also take place in concrete pits

Ensilage of high-moisture biomass has been commonly used for longer-term storage to produce animal feed (Fig. 7.5). Anaerobic digestion by bacteria ferments sugars to produce lactic acid. These changes in the quality parameters are desirable from an animal feed standpoint. However, that may not be true for biochemical processing of the feedstock. Moreover, the relatively long-term storage, a part of ensilage, may not be desirable from the overall supply chain standpoint.

Steel bins/silos or concrete bins are currently being used for grain storage, and they can potentially be used to store biomass feedstock. A demonstration plant setup by Genera Energy (http://www.generaenergy.com/) at Verona, Tennessee, USA, uses silos to store ground switchgrass before transportation. Storage in bins of containers, though, would necessitate grinding, chopping, or pelletization of biomass. This may lead to additional costs in the overall supply chain. The handling and conveying of feedstock however is significantly more efficient. The applicability of this method on a large scale appears to be limited at this stage.

7.3 Plant Material Properties Relevant to Storage

The important engineering properties of biomass feedstock were discussed in Chap. 2. Here, the properties important and relevant from a storage standpoint are highlighted and the methods used to measure those properties are described.

7.3.1 Moisture Content

Gravimetric moisture analysis, by oven drying at 103 °C, results in volatile organic compound losses and consequently overestimates moisture content. Karl Fisher titration is a method in which an iodine-based titrant and methanol react to produce iodide but only in the presence of water. The presence of iodide alters the electric potential of the solution. In a voltametric Karl Fischer titration, a solution consisting of methanol and the sample is titrated with incremental known volumes of iodide-based titrant until an equilibrium voltage is reached. Voltage is measured by an electrode immersed in the solution. Thiex and Van Erem [9] demonstrated that Karl Fisher titration, where the methanol titrant is maintained at boiling point (60 °C), can be used for accurate moisture content measurement in forages and without homogenizing the sample.

7.3.2 Cutting Force and Shear Force

Measurements of cutting and shearing forces, and mathematical relationships predicting changes in these forces in response to storage conditions, can allow predicting the pretreatment requirements and costs. Pretreatment consists of mechanical and possibly chemical and biochemical methods of breaking down the cellulose-hemicellulose-lignin complex. If, for example, a storage system was optimized to decrease cutting forces in biomass segments, it would result in reduced milling cost at the preprocessing plant, since less force and less energy will need to be exerted to mill the material.

Kaack and Schwarz [10] measured the force exerted by a plunger before the rupture of *Miscanthus × giganteus* and *M. Sinensis* node and internode segments. They also measured the distance by which nodes and internodes bent before breaking, and derived the modulus of elasticity of the point of inflection. Womac et al. [11] measured the cutting force of switchgrass stems by using a double shear setup.

Stiffness of plant nodes and internodes is a measure of the cutting forces needed to cut shoot segments. In Chaoui et al. [12], an LRX Plus Materials analyzer (Lloyd Instruments Ltd., UK) was used to evaluate the stiffness of Miscanthus. Materials testing machines are test frames used to test the tensile and compressive properties of materials. Stiffness is the highest slope of a strain versus time graph when a blade with a 1 mm edge is pressed into a Miscanthus sample. The height and horizontal diameter of the sample are measured and factored by the LRX Plus Materials analyzer (Lloyd Instruments ltd., UK) program when calculating stiffness. The effect of plant age, storage temperature, and packing density on stiffness were demonstrated and expressed in models by Chaoui et al. [12]. Nodes were significantly more resistant to cutting than internodes. Lignin, hemicellulose, % solids, and segment diameter were the other factors that significantly affected stiffness. Packing density, cellulose content, time in storage, and storage temperature did not affect stiffness. These effects were modeled as:

- Stiffness of a node (N/mm) = 2,989.0 + 130.17 *Lignin (%) + 54.91*Hemicellulose (%) + 2.92*Solids (%) + 1.69*Diameter (mm)
- Stiffness of an internode, N/mm = 130.17 *Lignin (%) + 54.91*Hemicellulose (%) + 2.92*Solids (%) + 1.69*Diameter (mm)

These results show that older and drier plants are more resistant to cutting, regardless of storage conditions. Therefore, it might be more effective to store and process Miscanthus plants (or other cellulosic biomass) harvested before senescence.

7.3.3 Coefficient of Friction and Angle of Repose

The coefficient of friction and angle of repose would allow designing container walls that can withhold the pressure exerted by the biomass pile within them. These coefficients also facilitate designing the slanted surfaces of augers, which would be placed inside storage containers to allow the interspacing of air and biomass volumes, for better drying or diffusion of gaseous additives. The coefficient of friction is derived from the angle at which a surface is inclined when friction forces no longer keep an object, a biomass particle, adhered to the given surface. The coefficient of friction μ is defined as

$$\mu = \frac{F}{N} \tag{7.1}$$

where F = friction force of the particle against the surface and N = normal force from the surface in reaction to the object weight.

The angle of repose is related to material density, surface area, and coefficient of friction. It is the angle formed by the sides of the biomass pile relative to the ground surface.

Chaoui et al. [12] measured the angle of friction by placing two superimposed molded slabs of milled Miscanthus on a hinged platform. The platform had a ledge that mobilized the lower slab only. The platform was pulled by a cord as the analyzer's automated moving part traveled upward. The operation was manually stopped when the top slab first slid off the lower slab. The radius of the arc formed by the moving lever, and the distance traveled by the tip of the cord were used to calculate the angle of friction. The angle of friction was significantly affected by solids content; the drier the plant, the smaller the angle of friction. Solids content affects the angle of friction as follows:

$$\text{Angle of internal friction (Degrees)} = 55.87 - 0.25 * \text{Solids } (\%)$$

Storage conditions, plant composition, and time in storage did not affect the angle of friction. A lower angle of friction implies more pressure on walls of containers holding milled Miscanthus. It also determines the inclination angles of platforms along which Miscanthus should slide.

7.3.4 Density

Bulk density, also reported as biomass wet density, is determined by the amount of pore space and biomass particle density. It is a very important property of the biomass since the large volume of feedstock often creates storage and transportation challenges as highlighted in the introduction section. Bulk density determines the weight capacity of the structure where biomass is stored before transport and the cost of transport as well. Chapter 2 has a detailed section on bulk density.

7.3.5 Chemical Composition: pH, Lignin, and Cellulose

In the unusual case where biomass is stored wet, a pH different than that for a neutral case (pH = 7) would influence the rate of microbial oxidation in anaerobic conditions. Extreme pH levels can denature proteins, including the enzymes, which hydrolyze substrates into the simple sugars consumed by microbes for energy. The pH level can also influence the solubility of metals used as cofactors by these enzymes. Extreme pH level can also inhibit the hydrolysis of cellulose and fermentation of sugars into alcohol. If biomass became too acidic during storage, or was treated with strong bases, pretreatment would be necessary to adjust the material pH before conversion.

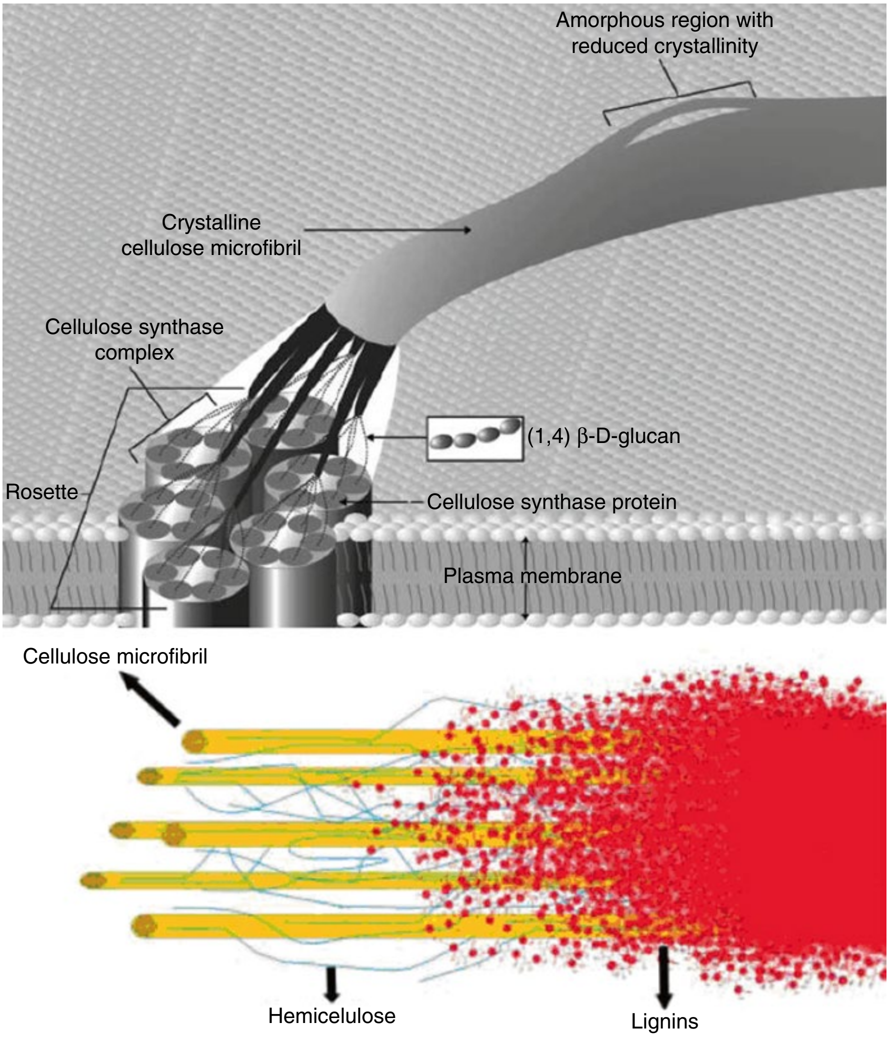

Fig. 7.6 Production of microfibrils (*top*) and cellulose microfibrils-hemicellulose-lignin complexes (*bottom*) as shown in Gomez et al. [16]

As shown in Fig. 7.6, lignin coats the cellulose and hemicellulose which can potentially be hydrolyzed into water-soluble sugars available for microbial oxidation. During storage, lignin can protect biomass from degradation and dry matter loss. However, reducing biomass recalcitrance due to lignin, during storage, could simplify subsequent conversion.

Enzymatic activity on biomass is influenced by cellulose, hemicellulose, ferulic acid, para-coumaric acid, xylose, glucose, arabinose, and ash [13]. The lignin content and the cellulose-hemicellulose bond affect the accessibility of polysaccharides to the enzymes degrading it to monomers and subsequently to alcohol. McNeil et al. [14] noted that linear xylan, a type of hemicellulose, has a high affinity for cellulose fibrils. An increase in hydrogen bonding between xylan and cellulose microfibrils could lower the ability of enzymes to degrade biomass. Chesson [15] described the shortcomings of analyzing the plant cell wall for its content in individual compounds, isolated through oxidation and hydrolysis, and recommended instead the study of plant cell wall degradation as affected by interactions between its components.

7.4 Prevention of Dry Matter Loss During Storage

Dry matter losses are sometimes described as plant wilting. Reported dry matter loss estimates vary substantially in literature since the total loss is a function of a number of factors such as feedstock type, particle size, and local weather. Some representative numbers published in the literature include 5 % loss in net-wrapped bales stored on crushed rock [17], 7 % loss in switchgrass bales in covered storage [18], and 13 % losses in switchgrass [19]. Mani et al. [20] report that field wilting occurs due to three possible reasons. The first is mechanical, which includes handling of the crop during harvesting and transport. The second is biochemical, which includes dry matter losses due to respiration and enzymatic processes in the plant. The third is leaching due to rain, which doubles dry matter losses in wilted material. Wind erosion also causes dry matter particles to be lost from bales in the field, a loss that is reduced by net-wrapping bales [17]. The mechanism of dry matter loss during wet storage has been studied extensively [20, 21]. The important factors affecting the dry matter loss during wet storage are high temperature [20, 22] and microbial dry matter oxidation [21, 23].

This section reviews methods that can be used to reduce or prevent dry matter loss in biomass feedstock. Some methods, such as drying, are well known and practiced regularly for conventional agricultural crops, while others like freezing and addition of additives are relatively novel.

7.4.1 Drying

Drying is perhaps the most well-known approach to reduce dry matter loss due to degradation. Drying reduces available water and therefore water activity, which reduces microbial activity level and the consumption rate of water-soluble carbohydrates. Anaerobic microbial activity is inhibited at water potential below –4.0 MPa. In the absence of salts as additives, a moisture content below 15 % is reported to inhibit anaerobic microbial activity [24].

Drying can be achieved through exposure to sunlight or by air convection [24]. Solar dryers may also be used. Air convection can be achieved by electric- or gas-powered fans and by exposing the biomass to an air flow at either ambient temperature or heated conditions. Alternatively, the exhaust gas from harvesters, other vehicles, or other engines used in biomass handling operations can be injected into a biomass container with an interior structure designed for maximum exposure of biomass to air. Such an exhaust gas would be both hot and rich in CO_2, which inhibits microbial oxidation. Drying is facilitated as particle size is reduced, due to higher surface area to volume ratio in the particles from which water is to be evaporated and more disrupted plant tissue from which water can evaporate.

Typically, the targeted moisture level commonly reported in literature for safe, long-term storage of biomass is 15 % on a dry basis. Additives such as salts may also be added to allow reaching the inhibiting water activity level while maintaining higher moisture content. However, drying can be quite expensive, especially at the scale envisioned for the lignocellulosic biomass feedstock system. The energy cost depends on the heat capacity of the biomass pile, its moisture content, the ambient temperature, and relative humidity. Thus, achieving 15 % moisture content may not always be feasible. Moreover, the relative humidity and temperature have a significant impact on the equilibrium moisture content of the biomass. A more fundamental understanding of the drying process by developing the moisture isotherms as a function of these factors thus becomes important. Recent literature shows some interest in generating these moisture isotherms for the novel energy crops [25–27]. A thermodynamic calculation can then be made to compute how much energy is needed to evaporate enough water from biomass in order to reach a target moisture level. Well-known sorption/desorption models such as the Chung-Pfost model or the modified Oswin model may also be fitted to the experimental data. This facilitates the drying facility design calculations.

It is important to note that drying also causes dry matter losses before having a preserving effect on dry matter by inhibiting microbial activity [28]. This is due in part to the volatilization of volatile organic compounds during drying. If heated air is used for drying, the dry matter loss could also be due to the increase in cellulose hydrolysis into water-soluble sugar as temperature increase catalyzes the activity of the cellulose enzyme-producing *Trichoderma* sp., up to a limit. Bacterial oxidation of sugars also increases with temperature up to a certain limit, adding to the losses in dry matter. Oxidation rate doubles with every 10 °C increase in temperature [22].

7.4.2 Compaction and Sealing

Oxidation by aerobic bacteria can be prevented by rapid packing, dense packing, and sealing [29]. In the case of pre-compacted silage, the model by Mani et al. [20] assumed 1-day pre-seal phase, 1- to 3-month fermentation phase, and 6- to 9-month oxygen infiltration phase. The maximum dry matter losses were 3 %. When samples with varying dry matter content were compared, losses increased as silage % dry matter increased. In Mani et al. [20] dry matter losses were up to six times higher in the oxygen infiltration phase than in the fermentation phase. In the case of

Table 7.2 Effect of bale size and storage conditions on dry matter losses[a]

Experiment	Start data	Months in storage	Bale diameter in m	Bale weight in kg	Total dry matter losses (%)	Storage conditions	Dry matter
1	August 1992	6	1.39	275	13	–	3.4
2	November 1993	12	1.76	370	5.6	Outside on grass sod	6.0
					4.0	Outside on gravel pad	
					0	Inside on concrete	
3	November 1994	12	1.76	370	6.0	Outside on sod	4.4
					4.7	Outside on gravel	
					2.2	Inside on concrete	

[a] Adapted from Sanderson et al. [32]

self-compacted silage, losses during infiltration reached 10 %. During the fermentation phase, as in the case of pre-compacted biomass, dry matter losses were up to 0.6 %. More specifically, compaction reduces porosity, which in turn affects oxygen infiltration rates and consequently respiration levels. The model described in McGechan and Williams [23] predicts dry matter oxidation due to oxygen infiltration. They suggested that compacting and sealing ensiled material can reduce dry matter loss. Improved sealing with a plastic sheet is theoretically possible but effective sealing is a challenge.

Densification is also a means to compact biomass and to reduce porosity. This can be achieved by pelleting, baling, briquetting, or bundling to obtain different bulk densities [30].

Dry matter loss significantly decreases as the packing density at the onset of storage increases [12]. Dry matter loss is in part due to the microbial consumption in cellulose. This consumption increases with time, and the microbial activity increases as temperature rises and aeration decreases [22]. Packing densities in a bunker silo of 160 kg dry matter m^{-3} (10 lb dry matter ft^{-3}) and 480 kg m^{-3} (30 lb dry matter ft^{-3}) result in 20–10 % dry matter losses [31], showing a decrease on dry matter loss as packing density increases. Packing density of 56 kg dry matter m^{-3} (3.5 lb dry matter ft^{-3}) to 112 kg dry matter m^{-3} (7 lb dry matter ft^{-3}) significantly decreases the rate of dry matter loss, according to the model.

7.4.3 Bale Size and Storage Conditions

As discussed in Chap. 5, balers produce either round (cylindrical) bales or rectangular bales. In terms of dry matter loss, round bales are more resistant to water penetration. Also a round bale with a diameter equal to its width will have the minimum surface area to volume ratio, thus minimizing surface degradation relative to volume. However, rectangular bales are easier to handle, ship, and stack, and greater bale densities can be generated with this bale shape.

Data on bales of different sizes (Table 7.2) adapted from Sanderson et al. [32] showed that the average loss of biomass decreases as bale diameter increased, with all other conditions being equal. However, losses at baling due to runoff and wind erosion increase as the bales become larger. Significant runoff from bales was found for larger bales, but the depth of weathered layer in bales stored outdoors increased quadratically over a 6-month storage period, reaching a depth of 7.5 cm.

The effect of type of surface that a switchgrass (*Panicum virgatum L.*) bale is in contact with, and shelter from the elements, was correlated with dry matter losses by Sanderson et al. [32]. They modeled dry matter losses in 275 kg round bales of switchgrass (1.39 m diameter and 1.19 m long) with less than 10 % moisture at the point of baling as

$$\mathit{Final\,dry\,weight\,in\,kg} = 278 - 0.19 * \mathit{days\,after\,baling} \tag{7.2}$$

A more accurate way of calculating dry matter loss would be through a storage technology-agnostic model, in which the bale and ground surface interface would be substituted with the level of water activity (also known as water potential) and microbial activity. Since the soil is a source of water and microbes, these factors would be elevated in the bale region close to the ground relative to other regions in the bale. A water diffusion factor would determine the extent of spread of microbial oxidation of dry matter from the soil/bale interface. The total dry matter losses due to the surface area of this interface can be calculated by running a simulation on a model to account for the above mentioned factors. Development of such a model is one of the important research directions of this field.

7.4.4 Freezing or Cooling

Freezing has both the effect of reducing water activity and reducing temperature. Microbial activity ceases at 4 °C; however, reaching and maintaining this temperature requires more energy than drying biomass to a 15 % moisture level. After biomass is refrigerated, its temperature tends to increase under the effect of entropy and the equilibrium with ambient temperature. This is attenuated by good insulation, but energy is still used to keep the biomass at 4 °C. Cooling reduces but does not inhibit microbial activity. Oxidation rate is halved with every 10 °C decrease in temperature [22].

Freezing and cooling can be achieved by fitting storage tanks with compressors and cooling reagents. The energy requirements of such a compressor can be calculated based on the compressor efficiency, power, ambient temperature, biomass heating capacity, and moisture content which influence heating capacity. Ice blocks can also be used if the biomass is to be kept cool only for the length of transportation time, from the harvest site to the production plant. In the Midwestern region of the USA, switchgrass and Miscanthus would be harvested in the winter months of November to March. One argument in favor of freezing is that the ambient temperature during these months is quite low and there is snowfall. Freeze drying, therefore, may not be such an energy intensive operation for such a situation. Recently, Eckhoff [33] studied this option for storing high-moisture corn so as to enable the use of corn stover for ethanol production or as animal feed. He developed a preliminary system design using this concept, which showed promise.

7.4.5 Ensiling

Ensiling consists of fermentation that occurs in anaerobic conditions and in the presence of molds and yeasts [20]. The by-products of fermentation are organic acids, and their dissociation results in protons and a lower pH. Low pH levels inhibit microbial activity and the resulting dry matter loss. The model adapted from Pitt et al. [22] includes the factored effect of pH change on the rate of microbial oxidation and can be developed to predict the effect of pH change on anaerobic microbial activity. Tanjore et al. [28] compared the impact of drying, freezing, and refrigeration prior to ensiling on the corn stover quality. They concluded that drying and refrigeration led to irreversible changes in the biomass quality.

7.4.6 Additives

A number of additives have been investigated for the purpose of reducing dry matter loss. In particular, salts and acids have been applied to biomass and carbon dioxide is a commonly used gas for inhibiting microbial activity.

7.4.6.1 Salts

Salt is one additive that would reduce the water activity as it increases osmotic potential and would avoid the high costs associated with drying. If salt is obtained as an industry by-product, and from a nearby location with manageable transportation cost, it might be cost-effective to add it to the stored biomass. Water activity affects microbial respiration and, therefore, dry matter losses by oxidation. Microbial activity is reduced as water availability reduces.

