INTEGRATED SUSTAINABILITY ASSESSMENT FOR BIOENERGY SYSTEMS THAT PREDICTS ENVIRONMENTAL, ECONOMIC, AND SOCIAL IMPACTS

by

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ABSTRACT

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In the U.S., bioenergy accounts for about 50% of the total renewable energy that is generated. Every stage in the life cycle of using bioenergy (e.g., growing biomass, harvesting biomass, transporting biomass, and converting to fuels or materials) has consequences in terms of the three dimensions of sustainability: economy, environment, and society. An integrated sustainability model (ISM) using system dynamics is developed for a bioenergy system to understand how changes in a bioenergy system influence environmental measures, economic development, and social impacts.

Biomass may be used as a source of energy in a variety of ways. The U.S. corn ethanol system forest residue system for electricity generation, and cellulosic ethanol system have been investigated. Predictions, such as greenhouse gas (GHG) savings, soil carbon sequestration, monetary gain, employment, and social cost of carbon are made for a given temporal scale. For the corn ethanol system, the annual tax revenue created by the ethanol industry can offer a significant benefit to society. For the forest residue system for electricity generation, different policy scenarios varying the bioenergy share of the total electricity generation were identified and examined via the ISM. The results of the scenario analysis indicate that an increase in the bioenergy contribution toward meeting the total electricity demand will stimulate the bioenergy market for electricity generation. For the cellulosic ethanol system, the compliance of cellulosic ethanol can be achieved under the advanced bioconversion technologies and the expansion of energy crops. However, nitrate leaching and biodiversity change should be considered when expanding energy crops on marginal land, pasture, and cropland. Moreover, three bioenergy systems reduce GHG emissions significantly, relative to fossil fuel sources that are displaced, and create economic benefits (e.g., GDP and employment). Additionally, a spatial agent-based

modeling is developed to understand farmers' behaviors of energy crop adoption and the viability of cellulosic biofuel commercialization.

CHAPTER 1. INTRODUCTION

1.1 Global Bioenergy Development

Recently, there has been increased interest in more sustainable resource management and the use of renewable energy sources. Biomass has been identified as a carbon-neutral alternative energy source for heating, electricity, and transportation fuel, which can help reduce greenhouse gas (GHG) emissions. The growing interest in bioenergy is also driven by the fact that it can help restore unproductive and degraded lands, while increasing biodiversity, soil fertility and water retention [1].

Bioenergy is mainly used for three energy uses: heating, electricity, and transport. Smeets et al. [2] estimated the global potential of bioenergy production from agricultural and forestry residues and wastes as 76–96 EJ/year, and the total technical potential for biomass could be as high as 1500 EJ/year by 2050. According to the International Energy Agency (IEA) statistics [3], 10% of the global energy demand is provided by bioenergy and 3% of the global road transport fuel is provided by biofuels. Figure 1.1 shows the global ethanol production from 2007 to 2015 and indicates that the United States has the largest annual ethanol production in the world. Global biofuel production has grown from 16 billion liters in 2000 to more than 133 billion liters in 2015. Bio-power capacity increased by an estimated 5% in 2015, to 106.4 GW, and generation rose by 8% to 464 TWh (1.67×10^{11} MJ) (see Figure 1.2). In the globe, bioenergy industry provided the largest numbers of employment (2,882,000 jobs) including indirect and direct jobs compared to the other renewable energy sectors in 2015 [4]. Challenges to bioenergy deployment include low fossil fuel prices and rapidly falling energy prices of some other renewable energy sources, especially wind and solar PV. Ongoing debate about the sustainability of bioenergy, including indirect land-use change and carbon balance, has also affected development in the sector.

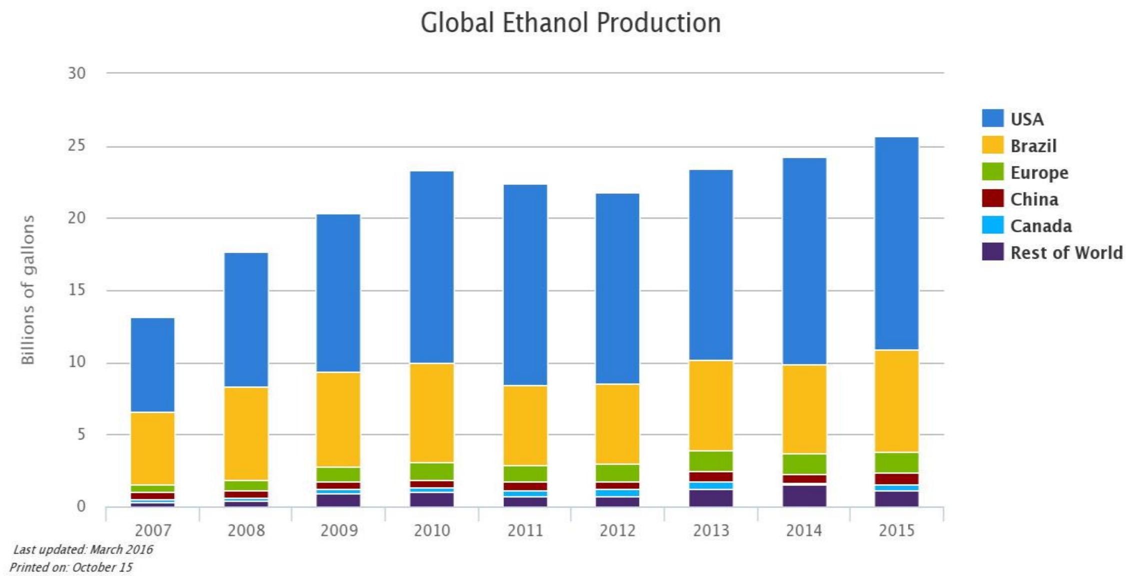

Figure 1.1. Global ethanol production [5]

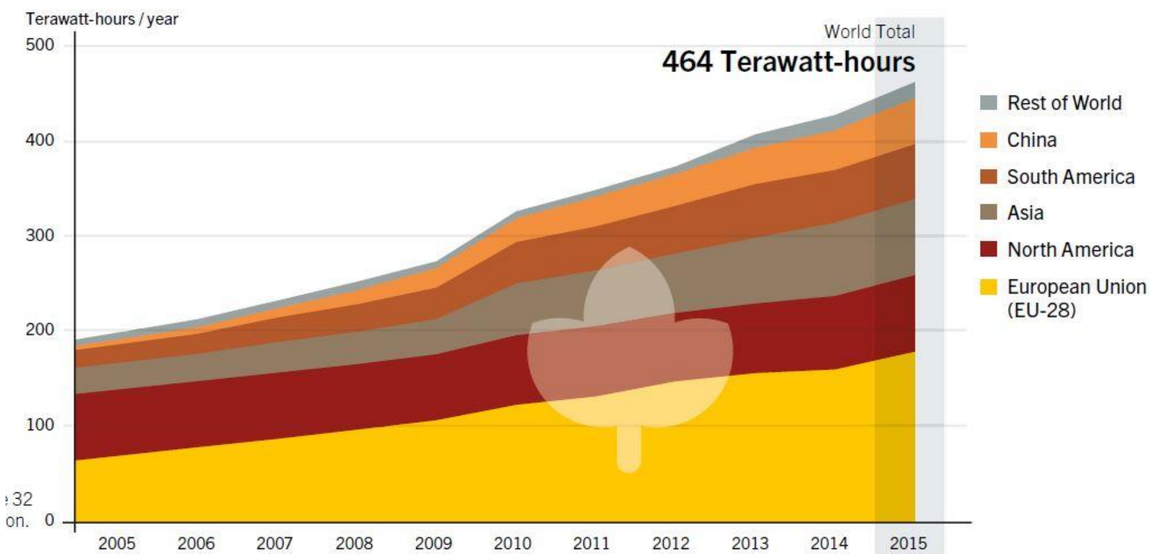

Figure 1.2. Global bio-power generation [4]

1.2 Current Bioenergy Development Status in the United States

The U.S. Department of Energy reports that nearly 10% of energy consumption in the U.S. is derived from renewable energy sources and in 2014, biomass accounted for 50% of the renewable energy portfolio [6]. It also concludes that the total projected consumption of biomass feedstocks may be roughly 330 million dry tons per year by 2030, a 54% increase over today [7]. The main reason for more biomass feedstock use is the increasing demand associated with biofuel production. The Renewables 2016 Global Status Report points out that the United States ranked first in biodiesel production, fuel ethanol production, and bio-power generation in 2015 [4].

1.2.1 *Biomass resources*

Biomass can be derived from forest, agriculture, and municipal waste. The biomass sources could be woody biomass, agricultural crops and wastes, municipal solid wastes, food wastes, and aquatic plants. Fuelwood (e.g., poplar, willow, and eucalyptus) and waste wood from the forest products industry (e.g., logging residue, bark, sawdust, and board ends) are widely used for heating, electricity, and biofuels production. Agricultural crops (e.g., corn, soybean, and sugar cane) and residues (e.g., corn stover, cotton stalks and wheat straw) are usually used as feedstocks for bioethanol and biodiesel production. In 2012, more than 42% of corn production was used as a feedstock for ethanol production. In 2013, 54% of biodiesel was produced from soybeans [8]. The 2011 U.S. Billion-Ton Update reported by the U.S. Department of Energy concluded that the available amount of logging residues for bioenergy will be 47 million dry tonnes per year at a roadside price of $40 per dry tonne [7].

1.2.2 *Biofuels*

The most common biomass-based energy is from liquid transportation fuels, which includes bioethanol and biodiesel. The U.S. Energy Independence and Security Act of 2007 expanded the mandated use of biofuels based on the first Renewable Fuel Standard (RFS) established by EPA that required the annual use of 9 billion gallons of biofuels in 2008, rising to 36 billion gallons in 2022 [9]. The RFS has capped the conventional ethanol production (corn starch ethanol) at 15 billion gallons per year starting at 2015 and enhance the development of cellulosic ethanol production in the future years (see Figure 1.3). In the United States, the share of biofuels was 4% for road transport fuel and in the European Union (EU) around 3% in 2008 [3]. The U.S. ethanol production has increased to 14,806 million gallons, which is equivalent to 10.5 times of the ethanol production in 1998 (see Figure 1.4). The annual ethanol consumption was tied up with the production. Compared to the ethanol production, the biodiesel production has a smaller market. The annual biodiesel production and consumption in 2015 were 1,556 million gallons (5.89 billion liters) and 2,060 million gallons (7.8 billion liters), respectively (see Figure 1.5). The use of food crops for biofuels on a large scale is controversial due to the impacts on food and energy security. Therefore, cellulosic biomass has been found to be the most promising feedstock for producing biofuels due to its availability, low cost, and the absence of competition with food production.

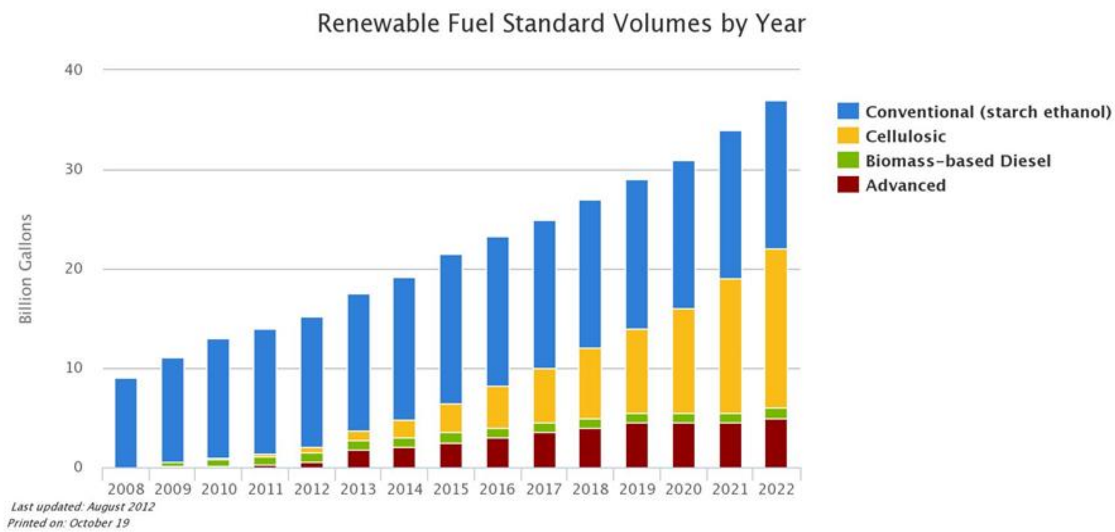

Figure 1.3. Renewable fuel standard volumes by Year [10]

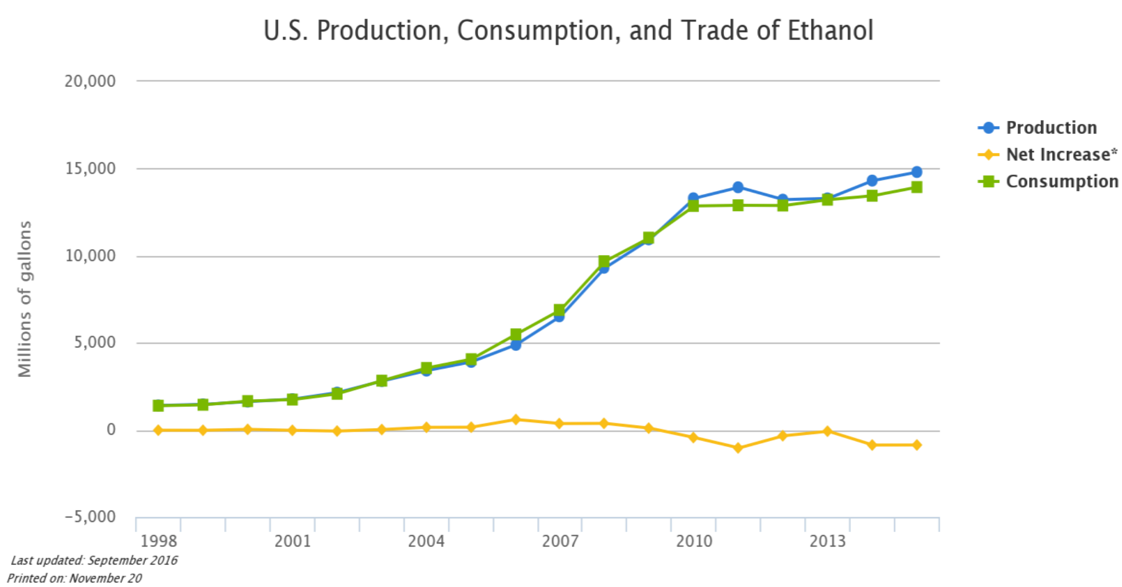

Figure 1.4. U.S. ethanol production and consumption [10]

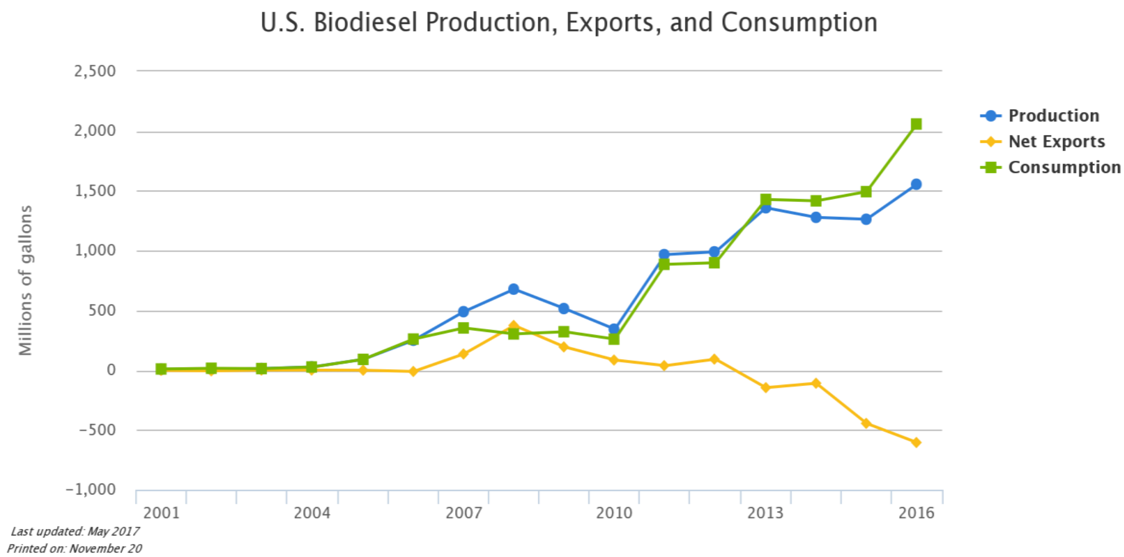

Figure 1.5. U.S. biodiesel production and consumption [10]

1.2.3 *Heat and bio-power*

Heat and electric power generation (bio-electricity) from biomass accounted for 7% of $38 billion invested in new renewable energy capacity worldwide in 2005 (excluding large hydro). A bio-electricity production chain starts with cultivation of the biomass fuel or its collection as residues or waste products from other operations [1]. Fuel storage, transport and pre-treatment are usually significant logistical and cost components of bio-electricity production.

Biomass co-firing is an attractive option of converting biomass into power and heat. According to the U.S. Energy Information Administration (EIA) [11], biomass and biomass-derived gases produced nearly 1,400 billion MJ, and provided nearly 226 billion MJ of electricity across all sectors. Types of biomass fuel and associated logistics can significantly affect the performance of biomass co-firing. According to Galik et al. [12], forest biomass including marketable and non-marketable wood, is a potential source of biomass supply for electricity generation. Moreover, woody biomass such as forest residues is favorable for co-firing with coal owing to its low ash, sulfur and nitrogen content [13]. In both North American and Europe, many power plants have successfully used woody biomass in co-firing applications with coal [14] . In 2015, US bio-power capacity in operation increased by 4% to 16.7 GW and bio-power generation was close to the 2014 level of 69.3 TWh (2.5×10^{11} MJ) [4]. However, some existing bio-power in the United States is not financially competitive with low-cost generation from natural gas and with generation from other lower-cost renewables.

1.2.4 *Sustainability of bioenergy development*

The sustainability of a bioenergy system is evaluated by three dimensions: environment, economy, and society. For example, one environmental advantage of using forest biomass for electricity generation is that it can enhance the soil carbon sink process when agricultural land is converted to forest land (afforestation). Post and Kwon [15] observed that the average accumulation rates of soil carbon were 33.8 g C m^{-2} yr^{-1} and 33.2 g C m^{-2} yr^{-1} in re-established forest land and grassland after agricultural use, respectively. Afforestation of former cropland was reported to increase total soil carbon stocks by 18% [16]. Moreover, substitution of forest biomass for coal contributes to the reduction of the greenhouse gas (GHG) emissions in the co-firing system. The U.S. Forest Service also indicated that co-firing biomass with coal is the best short-term strategy for reducing GHG emissions in the electric power sector [17] . For example, Loeffler and Anderson [18] estimated that a co-firing system at a 20% displacement rate (20% of the coal is replaced with biomass), could decrease CO_2 emissions by 15%, CH_4 emissions by 95%, NO_x emissions by 18%, and SO_x emissions by 27% in southwest Colorado. Corn ethanol produced by a natural gas biorefinery can have a 38.9% reduction of GHG emissions relative to gasoline production and the reduction in GHG emissions could vary from 39.6–57.7% by integrating biomass to produce heat [19].

Some negative environmental impacts of bioenergy development have been examined as well, broadly considering such issues as water, soil, and biodiversity. The land-use change from forestry to agriculture can lead to a decrease in soil carbon stock, and harvesting whole trees (including branches and residues) can reduce soil nutrients. Water availability is a possible constraint for large-scale biomass cultivation in several countries facing water scarcity. Moreover, monocultures should be avoided to prevent pests and disease spreading into surrounding areas.

Use of bioenergy is increasingly viewed as an opportunity, not only to enhance energy security and provide environmental benefits, but also to accelerate economic development, particularly in rural areas [20]. Socio-economic aspects of bioenergy systems have also been discussed as drivers for bioenergy development [21]. For example, potential economic impacts of forest biomass production have been analyzed in terms of regional job growth and economic development. Solomon [20] found that existing biofuels industries have been a major contributor to rural economies and small farmers in several countries. Neuwahl et al. [22] also explored the employment impacts of biofuels development in the context of the Renewable Energy Roadmap for the European Union market and found that the biofuel industry has a positive impact on employment. Timmons et al. [23] estimated a total annual revenue of $57 million and 440 jobs created through the operation of biomass co-firing energy facilities with a total energy generating capacity of 165 MW in Massachusetts over a five-year period. English et al. [24] ascertained that the total economic impact of co-firing bio-residues for electricity generation would be more than $7 million per year, and nearly 100 additional jobs would be created based on a demand of 0.51 million tonnes of mixed biomass residues for producing 2,478 kWh (8920.8 MJ) electricity in the Southeastern United States. Perez-Verdin et al. [25] used an economic input-output model to estimate economic impacts of logging residues recovery and bio-power operation of a 100MW power plant in Mississippi, and the authors concluded that the bio-power industry could generate total gross output of $386 million and 2,343 jobs annually.

On the other hand, there may be socio-economic concerns associated with bioenergy development, e.g., competition with food production, land ownership changes, low wages, and child labor [26]. Very often, a bioenergy system can be beneficial to the environment, economy and society if sustainably managed. Considering these potential sustainability issues, a proposal for a sustainable bioenergy policy in the EU sets up several criterion for ensuring the bioenergy sustainability: 1) limit the amount of bioenergy use; 2) Avoid producing bioenergy from high risk sources of biomass; 3) Protect soil, water and biodiversity during harvesting biomass; 4) Respect rights to land tenure, food security and human and labor rights; 5) Cause no displacement of other use of biomass; 6) Produce bioenergy in the most efficient applications [27].

To better understand the potential consequences of establishing bioenergy system, it is necessary to adopt an integrative perspective that considers all three sustainability dimensions. This proposal presents an integrated sustainability model (ISM) for a bioenergy system that aims to predict its comprehensive performance. The objective of the ISM is to understand whether the use of bioenergy improves the environmental, economic and societal dimensions of sustainability through metrics such as CO_2 emissions, soil carbon sequestration, monetary gain (gross output and value-added), and employment. These metrics are used to determine if the current markets for, and implementations of, bioenergy are favorable for the sustainability of the local environment, economy, and society. System dynamics will be used to provide causal linkages between variables associated with the bioenergy system established that addresses the environmental and socio-economic impacts.

In order to promote the development of bioenergy, it is desired to have an understanding of the sustainability of a bioenergy system across all three dimensions of sustainability: environment, economy, and society. Chapter 2 will discuss the state of the art in sustainability assessment for bioenergy systems and identify the knowledge gap of the integrated sustainability assessment for bioenergy development in the literature. The existing approaches for sustainability assessment of a bioenergy system often do not consider all three dimensions. Moreover, existing approaches do not adequately address future behavior of metrics associated with the three sustainability dimensions. Given the goal of this research, and the gaps in the research literature, the following research objectives are proposed:

1. Create an integrated sustainability model framework that incorporates knowledge of environment, economy, and society relating to bioenergy systems.
2. Develop sub-models that can evaluate the environmental, economic, and social impacts generated by a bioenergy system.
3. Predict the sustainability performance of bioenergy systems by quantifying key indicators, such as GHG emissions, biodiversity, money gain, employment, etc.
4. Provide useful insights to develop bioenergy production more sustainably.

In addition, this study will employ the approach of agent-based modeling to understand how the decisions of farmers and biorefinery investors on the expansion of new energy crops affect the commercialization of cellulosic biofuels. The implementation of agent-based modeling can explore the effect of social interactions between individual agents on their decision making processes and provide useful insights for the sustainable development of bioenergy from a more practical perspective.

CHAPTER 2. LITERATURE REVIEW

A bioenergy system is a complex system of interactions between the environment, the economy, and society. It is essential to understand how changes in key variables affect the environmental, economic, and social behaviors of the system. In this literature review, key factors such as biomass feedstock, biorefinery technologies, and bioenergy policy are examined in order to identify the structure of a bioenergy system. All these variables play a substantial role in the sustainability performance of the system. This chapter also discusses some key environmental and socio-economic issues associated with bioenergy development. The state of the art in the sustainability assessment of bioenergy systems is discussed and the gaps between the current analysis methodologies and the integrated sustainability model are identified in this study.

2.1 Key Factors Affecting Bioenergy Development

The most effective ways to accelerate the commercialization of bioenergy production are to i) improve the efficiency of biorefinery technologies and ii) reduce the bioenergy production cost. Kim and Kim [28] concluded that technical challenges in bioconversion were one of barriers in the advanced biofuels industry. The technical challenges exist in various processes regarding different conversion technologies. For example, the pretreatment of lignocellulosic biomass is one of the key elements in the bioconversion for ethanol. Purification of the output gases from the gasification is the major step to improve the yield of biogas. A recent study indicated that the various bioenergy pathways using different biomass feedstocks can result in huge ranges of GHG emissions of heat generation in the U.K. [29]. The bioenergy production cost can briefly break down into feedstock cost (36-38%) and bioconversion cost (62-64%) [30]. Therefore, choosing the optimal feedstock and biorefinery technology are the key ways to reduce the bioenergy production cost. Moreover, bioenergy policy plays a key role in the implementation of bioenergy in transportation and electric power sectors.

2.1.1 *Biomass feedstock type*

Raw materials that can be used to produce bioenergy are widely available in the U.S. and come from a large number of different sources, and in a wide variety of forms. These include food crops, energy crops, herbaceous plants/grasses and woody plants, and residues from timber processing, agriculture or forestry. The supply of these biomass resources mainly comes from traditional plantation, natural forests, forest plantation, home gardens, and other agricultural lands [31]. In addition, oil-rich algae, animal wastes and the organic component of municipal and industrial wastes account for important biomass resources [31]. A general classification of biomass according to the origin is presented in Table 2.1. According to the Billion-Ton Update released by the U.S. Department of Energy, logging thinnings, logging residues, and pulpwood are considered primary woody sources for biofuels and corn stover is the largest fraction of collectible agricultural residue [32].

Table 2.1. General classification of biomass according to the origin [31]

Biomass category	Biomass varieties
Woody biomass	Soft or hard; Stems, branches, foliage, bark, chips, lumps, pellets, briquettes, sawdust, sawmill and others from various wood species
Energy crops	Annual or perennial grasses and flowers (alfalfa, arundo, bamboo, bana, brassica, sugar cane, miscanthus, switchgrass, timothy, etc.)
Agricultural residues	Straws (barley, rice, wheat, sunflower, oat, rape, rye, bean, etc.) Other residues (fruits, shells, husks, hulls, pits, grains, seeds, coir, stalks, cobs, kernels, bagasse, food, fodder, pulps, etc.)
Municipal solid waste	Putrescible/organic matter, glass, paper, plastic, textiles, metal, rubber, yard trimmings etc.

2.1.1.1 Wood and Wood Processing Residues

The use of wood for electricity generation and heat has grown rapidly in recent years. Wood fuels consists of woody biomass, e.g., stems, branches, twigs, and sawdust and other residues from logging and wood processing activities (such as saw-milling, manufacturing of pulpwood and particle board), as well as charcoal from these sources [31]. The primary sources of wood fuels are derived from forest land including natural forests, scrub lands, wood and timber plantations, woodlots and dedicated fuel wood plantations. Non-forest land including agricultural land, agro-forestry systems, and wasteland can also produce woody biomass. In the Midwest United States, the woody biomass production from forests and short rotation woody crops was estimated to be 19.9-47.6 million tonnes per year [33]. Primary forest residue biomass consists of a composite estimate from two sources—removal of a portion of what is called logging residue that is currently generated during the harvesting of timberlands for sawlogs and pulpwood and removal of excess biomass from fuel treatment thinning operations [34]. The wood processing residues are considered as the secondary forest residues including bark, coarse and shavings. The secondary forest residues are mainly used for heat and power in the forest products industry.

2.1.1.2 Energy Crops

Energy crops are grown specifically for the use as fuel. Classes of energy crops include short rotation energy crops (e.g., willow, eucalyptus, poplar, and pine), grasses and non-woody energy crops, agricultural energy crops and aquatic biomass. The first generation biofuel feedstocks are some food crops containing starch and sugar, such as corn, sugar cane, and soybean. The second generation biofuel feedstocks mainly refer to the lignocellulosic feedstocks such as perennial grass and forest residues. The main disadvantage of first generation biofuels is the food-versus-fuel debate, one of the reasons for rising food prices is due to the increase in the production of these fuels [35]. The second generation energy crops can be planted on the marginal lands while improving the ecosystem services, and help to minimize the competition between food and energy production. In general, the second generation energy crops require fewer herbicide and fertilizer inputs and produce larger quantities of biomass compared to the first generation [36]. For instance, the average yield of Napier grass has been reported to be over 100 dry tons/ha/yr. An assessment of 10 managed farms produced switchgrass yields between 5.2 and 11.1 t ha^{-1} sustainably on marginal cropland in the upper Midwest [36].

2.1.1.3 Agricultural Residues

Agricultural crop residues are abundant, diverse, and widely distributed across the United States. These potential biomass supplies can play an important role in a national biofuel commercialization strategy. Crop residues require no additional cultivation or dedicated land and are considered potentially available in the near term [37]. Crop residues briefly include residues from the production of corn stover, wheat straw, oat straw, barley straw, and sorghum stubble, etc. Some residues (e.g., corn stalks, rice straw, and sugar cane tops) are generated on the agricultural farm or field and others (e.g., rice husk and peanuts shell) are generated during processing of agricultural products. The field-based residues protect arable land against soil and water and wind erosion, nutrient loss, and provide soil organic carbon. Removals of agricultural residues for energy recovery is a promising way to manage the waste. However, determining harvestable amounts of crop residues without causing negative impacts on the soil resource and subsequent yields should be concerned [35].

2.1.1.4 Municipal Solid Waste

The utilization of municipal solid waste (MSW) for energy recovery is a promising alternative to traditional waste management. The majority of substances composing MSW include putrescible/organic matter, glass, paper, plastic, textiles, metal, rubber, yard trimmings, etc. The U.S. Environmental Protection Agency (EPA) has reported that over 33 million tonnes (12.8%) of the 258 million tonnes MSW generated in 2014 were combusted for energy recovery [38]. Waste to energy option is thus considered to be one of the most effective ways of final disposal. State-of-the-art MSW-to-energy (MSWTE) technologies including incineration, gasification, and anaerobic digestion can convert MSW into heat, electricity, and biofuels. The major barriers of waste to energy option are the feasibility of the waste collection, scavenging and waste disposal practices in that city and by the composition of residential wastes.

2.1.2 *Bioconversion technologies*

There are a number of different technologies for converting biomass into heat, power, and fuels with specific pros and cons. Different biorefinery technologies can achieve different conversion efficiencies, costs and commercial scales with suitable biomass feedstock. The most common biorefinery technologies includes combustion, pyrolysis, gasification, torrefaction, and fermentation. The bioconversion technologies are summarized in Figure 2.1.

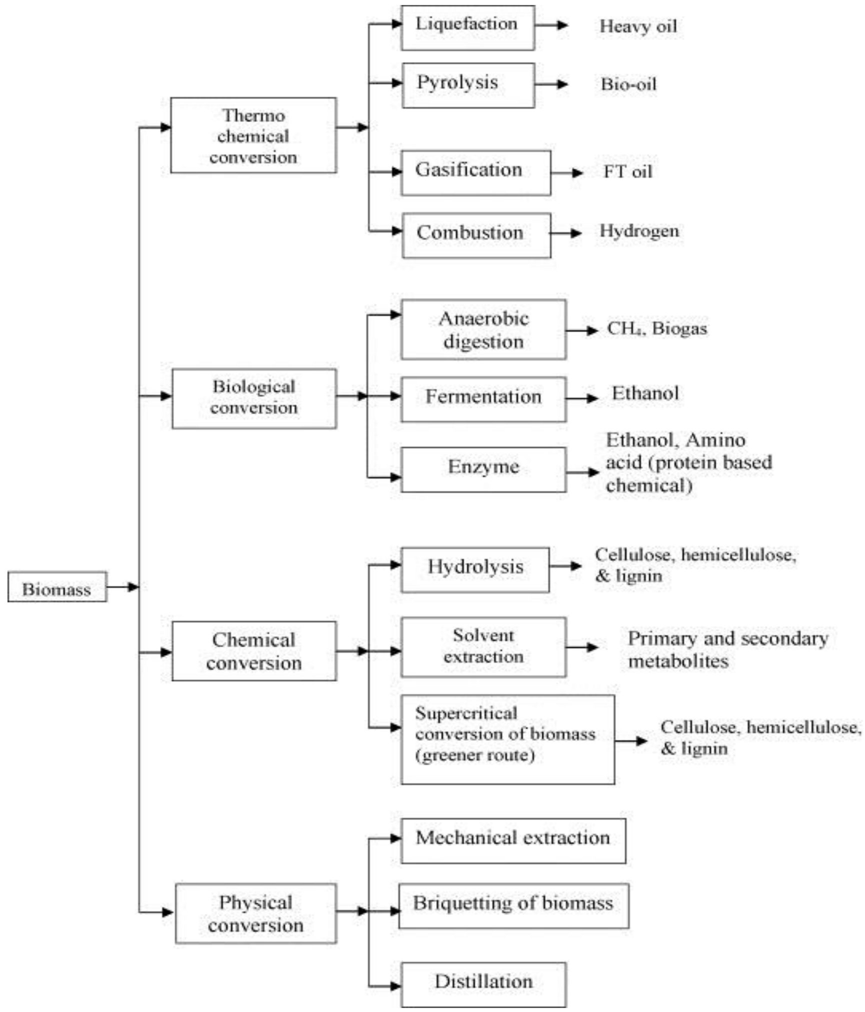

Figure 2.1. Biomass conversion processes [35]

2.1.2.1 Combustion

Technologies of thermal conversion are commonly classified as combustion (direct combustion and co-combustion), gasification, pyrolysis, carbonization, etc. [39].

Biomass co-firing is co-firing the coal partially with biomass in the combustion process [39]. Co-firing can be applied in existing coal firing systems (e.g., pulverized coal firing systems and fluidized bed combustion systems) where the proportion of biomass is up to 20% of the total fuel weight or energy content [39]. Co-firing technologies used in coal-fired power plants can be classified with three different ways, which are shown as following [14]:

- Direct co-firing: Direct co-firing is the cheapest and the most common approach. Biomass and coal can be either milled separately or together before they are fed into the furnace. The fuel mixture is then burned in the burner. The direct co-firing rate can be in the range of 3%- 20% on a mass basis [14].

- Indirect co-firing: Biomass is gasified and the product gas is then fired together with either natural gas or gasified coal in the main boiler. In a gasifier, the solid biomass is converted into a fuel gas and burned in the coal boiler [39]. The product gas is called syngas which is rich in CO, CO_2, H_2, H_2O, N_2, CH_4, and some light hydrocarbons. Indirect co-firing technology allows biomass to be co-fired in an oil- or gas-fired system. Gases generated from indirect co-firing technology has higher operation cost due to gas cleaning process, while it offers more flexible ways to use the fuel [39].
- Parallel co-firing: In this co-firing approach, biomass is pre-processed, fed, and combusted separately in a dedicated biomass burner [14]. Parallel co-firing involves the installation of a separate external biomass-fired boiler in order to produce steam used to generate electricity in the power plant. This technology also offers lower operational risk and greater reliability due to the availability of separate and dedicated biomass burners running in parallel to the existing boiler unit. Parallel co-firing is very common in the pulp and paper industries as dedicated biomass boilers are used for the utilization of by-products like bark and waste wood [39].

Co-firing in large-scale power plants can lead to an overall saving of fuels compared to conventional coal-fired plants [39]. Comparing with coal, biomass is a less carbon-intensive energy with lower emissions of SO_2, NO_x, heavy metals. On the other hand, co-firing of coal and biomass has some shortcomings. For direct co-firing, depending on the type of biomass feedstock used, some challenges may be encountered when biomass is directly blended on the coal pile. Biomass feedstock with large particle size after milled and high ash concentration may cause plugging, slagging and fouling issues, and corrosion of the boiler heat transfer surfaces. For indirect co-firing, the biomass feedstock with high moisture content can consumes more energy to convert the biomass into syngas, and lead to higher vapor content. For parallel co-firing, it needs higher capital investment than direct co-firing due to the external biomass boiler system. In general, operating costs are typically higher for biomass than for coal [39].

2.1.2.2 Pyrolysis

Pyrolysis is a thermochemical decomposition of biomass in the absence of oxygen and produces a wide range of useful products [40]. The major products of biomass pyrolysis are charcoal, syngas and vapors/liquids (bio-oil). Depending on the operation conditions (e.g., temperature and vapors residence time), pyrolysis can be classified into three modes: slow, intermediate and fast pyrolysis (see Table 2.2).

Table 2.2. Typical operating conditions and product yields for biomass pyrolysis [40]

Pyrolysis mode	Temperature (°C)	Vapors residence time	Liquid yield (%wt)	Gas yield (%wt)	Char yield (%wt)
Fast	500	1-2 s	60-75	13-20	12-20
Intermediate	500	5-30 s	40-50	25	25-30
Slow	400	hours-days	25-30	25-35	30-40

Fast pyrolysis is the most promising process for the production of fuel oil for power generation, production of fuels, chemicals and polymers [40]. Bio-oil can be used for heat and power in boilers and gas turbines, and can be combined with diesel as a transport fuel. Char can be used as a heat supply for the pyrolysis process and also can be used as a fertilizer alone or mixed with soil providing recycling of valuable minerals to the soil. Moreover, char from biomass pyrolysis can be used for activated carbon production increasing the added value of the material [40]. The main challenge of biomass fast pyrolysis is to improve the quality of the bio-oil for fuel and chemical production and to reduce the overall cost through lower biomass cost and longer catalyst lifetime [41].