7.4.6.2 Acids

Acids are typical additives in biomass storage systems. Lower pH inhibits microbial activity, both in the case of aerobes and anaerobes. In ensiling, acids are self-generated by the anaerobic fermentation, leading to a negative feedback and the inhibition of microbial activity in the ensiled biomass. Sulfuric or hydrochloric acid is typically used, but they are costly to remove [16]. Acids need to be removed to raise the pH and create a suitable environment for cellulase-producing fungi for hydrolysis and yeasts for fermenting the resulting sugar to alcohol. The pH levels affect the fermentation of glucose into alcohol by the β-glucosidase enzyme as shown in Table 7.3. β-glucosidase was used at its optimal level to obtain the shortest conversion time of cellulose to ethanol, 0.7–0.8 unit/mL. To maintain the optimal level of β-glucosidase, pH value is critical at the beginning of ethanol production process (see Table 7.3), and an optimal pH was found to be 4.5.

Table 7.3 Effect of pH on the production of ethanol from glucose as catalyzed by an enzyme[a]

pH	Ethanol production (g/l) with β-glucosidase in 3–4 days
3.5	0.5
4.5	9.1
6.0	7.6

[a]Adapted from Christakopoulos et al. [34]

7.4.6.3 Carbon Dioxide

Carbon dioxide (CO_2) is an additive that can be obtained from the exhaust of engines used in harvesting, transporting, and preserving biomass. Such exhaust gases would have high temperature that can dry biomass. However, CO_2 is also an inhibitory agent to aerobic respiration. This exhaust gas can be routed from the engines into closed storage containers. A pressure-release valve can be added to the conduits to prevent exhaust gas backflow into the engine when gas pressure becomes too high in the storage containers. Organic matter-based biofilters can also be added to the storage container to allow CO_2 gas to precipitate or be fixed into the organic matter as the excess gas exits into the atmosphere. The economic feasibility of such a system, especially for large scale biomass storage, will need to be studied.

7.5 Reduction of Biomass Recalcitrance to Breakdown

As mentioned in the introduction, the goal of biomass feedstock storage is not only to preserve total biomass dry matter and the carbohydrates, but also to effect changes that aid further processing of biomass to ethanol or other products. The proposal of regional or centralized storage and preprocessing centers uses this concept to combine preprocessing with storage. Therefore, it is important to summarize the main factors that make biomass recalcitrant, thereby creating barriers for decomposition. A better understanding of the recalcitrance will enable selective breakdown of biomass to recalcitrance while preserving the total dry matter and carbohydrate content. This section presents the important source of recalcitrance and the options to reduce it.

7.5.1 Sources of Recalcitrance

Recalcitrance is strongly affected by plant structure with reference to lignin, cellulose, and hemicellulose components. In addition, moisture content and particle size both play an important role in both material compression and preprocessing.

7.5.1.1 Plant Structure

Kenney [35] described the components of dry lignocellulosic biomass, their typical composition, and expected variability. The first is cellulose, 30–50 % of dry matter, which is hydrolyzed to C6 sugars. The second is hemicellulose, 20–40 % of dry matter, hydrolyzed to the C5 sugars xylose, arabinose, mannose, and galactose. The third component is lignin, 15–25 % of dry matter. Lignin coats and protects the cellulose-hemicellulose complexes from degradation [16]. These complexes are the building blocks of secondary plant cell walls, and they consist of cellulose-based microfibrils coated with hemicellulose and lignin. Chains of microfibrils are produced six at a time by protein complexes (rosettes) embedded in the cell wall. These microfibrils have a semicrystalline structure due to the bonding across the chains. The fibrils are insoluble oligosaccharides, with more than five molecules per polymer. Some amorphous (easy to digest) regions in the fibrils are due to faults in the order of strands produced by the rosettes. Hemicellulose molecules coat theses microfibrils made of β-1,4 glucan strands, connected by extensive hydrogen bonds. Hemicelluloses plasticize the cellulose strands apart to allow for flexibility in the cell wall. Hemicelluloses also bind with lignin, which covers the fibrils, protects them from water, gives mechanical reinforcement, and acts as a barrier to microbial digestion. It is this complex structure, shown in Fig. 7.6, adapted from Gomez et al. [16], that makes the lignocellulosic biomass (plant cell walls primarily) resilient to break down. According to Kurasawa et al. [36], NDF (neutral detergent fiber) from a food sample contains cellulose, hemicellulose, and lignin as cell wall constituents. ADF (acid detergent fiber) contains most of the cellulose, lignin, a portion of the pectin substances, and variable but small amounts of the hemicellulose. Hemicellulose is obtained by subtracting the ADF from the NDF, and the value of cellulose is estimated by the difference between the values of ADF and lignin. Since cellulose is a portion of dry matter,

$$Cellulose\,loss = \%\,dry\,matter\,loss \times \%\,cellulose\left(d.b.\right)$$

7.5.1.2 Moisture

Higher moisture content increases the elasticity of the biomass, making cutting or shredding, as part of preprocessing, less effective. In contrast, compaction treatments to increase material density before packing are less effective when biomass is too dry. A range of biomass moisture content, which does not impede preprocessing yet facilitates compaction, needs to be determined. In the case of corn stover, relatively dry biomass also causes dry matter losses due to wind erosion and scatter, compared to wet biomass [37]. A study by Chaoui et al. [12] showed that as moisture content decreases, the stiffness of shoot segments from Miscanthus plants increases. Stiffness affects milling of the harvested biomass.

7.5.1.3 Particle Size

Shredding biomass to smaller particle sizes creates more surface area to be exposed to enzymatic activity. Particle size reduction also mechanically breaks down the lignin coat surrounding microfibrils, thus exposing some of the cellulose to cellulase enzymes. Particle size can be reduced either by shredding to a small particle size during harvesting or by milling (wet or dry) or crushing (dry). Hammer mills are used for dry crushing. However, smaller particles are more susceptible to erosion by wind and rain. Therefore, from a bale or outdoor storage perspective, larger particle sizes may be desirable.

7.5.2 Pretreatment

In this section, the possible pretreatment options to reduce the biomass recalcitrance are presented.

7.5.2.1 Acid Hydrolysis

Acids used as additives include hydrochloric and sulfuric acids. These acids break down lignin into acid soluble lignin (ASL), but are costly to remove. It is necessary to rinse acids form biomass to increase the pH back to levels at which sugar-fermenting yeasts can ferment C6 sugars to alcohol. Raising the pH after acid treatment could result in dry matter losses through leaching of water-soluble sugars during the temperature increase process. Lignin and lignin residues can affect further cellulose hydrolysis by cellulase enzymes. Gregg et al. [38] showed that cellulases are absorbed on lignin as well as the lignaceous residues from hydrolyzed biomass. Cellulases then become unavailable for further hydrolysis reaction, and therefore an increase in lignin lowers cellulose hydrolysis rate (Fig. 7.7).

7.5.2.2 Use of Enzymes

Enzymes including laccase, lignin peroxidases, and manganese peroxidases can degrade lignin. The latter two enzymes are produced by the groups of the white-rot fungus *Phanerochaete chrysosporium*. Hatakka [39] tested several fungi groups according to the lignin enzymes they produce and found that the lignin-manganese peroxidase fungi was the most efficient at breaking down lignin.

7.5.2.3 Ultrasound

Khanal et al. [40] reported that corn mash was sonicated (treated with contact ultrasounds) at a peak to peak amplitude of 180–299 μm. With ultrasonic treatment for 40 s at a power output of 475 ± 15 W, cells were almost completely disintegrated and

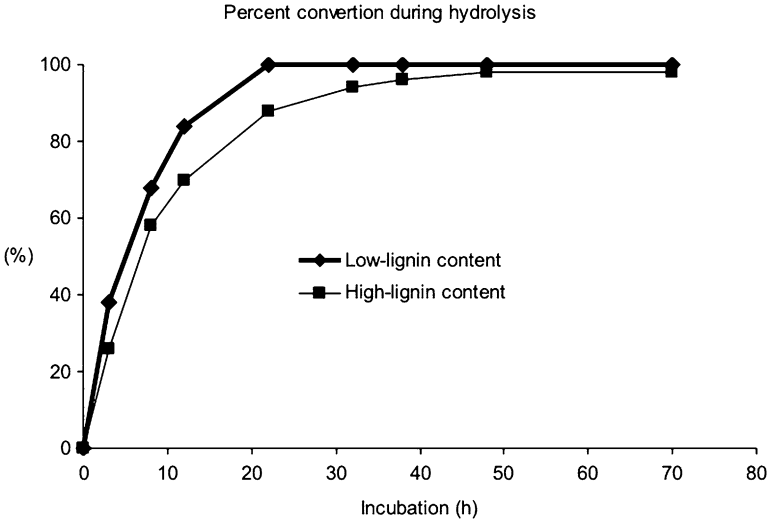

Fig. 7.7 Percent conversion of cellulose to glucose, during hydrolysis, in the presence of lower-lignin and higher-lignin content

particle size was reduced based on images from scanning electron micrographs (SEM) of raw and cooked corn slurry samples before and after sonication. About five times more glucose can theoretically be released from the sonicated samples relative to the control. An ultrasonic unit with a power output of 2.2 kW and a frequency of 20 kHz was used, and its energy efficiency was calculated based on the calorific content of the sugar (glucose) released from the treatment samples.

7.5.3 Harvest Time as a Method for Minimizing Lignin Content

Plant age decreases the percent of plant dry matter that can be degraded. Chaves et al. [41] empirically modeled the rate at which an increase in the age of ryegrass shoots decreased plant fiber digestibility. Even though for ethanol production purposes it is the free sugar and lignin content that is relevant, plant fiber digestibility is an indirect measure of the biomass's resistance to degradation, which is relevant when breaking down plant cellulose to sugars. In Chaves et al. [41], the fraction of dry matter disappearing per hour upon incubation in a liquid-permeable bag in a cow's rumen decreased from 0.11 to 0.03 as the plant shoot aged by about 80 days. As plant shoots aged, plants gained in fiber content and lost in nutrients. According to Chaves et al. [41] neutral detergent fibers (fibers that would be accessible to amylase if there was no pretreatment with acid) are correlated to plant age as follows ($R^2 = 0.80$):

$$\begin{aligned} &\textit{Neutral}\ \det \textit{ergent fiber content} = \\ &\quad 486.0 - 1.6(\textit{shoot age in days}) + 0.033(\textit{shoot age in days})^2 \end{aligned} \tag{7.3}$$

Jung et al. [42] correlated lignin content and neutral detergent fiber digestibility. The Klason method detected the most lignin in plant material, which for ethanol production purposes is the conservative estimate. According to Jung et al. [42], the neutral detergent fiber digestibility in grasses is correlated with Klason-determined lignin amounts (KL) in a relationship that fits both C3 and C4 plant types and might therefore apply to Miscanthus:

$$\%\, of\ neutral\ \mathrm{det}\, ergent\ fiber\ digestibility = -3.59KL + 103.9\left(R^2 = 0.49\right) \quad (7.4)$$

Plant degradability decreases with plant age because of an increase in plant lignin with age. For the purpose of ethanol production from cellulose, it is therefore useful to find an optimal balance between relatively high-fiber and low-lignin content as we select the plant shoot age at harvest. Jung et al. [42] also determined the % dry matter digestibility in grasses as a function of Klason lignin % as follows:

$$\%\, Dry\ matter\ digestibility = -2.20\%\, KL + 84.5\left(R^2 = 0.67\right) \quad (7.5)$$

where % KL is the acid digestible lignin by the Klason method in % of total dry matter.

Cherney et al. [43] also reported data showing a correlation between percent lignin content (of dry matter) and in vitro digestibility of dry matter. The following trend line was extrapolated from the data in Cherney et al. ([43], Table 3):

$$\%\, Dry\ matter\ digestibility = -0.6993\left(\%\,\mathrm{L}\right)^2 - 4.1735\left(\%\,\mathrm{L}\right) + 96.77 \quad (7.6)$$

where % L = % lignin (dry basis).

Cherney et al. ([43], Table 3) reported data from which the following relationship correlating perennial grasses shoot age with digestibility was extrapolated, assuming a grass emergence date of April 15 in New York state (44′ 35 min latitude, 75′ 7 min longitude):

$$\%\, Dry\ matter\ digestibility = -26.34\ln\left(A_d\right) + 174.94 \quad (7.7)$$

where A_d = plant age in days. The following correlation between lignin dry matter content and plant age was also extrapolated from the lignin % of dry matter and plant age data reported in Cherney et al. ([43], Table 3):

$$\%\, L = 3.1751\ln\left(A_d\right) - 8.82 \quad (7.8)$$

Chaves [41] correlated plant age with the content in nonstructural sugars, which are readily fermented to alcohol ($R^2 = 0.28$)

$$\frac{\mathrm{g}\ \ non-structural\ \ carbohydrates}{kg\ \ dry\ \ matter} = 53 + 1.74\left(A_d\right) - 0.016\left(A_d\right)^2$$

$$\%\ \ non-structural\ \ carbohydrates = 5.3 + 0.174\left(A_d\right) - 0.0016\left(A_d\right)^2 \quad (7.9)$$

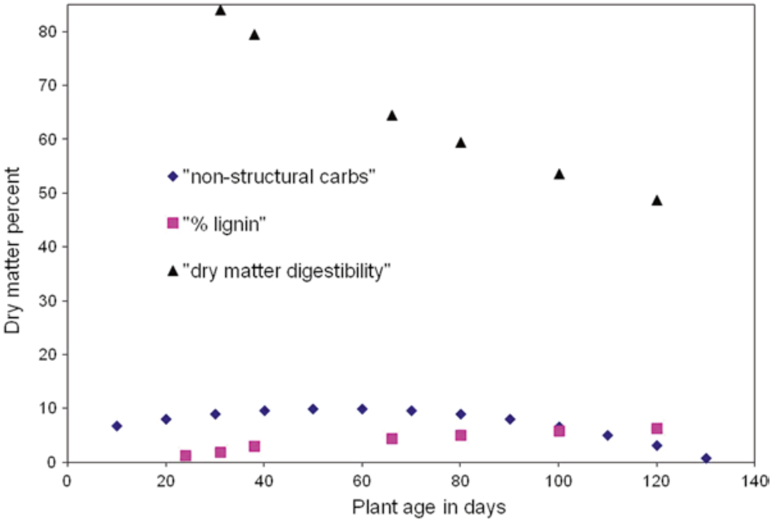

Fig. 7.8 Trends in dry matter digestibility, % lignin content, and nonstructural carbohydrates content (all as percent dry matter), as a function of plant age. These relationships were extrapolated from data reported in Jung et al. [32] and Cherney et al. [33] on 36 forages including C3 legumes and C3 and C4 grasses

The digestible dry matter, nonstructural carbohydrates, and lignin contents versus plant age shown in Fig. 7.8 were extrapolated from findings reported by Chaves et al. [41], Jung et al. [42], and Cherney et al. [43].

Models resulting from analytical methods for estimating lignin and sugar content and biomass digestibility based on plant age can be used to select a biomass harvest date at which biomass quantity and digestibility are optimized.

7.6 Selecting a Storage Method

As explained in Rentizelas et al. [44], storage can be the costliest step in the supply chain of biomass. The supply is seasonal while the storage facility cost has to be justified year round. Therefore, selection of the appropriate storage method is critical. Table 7.1 provides a qualitative comparison between different storage options, which can be used as a basis for further selection using quantitative information. The final selection of the storage option will depend on a number of factors such as quantity of feedstock to be handled, form of the feedstock, expected duration of storage, regional weather conditions, end use of the feedstock, transportation distances before and after storage, availability of land, availability of capital, and infrastructure availability.

Fig. 7.9 Outdoor storage of square bales of Miscanthus in Pena, Illinois, 2 years after harvest. The blue protective tarpaulin breaks down in extreme weather conditions. Photograph courtesy of the Department of Agricultural and Biological Engineering of the University of Illinois

Outdoor storage of baled biomass (Fig. 7.9) is most common. Cundiff et al. [45] showed that storing biomass in the field is the most cost-effective for the specific case they analyzed. However, outdoor storage method makes it impossible to control biomass quality and losses, or dry the harvested material to reduce its weight and transport cost. Moreover, baling poses health hazards due to the growth of mold (Fig. 7.10) and self-ignition risks [44] due to self-heating, which is a function of moisture content in bales [20]. Open storage may be acceptable in arid or dry regions but may be problematic in regions with frequent precipitation events.

Indoor or temperature-controlled storage provides better biomass quality control. In a case study on cotton stalks and almond tree prunings representing two types of cellulosic biomass, Rentizelas et al. [44] compared three storage scenarios: ambient storage, in a warehouse after drying, and covered without drying (Table 7.4). The results showed that ambient storage caused twice the dry matter loss as compared to covered storage, and that losses were negligible in dried warehoused biomass. However, the investment cost of a biomass warehouse is ten times that of ambient storage, and the gain is 1 % of dry matter preserved per month. Rentizelas et al. [44] demonstrated that using multiple biomass streams allows maximizing the use of a storage facility and staggering harvest dates. This increases the cost-efficiency of a drying and storage facility.

Mooney et al. [46] compared the storage options of baled switchgrass using different combinations of baling technology, covering, and storage methods. They observed that bale shape (round or square) and cover type impacted the dry matter

Fig. 7.10 Weathering of the outer layer of a switchgrass square bale in Pena, Illinois. Photograph courtesy of the Department of Agricultural and Biological Engineering of the University of Illinois

Table 7.4 Biomass losses and investment costs were analyzed for three biomass storage methods: ambient storage (outdoor, covered with a thin plastic film), covered storage without drying, and dried biomass stored in a warehouse[a]

	Dried—warehoused	Covered—no drying	Ambient storage
Material loss (% per month)	Negligible	0.5 %	1 %
Storage investment cost (€/m^2 present value)	222	110	22

[a] Adapted from Rentizelas et al. [44], based on a case study of cotton stalks and almond tree prunings

loss the most. They concluded that although covered rectangular bales had higher dry matter loss, they were still profitable due to lower harvest, storage, and transport costs. Uncovered storage of round bales was recommended only for high prices at the farm gate and long-storage durations.

Recently, there has been greater interest in exploring the option of wet storage or ensilage [47]. Li et al. [6] summarized the advantages of using wet storage, including lower harvesting cost, lower dry matter loss, increased product uniformity, improved feedstock susceptibility to further processing, reduced risk of fire, and value addition to the feedstock. They concluded that these advantages make wet storage a potentially suitable option, especially for wet and humid regions where drying of feedstock can be challenging.

From a point of view of the complete biomass production and provision system, the optimal storage option may be a combination of multiple storage methods and locations. For example, Shastri et al. [1] recommended a combination of on-farm open, on-farm covered (shed with no walls), and centralized (shed with four walls) storage for the Miscanthus production system. Similar results were reported for switchgrass [48]. In such a configuration, biomass stored in open can be shipped to the biorefinery within a limited number of days while biomass stored in a covered facility may be shipped towards the end of the season. However, such design requires coordination of the whole system since all the farmers providing biomass must know the delivery date. The implementation of systemic viewpoint, as highlighted in the next section, is therefore, critical.

7.7 Summary and Future Work

Storage of biomass feedstock is necessary to balance the seasonal availability of biomass with the year-round biorefinery requirement. The low-density and low-value, high-volume nature of the feedstock creates challenges for cost-effective storage. Moreover, quantity and quality preservation during storage is important. An ideal storage facility would minimize the dry matter loss, minimize the carbohydrate loss, and prepare the feedstock for subsequent processing into fuel. This chapter reviewed literature along these lines to present the current understanding of these issues.

The review showed that considerable efforts have been made to develop a mechanistic understanding of the biomass loss during storage, especially the loss of cellulose. Different factors such as temperature, microbial activity, and moisture content have been independently studied in the literature. The possible remedies to minimize dry matter loss have also been proposed. Some options such as drying are well known and practiced for conventional agricultural products. Therefore, theoretical foundations and design guidelines already exist, which can be used for biomass feedstock. Some novel methods such as freezing though need to be studied more rigorously. A combination of various alternatives as part of the same storage facility may also be the optimal solution.

The topic of preparing biomass for further processing as part of storage has not been studied that much. Mechanical treatments such as size reduction to increase the surface area for enzymatic activity have been proposed and also implemented. The suitability of causing chemical/compositional changes to the biomass needs to be studied further. It would be important to ensure that the resultant intermediate product is stable enough for further storage, transportation, and handling, before its conversion to ethanol.

In addition to this, the following specific topics of future research have been identified:

- A holistic model for biomass dry matter loss and quality degradation needs to be developed. Such a model would combine the biomass properties, storage attributes, and environmental conditions to provide accurate estimates of total dry matter loss as well as the loss in individual components of the biomass. The mathematical models can then be incorporated in model-based studies, similar to those highlighted in the next chapter, for whole-system design.

- The comparison of different storage methods needs to be performed using realistic setup and storage facilities. The Energy Biosciences Institute has set up a test facility where biomass in different forms, such as bales, chopped, and ground, can be stored for long duration, with and without treatment [49]. The results from such studies are likely to provide a realistic comparison of storage alternatives.
- The analysis of the bulk storage, such as a stack of bales or a pile of biomass, needs to be performed. When biomass is stored in a stack, material found in the outer layer is exposed to different conditions than that which is at the center of the stack/pile. Therefore, better understanding the parameters such as temperature and moisture inside the stack/pile is necessary to improve quality and safety. Bedane et al. [50] conducted a similar study for a pile of woody biomass in open storage. Computational fluid dynamics (CFD) studies must be used to complement the experimental studies to generate fundamental understanding of the underlying processes.
- Once the storage facility has been designed, the operation of the storage facility also needs to be optimized. Scheduling the intake and removal of the biomass as a function of time and biomass properties is a complex problem. Eriksson [51] conducted an analysis for wood chips stored in open piles and concluded that last in first out (LIFO) policy performed better than first in first out (FIFO). Such studies for additional crops and storage options need to be performed.
- An easy to use, instantaneous, hand-held quality meter needs to be developed [52]. Such a meter can be used to monitor storage conditions as well as to evaluate biomass feedstock at the refinery gate and decide the value of the feedstock.
- The setup of regional storage facilities that also perform preprocessing has been generating interest. The design of a storage facility that enables this will be a challenging problem and must be addressed in the future.