2.1.2.3 Gasification

Gasification, one of thermo-chemical conversion routes, is widely recognized at present because its end product gas can find flexible application by industries or by home users, particularly in decentralized energy production coupled with micro turbine/gas, turbine/engine, boiler, and even fuel cell [42]. The gasification of biomass is a thermal treatment, which results in a high production of gaseous products and small quantities of char and ash. At temperatures of approximately 875–1275 K, solid biomass undergoes thermal decomposition to form gas-phase products that typically include H_2, CO, CO_2, CH_4, and water. In most cases, solid char plus tars that would be liquids under ambient conditions are also formed [43]. The product distribution and gas composition depend on many factors including the gasification temperature and the reactor type. Gasification processes provide the opportunity to convert renewable biomass feedstocks into clean fuel gases or synthesis gases. The advantages of gasification to produce syngas includes low capital investment, low heating cost, and low equipment maintenance cost. It should note that producing bio-syngas from gasification the following procedures are necessary: (a) gasification of the fuel, (b) cleaning of the product gas, (c) usage of the synthesis gas to produce chemicals, and (d) usage of the synthesis gas as energy carrier in fuel cells [42].

2.1.2.4 Fermentation and Anaerobic Digestion Process

Biological conversion of biomass is completed through alcoholic fermentation to produce liquid fuels and anaerobic digestion or fermentation, resulting in biogas. Fermentation is a natural process initiated by microorganisms of the saccharomyces type, similar to common yeast cultures under anaerobic conditions [31]. The reaction in the fermentation process is basically that hexose/pentose sugars such as glucose, fructose and sucrose are converted into ethanol and carbon dioxide as metabolic waste products [31]. The raw materials used in the production of ethanol via fermentation are mainly classified into three types as sugars, starches, and cellulose materials [31]. Ethanol fermentation from carbohydrates is widely regarded as an important potential alternative source of liquid fuels for the transport sector. Production of ethanol is mainly depending on the rate of growth of microorganisms. Temperature, water amount, pH and nutrients are the key factors that can influence the microbial growth [31].

The whole process of biogas production from anaerobic digestion using organic wastes occurs in main three steps namely hydrolysis, acidification, and methane formation. Factors that influence the biogas production include substrate temperature, changes in temperature, available nutrient, retention time, pH value, nitrogen inhibition, C/N ratio, substrate solids content, and agitation [31]. Production technology from these sugar/starch containing crops is relatively mature and most likely will not be improved to decrease production costs. However, production cost from cellulosic materials can be lower that the production cost from sugar and starch materials.

2.1.3 *Bioenergy policy*

2.1.3.1 Green Electricity Policy

The renewable portfolio standard (RPS) is one of the most prevalent and innovative policy instruments for states to adopt to reduce future emissions in the electricity market. The United State Department of Energy defines an RPS as "a policy that obligates each retail seller of electricity to include in its resource portfolio a certain amount of electricity from renewable energy resources, such as wind, solar, geothermal, hydropower, and various forms of biomass and ocean energy" [44]. Under an RPS program, utilities are required to invest in renewable energy systems in order to meet their percentage requirement. In1998 only three states had adopted an RPS policy. By 2001, nine states (18%) had adopted an RPS and by May of 2017, 27 states (54%), plus the District of Columbia, had adopted RPS programs [45]. An additional 9 states (Alaska, North Dakota, South Dakota, Utah, Kansas, Oklahoma, Virginia, South Carolina, and Vermont) have set voluntary targets for the adoption of renewable energy instead of an RPS.

The majority of policy objectives aim to facilitate the diversity of electricity generation mixes, increase renewable energy deployment, reduce state reliance on fossil fuels, help renewable energy sources become cost-effectively on a large scale, reduce carbon emissions, or various environmental benefits [46]. Eligible technologies in most programs include wind, solar, landfill gas, and biomass, but hydropower also qualifies in several states [47].

There are various policy instruments to be implemented to promote renewable energy in the electric power sector. State and local policy instruments are categorized as financial incentives, rules and regulations, and voluntary measures [47]. Financial incentives include various subsidies and funding in direct support of green electricity projects, tax incentives (credits, deductions, or exemptions), and provisions for low-interest loans [47]. For example, state income tax can be deducted for customers to purchase the electricity from renewable energy systems. The sales taxes of renewable energy equipment such as solar photovoltaic, wind turbine can be exempted in some states. Some states provide research and development grants to support and facilitate commercialization of new renewable technologies [47].

The state rules and regulations (e.g., RPS) are widely used to promote electricity from renewable energy systems. Renewable electricity funds are from the collection of surcharges from electricity customers and these funds have been used to stimulate renewable technologies, especially effective in wind energy [48]. Although RPS programs had been adopted by many states the RPS can be met only through investments in new renewable sources. Five states (Iowa, Minnesota, Montana, New Mexico, and Washington) have recently adopted mandatory green power options that require electricity providers to offer customers the option to purchase electricity from renewable sources [47].

State voluntary measures include some market-based measures and educational programs for commercial and residential electricity customers. For example, green-pricing programs give utility customers the option to pay a premium on their electric bull to cover the incremental cost of producing electricity from renewable energy systems [47]. The tradeable renewable energy certificates give the holder contractual rights to the value of the non-electrical benefits of using a renewable energy resource, and can be priced and traded separately from the electricity [49]. Educational and outreach programs include renewable energy awareness campaigns, workshops, technical assistance, and demonstration projects [47]. The function of these program aims to remove market barriers to renewable energy use and improve local demand for electricity from renewable sources.

2.1.3.2 Biofuels Target

Renewable energy policy has played a key role in the development of the U.S. bioenergy industry. The Renewable Fuel Standard (RFS) was established to mandate minimum usage requirements of biofuels used in the national transportation fuel supply each year [9]. The initial RFS (referred to as RFS1) mandated that a minimum of 4 billion gallons biofuels be used in 2006, and that this minimum usage volume rose to 7.5 billion gallons (28 billion liters) by 2012 [9]. The expanded RFS (referred to as RFS2) established in the Energy Independence and Security Act of 2007 (EISA) required the annual use of 9 billion gallons (34 billion liters) of biofuels in 2008 and expanded the mandate to 36 billion gallons (136 billion liters) annually in 2022, of which no more than 15 billion gallons (57 billion liters) can be ethanol from corn starch, and no less than 16 billion must be from cellulosic biofuels [9].

The total renewable fuel requirement is divided into four nested categories (see Figure 2.2): total renewable fuels (136 billion liters), advanced biofuels 79.5 billion liters), biomass-based biodiesel (3.8 billion liters), and cellulosic and agricultural waste-based biofuel (60.6 billion liters). Figure 2.3 shows that the volume of corn-starch ethanol is capped at 15 billion gallons (57 billion liters) by 2015 and it is fixed thereafter. The RFS2 is likely to be a major driver in the development of the U.S. biofuels sector in a long term.

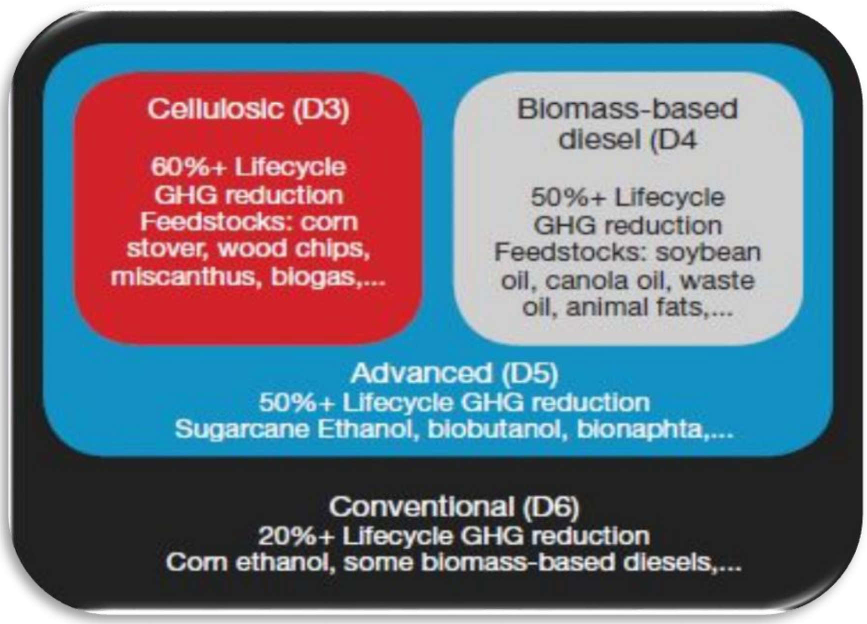

Figure 2.2. RFS fuel nesting scheme [50]

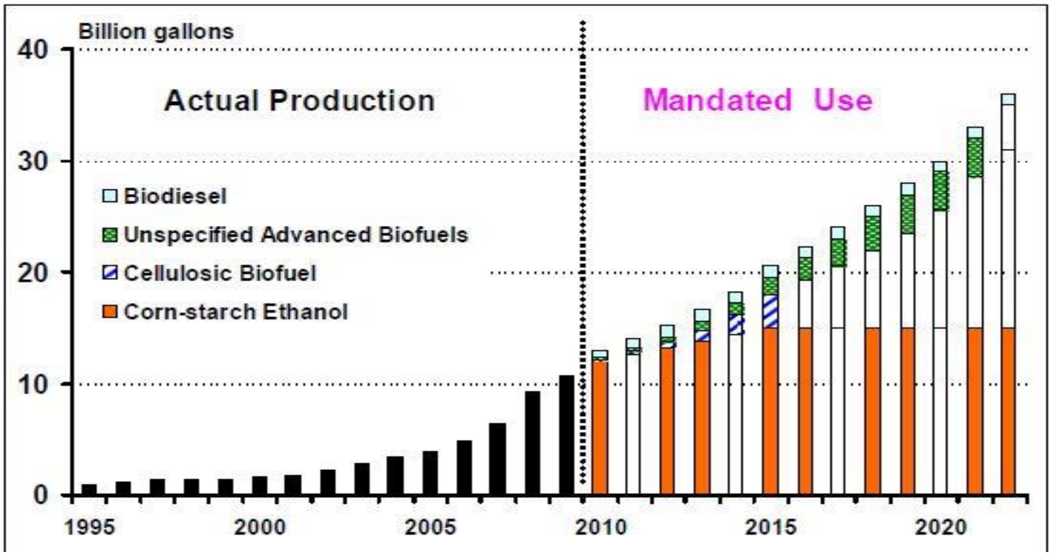

Figure 2.3. RFS2 vs. U.S. ethanol production since 1995 [9]

In addition to volume mandates, EISA specified that the lifecycle GHG emissions of a qualifying renewable fuel must be less than the lifecycle GHG emissions of the 2005 baseline average gasoline or diesel fuel that it replaces. Conventional biofuels (e.g., corn ethanol) must achieve a 20% reduction in life-cycle greenhouse gas (GHG) emissions, relative to petroleum fuels, on an energy-equivalent basis [50]. For an advanced biofuel, the fuel must achieve at least a 50% lifecycle GHG reduction—60% in case of cellulosic fuels—relative to the gasoline or diesel fuel that it replaces [50].

The RFS2 also contains protections to prevent land-use change and its associated greenhouse gas emissions. The RFS2 explicitly excludes from accounting for renewable credits of any feedstocks produced from land converted to cropland after 2007 [51]. To monitor this regulation, the U.S. Environmental Protection Agency (EPA) relies on nationally aggregated measures of total cropland from the Department of Agriculture's Farm Service Agency and National Agricultural Statistics Service [51]. However, it is not possible to identify the land sources being converted or types of cropland expanding because these data are not spatially explicit [51]. The implementation of RFS2 will ensure the demand for biofuels and accelerate the market penetration of biofuels in the transportation sector while achieving the goals of greenhouse gas mitigation and atmospheric pollution reduction.

2.2 Environmental Issues of Bioenergy Development

Biomass can have positive and negative impacts on soil, water, and biodiversity resources through direct and indirect land-use change. At the global scale, a common controversy is that if biofuel is good for slowing climate change via international indirect land-use change [52]. Melillo et al. [53] implied that the expanded use of bioenergy could lead to land conversion worldwide – from forest and grassland to cropland – that would lead to the release of carbon from indirect land-use. While global-level analyses have focused on broad climate impacts, other environmental and ecosystem impacts from developing bioenergy have been paid more attention. These impacts include soil erosion, nitrate and phosphorus loss, and air quality degradation, biodiversity loss, etc.

Water consumption for biofuel production is much higher than that for petroleum production on a life cycle scope due to the crop irrigation [54]. Expansion of biofuels on a large scale may cause water scarcity and groundwater salinization [55].

Intensive harvest in agricultural management has the potential to lead to soil degradation and nutrient depletion. For instance, the removal of large amounts of crop residues for co-firing may cause loss in soil nutrition and productivity. Chemical inputs (e.g., fertilizers and pesticides) can pollute the soils and lead to soil erosion [55]. On the other hand, planting suitable biomass on marginal and degraded lands can improve soil quality.

A loss of biodiversity can happen when a monoculture replaces a natural area. The magnitude of biodiversity loss depends on the type of land-use that is changed and the energy crop that is planted. For instance, converting tropical forest into cropland is more likely to cause a critical loss of biodiversity. Agroforestry and intercropping systems can mitigate biodiversity loss in a certain degree for small-scale plantations [55].

For assessing the sustainability of bioenergy development on the environmental perspective, other environmental impacts rather than GHG emissions should be incorporated associated with different bioenergy systems.

2.3 Socio-economic Issues of Bioenergy Development

Since food crops are used for biofuels, the food security is one of the social concerns with bioenergy development. The impact of biofuels on global food prices is highly variable. It depends on the feedstock used and whether agricultural land is diverted for production. With the growing use of agricultural commodities for bioenergy production, energy prices and feedstock prices are increasingly being linked [56]. The poor communities are more vulnerable to high prices of key commodities. In developing countries, urban and rural landless households, wage-earning households, rural households that are net purchasers of food, and urban consumers suffer most from high food prices [56]. Food security may be compromised if high-quality agricultural lands are used for energy crops, and planting energy crop on the marginal land.

Rising demand for bioenergy may lead to rapid expansion of large plantations. This expansion may happen through the force from government to plant energy crop on the land owned by privates or states. In addition, landowners may be mandated to sell the land at low prices [55]. For instance, smallholders in Indonesia and Colombia have been forced from their land. In 2000 land disputes with local communities were reported by each of the 81 oil palm plantation companies in Sumatra, Indonesia [57].

The most common benefits of developing bioenergy are the contribution to the labor income and employment. When the food price is low, making biofuels from crops is a better option. Growing global demand for biofuels raises feedstock prices, which in turn raises producer income and land value. Higher feedstock prices and higher volumes of marketable produce can supplement rural producer income and create jobs. For example, ethanol industry employees in São Paulo received wages 25.6 percent higher than the average Brazilian; wages of workers who worked directly on the sugarcane crop were 16.5 percent above average in 2005 [55]. Jobs associated with bioenergy production tend to provide more stability and better benefits than other rural jobs. However, there are some concerns regarding the quality and safety of these jobs, especially for child labor issues.

To assess the social impacts of the bioenergy development, it is applicable to choose some key indicators, such as jobs and tax revenues, which can be quantified in order to provide useful insights for stakeholders.

2.4 State of The Art in Sustainability Assessment of Bioenergy System

2.4.1 *Environmental and socio-economic indicators*

The metrics and indicators of sustainability assessment used in contemporary research on bioenergy systems have a huge diversity. There is only limited agreement among scientists and stakeholders about the indicators needed to measure the sustainability of a bioenergy system [58]. Researchers can develop new sustainability indicators based on their own interested in the three principal pillars of sustainability. Rasmussen et al. [58] found that the most common indicators for assessing the sustainability of agricultural commodities include soil fertility, GHG emissions, soil erosion, land cover composition, nitrogen balance, crop yield, and farm net income. The GHG emissions and nitrogen balance were identified as indicators that have characters including cost-effective, comparable across countries, and comparable across commodities. Biodiversity, soil carbon, and water quality appear to be more discussed as environmental indicators for the sustainable agriculture analysis [59]. Mcbride et al. defined several categories of environmental indicators for the sustainability of bioenergy systems, which includes soil quality, water quality and quantity, GHG emissions, biodiversity, air quality, and productivity of biomass [60]. Similarly, Dale et al. [61] recommended some categories of socio-economic indicators for bioenergy sustainability that includes social well-being, energy security, external trade, profitability, resource conservation, and social acceptability. In general, the sets of indicators should be adapted to the different local concerns and purposes for measurement, the varied characteristics of biofuel and alternative energy systems, the range of stakeholders and their priorities, diverse regional environments, and differing scales of application [62].

2.4.2 *Life cycle assessment*

Life cycle assessment (LCA) is a widely used methodology for evaluating environmental impacts of a bioenergy system from “cradle to grave”. GHG emissions and energy use are two of the most common impact categories that are compared with the impacts of the conventional fuels (e.g., coal and gasoline). Other results of impacts, such as eutrophication acidification, and biodiversity, are also quantified. Other environmental impacts apply particularly to bioenergy crops, where intensive agricultural practices coupled with use of fertilizers (especially nitrogen based) can cause environmental concerns in soils, water bodies and atmosphere [63]. However, the variations in input data, functional units, allocation methods, reference systems and other assumptions cause a wide range of final results of LCA bioenergy studies [63]. Cherubini and Strømman [63] found that the functional unit, reference system, and allocation play key roles in the estimation of the environmental impact savings of the bioenergy system. In addition, including the effect of land-use change can significantly change the results of environmental impacts, especially for the GHG emissions. Gnansounou et al. [64] also concluded that the results of the reduction in the GHG emissions are highly sensitive to the following factors: the method used to allocate the impacts between the co-products, the type of reference systems, the choice of the functional unit and the type of blend. For example, the GHG emissions of producing ethanol by sugarcane in Brazil ranges from 36 g $CO_{2\ eq}$/MJ to 48 g $CO_{2\ eq}$/MJ, the GHG emissions of producing ethanol by corn in the U.S. ranges from 72 g $CO_{2\ eq}$/MJ to 129 g $CO_{2\ eq}$/MJ, and the GHG emissions of producing ethanol by wheat in the EU ranges from 77 g $CO_{2\ eq}$/MJ to 144 g $CO_{2\ eq}$/MJ [65]. A comprehensive LCA conducted by Murphy and Kendall (2015) estimated that the GHG emissions from cellulosic biofuel production ranges from 20 to 60 g $CO_{2\text{-}eq}$ MJ^{-1} under conservative scenarios, which means that cellulosic biofuel production can reduce GHG emissions by 34.8% - 78.3% compared to gasoline.

2.4.3 *Economic analysis*

Techno-economic analysis is a fundamental method to evaluate the production cost of bioenergy based on the process simulation, and it is commonly used to identify the economic feasibility of a new bioprocess technology. This economic evaluation can determine the minimum selling price and the net present value of producing bioenergy production in a specific technology. The cash flow of a bioenergy production generally includes the total capital investment, fixed operation costs and variable costs [67]. The key factors that can influence the production cost are the feedstock cost, productivity, conversion efficiency and the capacity of bioenergy facility [30], [67]. In recent years, techno-economic analysis has been applied to the lignocellulosic ethanol since it is expected to become an alternative transportation fuel. Similar to the LCA studies, the results of production cost give a wide range from \$0.59 gal^{-1} to 1.76 gal^{-1} (\$0.16 L^{-1} to \$0.47 L^{-1}) [30].

The Impact Analysis for Planning (IMPLAN) method, designed by the USDA Forest Service, is another economic related modeling to assess the economic impacts of a bioenergy industry. The method employs a linear input-output model (I-O model). In an IMPLAN I-O model, commodity flows from producers to intermediate and final consumers across all economic sectors in the United States are captured [25]. For example, the forest industry purchases $10 worth of commodities (such as capital equipment) from the manufacturing sector and sells $6 worth of forest products (such as timber) to the manufacturing sector. The IMPLAN model estimates the economic impacts in terms of gross output, value-added, and employment. Gross output means the total value of production. Value-added is the net benefit available for disbursement in the form of wages, owner compensation, and taxes [25]. Employment represents the number of full jobs created in the sector. The IMPLAN model also provides multipliers that estimate economy-wide effects, i.e., changes in final demand impacts on the entire economy [68]. Total economic impacts include direct, indirect, and induced impacts that are caused by a one dollar ($1) change in the final demand. Various multipliers generated in IMPLAN can be used to estimate economic activities, such as output, value-added, employment, and labor income. It was reported that the financial output effect of corn ethanol production was $4,994 million in 2014, and the total employment effects varied between 3,900 and 4,900 jobs for a five-year period in Nebraska (according to IMPLAN) [69]. A recent study estimated the economic impacts of woody biomass utilization on bioenergy development, and revealed the direct economic impacts and multipliers related to logging residues recovery, bio-power generation, and biofuels production [25].

2.4.4 *Integrated models*

To better understand the potential consequences of establishing bioenergy system, it is necessary to adopt an integrative perspective that considers all three sustainability dimensions. Onat et al. [70] proposed the life cycle sustainability assessment (LCSA) framework using system dynamics to deep and broad the concept and capability of traditional life cycle assessment. The LCSA model was employed in an electric vehicle case study to evaluate the environmental, economic and social impacts in terms of atmospheric pollution, gross domestic product (GDP), employment public welfare and human health. Several studies [71]–[73] proposed a sustainability assessment framework for bioenergy systems that employed a multi-criteria decision analysis. These frameworks sought to make sustainable decisions for bioenergy development by optimizing the performance in terms of environment, economy, and society. These efforts did not, however, endeavor to predict these impacts. Thus, a limitation of studies using this approach is that they focus only on the present situation and do not consider potential future impacts or changes that may occur within one of the three sustainability dimensions. MILESTONES, an integrated modeling framework for bioenergy strategies, incorporated three sub-models that focus on the global agricultural products market, global land-use change, and bioenergy provision and demand [74]. Two coupled sub-models manually exchanged data so the output from the source model must be adapted before it is input in the target model over multiple steps. While this approach is effective, these data exchange and feedback loops can be performed using system dynamics modelling without iterative simulation steps. Moreover, the MILESTONES modeling framework has not included the assessments of economic and social impacts.

System dynamics is a comprehensive methodology that can analyze the dynamic behaviors of economic, environmental and social aspects in a complex system. Peterson et al. [75] developed a system dynamics-based Biomass Scenario Model (BSM) to better understand the impacts of biofuel policy on the biofuel supply chain in the United States. Barisa et al. [76] used a system dynamics model to analyze the biodiesel market behavior associated with various policy instruments on increasing the proportion of biofuel in Latvia. Blumberga et al. [77] employed system dynamics modeling to understand how policy instruments can facilitate the bioeconomy in the forest industry. However, no model considered sustainability performance of the associated bioenergy system. Musango et al. [78] developed a system dynamics-based model to assess the effects of biodiesel development on selected sustainability indicators for the Eastern Cape Province of South Africa. The indicators focused on the biodiesel production and profitability, biodiesel crop land, and avoided CO_2 emissions. Similarly, the economic and social impacts were not addressed in this study.

2.5 Summary

A bioenergy system includes sequential processes which are biomass cultivation, harvest, transportation, conversion to fuels, and the end use. All of these processes can vary depending on the bioenergy system. Based on the literature review, the type of biomass feedstock, biorefinery technologies, and bioenergy policy are identified to be key factors that can significantly affect the sustainability performance of a bioenergy system. For example, forest crops can sequestrate more carbon in the soil than agricultural crops. Biofuels generated from second generation biomass (e.g., switchgrass) can reduce food security issues when food crops (e.g., corn) are used for biofuels.

Using lignocellulosic biomass as a feedstock to produce biofuels through pyrolysis is more expensive than other biomass to pretreat. The bioenergy policy can influence the magnitude of the impacts of bioenergy systems on the environment, the economy, and society.

Life cycle assessment, techno-economic analysis, and the economic input-output model can each only address one dimension of sustainability. Other integrated models from the literature do not predict the dynamic changes in system behaviors well. In summary, the literature of the integrated models provides little insights on the sustainability performance of a bioenergy system and cannot incorporate all the three dimensions. The ISM proposed in this research will try to fill the research gaps by integrating all the pillars of sustainability.

CHAPTER 3. ISM FOR U.S. CORN ETHANOL SYSTEM

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3.1 Overview of the ISM

A bioenergy system is a complex system that involves multi-disciplinary interactions among human, natural and technical factors. The bioenergy system includes such activities as cultivation of biomass, harvest and pretreatment, transportation, conversion to fuels and end use of bioenergy [79]. The structure of the proposed integrated sustainability model incorporates exogenous factors, the bioenergy life cycle, and measures related to the three sustainability dimensions into a dynamic system. A variety of exogenous factors (e.g., population demographics, feedstock type, renewable fuel standard, land use policy, price of fossil fuel) are selected due to the fact that they play a highly important role in the dynamic behaviors of system indicators. For instance, the changes in population and price of fossil fuel can affect the demand of bioenergy use, different feedstock types result in different costs of bioenergy production, and incentives or tax deductions regulated by renewable energy policy can impact the structure of the bioenergy market. Several studies [76], [80], [81] also considered the exogenous factors, such as policy, population growth, and fossil fuel price, as important drivers for bioenergy development. Environmental, economic, and social impacts that are generated both upstream and downstream of a bioenergy system can be addressed via key indicators associated with major concerns.

A conceptual view of the model is shown in Fig. 3.1. Math-based sub-models focusing on environmental and socio-economic effects have been developed to describe the dynamic character of the system, and aim to anticipate such consequences as GHG emissions, soil carbon sequestration, monetary gain, and employment. Through the ISM for a bioenergy system there are two key questions that can be answered: 1) what are the potential environmental and socio-economic impacts that can be generated by the bioenergy development? 2) how do changes in the demand of bioenergy affect bioenergy market and the economics of bioenergy industry?

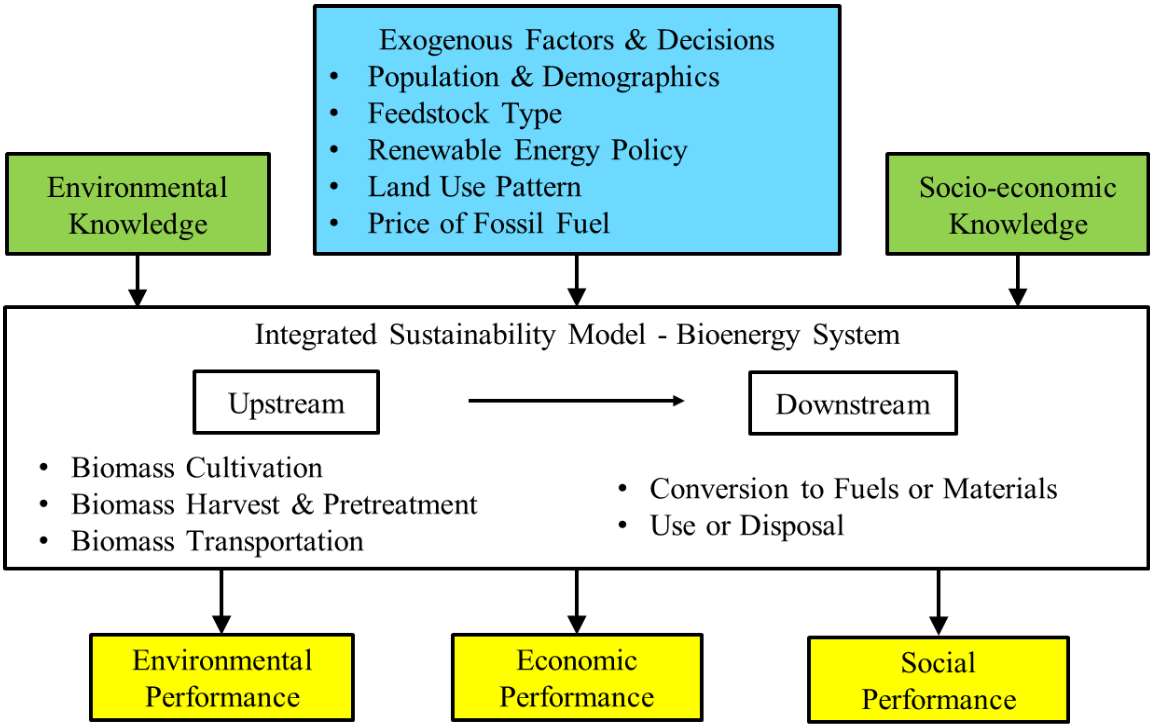

Figure 3.1. Integrated sustainability model concept for a bioenergy system.

3.2 ISM for Corn Ethanol System

The field of system dynamics emerged in the late 1950s and was led by Forrester [82] . System dynamics is a modeling method that can be utilized to characterize the behavior of complex, often nonlinear, systems and may include feedback loops, feedforward loops, time delays, and other dynamic elements. System dynamics modeling is viewed as a powerful method to provide useful insights into situations of dynamic complexity and policy intervention [83].

The first step in developing a system dynamics model is to construct a causal loop diagram (CLD). A CLD helps to visualize the interrelationships among the different elements in the system. A CLD for the biofuel system is shown in Fig. 3.2. The CLD shows the causal linkages and key variables, and reflects consideration of environmental, economic, and social performances. Within a CLD, factors connected by arrows indicate causal relationships. If the sign on an arrow is a “+”, then when the variable at the start of the arrow (driving variable) increases, the variable at the tip of the arrow (driven variable) increases as well. If the driving variable decreases, so does the driven variable. If the sign on an arrow is a “-” sign, then when the driving variable increases, the driven variable decreases and vice versa. For example, one of the arrows in Fig. 3.2 relates "Demand for biofuel production" to "Biofuel price." Since the indicated sign is "+", this means that when the demand for biofuel production increases, there will be an increase in biofuel price.

As the CLD of a biofuel system shown in Fig. 3.2, the key factor relevant to the reduction in GHG emissions is the biofuel production which is influenced by the demand for biofuel production. The level of demand for biofuel production is influenced by the economic and population growth. An increase in the demand for biofuel production leads to an increase in biofuel price in a large market. However, an increase in biofuel price negatively affects the demand for biofuel production. Such a relationship could attenuate the growth in the demand of biofuel production and make the biofuel price stable over time. Land-use change effect plays a negative role in the reduction in GHG emissions of biofuel production. The amount of biofuel sales depends on the biofuel price and production. The biofuel price is also affected by the feedstock price which is negatively influenced by feedstock production. The economic impacts of biofuel production, such as GDP, labor income, and employment, are positively related to biofuel sales. On the other hand, the tax paid by the biofuel industry will be increased by an increase in biofuel sales. Additionally, with an increase in tax revenue, more funds will be spent on social welfare, and will increase the quality of life.

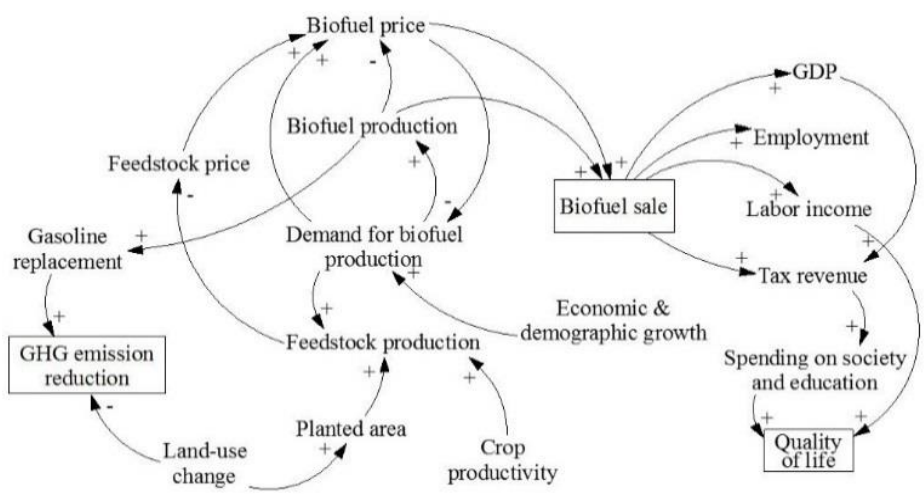

Figure 3.2. Causal loop diagram for a biofuel system

3.3 Corn Ethanol System

In 2012, corn ethanol production represented 94% of all biofuel in the United States. For this work, the corn ethanol life cycle was selected as the bioenergy system of interest. In 2003, corn ethanol was only used as an alternative to methyl tertiary butyl ether (MTBE) to be blended with gasoline. Today, the major use of corn ethanol is blending into gasoline to create E10 (10% ethanol/90% gasoline) or E85 (85% ethanol/15% gasoline). In 2004, 12.9 billion liters of ethanol were blended with gasoline (about 2% ethanol by volume) and sold as a fuel in the U.S. The mix is 1.3% ethanol (2.5×10^{11} MJ) in terms of the energy content [84].

3.4 Sub-models for Corn Ethanol System

The sub-models for the case study of corn ethanol system includes the corn ethanol market, the GHG reduction of corn ethanol production, the socio-economic benefits of GDP, labor income, employment and tax revenue created by corn ethanol industry.

3.4.1 *Corn ethanol market*

Bioenergy demand is largely driven by total energy demand, which in turn is driven by population and economic growth. From 2000 to 2014, the U.S. bioenergy consumption per capita increased by 38.7%, and the percentage of bioenergy relative to total energy use has increased from 3.37 to 4.63%. Although in reality there could be a slight gap between biomass energy production and actual consumption. As is often theoretically assumed, the demand and the supply are virtually the same. Based on the IEA's historical data, the biomass energy production and consumption were the same during these fifteen years, so the biomass supply satisfies the demand for bioenergy. Therefore, any gap between supply and demand is neglected in this study. In the U.S., ethanol demand is expected to be proportional to population and GDP. Based on examining the U.S. population and GDP from 2010 to 2014, the population has a constant growth rate of 3.106 million people per year and a GDP growth of $1,056.8 billion per year. A regression analysis was performed with ethanol consumption as the response, and population and GDP as independent variables. The resulting linear model fit was $R^2 = 0.97$.

Supply and demand curves (see Fig. 3.3) are used to estimate the equilibrium corn ethanol price. The supply for corn ethanol is based on the data for U.S. corn ethanol production and price from

2000 to 2014 [10], [85]. The demand for corn ethanol is based on two values. The first value is for 5 billion gallons (19 billion liters) – when ethanol was introduced as an alternative to MTBE – and the corn ethanol price was 1.1 times the gasoline price. The second value is for the most recent corn ethanol demand (corresponds to E10 blend) and the current ethanol price.

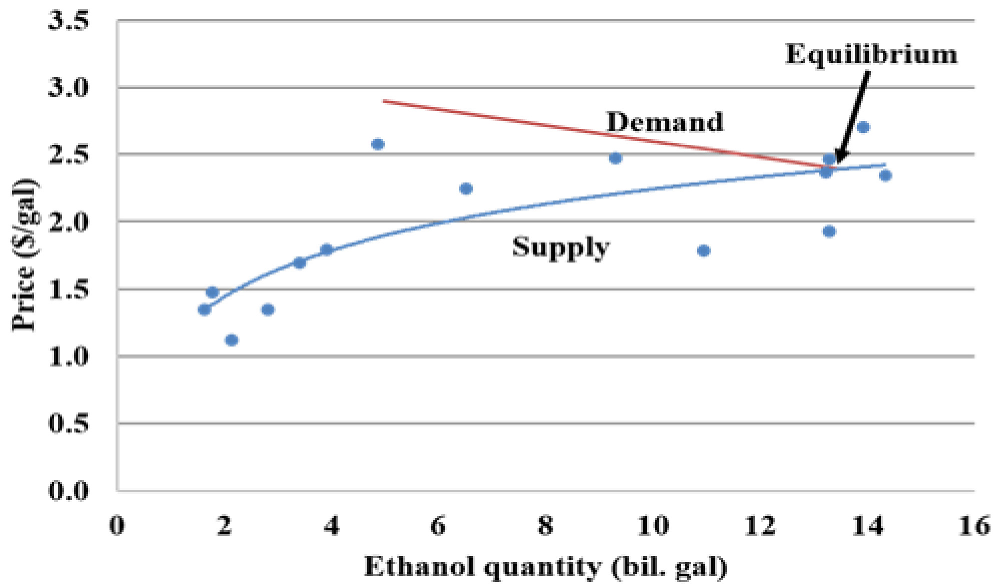

Figure 3.3. Supply and demand curves for ethanol

The prices of corn production and crude oil can influence the corn ethanol price. To be more specific, an increase in crude oil prices leads to higher ethanol prices and therefore higher corn prices [86], [87]. However, the commercial market of the corn ethanol in the U.S. has been stable since 2015 and the relationship between corn ethanol price and production can be simply estimated based on the available historical data. Therefore, the corn price and crude oil price are not included in this study.

3.4.2 *GHG emission model*

The GHG emissions of corn ethanol were examined using the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model. The GREET model was used to calculate the total energy consumption and GHG emissions including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) for a given fuel system [88]. For corn ethanol, the system boundary of the GREET model covers the life cycle GHG emissions of corn ethanol production and use, including corn farming, transport to the ethanol facility, fermentation, and ethanol delivery. The land-use change effects that may increase GHG emissions directly or indirectly are also included in GREET. Co-products of corn ethanol, such as distiller grains with solubles (DGS) and corn oil, are considered as credits for GHG emissions. For this case study, the values of GHG emissions of corn ethanol production were obtained from the literature (papers that used the GREET model) to estimate the GHG emission reduction compared to gasoline. The data used to explore the trend of average GHG emissions of corn ethanol by year is shown in Table A1 in Appendix. Based on Table A1, the average rate of reduction in GHG emissions from corn ethanol is 1.34% per year. One reason why the GHG emissions for ethanol (relative to gasoline) continue to reduce is an increasing utilization of natural gas (in place of coal) as a heat source. In addition, allocating credits for co-products, such as wet or dry DGS, corn syrup, and corn oil, can lower the GHG emissions profile for ethanol production.