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Chapter 8
Systems Informatics and Analysis

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Abstract Various biomass feedstock production and provision (BFPP) tasks discussed in earlier chapters are highly interconnected. Design and operational decisions for any task impact decisions for most other tasks. In view of such complex interactions, it is critical that we also look beyond an individual task and focus on the techno-economic feasibility of the complete production and provision system. This calls for a holistic view of the BFPP system. Systems theory based approaches that integrate systems informatics and analysis methods are ideally suited to achieve this objective. This chapter reviews the literature on the application of such approaches for BFPP. The basics of informatics, modeling and analysis, and decision support are first discussed. Then their applications for different system classes, namely, crop growth and management systems, on-farm production systems, local biomass provision systems, and regional/national/global systems, are presented. The literature review illustrated that applications of the systems-based tools at the crop growth, establishment, and management levels as well as the local biomass provision level have been numerous. Many of these developments have built on tools already existing for conventional crops. Systems theory applications to the on-farm production scale have been limited, possibly due to lack of field study data as

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Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4_8,

well as limited commercial farming. In contrast, interest in studying the regional/national/global systems has increased in recent years. We conclude that greater efforts are needed to validate these tools and to study issues cutting across multiple scales. We also recommend that seamless integration of informatics, analysis, and decision support tools is necessary to achieve a truly concurrent science, engineering, and technology-based platform for decision making in the future.

8.1 Introduction

The preceding chapters discussed the important tasks in the biomass feedstock production and provision (BFPP) value chain. The basic concepts in each task were presented, and the major challenges and potential solutions were also identified. The implementation of the proposed solutions is expected to contribute towards optimizing the individual tasks. However, focusing on individual tasks is often not enough. These production and provision tasks are highly interdependent, with decisions for one task having implications on upstream and downstream design and operating constraints and decisions. The following examples highlight this aspect:

- Harvesting operations of Miscanthus in temperate regions are proposed in winter, typically from January onwards. This allows translocation of nutrients to rhizomes and also reduces moisture content of the harvested biomass. However, late harvest reduces the harvestable biomass by more than 30 %. Moreover, field operations in winter are difficult due to extreme weather conditions.
- Single-pass harvesting such as with a self-propelled forage harvester (SPFH) that combines mowing as well as further preprocessing has been recommended for improved harvesting efficiency and quality. However, chopped biomass from an SPFH is of considerably low density (~80–100 kg m^{-3}) as compared to baled biomass. This makes storage and transportation highly inefficient and costly [1].
- Pelletized biomass is very efficient for transportation and storage due to high bulk density of the feedstock (~650 kg m^{-3}) and availability of existing materials handling equipment. Shastri et al. [1] showed that pelletization of Miscanthus reduced the storage and transportation cost by about 60 % over baling. However, much higher cost of pelletization increased the total Miscanthus production cost by about 8 %. The energy consumption was also substantially higher for pelletization.

These examples highlight the conflicts that are often encountered in designing and operating the BFPP system. Such interdependencies cannot be captured by studies focusing on a specific task. Therefore, it is critical to go beyond addressing the task-specific challenges and instead focus on the compatibility of various tasks, and thus try to achieve an overall optimal value chain configuration. Systems-based approaches that integrate systems informatics and analysis (SIA) techniques, such as database design, simulation modeling, optimization, and decision support systems (DSS), provide the necessary tools to achieve these goals. The objective of this chapter is to review the application of various SIA methods to study the BFPP systems. We highlight the important developments, identify research gaps, and provide future research directions.

Modeling is an important tool and constitutes the basis of all systems theory based research. Computer models are attractive because of multiple reasons:

- Models provide cheaper alternatives to expensive field studies and experiments. This benefit is obvious in the case of crop growth models where field trials are expensive, time consuming, and can only be conducted at limited locations.
- Models cutting across different tasks can be developed to study interdependencies. For example, whole-farm simulation models allow us to study long-term impacts of soil erosion or fertilization on yield and, therefore, on farm management practices.
- Models may be the only alternative to study large-scale, long-term impacts, such as life-cycle impacts over years and decades.

Therefore, special emphasis must be placed on understanding the modeling work in this area. This chapter will discuss some of the important models proposed for BFPP and will also present representative results from their applications.

The chapter is organized as follows: First, an overview of SIA is provided. Then the SIA applications are discussed at different system levels constituting the overall BFPP system, namely, crop growth and management, on-farm production, local production and provision, and regional/national/global. The important observations from this review are summarized, and the chapter ends with recommendations for future research.

8.2 Systems Informatics and Analysis

Although the primary objective of this chapter is to focus on the application of SIA approaches to BFPP, it is first prudent to summarize the key features of SIA in order to set the foundation for further discussion in the chapter.

A system is a set of interrelated components, in the physical as well as information space, organized with the purpose of conducting a particular task [2]. A system can be a part of a larger system and can also be a collection of multiple smaller systems, known as subsystems. Figure 8.1 shows this concept for a bioenergy system, where BFPP is a part of the larger bioenergy system. Similarly, Fig. 1.1 shows a systemic view of the BFPP system. It includes harvesting as one of the subsystems. However, harvesting equipment is a system in itself consisting of cutting, gathering, conveying, and processing subsystems, as described in Chap. 5. This property provides systems theory with a distinctly multi-scale character.

8.2.1 Systems Informatics

Informatics is the multidisciplinary science that has as its domain the information aspects of phenomena in nature and society [3] and finds broad applicability in areas such as science, engineering, medicine, and economics. It is based on the collection, storage, transmission, processing, and utilization of data. Examples of informatics techniques include coding technology, networking, data modeling, and user interfaces.

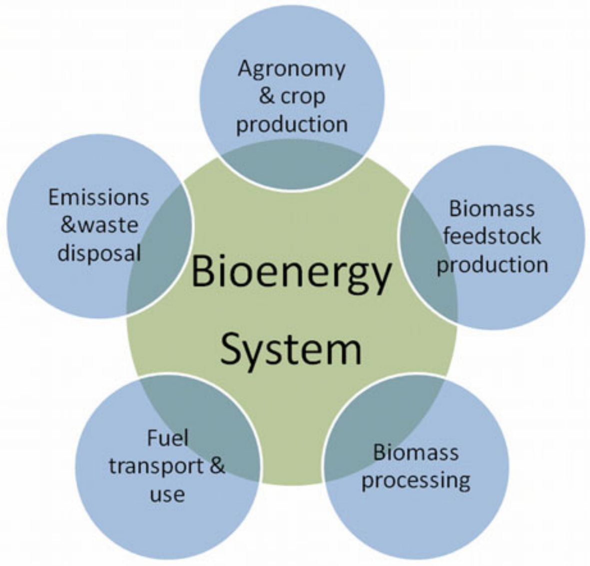

Fig. 8.1 Bioenergy system consisting of multiple subsystems including biomass feedstock production and provision; each subsystem is a system in itself

Systems informatics, therefore, is the application of the ideas in informatics for the study of integrated systems. The three major systems informatics techniques are:

- *Knowledge management*: Knowledge management attempts to enhance the performance of individuals and organizations through the maintenance and enhancement of the present and future values of knowledge assets [4]. Knowledge management focuses on knowledge and experience sharing.
- *Concurrent engineering*: Concurrent engineering, also termed simultaneous engineering, is the simultaneous progress of activities that are required in delivering new products to the customer. During the process of concurrent engineering, all the elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements, are considered [5]. Ting et al. [6] expanded this concept to include directed research activities necessary for the realization of long-term objectives.
- *Software engineering*: Software engineering is the branch of systems engineering related to the development of large and complex software systems [7], and some examples in agriculture are the BPSys [8], Integrated Biomass Supply Analysis and Logistics (IBSAL) model [9], and the Agricultural Production Systems Simulator (APSIM) [10].

8.2.2 Systems Analysis

Systems analysis refers to the functional aspect of a system. It involves developing models and using those models to perform explicit formal inquiry (scenario studies) and develop strategies to achieve desired objectives (optimization). The systems

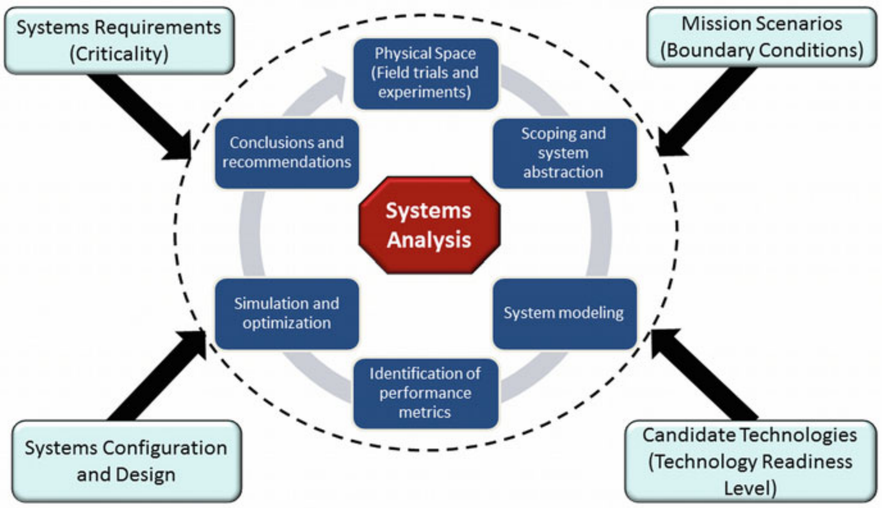

Fig. 8.2 The important stages of conducting a systems analysis and the boundary conditions or factors that must be considered while conducting the systems analysis

informatics techniques often enable these analysis methods. The important steps in systems analysis are the following (Fig. 8.2):

- *Definition of the system scope* (*and objectives*): The success of the systems approach often depends on identifying the conceptual, spatial, and temporal scope of the analysis. System boundaries are identified to limit the scope, and issues outside the boundary are represented as externalities. The scope should correspond with the intended objective of the proposed analysis.
- *System abstraction and modeling*: A model is a set of functions representing different aspects of the systems, such as a function correlating the harvesting with fuel consumption. In the broadest sense, these functions can be graphical, logical narratives, or mathematical representations of a concept or a physical environment [11]. Models can be classified as mechanistic, empirical, regression based, logical, and more. Models can also be static or dynamic, linear or nonlinear, and may also be classified as strategic, management, and operational based on their scope.
- *Identification of performance indicators*: The appropriate performance indicators are required to evaluate and compare system performance. In addition to the conventional economic indicators such as profit, cost, or net present value, sustainability-driven indicators such as energy consumption, life-cycle impact, and global warming potential are frequently considered.
- *Model simulation and scenario studies*: Scenarios are possible and relevant stories about how the system will behave or evolve under specific circumstances or inputs. From a BFPP perspective, a scenario refers to one of the many possible pathways of producing and provisioning the feedstock from farms to the biorefinery

while accounting for form, quantity, and quality criteria. The scenarios must be consistent with the model being used for prediction.

- *Performance improvement and optimization*: For performance improvement, the decision or control variables are first identified, and the feasible space of these variables is systematically explored to determine the optimal set of variable values. Some of the approaches used for exploring parameter space include mathematical/heuristics-based optimization, control theory, and rule-based systems.
- *Recommendations*: The final step in systems analysis is to use scenario study results to provide recommendations, which represent a shift from information space to physical space. For BFPP systems, these recommendations could include the crop management strategies, equipment selection, storage facility location and sizing, or the transportation logistics.

The systems analysis work must also consider the system targets (criticality), scenarios (boundary conditions), and the technology readiness levels (available options and their readiness) to provide a sound design or systems configuration (see Fig. 8.2).

A system-level study can be based on two modeling approaches. One can develop a case-specific, data-driven model, which is specific to the scenario being analyzed and uses data related to that scenario [12–15]. It is also possible to develop a generic model that is potentially applicable to multiple scenarios [9, 10, 16, 17]. Simultaneously, a database pertaining to different scenarios may also be developed and connected with the model. In the first approach, the model is not extensible and therefore the analysis results are case specific. The second approach is more desirable as the generic model and the accompanying database allow us to readily incorporate new scientific information generated through concurrent research. This enables a near-real-time analysis to study the implications of the new scientific and technological developments. Moreover, comparison of different scenarios is possible since the same set of assumptions is used. A generic model, however, is more difficult to develop and is computationally more challenging. We have primarily focused on such generic models and have discussed specific applications of those models. However, at selected places, we have also presented discussion on case-specific data-driven studies.

8.2.3 Decision Support Systems

Decision support systems (DSS) are information technology solutions that can be used in complex decision making [18]. Specifically, a decision-making system can be characterized as an integrated, interactive, and flexible computer system that supports all phases of the decision-making process [19]. Classic DSS include elements such as sophisticated database management capabilities with access to a range of data, powerful modeling functions accessed by a model management system, and powerful and simple user interface designs that enable interactive queries, reporting, and graphing functions [18]. The knowledge-based management subsystem is one of the core elements of the DSS. Examples of DSS in agriculture are I-FARM [20] and

WIMOVAC (Windows Intuitive Model of Vegetation response to Atmosphere and Climate Change) [21]. The importance of on-farm decision-making tools for biomass feedstock production has been recently highlighted by the United States Department of Energy [22].

8.3 Systems Informatics and Analysis in Biomass Feedstock Production and Provision

There are multiple approaches to classify literature on the application of SIA for BFPP systems. One approach is based on the methodologies used, such as databases, simulation models, optimization models, decision support tools, and web-based applications. The second approach is based on the temporal scope of the applications, such as strategic (years), management (weeks to months), and operational (hours to days). Lowrance et al. [23] instead proposed a spatially hierarchical approach including agronomic, microeconomic, ecologic, and macroeconomic levels. One can also discuss SIA literature specific to each task of the BFPP value chain represented in Fig. 1.2. However, it is often difficult to clearly delineate many such applications since they cut across multiple tasks.

In this chapter, we have used a classification approach that is based on the one proposed by Lowrance et al. [23] with modifications to account for the literature related to BFPP. These classes are:

- *Crop growth and management system*: This includes crop growth modeling, interaction of crops with soil and water, and the impact of management practices on crop yield.
- *On-farm production system*: This includes machinery selection, fertilization and irrigation management, and whole-farm management.
- *Local production and provision system*: This includes farm production as well as transportation and logistics management and local biorefinery system design, management, and operation.
- *Regional/national/global system*: This includes macroeconomic models for policy analysis as well as resource management.

The proposed classification involves spatial hierarchy where crop growth and management are of relevance to a specific field, while the regional, national, and global issues are relevant at a much larger scale (Fig. 8.3). For each of these classes, the important informatics, modeling, and analysis applications are discussed below.

8.3.1 Crop Growth and Management Systems

The research at the crop growth and management system level is often aimed at optimizing the interactions between the crop genotype, environment, and crop management [24]. Specific focus areas include estimating and maximizing the potential/

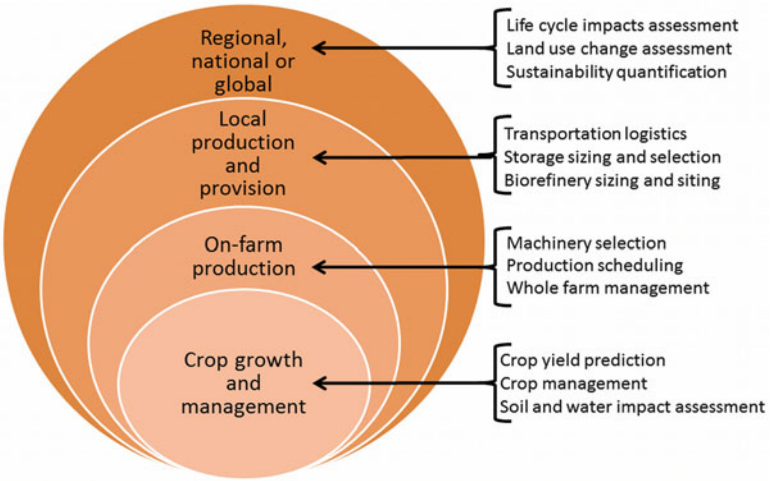

Fig. 8.3 Classification of the SIA applications to biomass feedstock production and provision with important decisions being considered within each class. The spatial scale increases as we move in the outward direction

achievable yield, optimizing resources such as nutrient and water, and minimizing the impact of disturbances such as pests and drought. The selection of the right crop and cultivar for a particular region is also important because the local/regional attributes such as soil type, rainfall, and temperature impact the achievable yield. Field experiments to study these factors are time consuming, expensive, specific, and often non-repeatable. Therefore, model-based approaches, especially crop growth models that predict the harvestable yield, have been frequently implemented. These models are not only important from an agronomy and crop management standpoint, but they also provide valuable inputs to engineering, economic, and policy research. Consequently, a substantial amount of effort has been given to developing such models.

Nair et al. [25] and Miguez et al. [26] provided an excellent review of the various bioenergy crop models. Figure 8.4 illustrates various factors, essentially subsystems as per the previous discussion, impacting growth modeling. While empirical models have been proposed in the literature [27, 28], mechanistic models have been more popular due to their greater adaptability. Mechanistic models can further be generic, where model parameters differ for different crop, or can be crop specific, where the model structure itself changes for each crop. Among both classes, some models simulate the growth of an individual plant, while others simulate crop growth on a per unit area basis [26].

All models include three important steps to model biomass production:

- Light interception by crop: Most models use Beer's law or its variation, which relies on crop-specific leaf area index (LAI) and the light extinction coefficient to calculate the intercepted radiation.

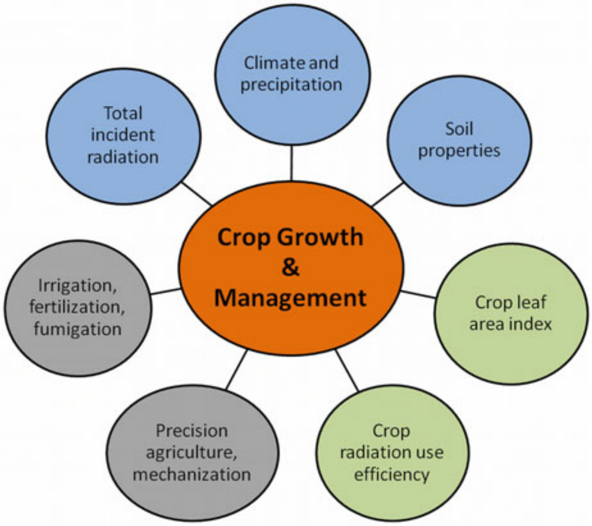

Fig. 8.4 Factors impacting the crop growth and management system that are often incorporated in system-level studies. Factors in *blue circles* are related to the environment, factors in *green circles* are related to the genotype, and factors in *gray circles* are related to the management

- Biomass production: Most models use the crop-specific radiation use efficiency (RUE) approach where the total intercepted radiation gives the total biomass production. However, the photosynthesis and respiration (PR) approach and the biochemical approach have also been used.
- Biomass partitioning: The total biomass produced is partitioned into different compartments. Many models use only two compartments, namely, aboveground and belowground. However, additional compartments have also been considered in some models.

Based on this background, some important models that have been used for bioenergy crop growth are discussed below and a summary is presented in Table 8.1. The informatics-related issues are presented towards the end of this section.

8.3.1.1 Review of Model

EPIC (Erosion Productivity Impact Calculator) model, also known as the Environmental Policy Integrated Climate model, was developed in the 1980s to study the relationship between soil erosion and soil productivity over many years [29]. One of the nine modules relates to crop growth and determines the total biomass yield per unit area for a crop using the RUE approach. The drainage area considered is generally small and about 1 ha [29]. Although the simulations are performed for a specific location, results can be extended to larger watersheds by assuming consistency in soil properties and climate. The model also has an interactive data entry system as well as data analysis options, which enable it to be used as a DSS. Brown et al. [30] used the EPIC model to simulate switchgrass yield for different nitrogen application rates as well as for different climate change scenarios

Table 8.1 Summary of crop growth and management models, their important distinguishing features, the applications, and important results at selected sites. WIMOVAC and BioCro use the biochemical approach to model biomass production, while all other models use the RUE (radiation use efficiency) approach. MISCANMOD/MISCANFOR is applicable only to Miscanthus, while other models are applicable to many other energy and agricultural crops

Model	Features	Region studied using the model	Annual yield (dry matter) prediction at selected sites
EPIC	Assesses the relationship between soil erosion and soil productivity; studies the impact of climate change	Missouri-Iowa-Nebraska-Kansas	Switchgrass: 12.8 Mg ha^{-1} (Ames, IA) and 9.8 Mg ha^{-1} (Mead, NE)
ALMANAC	Process-based model capable of simulating intercrop competition for nutrient, sunlight, and other resources	Southeastern USA (Texas, Arkansas, and Louisiana)	Switchgrass: 15.34 ± 3.57 Mg ha^{-1} (mean across five sites)
SWAT	Developed to study the impact of different land management practices on water, sediment, and agricultural chemical yield	Yazoo River basin, Mississippi, South Carolina, Arkansas, Kansas	11 Mg ha^{-1} (switchgrass at Yazoo River basin, MS); 34 Mg ha^{-1} (Miscanthus at Yazoo River basin, MS)
CENTURY/ DAYCENT	Developed to study the biogeochemistry of terrestrial ecosystems, in particular the relationship between climate, soil properties, human management, and plant productivity	Central Valley of California	2.0–41.4 Mg ha^{-1} in California, accounted for 66–90 % of observed variation
WIMOVAC	Enzyme-kinetic model using a semi-mechanistic understanding to calculate the photosynthesis and transpiration; strong informatics component with standardized Windows interface	Model parameterized for *Miscanthus* × *giganteus* for England but used to simulate yields across various European sites	*Miscanthus* × *giganteus* yields predictions ranging from very low to about 40 Mg ha^{-1} matched well with observed yields with $r^2 = 0.84$
MISCANMOD/ MISCANFOR	Daily simulation time step using climate data and Miscanthus-specific parameters	Various sites in Europe including England, Germany, Denmark, Portugal, Ireland, and the Netherlands; Midwestern USA	17.3 Mg ha^{-1} (Denmark); 23.1 Mg ha^{-1} (England and Germany); 41.1 Mg ha^{-1} (Portugal)
BioCro	Mechanistic; includes parameter estimation using optimization routines	Average *Miscanthus* × *giganteus* and switchgrass yield in conterminous USA over 32 years of simulation	Switchgrass: 1–40 Mg ha^{-1} with mean of 11.6 Mg ha^{-1}; *Miscanthus* × *giganteus*: good prediction for Illinois, validation at other locations limited

such as higher temperature and atmospheric CO_2 concentrations. The results indicated that switchgrass yields increased for the climate change scenario but the effect on soil erosion was region specific. The EPIC model has been recently used as the foundation to develop the HPC-EPIC to predict biomass productivity at the global scale [31]. The simulation platform developed in this work uses high-performance computing (HPC) simulation with a global natural resource and management dataset to predict yield of bioenergy crops (Fig. 1 in [31]). The switchgrass yields predicted using HPC-EPIC have shown good correlation with observed yields ($r^2 = 0.78$ for lowland cultivar and $r^2 = 0.55$ for upland cultivar). Such global datasets are extremely valuable for conducting national and global system studies, as highlighted later.

ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) [32] is another well-established process-based model that simulates plant growth, water balance, and soil nitrogen dynamics. The main focus of ALMANAC is to simulate the intercrop competition, including agricultural crops as well as weeds. Similar to EPIC, it calculates the total biomass per unit area. Many subroutines in this model are based on the EPIC model [33]. ALMANAC also considers varying conditions of soil, rainfall, temperature, and other biophysical conditions to simulate crop growth. The model has been applied successfully to study the growth of switchgrass in the USA [34–37]. Kiniry et al. [36] used the model to simulate switchgrass (*Panicum virgatum* L.) yield at five different sites in southeastern USA. The model predicted yields at all sites with reasonable accuracy, and it also accounted for 47 % of the variability observed in actual yields. This is important since it means that the model is capable of predicting seasonal variations in yield as a function of other driving variables.

Soil and Water Assessment Tool (SWAT) has been developed to study the impact of different land management practices on water, sediment, and agricultural chemical yield [38]. The model can simulate large watersheds over multiple years to understand the long-term impacts of management practices. It uses mechanistic relationships rather than regression models, thus enabling the study of watersheds with limited data. The plant growth model is a simplified version of the EPIC model. The model has been parameterized to determine the yield of energy crops such as switchgrass and Miscanthus [39–41]. The model was used to study the impact of growing switchgrass on agricultural land on environmental and water quality parameters such as nitrogen runoff, surface runoff, and erosion [40, 42].

MISCANMOD is a crop-productivity model to estimate *Miscanthus* × *giganteus* yields [43]. MISCANMOD uses LAI and RUE parameters related to Miscanthus combined with a range of climate data to perform simulations using daily time steps. The model was used to predict Miscanthus yield at various places in Europe, and the predicted yields matched fairly closely with the measured yield across various sites [43, 44]. The r^2 value across 32 sites, including rainfed as well as irrigated sites, was 0.6. The model can also simulate yield in the presence of water stress.

CENTURY model was developed to study the biogeochemistry of terrestrial ecosystems, in particular the relationship between climate, soil properties, human management, and plant productivity [45]. The model provides an important tool to study the impact of climate change such as higher temperature and altered rainfall patterns on the plant and soil properties. The CENTURY model was later modified into the DAYCENT model which provided daily simulation time steps, primarily to study the trace gases fluxes (CO_2, N_2O, NO_x, and CH_4) [46]. Lee et al. [47] used the DAYCENT model to predict switchgrass yield in Central Valley, California, in the USA.

WIMOVAC is a mechanistic ecophysiological model that has been used to simulate various aspects of plant photosynthesis, especially the effects of global climate change [21]. It differs from the other models in that it does not use the RUE approach to calculate biomass. Such models are known as the enzyme-kinetic models that use a semi-mechanistic understanding to calculate the photosynthesis and transpiration. These models, by virtue of their modeling approach, can quantify the impact of physiological trait improvement or ecosystem processes. WIMOVAC was adapted and parameterized for *Miscanthus* × *giganteus* by Miguez et al. [48] and was shown to realistically estimate the productivity at various sites in Europe. WIMOVAC has a strong informatics component supporting the model. It allows the control of simulation processes through a standardized Windows user interface and generates results automatically. WIMOVAC is written in Visual Basic so that the user can easily create user-friendly modules. Specifically, a number of controls are available so that the user is able to handle automatic graphing, clipboard, and data-handling facilities. In addition, the model uses the Windows Object Linking and Embedding (OLE) technology for the transfer of simulation results from WIMOVAC to other Windows-based applications. WIMOVAC can be installed with an optional Database Management System (DBMS), which enables the exchange of experimental data between the database files and the model modules for comparison and validation purposes. WIMOVAC also includes a database of standard soil types, with the ability to enter information related to the characteristics of other "user-defined" soils.

Miguez et al. [49] have recently developed BioCro, which is also a mechanistic model like WIMOVAC. However, it includes parameter estimation using optimization routines and diagnostics and graphics that facilitate integration of field experimentation. Written in C and R with a number of user-friendly features built in, the model has provided accurate yield predictions for *Miscanthus* × *giganteus* and switchgrass. Feyereisen et al. [50] developed a plant-soil-atmosphere model RyeGro to model the growth of cereal rye (*Secale cereale* L.) as a winter cover crop and a potential biomass feedstock. Recently, Feyereisen et al. [51] have used the model for further analysis to estimate the potential yield in corn-soybean areas in the eastern USA. However, instead of using the model itself, they have developed a quadratic regression model using field data for 30 sites across the region of interest. The independent parameters in the regression model were precipitation, temperature, crop rotation, and planting and harvest date. The simplified regression model was then used to determine yield for each county, thereby avoiding excessive simulations.

8.3.1.2 Importance of Data and Informatics

These biophysical crop growth models rely substantially on the availability of reliable data. Miguez et al. [26] have summarized the various useful data sources.

These include input data such as soil and weather for running the model simulations, as well as site-specific yield data for model validation.

Meteorological data, preferably with high temporal and spatial resolution, are extremely important. The typical parameters of interest are temperature, rainfall, wind speed, humidity, atmospheric pressure, and total incident radiation. Different sources at state, national, and global levels are available, and some of them, such as the Illinois State Water Survey, North American Regional Reanalysis (NARR), PRISM, and CRU, have been discussed by Miguez et al. [26].

There has also been greater interest recently in compiling the model results in the form of an accessible database. The generation of yield maps is one such example. Biofuel Ecophysiological Trait and Yield Database (BETY-DB) (https://www.betydb.org/) compiles the site-specific yield, the treatment and management information associated with each data point, and the traits of the different species. One of the advantages of this database is that it can be queried in multiple ways, including through Google maps, and therefore can be used for multiple applications such as visualization, data sharing, and model validation. Wullschleger et al. [52] developed a database of switchgrass yield at 39 different sites in the USA that is extremely useful for model validation. However, generation of such maps/databases is cumbersome and requires considerable computational efforts.

8.3.1.3 Other Applications

The crop growth models have been incorporated in larger farm-scale or regional-scale agricultural models. Khanna et al. [15] used MISCANMOD in combination with an economic model to estimate the break-even price for Miscanthus and switchgrass in Illinois. Jain et al. [53] extended the study for the Midwestern region of the USA. Adler et al. [54] used the DAYCENT model simulation results for various energy crops within an LCA (life-cycle assessment) framework to determine the net greenhouse gas (GHG) flux for these crops. Other than yield prediction, the crop growth models can also be used for crop design and improvement by identifying the traits that lead to desirable growth properties, such as increased weed tolerance [55]. However, such applications have not yet been reported for bioenergy crops.

8.3.2 On-Farm Production System

Farm production systems are highly complex and dynamic, consisting of biological, environmental, mechanical, and human inputs and operations. Many SIA-based tools have been developed for on-farm production systems for conventional agricultural crops. These tools deal with machinery selection, irrigation and fertilization management, harvesting and collection operations, and more [56–58]. Many applications have also used a rigorous optimization approach [59]. Similar approaches can potentially be applied to study bioenergy crop production. However, literature review showed that work focused solely on farm-level production processes has been limited for bioenergy crops. Many studies perform a case-specific analysis without developing a generic model [14, 60–63]. We believe that this lack of emphasis is due to following reasons:

- Lack of commercial, large-scale farming of energy crops means that issues such as optimal equipment selection and sizing have not come to the fore yet.
- Lack of field data pertaining to equipment performance, especially for novel crops such as Miscanthus, as highlighted in Chap. 5, hinders the application of modeling tools and limits the validation opportunities.
- It is generally believed that biomass transportation is a very important component of the feedstock production systems. Therefore, many studies that focus on the farm production also consider the transportation of biomass as a related activity [13, 64, 65].

8.3.2.1 Whole-Farm Management Tools

Some farm management models are designed to consider conventional agricultural crops as well as novel energy crops such as perennials. I-FARM is a database-driven farming system simulation model that integrates crop and livestock farming [20] (http://i-farmtools.org/). The main goal is to develop a framework for the agroecosystems in the USA that can be used by farmers as well as decision makers to study economic returns and environmental impacts of different farming practices. It is a web-based application accessible through the Internet, consequently requiring no installation, data collection, or programming from the user. This provides a significant advantage for nontechnical users, such as farmers. The model is an integration of multiple models from the literature such as a crop growth model, erosion model, soil organic matter model, livestock and manure model, and water quality model. The models are interconnected in a web-based application that uses a formal DBMS for data storage and as an input/output medium. In addition to many conventional agricultural crops, it can model switchgrass, poplar, and willow. The data for these crops, including tillage practices, fertilization, harvesting, are maintained on the database server. I-FARM gives estimates for erosion, carbon sequestration, nutrient balancing, required labor, energy consumption, costs, government payments, and expected revenues, which can be used for decision making and policy recommendations. Bioresource4Energy (http://bioresource4energy.eu/) is another web-based tool for farmers to investigate machinery and labor selection; evaluate field size, distance, and irrigation systems; and as a result determine the cost of biomass production.

FEAT (Farm Energy Analysis Tool) is a recently developed Microsoft Excel®-based static, database-driven model to calculate the energy consumption and GHG emissions for farm operations [66]. The spreadsheets can be used for data entry and modification. The user must enter data such as farm area, tillage type, and residue to be harvested to develop a scenario. Other parameters such as yield, moisture content, and fertilization and herbicide rates have default values that can be modified by the user. The model calculates the energy consumption in MJ and GHG emissions in grams of CO_2 equivalent. It can perform calculations for switchgrass, Miscanthus, hybrid poplar, and willow in addition to conventional crops.

The Integrated Farm System Model (IFSM), a whole-farm simulation model, has been developed to assist sustainable management of livestock farming for the dairy and beef industries [67]. Although the focus of this model is on livestock farming, it includes perennial grasses and forage crops. It is a long-term strategic planning tool. The model consists of nine major submodels including a forage cropping submodel, storage and animal submodels, tillage and manure handling submodels, and a corn growth model based on the CEREZ-maize model. Since it is a very generic model incorporating a large number of possibilities, scenario setup becomes an important task in which the user has to select many parameters. Rotz et al. [67] have emphasized the value of crosschecking and validating model parameters. The model has also been proposed as a teaching and extension aid.

The Farmdoc website (http://farmdoc.illinois.edu/index.html) maintained by the University of Illinois at Urbana-Champaign is an excellent source of information for on-farm decision making. In addition to documentation and extension presentations, the website provides web-based access to FAST (Farm Analysis Solution Tools). These are spreadsheet-based tools for various farming-related activities such as farm management, financial analysis, loan analysis, livestock management, and risk management. This is an excellent example of how simple to use decision-making tools can be made accessible via Internet. Easy to understand demos are also provided. Although the modeling component in FAST is relatively simple, the informatics aspects, including database management and web accessibility, are particularly impressive.

8.3.2.2 Equipment Selection and Management Tools

Optimization of farm machinery selection for energy crops is extremely critical. Although this topic has been extensively studied for conventional crops, unique challenges associated with energy crops require further investigation. These challenges include managing grain as well as residue collection simultaneously, sharing machinery with regular crop harvest, managing harvesting during severe weather conditions, and accounting for the perennial nature of these crops.

Wold [68] developed a simulation model to improve the efficiency of single pass crop harvest and residue collection. A variety of biomass collection options after grain harvest, such as direct unloading by the harvester and baling, are considered. For the baling option, bale collection was also simulated and three different heuristics-based algorithms were compared to solve the vehicle routing problem. For each of these options, varying cart capacity and number of carts were considered to model different scenarios. The delivered cost to the plant gate, after adding costs for fertilization and transportation, was between about $30 to $60 Mg^{-1}. The model has been developed in MATLAB and also provides a user interface in Microsoft Excel®. The user interface could be used for data entry and running simulations from a stand-alone executable file. This allows the program to be easily accessible for extension work without the necessity of a MATLAB license.

It is argued that specialized machinery might be needed to harvest novel bioenergy crops. Since farmers are expected to grow energy crops on only a part of the land, at least initially, farmers will avoid purchasing dedicated machinery and will instead rely on leased equipment or custom harvesting. In view of this, Bochtis et al. [69] proposed an optimization model using the flow shop problem formulation, where the aim was to efficiently use a limited set of equipment to perform multiple, sequential tasks on different fields in a region. The objective function in the problem was to minimize the total time requirement. FARMSYS is another farm machinery management system developed in PROLOG using an object-oriented modeling approach [57]. FARMSYS has been evaluated by farmers with satisfactory performance but is yet to be applied to study energy crops. Such machinery management tools will become increasingly important in the future.

Inclement weather impacts farm and machinery operations significantly. Therefore, Hwang et al. [70] developed a simple rule-based model to convert weather data into probabilistic estimates of the mowing and baling days in the state of Oklahoma, in the USA. They developed a decision-making sequence that classified a day as suitable or not. They also incorporated several smaller models, such as the soil-water balance model, within this framework. The estimates provided by such models were to be used by the machinery selection models or whole-farm simulation models.

8.3.3 Local Production and Provision System

The SIA tools have been commonly used to study the local production and provision systems, which include on-farm production, transportation, handling, storage, and final delivery to the biorefinery gate. In particular, a large number of studies have conducted case-specific, system-level analysis without the development of a generic model [15, 71, 72]. We focus primarily on studies that involved the development of a generic model and possibly supported by informatics and decision support tools. The review is not exhaustive by any means, and the goal is to describe some important, novel approaches in this area. Table 8.2 provides a summary of important results generated using these models. The bioenergy crop, region of consideration, important scenario features, and important results are reported in the table.

8.3.3.1 Simulation Models

Simulation-based approaches have been commonly used, and discrete event simulation (DES) has been of particular interest. DES is suitable to model a dynamic and stochastic system that is dependent upon events happening to entities at discrete (and possibly random) times in the simulation horizon. From a feedstock production perspective, a unit of biomass, such as a bale, or a transportation equipment

Table 8.2 Summary of important SIA applications for local BFPP systems. Important scenario features and results are reported here; interested readers should refer to the original papers for additional details

Model and/ or reference with year	Crop and region	Important feature of the scenario	Results
Grado and Strauss [84]; 1995 (costs based on 1990$)	Hybrid poplar-based biorefinery with option of using corn as feedstock; location not specified	9,020 ha area with 40 km transportation radius; 1,503 ha of actual plantation; 73.8 Mg ha^{-1} yield; 6-month harvesting window; biorefinery capacity of 10,000 Mg $month^{-1}$; processing (hydrolysis and fermentation) data taken from literature	Delivered cost of ethanol based on woody biomass was \$0.38 l^{-1}; cost with corn and wood together was \$0.403 l^{-1}; inventory control approach led to 62 % reduction in cost as compared to other solutions
Cundiff et al. [85]; 1997	Switchgrass-based biorefinery in Piedmont, Virginia, USA	Biorefinery capacity 5,600 Mg $month^{-1}$; 50 km collection radius; harvest over 6 months; open and covered storage; weather classified as "good" or "poor" with working probabilities of 1 and 0.9, respectively	Total cost between \$13 and \$19 dry Mg^{-1} depending on the scenario and weather impact; transportation cost between \$8 and \$10 dry Mg^{-1}
De Mol et al. [80]; 1997	Thinning, pruning, waste paper, sludge, and waste wood transport in North Holland, the Netherlands	Rail, road, or water transport; particle size reduction or drying as preprocessing; four possible energy plant locations	Simulation model: cost of thinnings about 38 Dfl (Dutch guilder) dry ton^{-1}; cost of prunings about 10 Dfl (Dutch guilder) dry ton^{-1} Optimization model: thinning not used due to high cost; transport a combination of road and water transport
Duffy [61]; 2007	Switchgrass production on a farm in Iowa; biorefinery in Iowa	Yield 4 tons per acre; land cost \$80 per acre; large square bales; tarped hoop type structure for storage spread over two acres	On-farm production cost = \$82 ton^{-1} Storage cost = \$16.67 ton^{-1} Transportation to storage cost = \$6.1 ton^{-1} Transportation to plant cost = \$8.65 ton^{-1}
Bee [79]; 2007	Switchgrass (Alamo) production in Italy	High, mild, and low cultivation possibilities in two different regions (south and north) of Italy; break-even yield (BEY) estimated for selling price of € 55 Mg^{-1}	BEY between 8.5 and 22 Mg ha^{-1} for different scenarios, which were higher than the observed yields
Hess et al. [72]; 2007 (costs based on 2002$)	Wheat straw-based biorefinery in western high desert, USA	Biorefinery throughput of 726,000 Mg per year; rectangular baling, roadsiding, storage, preprocessing, and transportation; open storage; preprocessing using tub grinder; average transportation distance of 76 km	Refinery gate cost of \$37 Mg^{-1}; baling \$12.8 Mg^{-1}; stacking \$1.7 Mg^{-1}; storage \$4.9 Mg^{-1}; preprocessing \$6.30 Mg^{-1}; transportation \$11.3 Mg^{-1}

(continued)

Table 8.2 (continued)

Model and/ or reference with year	Crop and region	Important feature of the scenario	Results
IBSAL [74]; 2009 (Costs based on 2006\$)	Switchgrass-based biorefinery; region not specified; input data from multiple locations in the USA	Biorefinery capacity of 2,000 and 5,000 Mg d^{-1}; comparison of baling, grinding, and pelletization; yields of 10, 20, and 30 Mg ha^{-1}; consideration of grinding and densification options; modeling of future technologies such as large loaf-collection system	\$80.64 Mg^{-1} based on current baling technology; \$ 71.64 Mg^{-1} based on future loafing technology; pelletization reduced transport cost by 21 % to \$12.16 Mg^{-1}; energy input for crop production = 3.36 % of HHV of switchgrass
IBSAL [9]; 2006	Corn stover; specific region not specified	Simulated cost for different scenarios using baling as packing options; collection cost calculated for smaller units; transportation cost calculated for total of 450.9 Gg	Collection cost = \$21.12 Mg^{-1}; transportation cost = \$32.45 Mg^{-1}
Ravula et al. [76]; 2008	Cotton for Mid-Atlantic cotton gin located in Emporia, Virginia, USA	Transport of cotton modules from 5,929 cotton fields to a single gin; gin processes 45 modules per day (4.5–8.2 Mg per module)	Two greedy algorithm strategies increased the truck utilization from 77 to 100 %; cost not determined
Dunnett et al. [108]; 2008	Hypothetical geographical region using agricultural residues such as wheat straw and corn stover	10 % land for biomass sourcing; harvested yield of 5 ton ha^{-1} y-1; farm-gate price of \$53.9 ton^{-1}; demand of 2,000 W per capita electricity and 980 W per capita gasoline with ethanol as a substitute for both; biochemical processing of feedstock	Production cost based on current technology between \$0.71 and 0.58 l^{-1} depending on the economy of scale; high-yielding crops and consolidated bioprocessing reduced the cost to \$0.33–0.36 l^{-1}
BioFeed [17]; 2010	Switchgrass-based biorefinery at Nashville, Illinois, USA; 13 counties in Southern Illinois	Optimized cost with round and square baling as packing options and optimized scheduling; biorefinery capacity optimized; average collection distance of 65 km; transportation distances calculated using Google maps; farms uniformly distributed	Cost = \$45–49 Mg^{-1} depending on the collection area (24–70 km); capacity = 1,400 Mg d^{-1}; fleet of 66 trucks with average utilization of 86 %; cost most sensitive to truck idling time
BioFeed [1]; 2010	Miscanthus-based biorefinery at Nashville, Illinois, USA; 13 counties in Southern Illinois	Optimized cost with baling (owned and rented), chopping, grinding, and pelletization as packing options and optimized scheduling; biorefinery capacity optimized; collection area fixed; 4-month harvesting window (January–April) extendible to 6 months (November–April)	Cost of \$47.88 Mg^{-1} for baling to \$62.92 Mg^{-1} for chopping; optimized cost was \$45 Mg^{-1}; capacity = 2,800 Mg d^{-1}; 16 % cost reduction due to single pass operation; 8 % cost reduction due to 6-month harvest