3.4.3 *Socio-economic model*

To assess the economic impacts of the corn ethanol system, the multipliers for corn ethanol industry generated from IMPLAN model were used. The economic impacts of corn ethanol are based on the data from Renewable Fuel Association (RFA) reports [89]. The RFA carried out the reports of the contribution of the ethanol industry to the U.S. economy from 2009 to 2014 (see Table A2) by applying expenditures of the relevant supplying industry to the appropriate final demand multipliers for value added output, earnings, and employment. The annual corn ethanol sales is dependent on the annual corn ethanol production and price. In 2010, the total corn ethanol production was 13.3 billion gallons (50.3 billion liters), a 21.6% increase compared to 2009, exceeding the renewable fuel standard made by U.S. Environmental Protection Agency (EPA) of 12 billion gallons (45.4 billion liters) corn starch-derived ethanol in 2010. Therefore, the highest GDP, labor income and employment created by the corn ethanol industry occurred in 2010 due to large corn ethanol output and expansion of additional 12 corn milling plants [90]. The economy of corn ethanol industry did not fluctuate too much after 2010. The multipliers of the three economic impact categories are calculated by dividing the total economic impacts by the annual ethanol sales. For example, the multiplier of labor income in 2014 was a labor income of $79,000 per one million dollars corn ethanol sales. Between 2011 and 2014, there was an increasing trend in multiplier of GDP, whose annual rate is estimated to be 11%. The average multipliers of labor income and employment are estimated to be \$0.9 per dollar of ethanol sales and 11.5 jobs per million dollars of ethanol sales, respectively. The multipliers used for estimating the socio-economic impacts of the corn ethanol system are provided in Table A3.

Taxes provide revenue to governments that financially support a variety of services, e.g., education, police, defense, and health care. In fiscal year of 2015, Federal spent 28.8% of the budget on health, 24.1% on social security and 3.3% on education. The annual tax revenue is estimated to be 11.5% of the combination of GDP and household income supported by the ethanol industry. The federal tax revenue accounts for 6.2%, and the state tax revenue accounts for the remaining 5.3%.

The simulation model developed using STELLA™ is shown in Fig. 3.4. The variables and parameters used in this model are based on the results of the GREET and IMPLAN models. In this scenario, corn ethanol demand and the corresponding impacts are projected from 2015 to 2020.

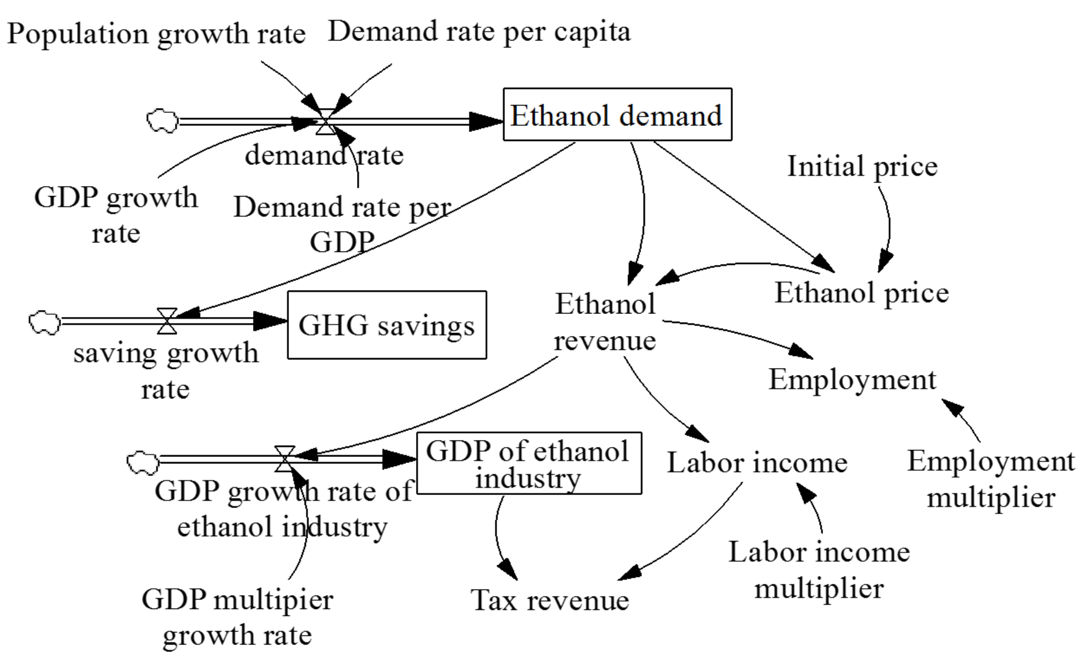

Figure 3.4. STELLA™ model of corn ethanol system

3.5 Results and Discussion

The projected corn ethanol demand and price are shown in Fig. 3.3(a). The demand for corn ethanol was approximately 14 billion gallons (53 billion liters) in 2015 and is expected to be about 16 billion gallons (60 billion liters) by 2020. These results are consistent with RFS targets set in 2012, which set a goal for conventional ethanol produced from corn starch at 15 billion gallons (58 billion liters) for 2015, maintenance of this level of corn ethanol production into the future, and an increasing amount of advanced biofuels beyond 2015 [90]. The corn ethanol price is expected to be \$2.38 gal^{-1} (\$0.63 L^{-1}) by 2020, an increase of 1.7% over the 2014 level. The demand for corn ethanol is expected to be stable due to the increased availability of advanced biofuels from 2015-2020. Therefore, the corn ethanol price is projected to change only slightly based on the supply and demand of corn ethanol.

As shown in Fig. 3.3(b), the reduction in GHG emissions due to the use of corn ethanol (as opposed to gasoline) is expected to continue to grow, and be 43.62 million tonne by 2020. The Global Renewable Fuels Alliance [91] reported that the United States experienced a 51.9 million tonne decrease in GHG emissions by displacing gasoline with ethanol in 2014. These predictions are likely conservative since only corn ethanol processing by natural gas was considered.

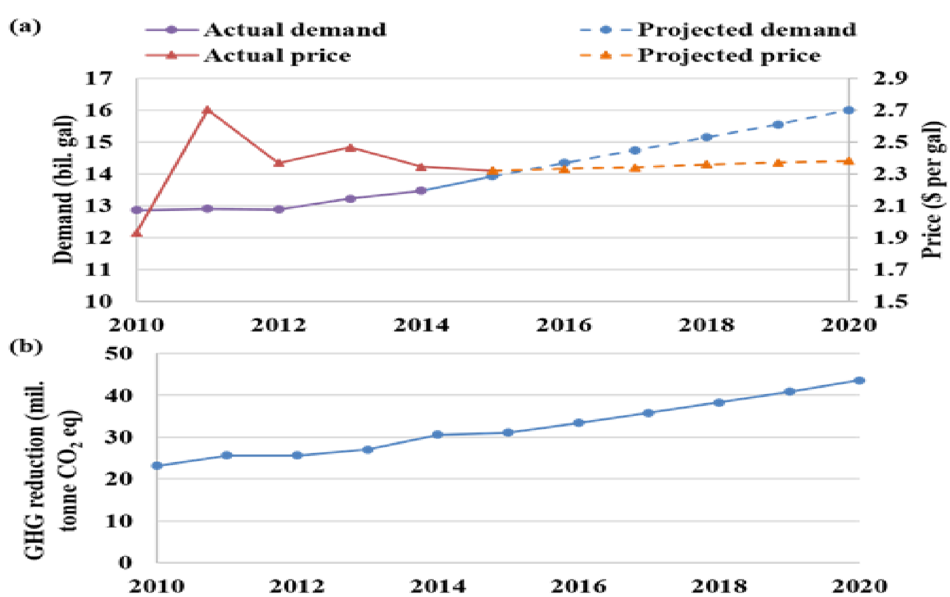

Figure 3.5. Behavior of ISM for corn ethanol bioenergy system (a) demand and price; (b) calculated GHG reduction

The economic impact of the corn ethanol industry cascades effects across the economy (e.g., corn seed providers, R&D services, and machinery). The economic impacts of the corn ethanol industry are shown in Fig. 3.4(a) and (b). The GDP created by the corn ethanol industry is projected to be over $82 billion by 2020, which is more than a 40% increase compared to 2010. In 2010, the ethanol industry had a high level of GDP due to the demand for ethanol as a gasoline-blending agent. The labor income is predicted to increase slightly from 2015 to 2020. Although the employment in 2020 is projected to be 15.5% larger than the 2014 employment, it is just 9% larger than it was in 2010. The employment during 2010 to 2013 decreased corresponding to a decrease in GDP associated with corn ethanol sales. The increasing employment evident may be attributed to the anticipated growth of corn ethanol sales and GDP that should directly and indirectly create job opportunities in agriculture, manufacturing, transportation, and service sectors. Therefore, the labor income and employment is fairly stable, and will not grow fast unless a significant expansion occurs in the corn ethanol industry. The estimated average income for the corn ethanol industry is roughly 49% higher than the U.S. average of $52,250 in 2015.

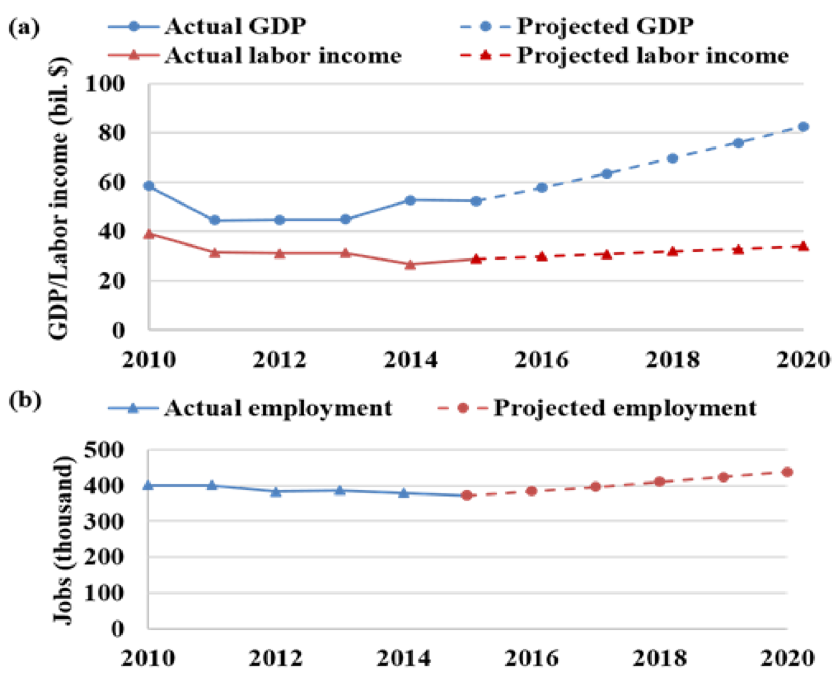

Figure 3.6. Behavior of ISM for corn ethanol system (a) GDP and labor income; (b) employment across all sectors

In addition to the positive direct impacts on the local economy through expenditures and society through employment, local governments also benefit from increased tax revenues. Such revenues can support increased spending on education and other activities that benefit society. The total tax received by the federal and state governments is projected to increase by 63% between 2011 and 2020 (see Fig. 3.5). The federal and state tax revenues are estimated to increase by 68% and 57% by 2020 (over the 2010 level).

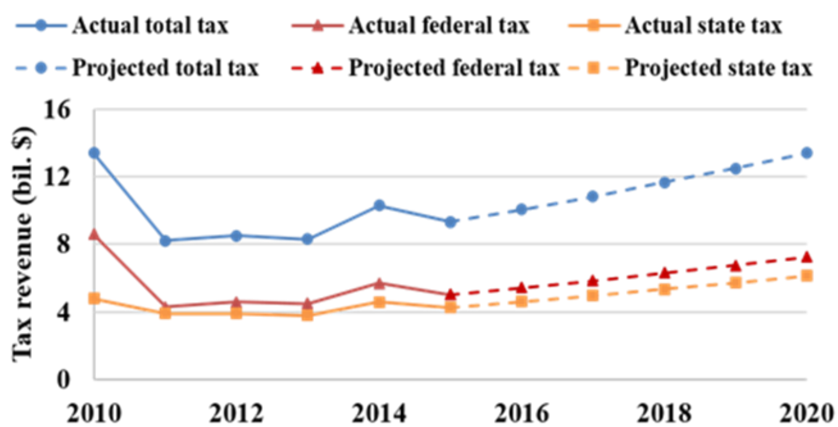

Figure 3.7. Tax revenue behavior of ISM for corn ethanol system

CHAPTER 4. ISM FOR FOREST RESIDUE SYSTEM FOR U.S. ELECTRICITY GENERATION

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4.1 ISM for Forest Residue System

The CLD of the forest residue system for electricity generation is shown in Fig. 4.1. The system boundary indicates that the system includes sections for the forest residue supply from timberland, and for the demand for electricity generation in the residential sector. The supply of forest residues is mainly affected by the harvested forest biomass. Either an increase in forest biomass planted or an expansion in the timberland causes an increase in harvested forest biomass production. The harvest ratio (percentage of timber removals relative to total growing stock) of forest biomass determines the amount of available forest biomass for use as feedstock. The harvest ratio can also be influenced by the demand in the timber product market. Thus, the availability of forest residues depends upon the forest biomass harvest and the ratio of logging residues to timber harvest. A change in land-use occurs when there is a higher benefit for timberland relative to crop land, i.e., a higher price for timber than agricultural crop price (e.g., corn and soybeans). Land-use may change the other way when crop price is higher than timber price. On the demand side of biomass energy, forest residue demand for co-firing with coal depends on total electricity consumption in the residential sector, which, in turn, is affected by population growth and electricity consumption per capita. Forest biomass prices vary based on dynamic changes in forest biomass supply and demand.

Variables outside the system boundary are exogenous factors and sustainability indicators. An exogenous factor example is bioenergy policy; demand for biomass energy changes when there are regulations related to bioenergy use, e.g., a Renewable Portfolio Standard (RPS). LUC when crop lands are transferred to timberland serves to increase soil carbon sequestration. Co-firing biomass with coal reduces CO_2 (GHG) emissions when compared to coal firing only. Socio-economic impacts in terms of gross output, value-added impact on the economy, and employment are generated by revenues in both forest residue recovery and the bio-power operation sectors.

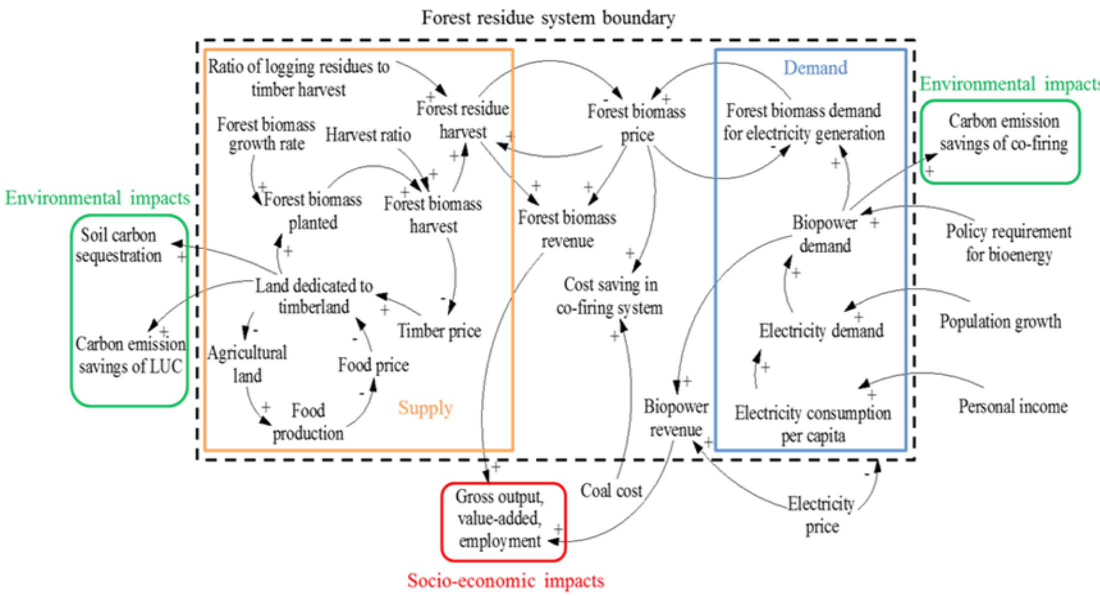

Figure 4.1. CLD for forest residue system for electricity generation

4.2 Forest Residue System for Electricity Generation

Logging residues, a byproduct of timber harvesting operations, includes tree tops, branches, small stems, and deadwood, are one of the major sources of forest biomass. Logging residues are usually left onsite for maintaining forest ecosystem functions, but have also been considered waste materials [92]. The emerging bioenergy industry and advancement of technologies opens a potential market for wood residues as an energy source. Gan and Smith [93] estimated, for the 1997 Forest Inventory and Analysis data [94], that the amount of recoverable logging residues in the U.S. were 36.2 million dry tonnes per year from both growing stock and other sources. The demand for wood residues is likely to increase with increasing fossil fuel prices and government policies seeking reduced environmental impacts via low carbon emission energy sources [92]. Coal is still the largest fuel used for electricity generation in the U.S., and the forecast of coal's share in electricity is expected to rise in 2018 due to an expected increase in the price of natural gas [95]. Direct co-firing is the most common and least costly technology for converting forest residues to power. Typically, biomass is co-fired with coal in a pulverized coal boiler. However, due to logistic, economic and technological challenges, only 5–10% of biomass can be viably co-fired with coal in commercial applications [14]. Moreover, the cost of retrofitting an existing coal power plant to co-fire biomass is significantly lower than the cost of building new systems dedicated only to biomass power [14]. Since coal combustion is the most widespread energy generation technology, it is practical to compare the impacts of biomass co-firing with conventional coal combustion. In this study, the electricity generated from co-firing power plants is assumed to be delivered to the utility grid for residential use. The forest residues can also be used for heat production in the industrial boiler, but the goal of this study is to understand how the behaviors of consumer electricity consumption affect the forest residue demand for electricity generation.