Leboreiro and Hilaly [91]; 2011	Corn stover-based biorefinery in eight counties in Central Illinois, USA	Evaluates biomass collection, transport cost, and optimal biorefinery size; nondimensional transportation parameter obtained using a detailed "farm model"; cost functions used for different transportation legs; three different supply schemes	Total production costs were \$0.45, \$0.47, and \$0.47 l^{-1}, with optimal biorefinery capacities of 4,550, 3,450, and 3,450 Mg d^{-1}, respectively; 57 % of the final cost was the cost of delivered corn stover to the biorefinery
Zhu et al. [92]; 2011	Switchgrass-based biorefinery; location not specified	Trucks and train for transportation; 10 fields, three potential warehouse locations, and two potential biorefinery locations; 120,000 tons per month biorefinery capacity; processing cost at biorefinery of \$50 ton^{-1}	Profit of \$0.76–0.80 per gallon; detailed monthly variation in harvesting, transportation, and storage amounts provided
Zhu and Yao [93]; 2011	Switchgrass-, corn stalk-, and wheat stalk-based biorefinery; location not specified	Trucks and train for transportation; 14 fields, three potential warehouse locations, and two potential biorefinery locations; 120,000 tons per month biorefinery capacity; processing cost at biorefinery of \$50 ton^{-1}	Profit with switchgrass as single feedstock = \$0.21 per gallon; profit with mixture of three feedstocks = \$0.32 per gallon
An et al. [97]; 2011	Biorefinery based on switchgrass, mill residue, and urban wood waste; nine counties in Central Texas	Base case switchgrass purchase cost of \$60 Mg^{-1}; average ethanol demand of 1,425 l $person^{-1}$ y^{-1}; average transportation distance of 19 km; transportation cost of \$6.81 Mg^{-1} + \$0.08 Mg^{-1} km^{-1}; 70 % conversion efficiency of biomass; comparison of 18 different scenarios	Base case ethanol price of \$0.77 l^{-1}; cost distribution in percentage: feedstock = 24.56, feedstock transport = 6.41, preprocessing = 8.41, refinery = 59.33, ethanol transport = 1.29; ethanol price less than \$0.66 l^{-1} makes the system uneconomical
Judd et al. [87]; 2012	Switchgrass-based energy plant in Gretna, Virginia, USA	Collection distances of 13, 32, and 48 km; 3,655 production fields, potential 589 SSLs, and 83 Mg h^{-1} biomass demand for 48 km case; possible densification at the SSL	Delivery cost using side-loading rack system for 48 km case was \$24.53 Mg^{-1}; densification not justified below 81 km transportation distance
Lin et al. [90]; 2013	Miscanthus-based biorefineries in Illinois, USA	Total annual Miscanthus demand of two million Mg; 2 % land allocated for Miscanthus production; 5 % loss rate at CSPs; grinding at CSP with density of ground biomass equal to 200 kg m^{-3}; 300 L ethanol production per Mg; number and location of CSPs and biorefineries and collection counties optimized	35 counties, 13 CSPs, and one biorefinery, primarily in the southern region of Illinois; optimal cost of \$220.6 Mg^{-1} or \$0.74 l^{-1}; 47.9 % of total cost due to biorefinery processing; cost reduction to \$198 Mg^{-1} with 20 % land allocated to Miscanthus

unit, such as a truck, can be an entity, while operations such as loading, unloading, and transportation can be various activities performed on those entities.

IBSAL (Integrated Biomass Supply Analysis & Logistics) is a dynamic, object-oriented modeling framework to simulate the collection, storage, and transport operations for supplying agricultural biomass to a biorefinery [9]. It is one of the first generic models developed to provide a holistic view of the BFPP system. It uses a DES approach and has been developed using EXTEND, an object-oriented high-level simulation language. Different modules representing processes/operations such as swathing, baling, storing, and transportation are developed and stored in the EXTEND library. Each module is represented using the mass balance and performance equations and is associated with a list of attributes. To develop a scenario, the user has to select the relevant boxes and connect them logically using the EXTEND interface. The discrete events (operations) are represented in the time domain, and the occurrence of an event adds to the cost and modifies the unit (biomass) properties. The model inputs comprise the parameters outside the scope of the supply chain, such as weather conditions, biomass yield and properties, spatial distribution of the supply locations, and equipment-performance parameters. The data can be provided through a spreadsheet. The model has been used as the basis for a number of analyses in the literature [9, 73, 74]. Sokhansanj et al. [74] have compared a number of production scenarios for switchgrass and have reported several cost and energy consumption values that are very useful.

Ravula et al. [75] used the DES approach to compare two different strategies to schedule truck delivery at a biorefinery of 1,200 Mg d^{-1} (50 Mg h^{-1}) capacity. In addition, they assumed a supply system consisting of several satellite storage locations (SSLs) being served by nine loaders for bale loading. The goal was to minimize the total number of trucks required by scheduling the biomass pickup from different SSLs in the collection region. Two different policies to schedule SSLs were studied. The total cost was \$14.68 and \$16.14 dry Mg^{-1} for different policies, and the number of trucks varied between 32 and 36 depending on the specific scenario. The DES approach was again used by Ravula et al. [76] to model cotton module transportation, arguing that several round bales can be put together to create a transportation module similar to cotton. They developed two management policies that increased the utilization of the transportation system from 77 to 100 %. They also developed a knapsack model to obtain a lower bound for the transportation system. Mukunda et al. [77] have also used DES to model corn-stover logistics from on-farm storage to a biorefinery in Indiana, USA.

The Biochains Economic Evaluation (Bee) model has been developed as part of the European Union-funded project titled “Bioenergy Chains from Perennial Crops in South Europe” to perform detailed economic assessment of the complete biofuel value chain, including biomass conversion to energy. Three different modules, focused on agricultural production, storage and transportation, and conversion, are integrated. Multiple feedstocks and multiple energy conversion processes can be studied. Three different scenarios of agricultural production, ranging from complete ownership of farms by an investor to ownership by farmers, can be modeled.

The model is freely downloadable (http://www.bee.aua.gr) and can be used to build user-specific scenarios. The model has been used to study the production of *Arundo donax L.* (giant reed) and *Miscanthus* × *giganteus* in Greece [78] and switchgrass in Italy [79]. Monti et al. [79] determined the break-even yield for different scenarios using the Bee model and data generated from an experimental plot in Bologna, Italy. Instead of calculating the cost of production, this study fixed the farm-gate price of € 55 Mg^{-1} and calculated the minimum yield necessary to achieve breakeven. The results showed that the actual observed yield was lower than the break-even yield for all the scenarios, suggesting that switchgrass cultivation was not a profitable venture in Italy. The main reason for this was the high cost of irrigation, harvesting/baling, and land rent, which accounted for 80 % of annual equivalent cost (€511–1,257 ha^{-1}).

De Mol et al. [80] developed a simulation as well as an optimization model to study the biomass supply chain logistics. However, instead of a process-based approach, as used by most other studies, they used a network-based approach. Various source locations and destinations were modeled as nodes while the transportation options were modeled as links. The same network structure and database were used to develop both models, and a user interface was also developed. The simulation model Biologics (BIOmass LOGistics Computer Simulation) using PROSIM was employed to calculate the costs and flows for different structures. It is a pull model where demand at the energy plant initiates movement of biomass units. In addition to cost and energy consumption, the simulation model also gives the number of transport units required.

Turhollow and Sokhansanj [81] developed a spreadsheet-based model to study corn-stover supply. Nilssen [82] developed a dynamic simulation model named SHAM (Straw Handling Model) in the Arena environment, which looked at the impact of climate and geography on the cost of straw collection and transport in Sweden.

One of the advantages of using a simulation approach is the greater flexibility to develop scenarios and run simulations. The object-oriented approach also makes the addition of new information, such as new equipment, easy. It is possible to conduct optimization by comparing simulation results for different scenarios through independent runs, known as simulation-based optimization. However, this approach is not feasible when the number of solutions is many. Rigorous optimization models, therefore, have become more prevalent in recent times. Development of such models is more complex, and their solution is also computationally more challenging as compared to simulation models. Some of these models are reviewed next.

8.3.3.2 Optimization Models

Work by Jenkins and Arthur [83] is perhaps the first application of optimization for biomass production systems. They used dynamic programming on a network model to determine the optimal transportation network using a formulation similar to the famous “stage coach” problem. Application of the model to a case study of rice straw led to the recommendation that cubing after chopping should be done on farm only if the maximum transportation distance was 50 miles. Otherwise, cubing should be done at the plant before direct combustion. Grado and Strauss [84] also proposed an inventory control model using dynamic programming to optimize the production of ethanol from woody biomass. The delivered cost of ethanol was \$0.38 L^{-1}, which was dominated by manufacturing (60 %) and harvest and shipment (18 %).

De Mol et al. [80] used a similar concept of network of nodes and arcs to develop an optimization model. The simulation model in this work, as explained previously, provided cost and energy consumption values as a function of time for a fixed network structure. In contrast, the optimization model was developed to select the optimum network structure. The mixed integer linear programming (MILP) model ignored the daily fluctuations as well as biomass losses. A knapsack model was developed to solve the optimization problem. Their work analyzed a number of possibilities, including mixed feedstocks (e.g., thinning and restwood, prunings, and sewage sludge), multi-model transport (road, rail, and water), and pretreatment (size reduction and drying). Their work highlighted the value of having a common model structure and database.

Cundiff et al. [85], in an extension of their earlier work focused on harvesting and baling [86], developed a linear programming model to optimize storage, loading, and transportation of biomass. They also addressed the uncertain impacts of weather by converting the problem into a two-stage problem with recourse. The model was applied to study the production for a 5,600 Mg month^{-1} biorefinery in Virginia, and the total cost for the operations was about \$14 to \$19 dry Mg^{-1}. The cost varied between these values depending on the exact scenario that was studied. The transportation cost was \$8 to \$10 dry Mg^{-1}. Judd et al. [87] have recently proposed another mathematical programming model that focused on the use of SSLs with possible densification (briquetting). The model optimized the location of SSLs as well as the machinery infrastructure to be used at those SSLs. In particular, they compared permanent and mobile loading equipment at these SSLs. They used GIS to generate input data such as farm and potential SSL locations and distances for a hypothetical plant in Gretna, Virginia. They concluded that densification was not justifiable for transportation distances less than 81 km.

The BioFeed optimization model has been developed using a philosophy similar to that of Cundiff et al. [85]. BioFeed integrates the complete production and provision activities, including on-farm production, and optimizes the design and management decisions [17]. It models a scenario in which many farms are producing biomass feedstock for one or more regional biorefineries and models the important operations along this value chain. This includes harvesting, postharvest packing, loading and unloading, on-farm or satellite storage, transportation, and preprocessing, such as size reduction and densification. In addition to using an optimization approach, a unique feature about the model is the integration of design and management decisions in a single framework. It is an MILP model, in which integer decisions are typically machinery selection decisions while the continuous decisions are management and operational decisions. The model has been extensively applied to study various scenarios [1, 17, 88, 89]. The BioFeed model has been developed such that users can select the equipment a priori and then optimize only their management decisions. This allows the model to simulate very specific cases and thus extends the scope of the applications. One of the important features of BioFeed is the consideration of different farm sizes based on actual farm size distribution in the Illinois, USA. This is quite important as Shastri et al. [1] showed that farm size significantly impacts the on-farm production cost.

Recently, Lin et al. [90] have developed a new optimization model, named BioScope (Biomass Supply Chain Optimization). This model proposes that intermediate centralized storage and preprocessing centers (CSPs) are essential to improve the supply efficiency of biomass feedstock, and optimizing their location is critical. The model uses an MILP approach to optimize the location and size of these CSPs as well as the biorefineries. The model uses GIS-based information to determine the potential biomass supply at county level and also employs GIS-based transportation data to calculate road transportation distances. An important feature of the model is that it considers the biomass supply and demand constraints over a number of years and, therefore, provides the optimal strategy to develop the biomass feedstock sector over a long time horizon (15 years). The model has been successfully integrated with BioFeed, which provides the detailed farm-level production cost estimates that are used by BioScope to perform simulations. BioTrAnS (Biomass Transportation Analysis System) is another optimization model that is currently under development by the same group, which optimizes the short-term (hourly to daily) transportation and logistical decisions. The current focus is on optimizing the dispatch timings of each truck for picking up biomass from farms or storage facilities and delivering it to the destination in order to minimize the idling time in queues for loading and unloading. It takes output from BioFeed, a strategic level model, and further optimizes the short-term logistics decisions.

Leboreiro and Hilaly [91] developed a model to study the collection, storage, and transportation of biomass and used it to optimize the biorefinery capacity. For two different scenarios with corn stover as feedstock, the optimal biorefinery capacities were 3,450 and 4,550 Mg d^{-1} and the optimal ethanol production costs were \$0.45 and \$0.47 l^{-1}. Zhu et al. [92] have developed an MILP model that optimizes the strategic decisions such as the locations of the biorefinery and warehouses and tactical decisions such as the transportation schedules. It covers the operations of harvesting, storage, transportation, and biofuel production. The model uses monthly time steps for decision making and 1 year as the simulation horizon. Zhu and Yao [93] modified the model to consider supply of multiple feedstocks and showed that the total profit increased by almost 50 % by using three different feedstocks instead of one. Sultana and Kumar [94] also optimized the transport of a mix of biomass feedstocks and determined that 30 % agricultural residue as bales and 70 % forest biomass as chips led to minimum transportation cost for a biorefinery of capacity 5,000 Mg d^{-1}. Other optimization-based studies include Zuo et al. [95], Mapemba et al. [96], An et al. [97], and Kim et al. [98, 99]. Results for some of these studies are reported in Table 8.2.

8.3.3.3 Complex System Models

The agent-based modeling approach has been used recently to study the complexity of the agricultural sector. This includes studying the technology adaptation by farmers [100], rural supply chains [101], and bioenergy networks [102]. This approach enables the incorporation of social and personal factors in decision making, which makes these models more realistic. Shastri et al. [103] have developed an agent-based model to study the development and functioning of the feedstock production system in the presence of stakeholder competition and uncertainty. The model takes an object-oriented approach and models the interaction between different stakeholders (agents) in the system. The key novelty of this model is the incorporation of economic as well as personal and social factors in decision making. The model simulation results have shown that the feedstock production sector may take multiple years to develop and reach stable productivity. Moreover, the competition would drive the actual cost of feedstock to almost 40 % more than the optimized cost. Lack of formalized theory or standardized modeling methodology for the agent-based models has resulted in great diversity in the model structure. This limits the comparison of different models in this domain.

8.3.3.4 Decision Support Systems

Shastri et al. [104] have described the development of the ConSEnT (Concurrent Science, Engineering, and Technology) platform for the production of biomass feedstock. This platform, as illustrated in Fig. 8.5, integrates database, modeling and analysis, and a web-based DSS, thereby incorporating all the components of the SIA approach. Domdouzis et al. [105, 106] have described the database, which is based on the concept diagrams for the system, and the application programming interfaces for efficient data entry and retrieval. The database is to be continuously updated to reflect the latest scientific and technology developments in this field. The BioFeed, BioScope, BioTrAnS, and the agent-based models described previously are part of the ConSEnT environment. BPSys is a web-based interface and constitutes the front end of the ConSEnT environment [107]. It provides seamless access to the database as well as the models. It is programmed in Java and integrates the functionalities provided by software packages such as Apache Http Server, Apache Tomcat, Drupal, MySQL database, and JFreeChart. The graphical user interface (GUI) of BPSys is a Java applet embedded in a web page executed on users' local machines and works as a front end. The GUI allows users to develop specific scenarios, import and modify data, add new equipment data, and run model simulations. The platform is currently being tested internally and will be made accessible to others in the near future.

8.3.4 Regional, National, and Global Systems

A number of issues, such as land use change and life-cycle emissions, become important at the regional, national, and global scales. The impact of new

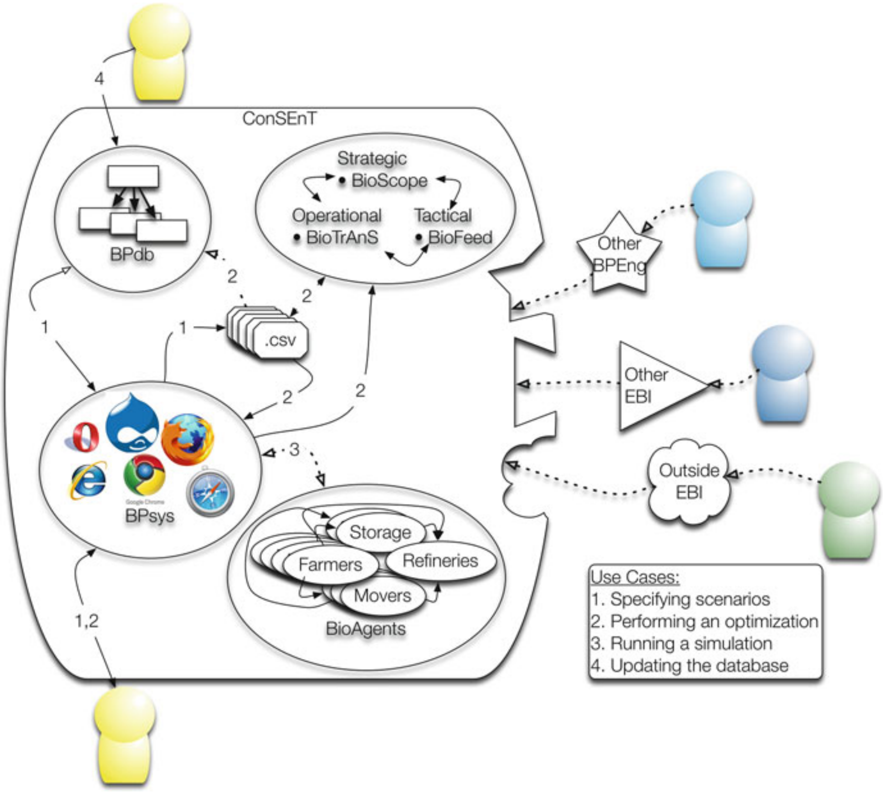

Fig. 8.5 The ConSEnT platform integrating various components in informatics, modeling, and decision support. BPdb is the database in MySQL; BioFeed, BioScope, and BioTrAnS are optimization models; and BioAgents is the simulation model. All models use the common database. BPSys is the web-based decision support system. The use cases show the different ways of utilizing the platform. BPEng stands for researchers involved in the biomass production engineering project and working in this area, while EBI stands for Energy Biosciences Institute, which funded the project

policies, regulations, and incentives must also be assessed at such larger scales. As pointed out previously, the spatial and temporal scales to be analyzed here rule out experimental/field studies and necessitate the use of model-based tools.

8.3.4.1 Land Use and Policy Models

Understanding and predicting changes in the agricultural landscape, including crop rotations and land use change, has been under focus, leading to several model-based studies. POLYSYS (Policy Analysis Systems) is a national-level agricultural simulation model for the USA to estimate agricultural production response, resource use, price, income, and environmental impacts of projected changes from an agricultural baseline [109]. The goal of the model is to study the policy decisions in agriculture by accounting for the environmental and social impacts in addition to farming practices and crop production. The model is an integration of a variety of self-contained modules, representing different sectors such as regional crop supply, national livestock, national crop demand, national income (IMPAL model), and regional environmental impact (EPIC model). The model considers three different energy crops, switchgrass, hybrid willows, and hybrid poplars, in addition to conventional crops and livestock farming. The lower 48 states of the USA are divided into 305 geographical regions based on similarity of the production characteristics. The core of the model focuses on making agricultural decisions such as crop selection, crop rotation, and acreage allocation. Simulation horizon ranges from 5 to 25 years. Walsh et al. [110] implemented the POLYSYS modeling framework to conduct an economic analysis of the development of the bioenergy market and its implications on the traditional crop prices and farm income. Kszos et al. [111] used the POLYSYS model in combination with another model (BIOCOST) that allowed one to study the effect of changes in yield, management practices, and rate of plant maturation of the bioenergy crops on the production cost and consequent effects on the agricultural sector.

Khanna et al. [15] determined the break-even price for Miscanthus and switchgrass in Illinois by using yield data from MISCANMOD and farm operations and transport cost from the literature. They reported a break-even farm-gate price for Miscanthus between \$41 and 58 ton^{-1} and the price at the gate of the power plant to be between \$44 and 80 ton^{-1}. Although these prices were better than those for switchgrass, they were considerably higher than the price of coal, indicating that strong policy incentives were needed to make biomass attractive. Jain et al. [53] extended that work to a larger Midwestern US region by using MISCANMOD that was parameterized based on observed yield data. The break-even price ranged from \$88 to 188 ton^{-1} for switchgrass and \$53 to 243 ton^{-1} for Miscanthus. It must be noted that these analyses take an economics-based approach by considering the land opportunity cost due to conventional crops such as corn. The operational aspects of feedstock production and provision were not considered in much detail, and values reported in the literature were used. Both these articles report a number of sensitivity studies that provide additional insights. Recently, Khanna et al. [112] have extended this work to develop a model called Biofuel and Environmental Policy Analysis Model (BEPAM). It is a dynamic, nonlinear mathematical programming model considering multimarket equilibrium. The scope of this model is therefore similar to that of POLYSYS. It determines land allocation, crop production, and crop prices in the market for fuel, biofuel, food and feed crops, and livestock. The model performs yearly simulations from 2007 to 2030 for the USA. The model has been used to simulate scenarios for different crop prices and study their impact on land allocation. For each scenario, the distribution of land allocated to different crops among the 295 crop rotation districts was identified. Such data become extremely valuable to identify likely biorefinery locations and provide incentives. Additionally, more detailed engineering models such as BioFeed and IBSAL can be applied to regions identified here to generate more accurate estimates of production costs.