4.2.1 *Forest residue supply*

Many researchers have investigated regional forest residue availability and developed supply curves associated with delivered biomass price. Logging residues are similar to pulpwood in that collection and transportation accounts for a high proportion of the delivered cost even though logging residues are low cost. To estimate the supply curve of logging residues, the pulpwood market is introduced to understand the general wood production supply, and then the difference between pulpwood stumpage price and delivered price was used to adjust the supply curve for logging residues. The pulpwood supply curve is assumed to be of the form [12]:

$$ln^{P_p} = \alpha + \varepsilon ln^{Q_p} \rightarrow P_p = exp^{\alpha} {Q_p}^{\varepsilon} \tag{4.1}$$

where:

P_p: price of pulpwood production ($ t^{-1});

Q_p: quantity of pulpwood production (Mt);

ε: elasticity coefficient;

α: coefficient.

In a forest, logging residues may be collected at no cost or at a comparable stumpage price to pulpwood (the act of collection will incur a cost). This analysis performed herein assumes that the stumpage price of pulpwood has the same function of pulpwood supply curve. Once the elasticity coefficient of stumpage price is estimated, the stumpage supply curve is generated based on a reference stumpage price (P_{p0}) and quantity of logging residue (Q_{p0}) associated with the elasticity coefficient. Then, the difference between delivered pulpwood price and stumpage price was added to the stumpage supply curve to generate the new delivered biomass price.

The U.S. timber market is closely related to the housing market and GDP. Due to the Great Recession in 2007 and over-built housing market from 2000 to 2005, sawtimber market that affects the pulpwood supply were depressed [96]. After the recession in 2009, the housing market and GDP improved gradually, and the timber market was back to the normal track. Therefore, the elasticity coefficient (ε) of the pulpwood stumpage price was estimated to be 4.6, which is based on pulpwood production and stumpage price from 2010 to 2014 in the U.S. Gulf Region [96]. While the forest biomass system in this study does not explicitly include the effects of timber use in the construction market, the impact of the timber market on the availability of forest residues is indirectly included through the harvest ratio factor. The harvest ratio of timber is assumed to increase as a constant rate based on the recovering housing market. The stumpage price and available logging residues are related to the values from 2012, which are 10.49 $ t^{-1} in 2015 dollar and 5.64 million tonnes, respectively. The difference between pulpwood stumpage price and delivered price was estimated to increase 0.6 $ t^{-1} annually based on the pulpwood stumpage price and delivered price from 2000 to 2013 in the Louisiana, U.S. [97]. The delivered biomass supply curve is shown in Eq. (4.2):

$$P_r = 0.0036 Q_r^{4.6038} + d_0 + 0.6k \tag{4.2}$$

where:

P_r: price of logging residues ($ t^{-1}) in *k*th year since 2012;

Q_r: quantity of logging residues (Mt) in *k*th year since 2012;

d_0: difference price ($ t^{-1}) between pulpwood stumpage price and delivered price in 2012.

4.2.2 *Demand of forest residues for co-firing*

As has been noted, biomass may provide a portion of the fuel needed for electricity generation via co-firing. The demand for wood residues for co-firing is driven by the total electricity demand for the residential sector. Demand for biomass will likely continue to increase as the energy sector becomes more environmentally conscious. Annual electricity demand may be expressed as a function of population growth and electricity consumption per capita as shown in Eq. (4.3):

$$D_e = Q_0 \cdot (1+\rho)^k \cdot EC_{cap} \tag{4.3}$$

where:

D_e: annual electricity demand (million MJ) in the *k*th year since 2012;

Q_0: population (in millions) for the reference year of 2012;

ρ: population growth rate (million yr^{-1});

EC_{cap}: electricity consumption per capita (MJ per capita).

The U.S. National Renewable Energy Laboratory (NREL) found that residential electricity demand depends significantly on population, electricity price, past electricity consumption, personal income, and climate [98]. To estimate the annual electricity demand, the present study followed the approach proposed by NREL, and developed a regression model (R^2= 0.95) of the personal electricity consumption as a function of personal income, electricity price, and the previous year's electricity consumption per capita as shown in Eq. (4.4):

$$EC_{cap} = -0.05 \cdot P_e + 0.53 \cdot L_e + 0.0000476 \cdot I \tag{4.4}$$

where:

P_e: electricity price (cent MJ^{-1});

L_e: electricity consumption per capita in previous year (MJ per capita);

I: personal income ($).

The data for P_e, L_e and I are based on historical electricity consumption in the residential sector and demographic information from the International Energy Agency Statistics [99]. In recent years, the electricity generation from woody biomass has accounted for an average of 0.26% of the total electricity generation in the U.S. The recent utilization of woody biomass in electricity generation is consistent with the projection made in EIA Annual Energy Outlook 2002 that 0.3% of the total electricity generation would be provided by woody biomass in 2020 [100]. The woody biomass demand will vary based on the requirements and characteristics of extant renewable energy policies. The EIA has projected various biomass demands for electricity generation based on different renewable energy policy scenarios within an RPS framework. According to the 2017 EIA Electric Power Monthly report [10], the net electricity generation from wood and wood-derived fuels accounts for 0.9% of the total electricity generation in all sectors. White et al. [101] projected and compared biomass production from the U.S. forest and agriculture sectors by examining different national-level Renewable Electricity Standard (RES) scenarios. Based on all these considerations, it will be assumed that the forest residue demand for co-firing will be at a level to meet 0.3% of the total electricity consumption in the residential sector as a base case. Owing to the uncertainty in the biomass demand, Section 4.5 will explore different scenarios to identify how changes in key variables, such as biomass demand and delivered biomass price influence the system cost.

Several studies [102]–[106] estimated the delivered cost of biomass for electricity generation based on the case of a co-firing power plant. The delivered cost of forest residue is mainly comprised of harvesting, transportation, and storage costs, and has a large range of 7.50-80.00 $ t^{-1} due to differing study assumptions (e.g., transport distance, biomass availability, and fuel cost). In this work, a relationship between the delivered price and available wood residue production is developed based on historical data on logging residues and pulpwood prices [97], [107] in the United States. The delivered biomass price will be determined by the equilibrium point where the forest residue supply and demand are equal.

4.3 Sub-models for Forest Residue System

4.3.1 *Soil carbon sequestration & GHG emission change due to LUC*

One of the environmental impacts of using forest biomass is the reduction in the net greenhouse gases emissions caused by the sequestration in soil organic carbon (SOC) and carbon in vegetation biomass due to land-use change (LUC). The effect of land-use change from natural forest to cropland can increase the net emission of GHG by 7.3 t $CO_{2\ eq}$ ha^{-1} yr^{-1}, while conversion of cropland to secondary forest can reduce total GHG emissions by 5.3 t $CO_{2\ eq}$ ha^{-1} yr^{-1} [108]. The key environmental impacts from a forest biomass system are the soil carbon sequestration, the corresponding avoided CO_2 emission, and the total GHG emissions change resulting from land-use modifications between forest land and crop land. Reduced contributions of CO_2 to the atmosphere from LUC (crop land to forest land) is owed to the gain in SOC stock and the total GHG emission change is the combined emission difference in biomass carbon, SOC, and CH_4 and N_2O emissions in soil processes. The sub-models of soil carbon sequestration and GHG emissions change are based on the change rates in soil organic carbon, associated CO_2 flux, and the net GHG emissions (Table 4.1) were estimated by Kim and Kirschbaum [108]. Their research also reported on the calculations of soil carbon sequestration and all the net GHG exchange were expressed in units of $CO_{2\ eq}$ through multiplication by the respective 100-year global warming potentials of different GHGs [108]. The numbers given in Table 1 represent the average change rates over 100 years.

Table 4.1. Change rate of soil carbon stock (ΔS), corresponding contribution to atmospheric CO_2 and net GHG emissions from LUC between forest and cropland over 100 years (adapted from Kim and Kirschbaum [108]).

Land use type		ΔS over 100 years	Contribution to the atmosphere	Net GHG emission to the atmosphere
Pre	Post	(tonne C ha^{-1} yr^{-1})	(tonne CO_2 ha^{-1} yr^{-1})	(tonne $CO_{2\ eq}$ ha^{-1} yr^{-1})
Natural forest	Cropland	-0.33	1.2	7.3
Cropland	Secondary forest	0.59	-2.2	-5.3

4.3.2 *Cost savings and CO_2 savings for a co-firing system*

There are few studies focusing specifically on the estimation of GHG emissions from a biomass co-firing system due to the fact that U.S. electric utilities are not employing biomass feedstock for co-firing on a large scale [109]. Therefore, the GHG reductions predicted in this sub-model focus on the potential GHG emissions that could be saved through co-firing compared to a 100% coal-fired plant. The reduction in equivalent CO_2 emissions is evaluated based on the amount of coal displaced by forest biomass. The reduction of CO_2 per year is calculated as [7]:

$$\Delta CO_2 = 3.67 \times (\Delta M_{coal} \times f_c) \tag{4.5}$$

where:

ΔCO_2: CO_2 reduction from a co-firing system (Mt);

f_c: mass fraction of carbon in coal;

ΔM_{coal}: annual mass of coal replaced by biomass in the boiler (Mt).

The annual forest biomass needed for electricity generation at a national scale is determined by the proportional energy content (P_b) provided by the biomass. The annual biomass requirement is determined through the equations below [110]:

$$ABU = \frac{ATD \times P_b}{\eta_o \times LHV_b} \tag{4.6}$$

$$\eta_o = \eta_b \times \eta_{rp} \tag{4.7}$$

$$\Delta M_{coal} = \frac{ABU \times LHV_b}{LHV_c} \tag{4.8}$$

where:

ABU: annual biomass use (Mt);

ATD: annual total electricity demand (million MJ);

P_b: ratio of biomass-based electricity to the total electricity demand;

η_o: overall power efficiency;

η_b: boiler efficiency of biomass co-firing;

η_{rp}: remaining power efficiency excluding the boiler;

LHV_c: lower heating value of coal (MJ kg^{-1});

LHV_b: lower heating value of forest biomass (MJ kg^{-1}).

The values of the variables assumed for the biomass co-firing are listed in Table 4.2.

Table 4.2. Assumed variable values for a biomass co-firing system

Variable	Coal (US anthracite)	Forest biomass
Carbon content (% wt)	83.7	52.3
Lower heating value (MJ/kg)	29.94	19.19
P_b (%)	N/A	0.3
η_b (%)	90	90
η_{rp} (%)	43	43
Cost ($/tonne)	45	Calculated using Eq. (4.2)
Density (kg/m^3)	N/A	608.12

In this study, the cost change from a biomass co-firing system only considers the cost savings from reduced coal consumption, and the incremental cost of consuming biomass. This is expressed by:

$$CS = \Delta M_{coal} \times UC_{coal} - ABU \times UC_{biomass} \tag{4.9}$$

where:

CS: annual cost savings in the biomass co-firing system (million $);

UC_{coal}: unit cost of coal ($ t^{-1});

$UC_{biomass}$: unit cost of biomass ($ t^{-1}).

4.3.3 *Land-use change mechanism*

The amount of available timber is likely to increase as land dedicated to other activities (e.g., crop land and pasture) is transferred to timberland. From 2007 to 2012, U.S. national forests increased by roughly 7 million acres or 1% of the 2007 estimated forest area [107]. Based on the 2007 estimation of major land use in the United States [111], forest land increased by 4.5% from 1997 to 2007. In particular, the timberland area increased by 29 million acres between 1987-2007, as more available forest land and marginal farm land were classified to timberland [111]. In contrast, the trend of cropland use generally has declined in recent decades. Total cropland dropped roughly 10% between 1997 and 2007 [111]. A variety of factors can affect land-use change. Land-use shifts may happen due to changes in commodity prices, land-use policies, and subsidy policies for bioenergy [112]. Farmers or landowners are sensitive to changes in price and policy, and maximizing net profits from owned land has caused changes in land-use. In this study, the land-use change mechanism aims to address the impact of changes in commodity prices on the collective choices that landowners make about their production (e.g., wood or crops). Planting trees or energy crops on marginal land is a potentially attractive way for bioenergy production. However, the low productivity of biomass production and high production cost are concerns for economic viability [113]. Moreover, the ownership of marginal land is unclear [113].

To predictively describe land-use change, it is assumed that a landowner will endeavor to maximize land-use efficiency. The land-use efficiency metric employed in this paper is a modified form of the proposed land-use efficiency indicator introduced by Papachristos and Adamides [114]. In the present case, land-use efficiency is defined as the economic performance of a unit land-use area. In this sub-model, land-use efficiency is used to explore the land-change pattern instead of developing the relationship among land area, production, and price. It assumes that land transitions only occur between forest land and agricultural land. The efficiencies of each land-use are:

$$\text{Forest land-use efficiency: } \eta_{timber} = P_{timber} \cdot Y_{timber} \tag{4.10}$$

$$\text{Agricultural land-use efficiency: } \eta_{crop} = P_{crop} \cdot Y_{crop} \tag{4.11}$$

where:

η: land-use efficiency (\$ m^{-2});

P_{crop}: crop price (corn price, \$ kg^{-1});

P_{timber}: timber price (pulpwood price, \$ kg^{-1});

Y_{crop}: yield of crop production (kg m^{-2});

Y_{timber}: yield of timber production (kg m^{-2}).

As is evident, timber and crop production are the forest and agricultural commodities, respectively. In the land-use change mechanism, it is assumed that a landowner will change the land-use if another land-use is more economically efficient than the current land-use. For instance, if $\eta_{timber} > \eta_{crop}$, crop land will be transferred to timberland (a landowner is unlikely to change all their land during a single year). On the other hand, if $\eta_{timber} < \eta_{crop}$, crop land will not be transferred to timberland (it is unlikely that timberland will be transferred to crop land in the short term). The amount of timberland change is assumed to be 0.904 million acres per year, based on the historical trend of timberland area. A 28- to 35-year harvesting rotation is typical for softwood sawtimber like pines. Thinning promotes the growth of individual trees within a stand by removing surrounding trees [115]. The first commercial thinning can happen between stand ages of 10 and 20 years depending on the rotation length [116]. If markets for pulpwood are favorable, pines can be harvested within 15 to 20 years [117], [118]. For this model, pines, such as loblolly pine (*Pinus taeda*), are selected as an example of trees because they have a short afforestation time and will generate revenue faster. It is hypothesized that pines planted on the transferred timberland are available to be either thinned or harvested for pulpwood at an average age of 20 years, when they are mature and the net growth rate is stable. Pulpwood and corn prices are selected to reflect timber price and crop price changes, respectively. The reason for choosing pulpwood and corn is that they are the major component in wood and crop production in the U.S., respectively, and the corresponding data of land area and price are readily accessible. Timber and crop prices are also influenced by the planted land, market demand, and government policies. To simplify the land-use change sub-model, the timber and crop prices are considered as exogenous variables that will change independently based on time.

4.3.4 *Socio-economic implications*

To assess the economic impacts of forest biomass used in electricity generation, the Impact Analysis for Planning (IMPLAN) method, designed by the USDA Forest Service, was used. The method employs a linear input-output model (I-O model). In an IMPLAN I-O model, commodity flows from producers to intermediate and final consumers across all economic sectors in the United States are captured [25]. For example, the forest industry purchases $10 worth of commodities (such as capital equipment) from the manufacturing sector and sells $6 worth of forest products (such as timber) to the manufacturing sector. The IMPLAN model estimates the economic impacts in terms of gross output, value-added, and employment. Gross output means the total value of production. Value-added is the net benefit available for disbursement in the form of wages, owner compensation, and taxes [25]. Employment represents the number of full jobs created in the sector. The IMPLAN model also provides multipliers that estimate economy-wide effects, i.e., changes in final demand impacts on the entire economy [68]. Total economic impacts include direct, indirect, and induced impacts that are caused by a one dollar ($1) change in the final demand. Various multipliers generated in IMPLAN can be used to estimate economic activities, such as output, value-added, employment, and labor income. A recent study estimated the economic impacts of woody biomass utilization on bioenergy development, and revealed the direct economic impacts and multipliers related to logging residues recovery, bio-power generation, and biofuels production [25]. The economic sub-model employs the estimated multipliers of gross output, total value-added, and employment in the processes of logging residue recovery and electricity generation from a co-firing system. The values of multipliers are listed in Table 4.3.

Table 4.3. Multipliers of economic impacts

Sector	Multipliers*		
	Gross output (M$/M$)	Total value-added (M$/M$)	Employment (jobs/M$)
Recovery of logging residues	1.86	0.64	11.28
Biopower	1.6	0.54	9.79

*Each multiplier is adjusted to be the ratio of the corresponding total economic impact to direct gross output

4.4 Integrated System Dynamics Model

A model following the logic of the constructed CLD (of Fig. 4.2) was implemented in Vensim® [119] and is presented in Fig. 4.3. Key elements of a forest biomass system for electricity generation are categorized as stocks and convertors. Stocks that can be calculated with a time-based function are represented as rectangular boxes. Corresponding flows are drawn as pipes with arrows and the rate of the flows as valves on the pipes. Cloud symbols are the sources of stocks outside of the system boundary. Other factors that are related to the stocks and flows are represented as convertors. The interrelationships among key elements are represented as arrows between stocks, flows and convertors. The input parameters are in black and the output parameters are in colors. The basic scenario of this model is to estimate forest residue supply and demand, and to project the corresponding impacts from 2017 to 2042 based on the reference year of 2012. The projected behaviors of sustainable metrics are expressed in an annual basis. Initial inputs of stocks used in the integrated system dynamics model are given in Table 4.4.