The Biomass Futures project has been initiated by the European Union (EU) to support policy decisions and evaluate the feasibility of the bioenergy targets [113] (http://www.biomassfutures.eu/index.php). One of the major limitations for achieving these tasks has been the limited availability of validated, up-to-date, and quantitative information pertaining to the supply and demand of biomass. The project, therefore, has taken a comprehensive model-based approach to develop tailored information packages that can be used by policy makers at the EU or national level. Some of the packages that have been developed include demand analysis, availability and supply analysis, energy modeling, and sustainability [114, 115]. Each of these packages involves the development of a quantitative model, either a generic model or a purely data-based model.

8.3.4.2 Life-Cycle Impact Assessment Models

Understanding the life-cycle impacts of the biofuel value chain, including biomass production, has also been under focus. A number of studies have recently indicated that the renewability of biofuels, especially the first-generation biofuels, may depend significantly on whether or not indirect impacts such as land use change, fertilizer production, and agricultural runoff are considered [116]. The debate, however, is still ongoing [117], necessitating a rigorous system-level analysis. The life-cycle impact assessment models are conceptually simple, because the focus is on executing the proper accounting of the inputs and outputs from the system. Therefore, many studies have used simple modeling platforms such as Microsoft Excel®. The collection and management of data are very important activities, which make the role of informatics more important.

GREET (Greenhouse Gases, Regulated Emissions, and Energy use in Transportation) is a well-known spreadsheet-based model developed by the Center for Transportation Research of Argonne National Laboratory in the USA [118, 119]. In addition to the GHG emissions associated with various transportation alternatives, the model also calculates the emissions of other critical air pollutants such as NOx, VOC (volatile organic carbon), methane, and particulate matter. GREET includes fuel-cycle and vehicle-cycle models, thereby covering the complete life cycle of fuel production and utilization. It can compare conventional fossil fuels with renewable alternatives such as ethanol, biodiesel, and electricity (for battery-powered vehicles). The model caters for the production of ethanol from corn, woody biomass, herbaceous biomass, corn stover, and sugar cane. The interface to the model is a Microsoft Excel®-based program that allows the user to define scenarios through selections and modify parameter values. The basic modeling framework has been extended to include a stochastic modeling capability [120].

Scown et al. [121] recently reported the life-cycle GHG implications of different scenarios of biofuel production from *Miscanthus × giganteus* to achieve the 2020 target for the USA. They modeled six different scenarios that captured different possibilities of land allocation for growing Miscanthus. Their results showed that the net carbon emission or sequestration during Miscanthus cultivation as well as the GHG offset credits for selling electricity to the grid were the two most important factors. They concluded that the GHG intensity was at least 80 % lower than that for gasoline. However, their analysis ignored the indirect land use change.

The ERG Biofuel Analysis Meta-Model (EBAMM) was developed in order to review the current state of ethanol energy analyses (http://rael.berkeley.edu/EBAMM/) [122]. It also enables the modeling of a number of biofuel pathways, such as the Brazilian sugar cane ethanol and "advanced" corn. Different biodiesel life-cycle analyses can also be compared with EBAMM. The model is developed as a Microsoft Excel® spreadsheet and is easy to use and modify. EBAMM can be used for the consideration of different energy types, the calculation of policy-relevant metrics, the addition of coproduct credit when this is required, and the application of a consistent system boundary through the addition of missing parameters and the removal of insignificant data.

Direct and indirect land use change is perhaps one of the most intensely debated topics on the life-cycle impacts of biofuels in recent years [116]. There are model-based conclusions on both sides of the argument. There are two major reasons for this disagreement that highlight some of the challenges in systems modeling. First, there is a disagreement over the system boundary (i.e., what is the correct spatial scale to use for such an analysis). Second, the input data that are entered into these models, such as the emissions associated with fertilizer production and use, have not been standardized. Farrel et al. [122] summarized the results obtained from various studies and the variability in results reported by different studies.

8.4 Summary and Discussion

The goal of this chapter was to review literature on the application of SIA techniques for BFPP systems. Some important basics of SIA were discussed followed by reviewing applications relative to four different classes. We have made notes of important conclusions drawn by these studies at various places in the chapter. Summarized below are some general conclusions about the work reviewed:

- The focus on addressing the system-level issues has increased considerably in recent years. This is possibly due to the realization that there are a number of complex interactions between different feedstock production and provision tasks. The initial focus for such studies was mostly on performing a case-specific analysis without the development of a generic model. However, greater interest has been generated in developing a generic model that can be used to study multiple crops in multiple regions. These model-based studies have led to valuable insights into the optimal design, management, and operational strategies for this sector.
- The applications at the crop growth and management level as well as the local production and provision level are numerous. For crop growth modeling, many models already developed for conventional agricultural crops have been modified to include bioenergy crops.
- For local production and provision levels, the interest in using optimization as a tool has recently increased significantly, as evident from the citations in Table 8.2. Optimizing the transportation logistics, including the locations of the farms,

biorefineries, and the satellite storage and preprocessing locations, has been of particular interest.

- Applications at the on-farm production level have been very limited. As pointed out before, this is possibly due to the lack of commercial farming of energy crops. This leads to lack of data to support such models.
- Many models have used Microsoft Excel® to store and retrieve data as well as to provide user interfaces for scenario development.
- The application of GIS-based approaches has recently increased, either to estimate the availability of biomass at a local or regional level [123–125] or as part of a decision-making model [90, 126–128]. Use of GIS provides accurate information, which means that the model predictions can be more realistic and readily implementable. A challenge is to make the information provided by a GIS system compatible with the decision-making model, which often requires work on software and informatics. Moreover, the computations become more challenging. However, with the availability of better computing facilities as well as greater accessibility to GIS data, the application of such approaches is expected to increase in the future.

8.5 Future Challenges and Recommendations

The review has also identified some research gaps that must be addressed in the future. These are summarized below:

- Reliable input data that are experimentally validated are needed for model simulations. Currently, there is a substantial lack of data related to actual yield of the crop, field losses, machinery performance, and storage losses. While most models use values reported in the literature, these data points are extremely limited. Recently, Shastri et al. [129] showed the value of incorporating experimental results in a modeling framework. Such approaches should be adapted more often.
- The models should account for the inherent uncertainties in the system, such as weather, yield, maturity schedule, and equipment breakdown.
- The input data, model constraints, and assumptions must be standardized. The life-cycle impact assessment studies have shown that differences in assumptions and system boundaries can vastly impact the results.
- Storage of biomass has often been ignored in many early models. However, seasonal availability will definitely necessitate storage. As pointed out in Chap. 7, quality degradation and total biomass loss can severely impact the feedstock supply. Therefore, storage costs and design of storage facilities must be a part of the models.
- Model validation is important to build trust among the users. There has been a considerable amount of work on validating the crop growth models with field studies. However, such efforts for other levels of models described here have been limited. Lack of a commercial-scale operational system for second-generation biofuels makes validation challenging. As an alternative, the models

could be designed to validate the agricultural residue system such as corn stover, which is more established.

- There is a disconnect between the assumptions and cost estimates among different models. In particular, the disconnect between models developed at different scales (i.e., farm, regional, and national levels) needs to be addressed. For example, national-level models often assume that biomass can be grown on degraded lands that are often small in terms of area. Shastri et al. [1] have shown that the per-unit cost of production for small farms (less than 100 ha) can be substantially higher than the average cost. Such trends, though, are ignored in national-level models.
- For realistic cost numbers, farms of all sizes typically observed in current agriculture must be considered. Costs are typically calculated assuming one farm size, which is often quite large. This will underestimate the actual costs [1]. This becomes even more important when we consider that farms may use only a fraction of their land initially for growing energy crops.
- One option to address seasonal availability of feedstocks is to process multiple feedstocks at different times in the biorefinery. This would reduce storage requirements substantially. Optimization of the BFPP system for such scenarios has generated interest in the last few years [93, 94]. Kenney et al. [130] have proposed mixing of feedstocks to address significant compositional variability in feedstock. The supply chain logistics considering such modifications needs to be further explored.
- Greater emphasis should be placed on incorporating the environmental and social performance indicators explicitly in the modeling approaches. This may require the solution of a multi-objective optimization problem to highlight the trade-offs between different dimensions of sustainability.
- Efforts should be made to integrate models developed at different scales as well as models addressing different aspects of BFPP (Fig. 8.6). There could be one single model that covers all the scales. This would be extremely challenging from a modeling and computational standpoint. Therefore, seamless integration of multiple models addressing different questions should be targeted. In process engineering, the CAPE-OPEN standard has been developed that enables the seamless integration of process and equipment models of different scales (http://www.colan.org/). Perhaps such an approach should be utilized. This opens up the field of multi-scale modeling for bioenergy systems.
- The role of informatics, including DSS, has been limited. This restricts the dissemination of decision-making tools that would be extremely valuable to a number of stakeholders. User-friendly DSS can enable even nonexperts to study specific cases for decision making. Efforts should also be made to make these DSSs web-based to further promote dissemination. Some model-based systems, such as BPSys, IBSAL, and APSIM, have successfully shown the integration of informatics with modeling and analysis. Jakku and Thorburn [131] emphasized the value of social learning and have recommended a framework to develop participatory DSS in agriculture.

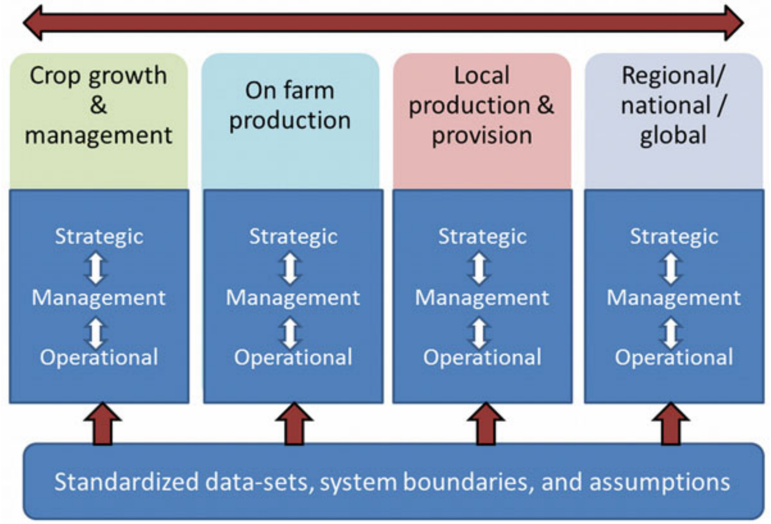

Fig. 8.6 Proposed integrated modeling approach supported by standardized datasets, assumptions, and system boundaries

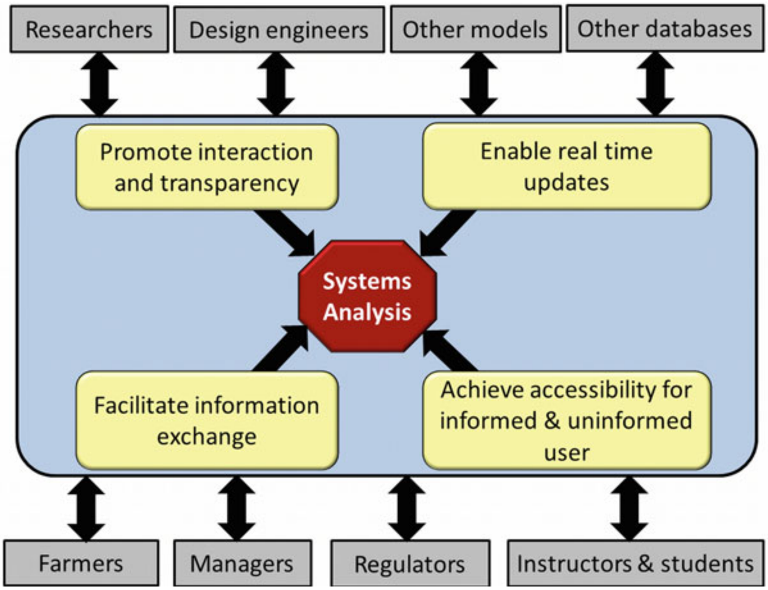

Fig. 8.7 The conceptual framework for concurrent science, engineering, and technology platform, as shown within the *blue box*, for the BFPP system. The core of systems analysis from Fig. 8.2 is enhanced through informatics-driven capabilities for concurrency with developments in science, engineering, and technology. Different users can interact with the platform, and two-way *arrows* indicate that the users can use the platform as well as contribute their domain knowledge to further enhance the platform

- The idea of concurrent science, engineering, and technology, as shown in Fig. 8.7, must be promoted. Successful implementation of this approach should provide a systems integration framework where information and knowledge regarding systems can be gathered, processed, analyzed, and disseminated in a timely manner [6]. To support that goal, it is of great importance to have the ability to capture the essence of the results from different tasks, to create value-added information and knowledge via modeling and analysis, to investigate interrelationships among tasks and their outcome, to provide decision support for prioritizing research and development activities, and to compute the degree of confidence on the results of predictive modeling and analysis. These components can be integrated to achieve concurrency in science, engineering, and technology by making the decision-making tools accessible to domain experts.

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Chapter 9
Sustainability Issues in Biomass Feedstock Production: A Policy Perspective

Jody Endres

Abstract Demand for energy biomass has led nongovernmental organizations, industries with interests contrary to biofuels, and even governments to question whether bioenergy policies truly result in environmental and societal improvements befitting of their "bio," "renewable," and "green" labels. Environmental concerns range from potential emissions of greenhouse gas emissions from indirect land-use change, in some cases making the footprint of biofuels worse than petroleum. Environmental groups also fear that forests' fragile ecosystems could be threatened by overharvesting that leads to water pollution and loss of biodiversity and soil productivity. In addition to environmental harms, social advocates predict that biomass production in developing countries could lead to loss of land tenure/rights, and labor and employment abuses. Laws and private standards have evolved in response to these concerns. Challenges remain, however, in implementing biofuels' sustainability standards, such as enabling farmers to practically and economically use practice and measurement tools, reconciling divergent standards among countries, and solving the seemingly intractable "food versus fuel" dilemma. This chapter examines sustainability requirements for biomass-to-bioenergy that have arisen through the convergence of energy, environmental, agricultural, and forestry policies; examines core "sustainability" definitions in United States, European Union, Brazil, and private policies; and asks how international policy can reconcile meanings of sustainability to foster the nascent bioenergy sector.

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Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4_9,

9.1 Introduction

Regeneration of plant and forest materials constitutes “renewability” in the strictest sense of the word. The ultimate definition of what a sustainable agricultural system should look like varies. One of the most commonly cited definitions of sustainability is a system that supplies a growing population with resources without destroying the environment within which they are used and provides resources for the present without compromising the ability of future generations to meet their needs [1].

Demand for energy biomass, however, has led nongovernmental organizations (NGOs), industries with interests contrary to biofuels (e.g., food and feed), and even governments to question whether bioenergy policies truly result in environmental and societal improvements befitting of their “bio,” “renewable,” and “green” labels [2]. In 2008, a vocal cadre of academics struck a blow to sustainability assumptions about biofuels [3]. They argued that greenhouse gas (GHG) emission reductions may be dramatically overestimated because of market-induced indirect land-use change (ILUC), in some cases making the footprint of biofuels worse than petroleum. NGOs jumped on the bandwagon with distress calls about fragile ecosystems threatened by overharvesting, particularly in forests. Other environmental and social concerns were added to the agenda of biofuels’ opponents, including water and air pollution, loss of soil productivity, loss of land tenure/rights, and labor and employment.

In response to these concerns, bioenergy laws and private standards have evolved to make biofuels more “sustainable” from both a GHG and “other” sustainability perspective. Generalized environmental and social policies, too, exist to fill in where gaps in bioenergy laws occur. Challenges remain, however, in implementing biofuels’ sustainability standards, such as enabling farmers to practically and economically use practice and measurement tools, reconciling divergent standards among countries, and solving the seemingly intractable “food versus fuel” dilemma. This chapter examines sustainability requirements for biomass-to-bioenergy that have emerged through the convergence of energy, environmental, agricultural, and forestry policies, and focuses on core “sustainability” definitions in United States, European Union, Brazil, and private policies. It concludes by examining harmonization and efforts to address perhaps the most formidable sustainability challenge in policy—biomass’ competition with food.

9.2 Sustainable Biomass Laws and Policies

The past 10 years have seen a significant proliferation of bioenergy policies, and as they have evolved, more and more focus has been placed on accounting for the potential environmental and social impacts of biomass-based fuels. Initial concern was whether from a lifecycle perspective biofuels deliver true GHG emission reductions. The United States, California, and the EU all have codified some form of GHG measurement for biofuels. Policies increasingly contemplate biomass’ other possible effects on air, water, and soil quality, and biodiversity, as well as fair labor practices and property rights in the wake of potential land grabs in undeveloped countries.

9.2.1 The United States

9.2.1.1 Federal Policies

Historically, US biofuels policy has relied primarily on corn as an ethanol feedstock. Although corn ethanol has served as an engine for rural development, the environmental implications of conventional corn production [4] were largely unaddressed in government energy policy until the enactment of the Energy Independence and Security Act of 2007 (EISA) [5]. In order to satisfy the mandatory blending levels of "renewable fuels" into transportation fuels, now, for the first time, all biofuels qualifying for EISA's Renewable Fuel Standard (RFS) had to achieve a certain level of GHG reductions and be derived from certain renewable sources. In addition, the 2008 Farm Bill established the first supply-side incentive for renewable biomass through creation of Biomass Crop Assistance Program (BCAP) [6]. The program conditions payments on whether the biomass was produced under a conservation plan [7]. At the state level, California is in the process of developing biomass sustainability standards to accompany its broader GHG reduction agenda embedded in programs such as the low-carbon fuel standard (LCFS) [8]. The following sections provide, in greater detail, the meaning of these sustainability provisions.

The US Renewable Fuel Standard

EISA increased the mandatory blending of renewable fuels to 36 billion gallons by 2020. Each category of qualifying fuel (renewable fuel, cellulosic ethanol, biomass-based diesel, and advanced biofuels) must meet minimum threshold GHG emissions reductions [5], and obligated parties under RFS must source renewable fuels from "renewable biomass" [5]. "Renewability" in the statute focuses on land conversion prohibitions [5], limits on biomass sourcing from nonfederal forests, and absolute bars against harvests from old-growth or late-succession forests and forests with ecological communities with a certain global or state ranking [5]. The environmental protection agency (EPA) is implementing a plan [9], in response to several instances of Renewable Identification Number (RIN) fraud [10], for quality assurance through independent third parties. EPA notes that the Quality Assurance Program will also verify that feedstocks are from "renewable biomass" and meet land-use restrictions.

EISA requires the US EPA to report triennially on the environmental impacts of the RFS [5]. In February 2011, it issued its first triennial report of the environmental impacts of the RFS [11]. EPA acknowledges in its report studies that confirm commodity crop production in the Mississippi watershed results in harmful nitrogen pollution. It concludes, however, that the effects of biomass cropping are yet to be fully understood due to the dearth of scientific research. Perhaps most significantly, EPA indicates in the triennial report that it will apply lifecycle analysis (LCA) in the next triennial report (2014) to determine the full range of environmental effects within the RFS supply chain. What methodology and data EPA will use, however, remain unclear.

Most significantly, the RFS has been under assault by livestock and grocer interests for raising prices of agricultural feed stocks. Both have lobbied Congress to end the RFS altogether [12] and have unsuccessfully sued EPA for diverting corn to ethanol from livestock feed [13]. Still, EPA has resisted adjusting the mandate down [14]. EPA may, under the RFS statute, adjust the mandate after 2013 if it determines that it negatively affects US food and feed prices [5]. According to a 2013 ruling by a federal court of appeals, EPA must be more accurate in its technology predictions when setting the mandate than it had been in the past [15].

The Biomass Crop Assistance Program

The BCAP is the United States' first federal subsidy for biomass-to-bioenergy feedstocks, which pays farmers over 5- to 10-year period for the establishment and production of "renewable biomass," which has two basic meanings under the statute and regulations [16]. First, crops eligible for the subsidy cannot be cropped on lands with native vegetation not previously tilled at the time the 2008 Farm Bill became law, or on land that receives conservation, wetland, or grassland reserve payments [16]. Second, food crops are not eligible for payment [17]. Thus, only second-generation crops, like perennial grasses, and short-rotation woody biomass, like poplar, are eligible.

Just like for a condition for any type of federal farm subsidy (whether direct and countercyclical payments or other conservation grant funding such as the Environmental Quality Incentives Program or Wildlife Habitat Incentive Program), BCAP producers must implement some form of USDA Natural Resource and Conservation Service (NRCS) conservation planning [18]. In addition, BCAP farmers must comply with some general environmental laws that protect fragile habitats such as the Endangered Species Act, Farm Bill proscriptions against wetland and native grassland conversion, and controls on pest control application in the Federal Insecticide, Fungicide, and Rodenticide Act. Otherwise, Congress has largely exempted agriculture from air and water pollution control requirements [19]. Federal labor and employment laws also contain certain exemptions for agriculture from overtime pay and minimum wage requirements.