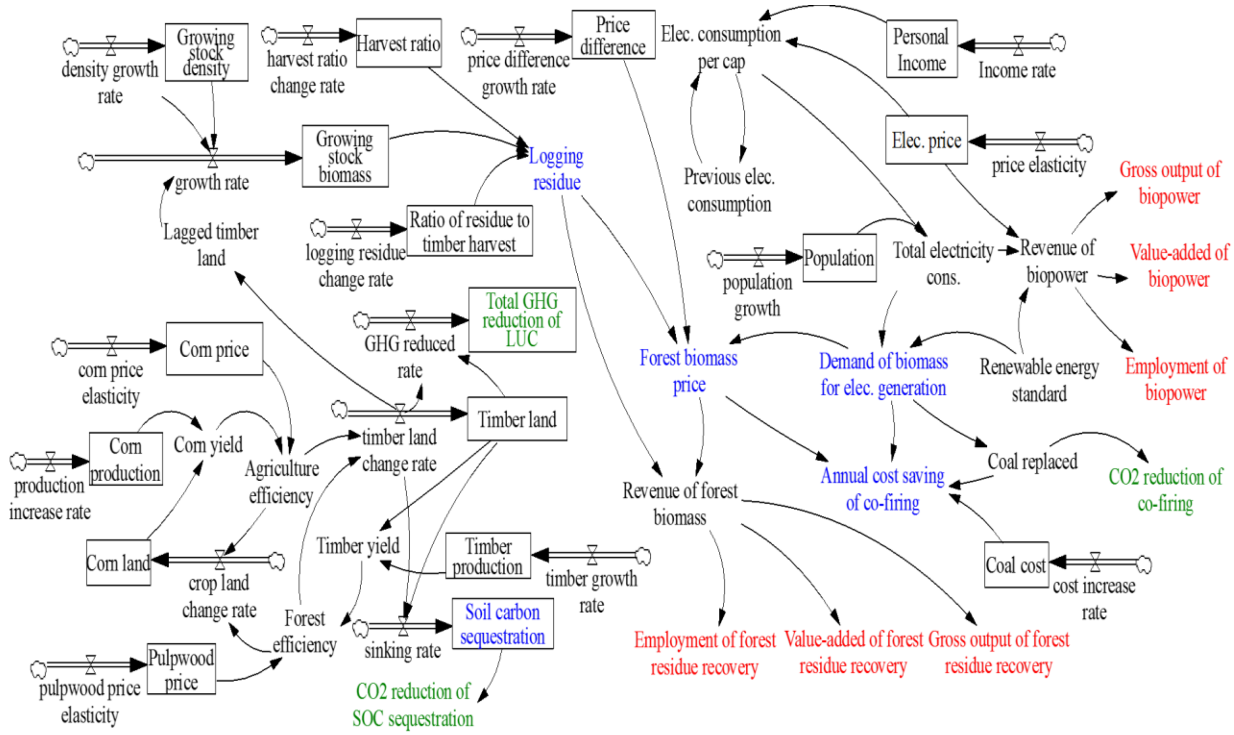

Figure 4.2. Vensim® model of forest biomass system in electricity generation

Table 4.4. Initial inputs of stocks in the ISM

Stock	Initial value
Growing stock density	0.013 m^3 m^{-2}
Growing stock biomass	2.75×10^{10} m^3
Harvest ratio	1.50%
Ratio of logging residue to timber harvest	9.58%
Timberland	2.11×10^{12} m^2
Corn land	3.52×10^{11} m^2
Timber production	2.75×10^{10} m^3
Corn production	2.74×10^{11} kg
Pulpwood price	0.05 $ kg^{-1}
Corn price	0.18 $ kg^{-1}
U.S. population	3.14×10^{8}
Personal income	37,166 $
Electricity price	0.033 $ MJ^{-1}
Coal cost	0.045 $ kg^{-1}

4.5 Results and Discussion

The amount of wood residue available for harvesting and the demand for wood residue are shown in Figs. 4.3 and 4.4. The available harvested wood residue is estimated to be 371 million tonnes by 2042, resulting from slow growth in stock biomass. The total biomass growing stock includes the existing forest biomass and the woody biomass grown on lands that have been transferred to timberland. Therefore, there is a jump in the amount of growing stock biomass in 2032 because the newly grown forest biomass planted on the transferred timberland is available to be harvested (see Fig. 4.3). Land-use change between timberland and crop land plays an important role in the availability of forest residue, and the decision on whether to change how land is used depends on the performance of the markets for forest and agricultural products. However, forest residue supply is also affected by the harvest management that determines the ratio of logging residues to timber harvest. It turns out that the growth in the supply of forest residue will reduce over time due to a decreasing ratio of logging residues to timber harvest.

In summary, the amount of available forest residue projected by the ISM is much higher than the demand for forest residue in electricity generation over a 25-year period. Meanwhile, the available forest residue is sufficient for feedstock, fuels, and heat generation in biomass processing and other industries. The predicted delivered price of wood residues is within the reasonable range of delivered biomass price and relatively high in this study compared to past estimates. It should be noted that the prediction of delivered biomass price consider the market price that reflects both supply and demand situations.

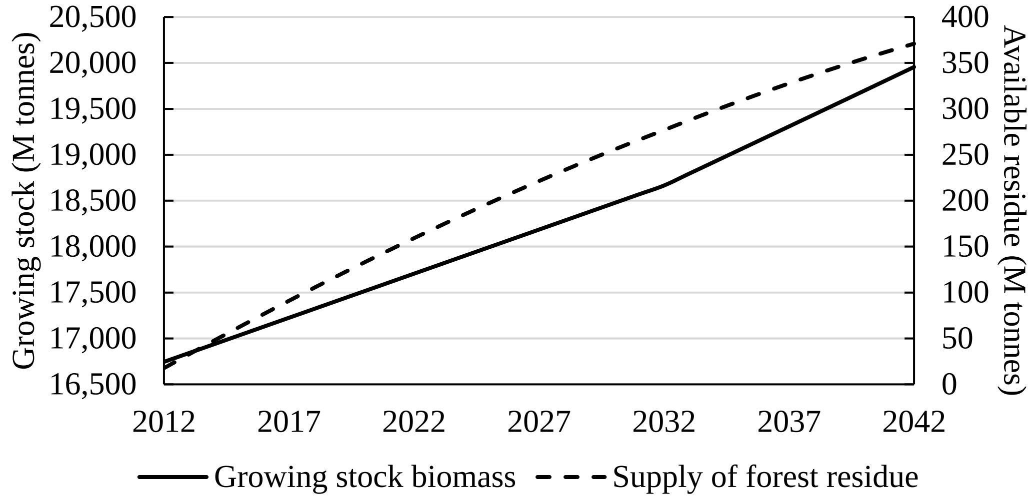

Figure 4.3. Projected growing stock biomass and available forest residue

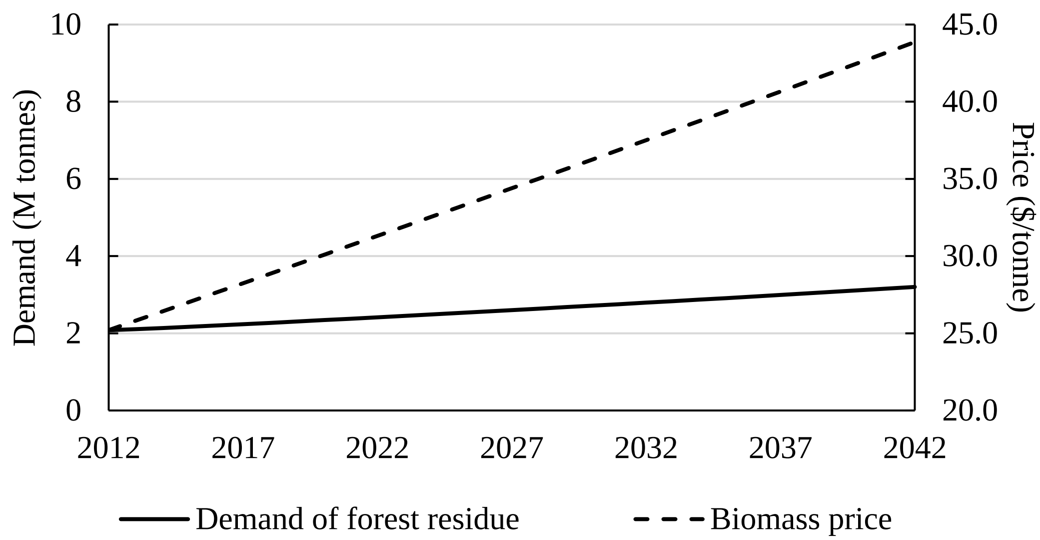

Figure 4.4. Projected forest residue demand and delivered biomass price

The accumulated changes in soil carbon sequestration and CO_2 savings caused by conversion of crop land to timberland are shown in Fig. 4.5. The sequestered soil carbon associated with cropland transferred to timberland will be 58.2 million tonnes by 2042, while the corresponding CO_2 avoided in the atmosphere is projected to be 213.3 million tonnes. Based on the proposed land-use change mechanism, timberland use is more efficient than crop land use in the years 2012-2022.

Crop land-use is predicted to become more efficient in 2023, and crop land stops being transferred to timberland. During 2012-2022, 9.04 million acres of crop land will be transferred into timberland, resulting in a steep increase in soil carbon sequestration and CO_2 savings. After 2022, the increasing rate of soil carbon sequestration and CO_2 savings is relatively stable owing to no land-use change between crop land and timberland. The total contribution to GHG emissions reduction by various changes in biomass carbon, soil organic carbon, CH_4 emissions, and soil N_2O emissions in the LUC process is estimated to be 522.5 million tonnes of $CO_{2\,eq}$ by 2042. The GHG reduction rate also becomes constant in 2027 owing to the projection that crop land will stop transferring to timberland.

The annual savings in CO_2 from co-firing systems (using a 0.3% bioenergy share) related to the use of "pure" coal is evaluated to be 6.3 million tonnes in 2042. The U.S. EIA reported that the CO_2 emissions from coal firing in the electric power sector totaled 1,350 million tonnes in 2015. Because only 0.3% of total electricity demand is assumed to be provided by forest biomass, the projected CO_2 savings from biomass co-firing in electric utilities accounts for less than 0.5% of the total emission amount in 2015. Therefore, there is great potential in terms of utilizing forest biomass to reduce the total CO_2 emissions in the electric power sector.

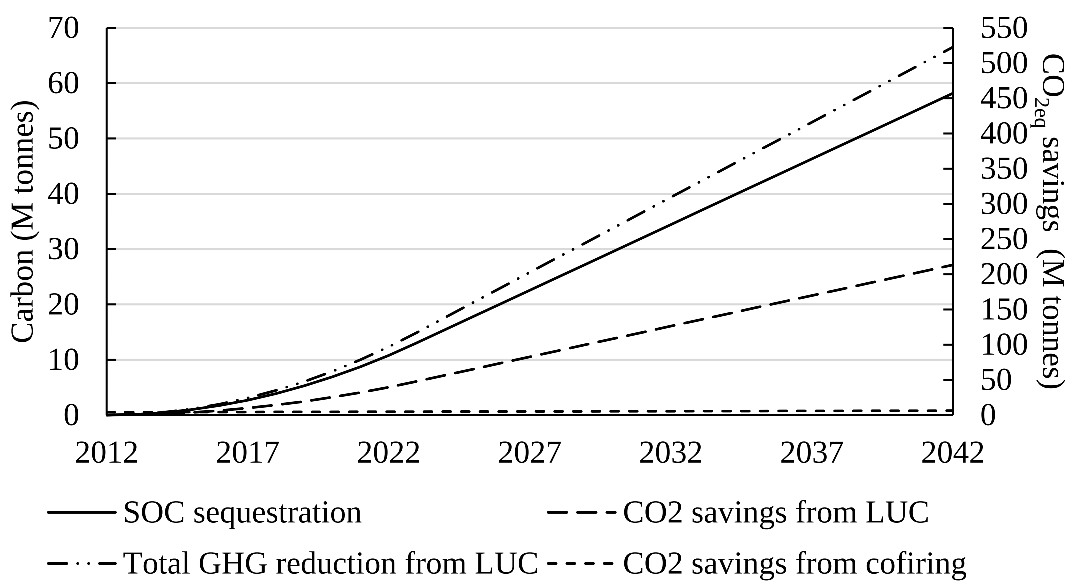

Figure 4.5. Changes in soil carbon sequestration and CO_2 savings

Economic impacts of using forest biomass for electricity generation are shown in Fig. 4.6. The gross output and value-added associated with harvested wood residues are projected to be $30.26 billion and $10.41 billion in 2042, respectively. The employment created in the United States for the recovery of wood residues is projected to be 183,538 jobs by 2042. The economic contribution of the forestry industry decreased from 2006 to 2009, and the gross output in 2015 is still lower than its peak in 2006 even with recent increases. In addition, the forestry industry in the United States has had a dramatic decrease in employment from 2000 to 2013 owing to the financial crisis of the late 2000s and the emerging use of digital media that has decreased the demand for printed materials, such as newspapers [120], [121]. Therefore, the utilization of wood residues for electricity generation can be a potential way to accelerate the growth in gross output and provide more jobs in the forest products industry. Moreover, bio-power generated by forest biomass can contribute more value to the economy in the electric power sector. Co-firing power plants will generate $1.86 billion in gross output, $0.63 billion in value-added activity in 2042, and 11,390 jobs across the country by 2042.

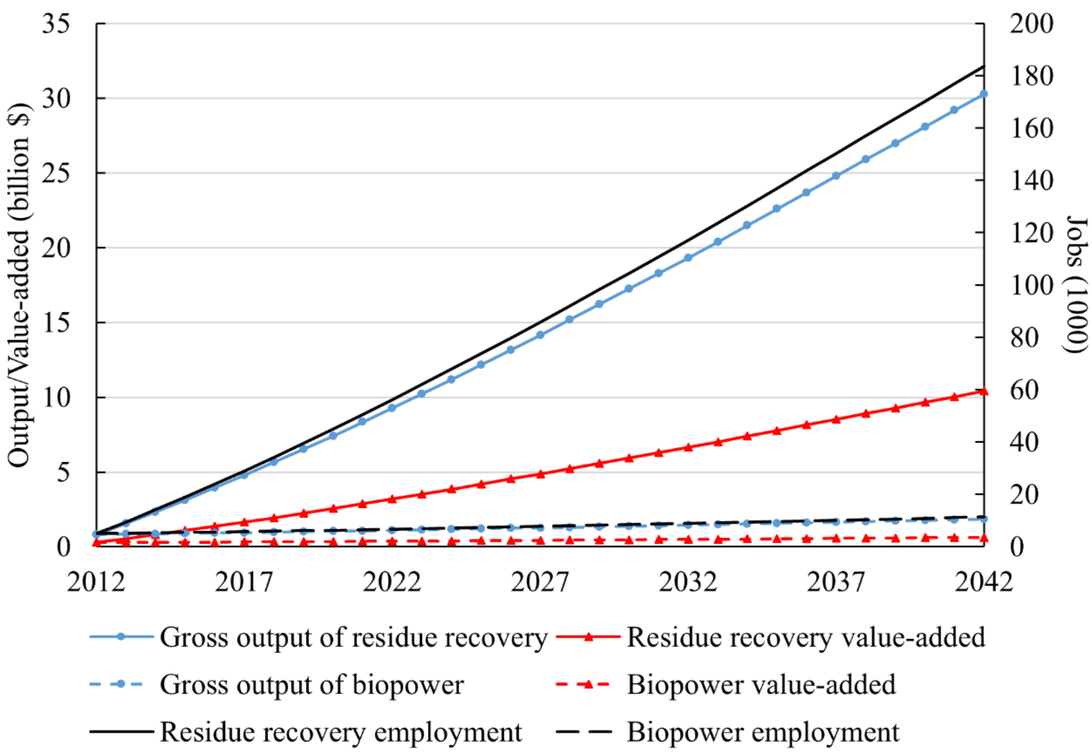

Figure 4.6. Economic impacts of forest biomass for electricity generation

Although bioenergy has advantages in reducing environmental impacts, it is still less competitive and accounts for a small portion of total energy consumption when compared to conventional (fossil fuel) energy in the electric power sector. Moreover, bioenergy has been policy-driven (as opposed to market-driven), and its growth, including new applications and improved cost-effectiveness, depends heavily on the advancement of existing and new technologies. In the scenario analysis of this section, future regulatory requirements for bioenergy use for electricity generation are assumed at four different levels: 0.3% (base case), 0.5%, 0.8% and 1% of the total electricity generation.

Since the projected supply of wood residue is much higher than the demand based on the current consumption of biomass for electricity generation, scenario analysis is carried out to explore dynamic changes in delivered price as it is affected by different levels of demand. Figure 4.7 shows the demand of wood residue for different levels of RPS or RES. The coal cost in the scenario analysis is assumed to be dynamic with an annual increase of \$1.38 tonne^{-1} yr^{-1}. Assuming other conditions remain the same, for a 0.5%, 0.8%, and 1% bioenergy portion of the total electricity consumption the delivered biomass prices are projected (in 2042) to be \$51.11 tonne^{-1}, \$112.86 tonne^{-1}, and \$237.98 tonne^{-1}, respectively. According to the estimated delivery cost range of wood residue (\$7.50-\$80 tonne^{-1}) from the literature [103]–[106] and the average coal cost for electric utilities (\$45 tonne^{-1}) [11] , for RPS/RES between 0.5% and 0.8%, the market for forest residue in electricity generation will be expanded.

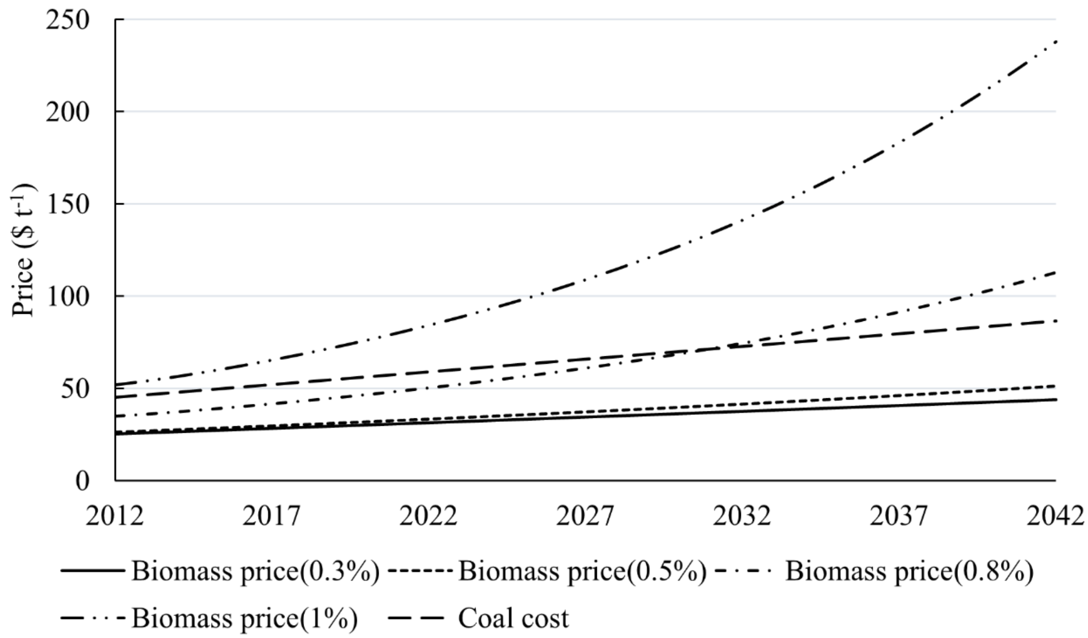

Figure 4.7. Scenario analysis of delivered biomass prices varied by different bioenergy shares

A requirement on bioenergy consumption for electricity generation can affect the cost of co-firing systems through changes in the delivered biomass cost. As is evident from Fig. 4.8, for several bioenergy scenarios (0.3% and 0.5% share), the biomass price is always less than the price of coal. For the 1% share scenario, the biomass price is always greater than the coal price. For the 0.8% share, the biomass price is initially less, but then in 2031 becomes greater than the coal price. Figure 20 shows the amount of annual savings a power plant could achieve (for 0.3% and 0.5% bioenergy share) for a co-firing system. Annual cost savings from reduced coal consumption in the co-firing system are estimated to increase to $36.9 million in 2042 under a 0.3% bioenergy share. For the 0.5% bioenergy share scenario, the highest annual cost savings is projected to be $24.8 million in 2036, but this will decrease to $22.8 million in 2042.