BCAP's requirement that all subsidy recipients complete conservation plans highlights the need for farmer education on sustainability practices. Research, education, outreach, and support are critical building blocks of agricultural knowledge [20]. Farmer assistance in the United States is primarily funded through the USDA's National Institute of Food and Agriculture (NIFA) at state land-grant universities [21]. Much of the services' and research funding focus, however, has been on traditional commodity crop production systems with less emphasis on sustainability [22]. Land-grant universities that sponsor extension services have been criticized for "neglecting important segments of the population," including small and family farmers, and have instead "allied themselves with the corporate interests that are at odds with promotion of rural life" [23, 24]. In light of new markets created by sustainable biomass mandates, extension services can counter these criticisms by refocusing their mission toward smaller, less corporatized farmers who want to improve the sustainability of their practices through biomass cropping. Although this transition may already be occurring, the research side of sustainable practices has much catching up to do [25]. New research must also be incorporated into NRCS practice standards, which inform farmers' conservation planning. Although somewhat analogous NRCS cover cropping and riparian buffer practice standards are in place, no standards exist that would guide producer's decision for energy cropping. It is believed that the Farm Services Administration and NRCS have worked together in devising practice standards for BCAP to prevent the spread of invasive species for individual participants, but these have not been published publically.

The Clean Air Act "Tailoring Rule" for Biomass-Based Emissions from Stationary Sources

In addition to bioenergy-specific statutes such as the RFS and BCAP that contain sustainability provisions for biomass, federal efforts to reduce GHGs from electricity generation also contemplate the sustainability of biomass. EPA is implementing stationary [26] GHG rules under the federal Clean Air Act (CAA) in response to the US Supreme Court's holding in 2007 that EPA must determine whether GHGs cause or contribute to air pollution (GHGs) that may be reasonably anticipated to endanger public health (which it did in 2010). For certain stationary sources such as electricity generators that combust biomass that EPA must permit under its "Tailoring Rule," EPA controversially ruled in July 2011 that it will treat biomass as "carbon neutral" while it studies the issue for 3 years [27]. Put another way, EPA deferred permitting of facilities that combust forest and agricultural biomass until studies can be completed on its carbon neutrality. EPA's Science Advisory Board (SAB) has conducted hearings to evaluate EPA's proposed "Accounting Framework for Biogenic CO_2 Emissions From Stationary Sources" and proposed to EPA that not all biogenic carbon is carbon neutral [28]. In July 2013, a federal appeals court struck down EPA's deferral. Citation: Center for Biological Diversity v. EPA, No 11–1101 (D.C. Cir. July 12, 2013). Despite a call for information related to other sustainability issues (particularly impacts on forests) in July 2010, EPA did not indicate in its neutrality rule any reference to what, if anything, it will do moving forward with regard to environmental issues other than GHG emissions [29].

Procurement Market-Pull for Sustainable Biomass: USDA, EPA, Department of Defense

In addition to compliance-based incentives to increase biomass sustainability, the primary potential market-pull in the United States for sustainable biomass likely will come from federal procurement standards. All executive agencies (e.g., the Department of Homeland Security) follow the Federal Acquisition Regulation (FAR) to make "sustainable acquisitions" (i.e., purchases) [30]. Ninety-five percent of new contract actions must require that the product is, among other qualities, water-efficient, biobased, and environmentally preferable. Each federal agency must establish affirmative procurement programs (APPs) (otherwise known as green purchasing plans [GPPs]) for biobased products. Products qualifying under the FAR include those covered by the EPA's Environmentally Preferable Purchasing (EPP) guidelines and USDA's biobased program, both of which delineate what products may qualify under their programs. The Farm Security and Rural Investment Act of 2002 (FSRIA) established USDA as the lead agency for the federal procurement of biobased products, including developing categories of qualifying "biobased" products.

EPA's Final Guidance on EPP is based on the goal of pollution prevention and consideration of multiple attributes from a lifecycle perspective. The guidance states that there is "no hierarchy that ranks which attributes or environmental impacts are the most important," but recovery time and geographic scale, differences between competing products, and human health are factors that agencies consider [31]. Although certification is not required, it is one way in which federal officials can evaluate a product for qualification. The guidance also maintains an annex with a list of "environmental attributes" including ecosystem impacts and water consumption and pollution.

USDA's Guidelines for Designating Biobased Products for Federal Procurement, issued as part of the biobased program referenced above, on the other hand, forbid a procuring agency from requesting more information from vendors of biobased products than required of other vendors generally but "encourages" them to provide information on environmental and public health benefits based on "industry accepted analytical approaches such as ASTM D7075 and ISO 14040" [32]. Biobased products do not include electricity or motor fuels or any other product for which there is a mature market. Two congressmen recently introduced the Forest Products Fairness Act of 2012, which would open up the program to forest-based products, regardless of market maturity, including pellets.

Congress required the Department of Defense (DOD) in 2009 to study ways in which alternative fuels could be procured and used to reduce GHG emissions. DOD's final study concluded that it remains uncertain whether alternative fuels can be produced sustainably. Its recent request for proposals required a reference to sustainability certification, which indicates that while DOD is interested in procuring biofuels (including those made from forest biomass), it must be assured at some level of their true sustainability.

9.2.1.2 State Programs: California's Multifaceted Assembly Bill (AB) 32 GHG Reduction Policies

In addition to federal bioenergy, environmental, and procurement laws, California leads the way among states in development of policies to combat GHGs through policies such as a LCFS, cap and trade, renewable electricity, vehicle emissions, and green subsidies. The LCFS requires each fuel supplier in California to reduce the overall carbon intensity of fuel sales each year, for an overall reduction by 2020 of 10 % relative to the 2005 baseline [33]. The California Air Resources Board (ARB) is in the process of developing concurrent practice-based sustainability standards to accompany the LCFS' carbon foot printing. ARB has developed a set of draft metrics (e.g., water, soil, biodiversity, and labor/employment) in consultation with a sustainability workgroup of stakeholders and other experts [34]. Similar forestry sustainability standards began through the Interagency Forestry Working Group but appeared to be stalled [35].[1]

Plaintiffs have challenged the constitutionality of the LCFS' carbon footprinting through LCA [36]. Specifically, a group of farmers and ethanol interests from the US Midwest claim that the Dormant Commerce Clause of the US Constitution prohibits California from imposing rules that substantially affect interstate commerce. These include the GHG penalties that Midwestern corn ethanol receive because of transportation emissions associated with logistics of shipping ethanol from the Midwest to California, and the use of high GHG intensity coal-fired electricity that is prevalent in the Midwest. While triumphant at the district court level, the Ninth Circuit Court of Appeals held the regulation valid in September 2013. Citation: Rocky Mountain Farmer's Union v. Corey, No. 12–15131 (Sept. 18, 2013).

In addition to ARB's LCFS efforts, the California Energy Commission (CEC) applies sustainability criteria to make green subsidies for alternative and renewable fuels and technologies [37]. For purpose-grown energy crops, these include "development and implementation of a sustainability best management practices plan developed by institutions such as the University of California at Davis," land use that does not disrupt food cropping, and crop selection that fits climate, water, and natural resource constraints [38]. On the other hand, renewable energy credits (RECs) generated through its Renewable Electricity Standard (RES) lack concrete definitions of "renewability" except as broadly defined through statute by source (e.g., biomass) and that which does not "cause or contribute to any violation of a California environmental quality standard or requirement" [39]. While it remains unclear how CEC will verify environmental compliance, presumably Cap-and-Trade regulations would cross-apply. CEC did recently issue a study of the lifecycle effects of certain energy systems [40]. Controversy surrounding the definition of "renewability" of RES feedstocks has emerged in other states such as North Carolina, where environmentalists have appealed the NC Utilities Commission's order, allowing whole trees to be combusted for electricity generation [41].

California's Cap-and-Trade regulation exempts biomass-based fuels from carbon accounting, but entities must still report GHG emissions from biomass under the mandatory reporting regulation [42]. In December 2011, ARB finalized additional reporting requirement that forest-derived biomass demonstrate compliance with environmental and forestry laws [33]. For international sourcing, California continues to work, through the Governors' Climate and Forests Task Force (GCF), on the integration of sustainability mechanisms such as Reducing Emissions from Deforestation and Forest Degradation (REDD) into the Cap-and-Trade program [43].

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[1] *CAT Forest Group/Inter-Agency Forest Working Group*, CAL. CLIMATE CHANGE PORTAL, http://www.climatechange.ca.gov/forestry/index.html (last modified Jan. 12, 2010).

9.2.1.3 Sustainability and the Forest Sector in the United States

While the aforementioned policies reach both agricultural and forest biomass, sustainability regulation within forests is more developed than in agricultural landscapes due to the historical exemption of farming activities from environmental regulation. Jurisdiction over forestry sustainability management depends on whether the land is publically or privately held. The US Department of Agriculture's Forest Service (USDA-FS) and the US Department of Interior administer sustainable forestry laws and rules on federal lands. These include the Organic Act leading to the modern-day establishment of the USDA-FS, the Sustained Yield Act of 1944, the Multi-Use and Sustained Yield Act of 1960 (MUSYA), and the National Forest Management Act of 1976 (NFMA). Since its inception, USDA-FS has come under criticism by forest-protection advocates that its interpretation of "sustained yield" and "multiple use" contained in these statutes favors harvest levels to the detriment of sustained ecological function of the forest. In addition to NFMA, however, federal forest actions also are subject to other general laws such as the National Environmental Policy Act, the Clean Water Act (CWA), and the Endangered Species Act. The USDA-FS' interpretation of these laws still is ever-evolving, however, as evidenced by the US Supreme Court's recent decision deferring EPA's decision not to apply CWA point source permitting to road building in federal forests [44]. How these laws are interpreted will affect the ability to harvest forest biomass on federal lands for bioenergy. The following sections detail the potential relationship between the applications of various federal forest policies for biomass energy.

The National Forest Management Act of 1976

Although NFMA does not allow environmental values to completely trump economic uses of federal forests, NFMA does require the USFS to prepare management plans that provide for "sustainable" yields and regulations that consider plant, animal, and tree diversity. The Forest Service Manual and other guidance (e.g., best management practices for water quality) play primary roles in implementation of forest plans. Until 2012, federal planning rules have been based on a 1982 rule. The Clinton administration proposed a revised rule in 2000, but the George W. Bush administration refused to implement the rule. Instead, it proposed its own rules twice that essentially eliminated environmental review and scientific assessment. Courts on both occasions struck down the rules, opening an opportunity for the Obama administration to finalize a new forest management rule [45, 46].

Whether or not the current rule will be similarly overturned is uncertain, but undoubtedly it has already caused controversy. The Center for Biological Diversity, the organization behind the two other successful suits, has criticized the rule for weakening longstanding biodiversity protections by eliminating the requirement that the Forest Service maintain viable populations of species in favor of deference to localized decisions. The rule instead focuses on ecosystem integrity and biodiversity that is dependent on the regional forester's discretion as to what species are of concern and whether the Forest Service has the authority and capability to maintain a viable population. That does not mean the Forest Service can choose to ignore species conservation; it must in its plans under the new rule "maintain or restore ecological conditions within the plan area to contribute to maintaining a viable population of the species within its range." Conservationists would argue that the rule's focus on species of concern lessens protections for all native species, and its diffusion of decision-making authority to lower levels risks capture by local economic interests. The Forest Service currently maintains technical guidelines for species monitoring, but it is unclear how those might change in light of the new rule.

USDA-FS states in the final rule that it "recognizes…that development of renewable and non-renewable energy resources are among the potential uses in a plan area. However, the final rule does not dictate the activities that may occur or not occur on administrative units of the NFS" [45]. Assessments for planning purposes must account for energy resources. The extent to which those resources are accessible depends on other sustainability factors incorporated into planning such as biodiversity and water-quality conditions. New Section 219.8 contains the core sustainability provisions for forest planning, spanning ecosystem integrity, air quality, soils, and water quality. Persistent violation of state water-quality standards led to an added requirement in the final rule that the Forest Service Chief promulgate national-level best-management practices to maintain and restore water quality and a system of ensuring that lessees implement them.

The Healthy Forests Restoration Act of 2003

While environmentalists were successful in blocking George W. Bush's changes to the NFMA forest planning rule that would have exempted leasing decisions from environmental review, he was successful in getting the Healthy Forests Restoration Act of 2003 (HFRA) passed [47]. HFRA contains similar exemptions from environmental review, such as (1) categorical exclusion from environmental review for logging projects up to 1,000 acres in size when the projects are intended to combat forest-damaging insects; (2) exemption of hazardous fuel reduction projects from the administrative appeal process, allowing the Forest Service to establish a "predecisional administrative review process"; and (3) limiting plaintiffs to specific written issues raised during this administrative review process unless a court determines the process is futile or inadequate with respect to the specific client or claim [48].

While these provisions can serve to facilitate the process of biofuel harvesting by limiting time-consuming public review and litigation that could hinder or completely halt harvesting, forest-protection advocates claim that destructive overharvesting and accompanying ecological degradation could occur and have pursued legal challenges against Forest Service HFRA decisions. The Forest Service and Department of Interior's Bureau of Land Management have issued an interim field guide for HFRA implementation, but substantive changes made by HFRA to the environmental assessment process governed by NEPA have been made through Council on Environmental Quality (CEQ) guidance. Other changes to the appeals process are found in general Forest Service regulations.

Despite the continuing controversy, HFRA plays a large role in the utilization of biomass for bioenergy. The Departments of Agriculture, Interior, and Energy signed a memorandum of understanding in 2003 setting “Policy principles for Woody Biomass Utilization for Restoration and Fuel Treatments on Forests, Woodlands, and Rangelands” [49]. The principles include mapping of potential biomass resources and encouraging sustainable development as sustainability “measures.” In 2008 the Forest Service issued its “Woody Biomass Utilization Strategy,” which recognizes the need to develop management practices for sustainability that presumably would apply to restoration and fuel treatments [50].[2] Part of USDA-FS’s national strategy, too, includes the “Woody Biomass Utilization Desk Guide,” which recognizes the environmental implications of increased harvest but does not recommend specific practices [51]. USDA-FS also contributed funding to a National Association of Conservation District’s “Woody Biomass Desk Guide and Toolkit” that recognizes specifically the environmental disadvantages of woody biomass-to-energy activities [52].

Private Certification on Federal Forest Lands

In 2007, the USFS commissioned a study gauging the effectiveness of its existing forest management practices when compared with certain third-party certification standards [53]. While auditors commended the thoroughness of planning, comprehensive use of scientific data, and stakeholder engagements, shortcomings in USDA-FS policy were found in relation to practices that related to forest sustainability. Delayed silvicultural treatments and unachieved ecological, social, and economic management goals were the primary lapses cited. The report cites increased pest and disease infestation, increased potential for “stand-replacing” wildfire, and the inability to achieve desired forest structure and composition (e.g., bird habitat) as some of the ramifications of the failure to manage forests for sustainability. Lack of financial resources and lack of capacity have led to these delays. Forest officials further admitted their inability to adequately enforce rules meant to reduce the detrimental environmental impacts of off-road vehicle use. Some inadequacies related to scale and access also were found with management of late-succession and old-growth forests.

The 2007 study reveals that public laws, standing alone, are in some cases not enough to ensure the sustainability of forest harvests. Assuming that federal forests will be opened to harvests for energy biomass, to combat the threat of overharvesting for energy biomass, future general federal forest laws could require regular

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[2] USDA, Woody Biomass Utilization Strategy (Feb. 2008), http://www.fs.fed.us/woodybiomass/strategy/documents/FS_WoodyBiomassStrategy.pdf.

audits of Forest Service policies to third-party certification principles, criteria, and indicators, or private leases in federal forests could be subject to actual third-party certification. A combination of both public and private requirements would ensure that both whole forest and site-level sustainability are better achieved.

The Lacey Act and Imports of Forest Biomass from Illegal Logging

The Congress passed the Lacey Act in 1900 as a way to prevent illegal fish and wildlife trafficking. The 2008 Farm Bill expanded Lacey Act prohibitions to the interstate or international trade in illegally harvested timber either under the United States or any foreign law covering theft, taking from protected or officially designated areas, taking without prior authorization, or taxes. All imports must file a declaration with USDA's Animal and Plant Health Inspection Service (APHIS) stating the scientific name of the tree, the quantity and value of the shipment, and the country from which the tree is taken.

While the declaration does not require importers to maintain a chain of custody regarding sustainability, it does carry stiff criminal penalties if the importer knowingly sources illegally harvested timber, including woody biomass for energy such as pellets. If the importer does not knowingly import such products, but fails to exercise "due care," the importer is subject to lesser misdemeanor charges and civil penalties. The US Department of Justice has stated that "due care means that degree of care which a reasonably prudent person would exercise under the same or similar circumstances" and that it "is applied differently to different categories of persons with varying degrees of knowledge and responsibility" [54]. The ambiguous nature of the "due care" standard has lead industry groups to issue their own guidance that includes a written company policy, standard operating procedures and checklists, asking suppliers to explain the due diligence they exercised in sourcing wood products, and knowing where the biomass is harvested from through third-party certifications.

State Sustainable Forest Biomass-to-Energy Initiatives

While federal policies can and do, in some instances, play a significant role in sustainable forest management (SFM) in relation to bioenergy, the lack of a coordinated federal-level bioenergy policy has left a vacuum for states to fill. States can set rules for activities within their jurisdiction. States can reach activities outside their borders, but only if the substantial state interest in regulating does not overburden interstate commerce. The Massachusetts Department of Energy Resources (DOER) finalized in 2012 a rulemaking specifically addressing the sustainability of forest biomass feedstocks qualifying for the state's renewable portfolio standard (RPS). The rules are based in part on the groundbreaking Manomet study, which assessed the possible impacts resulting from the state's proposed transition from traditional fossil fuels to a bioenergy model. The study analyzed three core energy and environmental questions: (1) the GHG implications of shifting energy production from fossil fuel sources to forest biomass; (2) the amount of available forest wood necessary to support the state's energy goals; and (3) the potential ecological impacts of increased biomass harvests in state forests and the policies necessary to ensure the continued sustainability of the harvests [55].

The new RPS rule defines eligible woody biomass as (1) forest-derived residues (i.e., tops and other portions of trees produced as a byproduct of the normal harvesting process, other woody vegetation that interferes with regeneration of natural growth but limited to locally invasive native species and nonnative invasive woody vegetation); (2) forest-derived thinnings (including whole trees that are weak or of low vigor and trees removed during thinning operations for the purpose of reducing stand density and enhancing growth and volume of the stand); (3) forest salvage (i.e., damaged, dying, or dead trees due to weather events or disease and trees removed to reduce fire hazard, but not those trees removed due to competition between plantings); and (4) non-forest-derived residues (including trees removed for nonagricultural and agricultural land-use change) [56].

Each year, the unit using eligible biomass woody fuel must document total tonnage through "biomass fuel certificates." The certificate also verifies the source of forest-derived residues and thinnings by citing either a Massachusetts Department of Conservation and Recreation (DCR) "cutting plan" or other equivalent state plan prepared by a licensed forester, or obtaining the signature of a professional forester [56]. The DOER has created a set of certificate guidelines on an Excel spreadsheet that place additional restrictions on biomass removal [57]. For forest-derived residues, the report must provide information detailing the residues' precise derivation—whether the residues are harvest by-products or the result of damage caused by invasive species. This is required to prevent prohibited material or materials in prohibited amounts from entering the supply chain, including material from old-growth forest stands, naturally down woody material, forest litter, forest floor roots and stumps, live cavity trees, den trees, and live but decaying trees and snags. In addition, the amounts of biomass eligible to be taken away from a harvest site are tied to the overall tonnage of biomass harvested and to the quality of the soil at the harvest site.

For areas deemed to be of poor soil quality, 100 % of the tops and branches from the forest material must remain on site in order to prevent erosion and to supplement soil conditions and quality. In cases where soil quality is "good," 25 % of the tops and branches from the harvest must remain on site. A soil designation of "good" or "poor" is determined by set criteria established by DOER and the NRCS. In all cases, 30 % of material eligible for thinning must remain. Beyond regulation and guidance specific to the RPS, any forest harvesting activity in the state above a certain volume must be conducted with an approved cutting plan pursuant to the Forest Cutting Practices Act (FCPA), including compliance with the Best Management Practices Manual [58]. Like most states, Massachusetts maintains its own Endangered Species Act that also applies to any forestry activities, including those conducted to qualify for the state's RPS.

9.2.2 The European Union

Unlike in the United States, which has only the RFS at the federal level as its bioenergy policy, and California, with its multifaceted A.B. 32, the EU Renewable Energy Directive (RED) and Fuel Quality Directive (FQD) combine both a mandate and LCFS. Both directives became final in April 2009. The RED requires that energy from renewable sources, such as biomass, makes up 20 % of the total EU energy supply by 2020 [59]. Ten percent of the total energy used for transportation must be from renewables, which would be counted toward the 20 % overall mandate. Member states bear responsibility for fulfilling these commitments through national action plans, including implementing schemes to guarantee that feedstocks for biofuels meet sustainability criteria enumerated in Article 17 of the directive. These criteria include meeting increasingly more stringent GHG minimum thresholds (concurrent amendments made to the FQD require all transportation fuels to reduce their emissions by 10 % by 2020 [60], like the California LCFS), land-based sourcing prohibitions (lands with high biodiversity or carbon values), and cross-compliance [61] with existing agro-environmental laws. "Economic operators" are required to seek independent audits to verify that these criteria are met and must report as part of verification "appropriate and relevant information on measures taken for soil, water and air protection, the restoration of degraded land, the avoidance of excessive water consumption in areas where water is scarce and appropriate and relevant information concerning measures taken" [59].

Cross-compliance measures required in Article 17(6) of the EU RED are contained in the Common Agricultural Policy (CAP) [59]. This requirement for bioenergy recognizes that since the early 1990s, the EU has shifted toward a policy of "multifunctionality" of agriculture—that agriculture should produce environmental and societal goods and services in addition to food, feed, fiber, and energy [62]. Beginning in 2003, the EU implemented changes to the farm subsidy program contained in the CAP in order to create better balance and consistency between rural development and sustainability objectives [63].

Whether a producer receives a direct payment for income support, or support under the EU rural development policy, the CAP requires producers to observe "cross-compliance" with environmental, food safety, plant and animal health, public health, animal welfare, and environmental condition rules [61, 64, 65]. Cross-compliance contains two elements. "Statutory management requirements," or SMRs, include 19 different pieces of EU legislation, including directives on wild birds, sewage sludge, wastes, nitrates, release of dangerous substances into aquatic environments, habitats, ground water, and plant protection products [61]. Second, all producers who receive subsidies must maintain lands in good agricultural and environmental condition (GAEC) [61]. The CAP establishes a minimum standards framework for GAEC relating to soil protection, organic matter and structure, avoiding deterioration of habitats, and water protection and management. Beyond cross-compliance and GAEC, producers can voluntarily adopt agri-environmental measures (AEMs) in return for payments under the EU rural development policy

[64]. The EU further has provided subsidies since 1975 for production on "less favored areas" (LFAs) (now under the Rural Development Policy) to both ensure income in low-productivity areas vulnerable to abandonment and maintain environmental values dependent on agricultural production.

Member states are responsible for implementing cross-compliance, GAEC, AEMs, and LFAs through national legislation and rules that define standards known as "good farming practices" (GFPs) or "good agricultural practices" (GAPs) [66]. GFPs vary widely between member states, due in part to variation in both ecosystems and types of farming operations throughout Europe [66]. For example, cross-compliance with the Nitrates Directive requires a determination of when application of fertilizer is appropriate (e.g., sloped or wet areas) and mitigation practices such as cover crops and good record keeping [67]. From an implementation perspective, some member states require farmers to practice nutrient accounting and keep records, while other member states take different approaches to reducing nutrient runoff [68].[3] This is not unlike the United States, where the federal NRCS develops Field Office Technical Guidance (FOTG) down to the individual county level to address site-specific and area resource concerns [69].

The EU places primary responsibility on member states to provide advisory services to producers related to agri-environmental programs. The CAP requires that member states operate a Farm Advisory System (FAS) to help farmers, on a voluntary basis, in complying with SMRs and GAECs [70]. Member states vary in how they deliver FAS services in terms of whether the service is provided by private, public, or hybrid entities, whether the service is free of charge, what type of service is offered, and to whom it is offered [71]. In some member states, responsibility is devolved to individual states (e.g., Germany) that differ in types of services provided. The majority of assistance consists of going through checklists one-on-one or with small groups. FAS advice also extends to occupational health and safety issues. One report has concluded that "experience of European farmers with energy crop plantations is very limited, and transition to lignocellulosic feedstock systems requires tailor-made agricultural extension services assisting farmers on the various aspects of production from planting to harvesting" [72].

Thus, what existing tools are available for biomass growers to certify their sustainability depends on the EU member state policy and practices in relation to the environmental principle in question [73]. Member states also vary between and within in the way they deliver advisory services to farmers. In the United States, on the other hand, despite the fact that AEMs apply much less than to farms in Europe, and the identification of ecosystem-level resource concerns is in its nascency, the federal NRCS does provide one central, consistent source for advice on designing agri-environmental planning and practices. However, with the US federal budget crisis severely curtailing agency funding, it is uncertain what level of service NRCS

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[3] European Commission, Report from the Commission, Implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources, Synthesis from year 2000 Member States Reports, COM (2002) 407 final, at 17–22.

will be able to provide in the future, particularly for biomass where capacity is almost nonexistent. Moreover, unlike the EU FAS, NRCS services are limited to environmental issues, so producers must seek out occupational health and safety information separately through CREES and the federal Department of Labor's Occupational Health and Safety Administration (OSHA).

The RED does not impose sustainability criteria on renewable sources used for electricity, heating, and cooling. Instead, it required the Commission to report on a similar scheme for these uses [59]. In its report issued in February 2011, the Commission recommends member states introduce sustainability schemes [74], although concurrently the Commission initiated a consultation based on "new developments" in the industry and policies to determine whether a need exists for additional measures at the EU level [75]. In its July 2011 findings, the Commission notes that 72 % of respondents "believed that additional measures at [the] EU level are needed to ensure the sustainability of biomass used in electricity and heating/cooling sectors" [76]. The respondents' reasoning was based on (1) increasing EU demand, (2) inadequate existing sustainability policy frameworks in the EU, (3) the need for a consistent approach, and (4) the lack of a binding EU sustainability scheme. The EU is currently considering existing forest sustainability laws and whether amendments to the RED are necessary.

9.2.3 Brazil

Brazil's federal requirement for mandatory blending of sugar cane ethanol, Proalcool program [77], does not contain practice-specific sustainability requirements. However, in response to international pressure to prevent deforestation resulting from energy biomass cropping, Brazil has codified an agroecological zoning plan for the expansion of its sugar cane-to-ethanol industry (ZAE-CANA) [78]. The multiagency federal effort used soil, climate, hydrological, biological, socioeconomic, and regulatory criteria to designate where cropping can occur. It automatically excluded areas of native vegetation and areas of high biodiversity, such as the Amazon and Pantanal, and focused on ensuring that land designation would support sustainability and protection of biodiversity and would reduce competition with food cropping. States must incorporate these land-use designations into their legal regimes permitting expansion of sugar cane cropping [79].

The Forest Code is the second key law related to constraining land-use change [80]. The Forest Code divides land categories into those for agricultural production and conservation. Conservation is further subdivided into "permanent preservation areas" (APPs) and "legal reservation areas" (RL). APPs must be established in areas next to drinking water sources and rivers and sloped lands. The RL requires between 20 and 80 % of land owned to be maintained in forest or native vegetation, depending on the location of the farm. These conservation provisions are controversial among private landowners. The Brazilian federal Congress approved a new version of the Forest Code in 2011, which kept the RL and APPs in place but at a reduced rate and with amnesty for some rural producers who did not comply with the Forest Code restriction prior to 2008. The World Bank contends that one side effect of the RL and APPs is that if productive land must be otherwise "reserved," agricultural land use could move to more sensitive areas such as the Amazon [81]. Future discussion, therefore, could revolve around how to make reserves more economically meaningful to producers (thus relieving the incentive to deforest elsewhere) and the application of ZAE-CANA zoning restrictions. One way to do this would be through certified biomass production.

From a cross-compliance perspective, environmental licensing is required for "high impact agricultural activities, including sugar cane ethanol facilities" [82]. Environmental licensing includes pre-project environmental review for compliance with other environmental laws [83, 84]. It remains unclear, however, whether responsible authorities (states) require compliance beyond the biorefinery to the field level. Pursuant to the "Green Protocol," financial institutions have agreed with the federal environmental agency to condition lending on obtaining environmental licensing [85].

The State of São Paulo has taken steps to phase out the burning of sugar cane prior to harvest by 2021 under pressure to reduce air pollution and lifecycle GHG emissions attributable to sugar cane ethanol [86]. In 2007, UNICA (the main Brazilian sugar cane industry group) voluntarily agreed with the State of São Paulo to reduce burning in all areas in anticipation of a 2013 deadline as well as no burning in new areas [87]. One significant societal side effect of burning bans, however, has been the elimination of hand labor in favor of mechanization. The UNICA Agreement also involves other areas of improved sustainability. Its "technical directives" provide that sugar cane growers will observe a variety of sustainable practices, including (1) assessing areas that could contribute to environmental protection, including biodiversity; (2) protecting water sources in rural areas; (3) implementing soil conservation and watercourse protection plans; (4) properly disposing pesticide containers and applicator training; and (5) adopting best practices to minimize air pollution from industrial practices. In return, the State agrees to fund research, install logistical infrastructure for exports, issue a "certificate of agro-environmental conformity" as contained in the technical directives, and consider small holders in designing anti-burning measures. The agreement establishes an executive committee of three technicians from the government and industry to establish criteria for the certificate. "According to the State Environment Secretary, 145 out of 177 plants in São Paulo have adhered to the Protocol" [88].

The 2007 National Plan on Climate Change recommends ways in which agricultural and forestry practices can reduce GHG emissions, such as the adoption of no-till techniques, strategies to deal with degraded pasture, integrated crop-livestock operations, reduction in the use of nitrogen fertilizers, and organic "enrichment" of cattle pastures to reduce nitrogen emissions [89]. The emphasis on improving pasture in Brazil, particularly if it involves intensification of cattle, has been activity forwarded as one way to reduce ILUC penalties placed on biofuels. The drive toward livestock intensification may result in trading one environmental problem, such as the ILUC, for another, because while biofuel sustainability standards may take into account GHG emissions from ILUC, they do not take into account the negative, indirect environmental effects of ILUC avoidance through livestock intensification that have been the subject of much environmental dispute in the United States [90, 91].

The sugar cane sector in Brazil has been subject to much criticism for its labor practices involving poor, uneducated workers, both internally and from international human rights groups. Although Brazilian authorities have pursued action under labor laws against poor working conditions, the conditions for laborers have only until recently began to improve [82]. Under pressure from critics and threat of further enforcement, UNICA signed a voluntary agreement with five Brazilian federal ministries to improve labor practices in sugar cane production in 2009 [82]. The industry has promised to provide work contracts, improved conditions for migrant workers, transparency in how workers are paid by unit of production, better health and safety mechanisms, improved transportation conditions, the provision of meals, the possibility of unionization, and reporting of practices.

Brazil does maintain the “Social Seal” program for biodiesel, which, in addition to mandating 5 % blending after 2013, forces biodiesel producers to buy at least 50 % of feedstocks from family farmers in order to qualify for the government’s price premium and other incentives [88, 92]. Criteria have been developed to monitor whether the Social Seal program requirements are met, and companies must submit quarterly data to the Ministry of Agriculture. These include reporting on technical assistance provided to farmers, maintaining food security, respect for cultural practices, sustainability systems that emphasize indigenous, local practice knowledge, appropriate management of soil and water resources, consideration of women and children in income generation, and measures to reduce poverty in rural areas.

9.2.4 Private Sustainability Standards

Thus far, the EU RED has recognized several voluntary schemes to verify sustainability criteria [93], including the International Sustainability and Carbon Certification (ISCC), Bonsucro EU, the Roundtable on Responsible Soy (RTRS) EU, the Roundtable for Sustainable Biofuels (RSB) EU RED, Biomass Biofuels voluntary scheme (2BSvs), Abengoa RED Bioenergy Sustainability Assurance (RBSA), Greenergy Brazilian Bioethanol verification program, ENSUS, Red Tractor, SQC, Red Cert, and NTA 8000 [94]. US-based stakeholders similarly have come together to form the Council for Sustainable Biomass Production (CSBP) and have issued a final standard and guidance in anticipation of verification requirements in the United States [95]. Standards share common principles of soil, water, and air pollution avoidance, biodiversity protection, GHG accounting, legality, and social (e.g., labor, land rights, food security) considerations.

Although neither the federal or state governments in the United States require sustainability certification at this time for transportation fuels or electricity, in 2013, California’s ARB will begin benchmarking its draft principles and criteria for its

LCFS to California and federal laws that already apply to agriculture in order to determine synergies and gaps, and in an effort to ensure that its sustainability provisions are as implementable as possible for farmers [34]. It will benchmark these results to the CSBP and RSB standards to determine also the standards' feasibility for farmers and the efficacy of third-party verification at the federal level. Third-party sustainability certification also could assist obligated parties in meeting EPA Quality Assurance Requirements.

9.3 International Standards and Harmonization

Without some level of public-level, international harmonization of sustainability standards, international trade could come to a standstill. The stage is being set. The American Soybean Association (ASA) formally complained to the Office of the US Trade Representative and USDA in early 2011 regarding the EU's application of its GHG calculations to disqualify soy biodiesel as a renewable source under the RED [96]. Argentina similarly is seeking consultation with in the WTO regarding what it sees as arbitrary, trade-distorting GHG thresholds [97]. Developing countries warned the EU in the early stages of RED development that if it implemented "unjustifiably complex" a third-party certification program, they might pursue a complaint under world trade agreements [98]. Some assert that only a binding international minimum standard can truly ensure all market players achieve a level of sustainability [99]. The notion ignores symptoms of the world's broader failures to reach consensus on how to address climate change, fair and equitable agricultural trade, and labor standards that protect vulnerable people against exploitation [100]. Parties to any harmonization of biofuels sustainability standards would have to agree on how to account for direct and indirect GHG emissions, and as post-Kyoto negotiations on carbon accounting demonstrate, this is highly unlikely, even as GHG emissions dangerously escalate even beyond previous estimates [101]. As for the "other" aspects of biofuels sustainability, such as soil, water, and biodiversity protection, the Marrakesh agricultural trade negotiations prove the difficulties in reaching consensus. They have yielded nothing, for example, in response to Brazil's request that biofuels be classified as an "environmental" good versus an agricultural good [102].

Regardless, any signatory to the World Trade Organization Agreement on Technical Barriers to Trade (TBT) treaty must give positive consideration to the exporting country's technical regulations in conducting conformity assessments, but where an international standard exists, such as the ISO standard being developed, this must be applied [103]. When the ISO process is complete for sustainability criteria for bioenergy [104], a country will be required under the TBT to apply ISO methodology for ILUC and food security calculations, if they are indeed included [103].

Perhaps in a somewhat duplicative way, the G8 countries "+5" (Brazil, India, China, Mexico, and South Africa) formed the Global Bioenergy Partnership (GBEP) in 2005 through The Gleneagles Plan of Action to increase the world supply of biofuels and biomass [105]. While fruitful in fostering dialogue, the GBEPs progress toward building biofuels sustainability standards, and its ultimate effectiveness, should not be exaggerated. Its framework to guide country-specific regulation consists of indicators that are vague and noncommittal, which reflects carry-over of these more general failures to agree internationally on GHG or agricultural sustainability metrics [106]. Its GHG accounting framework expressly refuses to promote or endorse "one methodology or approach over another" with regard to LCA "due to differences in national circumstances or legitimate differences of opinion regarding what should be included in LCA" [107]. This begs the question of how to resolve those differences when international trade occurs. While its social indicators emphasize food security through "assessment" and "allocation" of land resources, the GBEP has not explained how countries such as the United States, with well-developed private property rights regimes, would "allocate" lands for food and energy biomass production. Again, although the GBEP food security indicator may be intended only to apply in underdeveloped countries with food insecurity problems, arguably developed countries should be under the same requirement as major actors in a fully globalized market economy for food commodities.

Although science is increasingly recognizing that the most effective solutions to sustainability involve outcomes at the system level, the GBEP relies on actions within and between jurisdictional boundaries that typically do not coincide with ecological or social systems. Countries are only beginning to recognize that their regulation and other policies should take into account the complex interactions that occur environmentally within ecosystems or "sheds." The US EPA's recent efforts to reduce agricultural pollution loading in the Chesapeake Bay demonstrate aptly the challenges that countries face in tackling agriculture's environmental problems from a systems perspective. EPA has relied on modeling to establish maximum pollution loading for each state, but it has proved no panacea, however, as plaintiffs are now challenging in court the agency's use of modeled results that they argue are too uncertain and thus are unlawfully arbitrary in application [108]. If the United States lacks the scientific and legal infrastructure to design system-level solutions to sustainability, the GBEP must consider how producers in less-developed countries could comply with standards that seek system-level outcomes. The GBEP has great potential to serve as a global research network to test sustainability principles across ecoregions and to disseminate knowledge gained.

Even if scientific capabilities were in place, countries may not yet fundamentally share a common "web of norms" to form the foundation for agreement on biofuels' place within a sustainable system [109]. Although the GBEP involves the participation of over 45 countries and 24 international organizations and institutions constituting "the majority of bioenergy produced in the world," [110] developing countries have accused similar international processes as excluding their viewpoints [111]. While networks of association are important in coordinating globalized economies [112], "the legitimacy of decision making becomes more strained as the sense of community thins and the distance between those exercising authority and the public grows" [113]. The GBEP must be very careful, therefore, to observe tenets of legitimacy in standard settings, such as transparency, notice and comment, and stakeholder inclusion.

Another step toward public international harmonization of sustainability standards has been the success achieved by the United Nation's collaborative program for the Reduction of Emissions from Deforestation and Degradation (REDD+). For example, REDD+ may provide one "way out" of calculating ILUC—arguably the controversial aspect of biofuels' carbon accounting. That is, if REDD+ is successful in directly curtailing deforestation, then either ILUC would not have to be calculated at all or future emissions in ILUC models could be adjusted based on a predicted effect of REDD+ programs on deforestation. The UN REDD+ Programme has issued a guiding framework of environmental and social principles [114], but it remains to be seen whether REDD generally will receive enough support from the developing world to be effective.

Lastly, in anticipation of European requirements that the US aviation sector participate in its Emissions Trading System (ETS), the aviation sector has formed groups to discuss sustainability metrics for biomass-based aviation fuels such as the Sustainable Aviation Fuels Users Group [115] and the Midwestern Aviation Sustainable Biofuels Initiative (MASBI) [116]. The discussions mirror those that have occurred with private sustainability standards groups, with the exception that aviation is focusing on feedstocks that can be made into aviation fuels. The EU announced in November 2012 that it was suspending the requirement for 1 year, while the UN International Civil Aviation Organization attempts to develop a "global market-based measure" and a "policy framework to guide general application" of the measures to the aviation sector [117].

9.4 Food Security: The Biggest Policy Challenge Ahead for Biomass-Based Energy

The nascent biomass-to-bioenergy sector faces formidable challenges to its successful adoption as part of a balanced energy portfolio. Arguably, the greatest obstacle to second-generation transportation fuels is technology development to overcome cellulosic materials' recalcitrance to the degradation required to make ethanol [118]. EPA is trying to force accelerated technology development by refusing to waive RFS mandates despite claims that the program is causing food price inflation [119]. Despite these efforts, one of the potentially largest market players recently announced it would withdraw for the most part from developing cellulosic fuels in the United States [120].

Arguably the second greatest challenge for cellulosic biofuels, whether blended as ethanol or "dropped in" [121] as diesel, undeniably is how the sector will answer accusations that its indirect effects stemming from land-use changes for bioenergy crops create food insecurity and copious GHG emissions. One solution put forth in policy discussions has been movement of bioenergy cropping to marginal, idle, degraded, and abandoned (MIDA) lands. Because bioenergy statutes have fallen short of providing concrete definitions, the RSB has attempted to fill in gaps by developing (but not finalizing) an "indirect impacts" module in anticipation of EU measures to combat food insecurity and ILUC-induced GHG emissions [122].

The GBEP, too, has developed international guidance for land management to avoid competition between food and energy biomass cropping. Its indicators include assessment of several potential LUC impacts, including the extension of agriculture onto currently unused land [123]. Significantly, the GBEP recommends countries consider environmental, social, and economic impacts when evaluating land uses (including how to exploit unused lands such as degraded or contaminated land), and the particular benefit when this is done as part of a national assessment on the suitability of land for biomass cropping such as that conducted by the Brazilian ZAE-CANA [123]. The GBEP recognizes that such an assessment is most effective when coupled with a comparison to the land-use effects of other energy options such as coal and oil [123].

Assuming this policy course, significant obstacles remain to implementation. Preference for MIDA lands cropping in policy discussions to address the food and GHG dilemmas has not transformed into definitions in bioenergy statutes. One likely reason is that MIDA lands definitions are difficult to design. Economic models do use defined marginal land assumptions to determine carbon footprinting, but “economic marginality” for purposes of modeling does not translate easily into enforceable legal land definitions and ignores other environmental and social characteristics of marginal lands. Some methods do exist for balancing environmental and socioeconomic characteristics of land within countries’ subsidy and taxation policies, but questions remain regarding both their methods of measuring the complexity of interactions and the absence of biomass-to-bioenergy cropping systems in factor analysis. This is particularly acute when ecosystems span various landscapes and where ecosystem services must be accurately assessed and valued. These methods, too, lack tools for farmers to make valid marginality or degraded assessments.

9.5 Summary

Few have questioned whether it is reasonable for policymakers to expect bioenergy statutes to shoulder balancing of food, energy, and environmental needs that are mediated through an international market system. As demonstrated in this chapter, bioenergy policies, to varying degrees, incorporate concrete sustainability expectations for biomass feedstocks. In the United States, California’s LCFS is the furthest along in developing environmental and social metrics. Federal procurement in the near feature likely, too, will apply sustainability metrics to biobased fuels and products. Sustainability regimes have not been applied on a widespread basis to agricultural landscapes in the United States, however; thus, challenges lie ahead in developing tools and practices for farmers to deploy. The decisions made in this regard will most certainly impact all the feedstock production tasks previously discussed in this book and may make one or the other approaches described here more or less sustainable. While sustainability has been much more of a focus in forests, the prospect of increased demand for forest biomass for energy because of various government mandates most certainly will be much more highly controversial because of the ecosystem values inherent in forests. The EU has had sustainability requirements for fuels in place since 2010, and several private standards have emerged in response. In response to the "food versus fuel" argument that has predominated biofuels sustainability policy debates, the EU in late 2012 proposed limiting food-based feedstocks to 5 % of the mandate, decreasing to zero by 2020 [124]. Cellulosics also receive preference through double counting toward the mandate, although the EU has not added any additional land-based preferences beyond GHG bonuses for cropping on highly contaminated and degraded lands.

While the effort to develop sustainability metrics for biomass-to-bioenergy applications will continue to go forward—particularly in sectors like defense and aviation that cannot rely on electrification or natural gas—focus will increasingly be on technology advancements for economically feasible "drop-in" fuels. Concurrently, advancements continue to be made in the ability to assess, both in the field and through models, the environmental, social, and economic effects of biofuels. In the interim, policies must innovate to incorporate as many ways possible for biomass producers to feasibly reach sustainability expectations.

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Index

Y. Shastri et al. (eds.), *Engineering and Science of Biomass Feedstock Production and Provision*, DOI 10.1007/978-1-4899-8014-4,