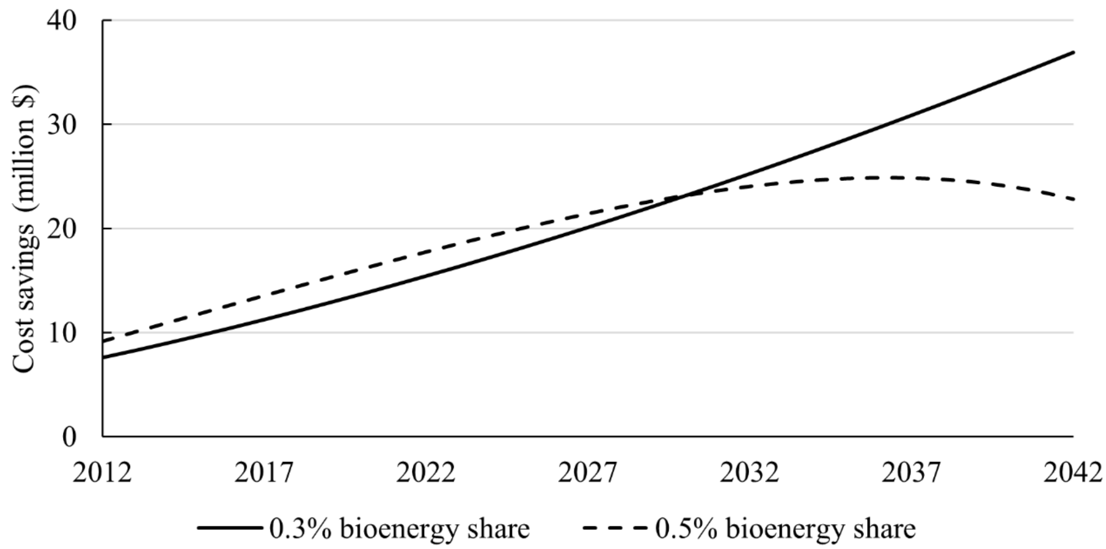

Figure 4.8. Scenario analysis of cost savings of co-firing systems by different bioenergy shares

Forest biomass for bioenergy electricity generation can be adjusted through market-based efforts versus regulatory initiatives, and can increase the demand for bioenergy in electricity generation, which serves to create environmental and socio-economic benefits. Moreover, increasing the demand for forest biomass for electricity generation can increase the price of delivered biomass and create a commercial market for forest residue. However, co-firing with high levels of forest biomass (e.g., biomass that results in more than 0.8% of the total electricity generation) may lead to less cost savings to a co-firing power plant (or even no cost savings) due to the long-term increase in delivered biomass price. The disproportionate increase in the delivered biomass price may increase the cost of bio-electricity, and the adoption of forest biomass for electricity generation will decrease in the co-firing system. This is an important consideration for a power plant; clearly, investing in a co-firing retrofit must provide suitable financial return or it will not be completed.

4.6 Model Limitation

The simulation of the ISM only provides a basic estimate of the sustainability performance of the bioenergy system. ISM is limited in its predictive capacity because it does not capture all the inherent aspects of reality. Model validation is one challenge for system dynamics problems. The field of system dynamics lacks formalized methodologies and tools for model validation [78]. Due to different system scopes relevant to the purpose and available information about the state of a system, it is hard to capture all key factors to reflect structure of a real system. For instance, the structure of the supply of forest residues is composite of the timberland area, forest biomass planted, growth rate of forest biomass, and the harvest ratio. All parameters included in the structure represent the real system of the supply of forest residues. The demand for forest residues is dedicated to local electricity generation. The utilization of forest residues for other biofuels may have influences on the supply of forest residue for bio-power. However, it was not taken into account in this study because of the uncertain economic feasibility of the technologies that convert forest residues into biofuels on a large scale. In addition, it is challenging to quantify and incorporate certain system behaviors, such as community perception, health impact, and biodiversity.

The output behaviors can either be validated based on available time-series data or the correlation of proposed models with reference models. For instance, in this study, the supply of forest residues and demand for electricity generation are conducted based on statistical analysis of the historical data of pulpwood production and the total residential electricity consumption, respectively. Unfortunately, there is no specific historical data for forest residue production for bio-power because a commercial market does not yet exist for forest residues. To address the uncertainties in quantifying the CO_2 savings from the utilization of forest residues in a co-firing system, the outputs are compared with other published results and were found to be in line with the previously published data. However, there exists lots of uncertainties for forecasting the behavior of CO_2 emissions associated with these assumed situations.

Another major limitation is the established land-use mechanism in this study. The land-use mechanism only considers the transition between forest land and crop land. Other land-use types, such as grass land, pasture and marginal land, can also be converted to forest land. In this land-use mechanism, the land-use change pattern is driven by the prices of timber and crop products. However, in reality, the adoption of biomass is also related to the familiarity to the biomass and the risk-aversion of a landowner, etc. [122]. Since the land-use change plays an important role in the supply of any biomass, it should consider some key social attributes of landowners to simulate how they make decisions on which products to grow.

Regardless of the limitations, the ISM does provide sustainability implications of the utilization of forest residues for electricity generation and opportunities to expand bioenergy market for electricity generation. The ISM method can inform business and policy decisions by capturing the decision tradeoffs of different parties in the utilization of forest residues for bio-power applications.

CHAPTER 5. ISM FOR CELLULOSIC ETHANOL SYSTEM IN THE U.S. MIDWEST

Jin, E., Sutherland, J. W. (2019). Integrated sustainability assessment for a bioenergy system: a system dynamics model of switchgrass for cellulosic ethanol production in the U.S. Midwest. in review for *Journal of Cleaner Production*.

5.1 Introduction

Dedicated energy crops including perennial grasses and woody crops have been identified as promising alternatives for conventional biomass (e.g., corn and soybean) to produce biofuels in the U.S. The revised Renewable Fuel Standard (RFS2) mandate under the Energy Independence and Security Act (EISA) requires that 16 billion gallons of cellulosic biofuels will be used for transportation fuel by 2022 [123]. Cellulosic biofuel has the potential to reduce 60% of the greenhouse gas (GHG) emissions including direct and indirect emissions compared to the 2005 baseline of petroleum products [123]. Furthermore, GHG emissions of cellulosic biofuels are also lower than the emissions of conventional biofuels [124]. Ethanol produced from corn starch still dominates the U.S. biofuel market, and commercial ethanol plant capacity reached 15.5 billion gallons per year in 2017. The U.S. Environmental Protection Agency (EPA) capped the annual conventional biofuel (e.g., corn ethanol) production at 15 billion gallons in 2015 and promoted the utilization of advanced and cellulosic biofuels.

Under EISA, the EPA mandates that obligated parties, such as gasoline and diesel producers, must demonstrate that they have met an annual Renewable Volume Obligation (RVO) for each renewable fuel category (conventional biofuel, advanced biofuel, cellulosic biofuel, and biomass-based diesel) [125]. To track compliance, Renewable Identification Numbers (RINs) are created by biofuel producers when the biofuel is produced. When the biofuel is purchased and blended into gasoline by the obligated parties, these RINs can be reported to the EPA to achieve compliance or can be sold to other companies to meet compliance needs.

In 2017, the EPA identified that the production of cellulosic biofuels was only 251 million gallons, which was only 4% of the annual mandated target (5.5 billion gallons) [125]. This shortfall was caused by the delayed commercialization of cellulosic biofuels, on account of costly and immature bioconversion technologies. Fuel blending requirements further limit the demand for biofuels, resulting in significantly slowed adoption of biofuel technologies. These technical and economic barriers to cellulosic biofuel commercialization can be addressed with emerging advanced technologies in the pretreatment process (e.g., two-stage dilute acid [126], ammonia fiber explosion [127], biological pretreatment by fungi, bacteria and enzymes [128]). While these technologies may be implemented in time, the commercialization of cellulosic biofuels may have other social or environmental benefits which warrant more rapid commercialization than would be driven by the market.

5.2 ISM for Cellulosic Ethanol System

Figure 5.1 provides the structure of the ISM and the interrelationships among sub-models. Cellulosic biofuel production depends on the biorefinery expansion and feedstock supply. The biorefinery expansion is determined by the economic viability for operating a biorefinery, which is related to the market prices of cellulosic biofuel and feedstock. LUC for energy crops is driven by the feedstock demand for cellulosic biofuels and is also affected by the profitability of growing energy crops. Feedstock supply relies on the land acreage for energy crops and the demand is driven by both the cellulosic biofuel industry and compliance with the regulatory mandate. Environmental impacts are assessed based on the LUC for energy crops and production of cellulosic biofuel. Economic impacts are calculated based on the economics of the industry. Finally, social impacts are related to GHG emissions and the revenues of the cellulosic biofuel industry. Details for each sub-model are discussed in Section 2.2.

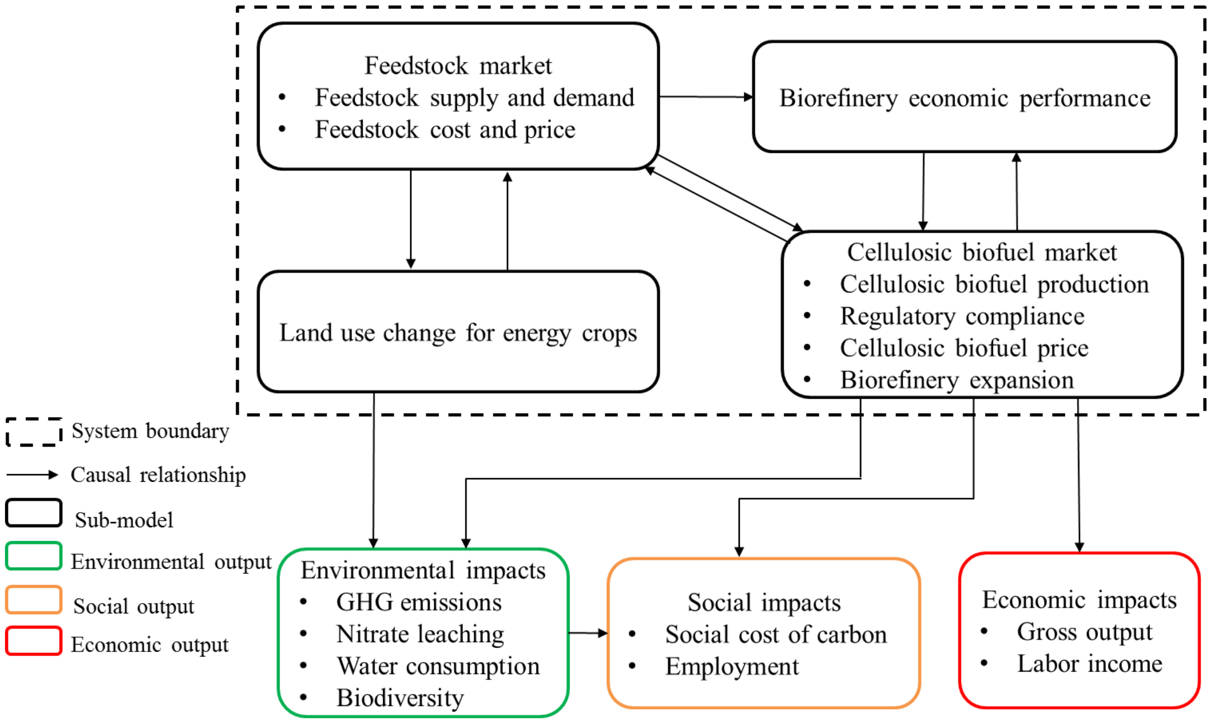

Figure 5.1. Structure of the integrated sustainability model

5.3 Cellulosic Ethanol System

The U.S. biofuels market is dominated by conventional starch-based ethanol. Corn grain accounts for more than 90% of the total feedstock for corn ethanol. According to the recent estimates from the Energy Information Administration (EIA) state energy data system [129], the 10 states (IL, IN, IA, MI, MN, NE, ND, OH, SD, WI) in the U.S. Midwest accounted for 84.2% of U.S. fuel ethanol production in 2016. 168 out of the 214 U.S. ethanol plants are located in these states [130]. Therefore, this study investigates these regions where energy crops and cellulosic biofuel facilities will expand. It is assumed that the cellulosic biofuel production generated in these states will meet 84.2% of the demand for cellulosic biofuels. Switchgrass (*Panicum virgatum L.*) and cellulosic ethanol are selected as the feedstock and biofuel product of interest, respectively, owing to the availability of data and the viability of widespread use. There were five commercial-scale cellulosic ethanol plants with a total production capacity of 61.6 million gallons in the U.S. by the end of 2016 [130]. The feedstock for cellulosic ethanol in these biorefineries was corn stover. However, the domestic generated volume of cellulosic ethanol was 6.4 million gallons in 2018

[131]. The remaining compliance of cellulosic biofuel was from renewable compressed and liquefied natural gas.

Other key information includes that the life span of a cellulosic ethanol biorefinery is assumed to be 15 years. It is assumed that switchgrass requires 1 year to become productive and will remain productive for 15 years before replanting is required [132]. In this study, the increasing demand for cellulosic biofuel is assumed to be met by cellulosic ethanol from switchgrass from 2015 to 2030. The sub-models used historical data based on the Midwest region of the U.S. in their assumptions.

5.4 Sub-models for Cellulosic Ethanol System

The cellulosic biofuel system develops sub-models for cellulosic biofuel market, feedstock market, land-use change for energy crops, and biorefinery economic performance. The ISM also predicts several environmental impacts and socio-economic measures.

5.4.1 *Cellulosic biofuel and feedstock markets*

The sub-model for cellulosic biofuel market imposes a compliance mechanism used by the RFS2 program to regulate the requirement for cellulosic biofuels. According to the annual compliance data between 2013 and 2017 for obligated parties [131], the annual RVOs and the projected volume obligations are increasing by 78.7 million gallons and 81.7 million gallons, respectively. The annual RVOs for obligated refiners is the sum of renewable fuel production in the current year and the deficit from the previous year.

In the sub-model for the cellulosic biofuel market, the demand for RVOs in the cellulosic biofuel system is investigated using two scenarios based on the current trends (baseline) and the RFS2 mandate (see more details in Section 5.6.2). The interrelationships among key variables in the sub-model of cellulosic biofuel supply and demand are presented in Fig. 5.2. The expansion rate of biorefineries is determined by the annual demand for cellulosic biofuels and the deficit of RVOs in the previous year. The internal rate of return (IRR) is used commonly as a metric for investors to estimate the profitability of a project. This study assumes that a cellulosic ethanol biorefinery will be built if the interval rate of return over a 15-year investment period is greater than the discount rate (10%). The annual RINs of cellulosic ethanol are set equal to the annual volume of cellulosic ethanol. The biorefinery expansion rate is the amount of new biorefineries that can meet the annual increase in demand for cellulosic ethanol. The available cellulosic ethanol production is determined by either the annual feedstock provision or the consumption, whichever value is lower. For example, if the supply of feedstock is less than the consumption, the cellulosic ethanol is limited by the available feedstock. The feedstock provision is related to the land acreage of switchgrass and the productivity of switchgrass. The annual consumption of feedstock depends on the total capacity of operating biorefineries.

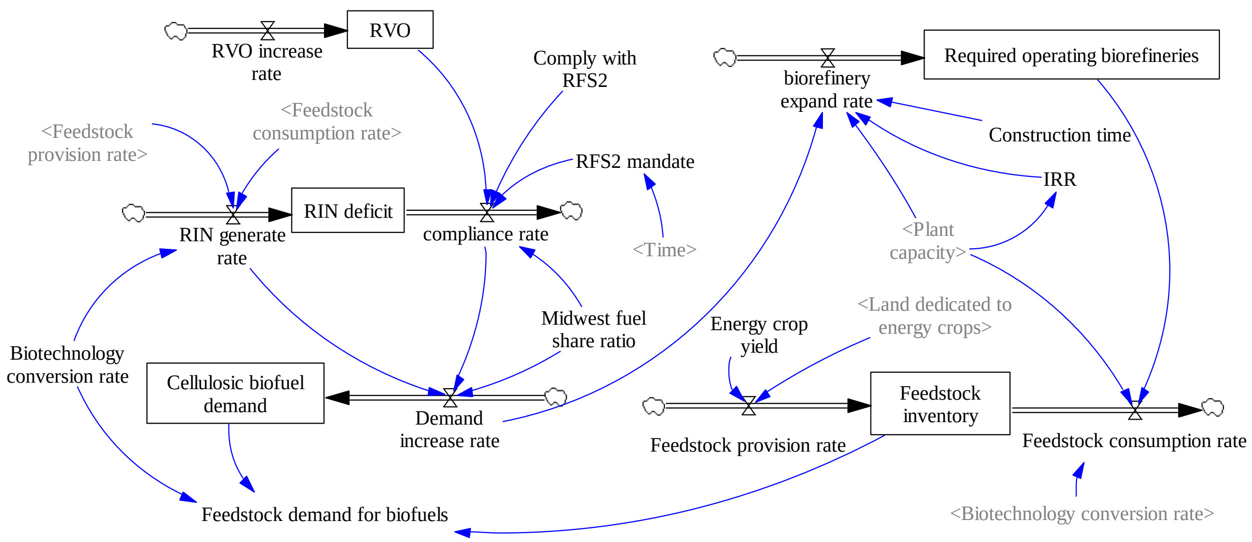

Figure 5.2. Stock and flow diagram for the cellulosic biofuel and feedstock markets sub-model

5.4.2 *Cellulosic biofuel price and biorefinery economic performance*

Since cellulosic biofuels have not yet been fully commercialized, the price of cellulosic biofuel is uncertain and may fluctuate due to several factors. In general, the price of cellulosic biofuel will change according to the gasoline price and the upper bound of the cellulosic biofuel price is equal to the gasoline blend value (GBV), which is the adjusted price for mileage and blending properties [133]. For example, use of blended fuel (E10) with a 10% ethanol blend causes a 3% mileage loss in typical flex-fuel vehicles. The GBV of cellulosic biofuel is the sum of adjusted price for mileage, RIN price, and the blender's tax credit (see Eq. (1)). When the supply of cellulosic biofuel is less than the demand, the price of cellulosic biofuel approaches the gasoline price. Conversely, when the supply exceeds the demand, the price of cellulosic biofuel approaches the marginal cost of cellulosic biofuel. The blenders and producers are assumed to share the difference between the GBV ceiling and the marginal cost floor that reflects the marginal gain available for blenders and producers to capture. The price of cellulosic biofuel (P_c) is calculated as Eq. (5.2).

$$GBV = P_g \cdot (1 - \varepsilon) + RIN_C + t \tag{5.1}$$

$$P_c = GBV - \rho_b \cdot (GBV - MC_c) \tag{5.2}$$

where P_g is the price of gasoline (\$ gal^{-1}); ε is the mileage loss of the blend fuel in a typical flex-fuel vehicle; RIN_c is the RIN price of cellulosic biofuel (\$ gal^{-1}); t is the tax credit (\$ gal^{-1}); ρ_b is the capture of blenders (assumed value is 20%); and MC_c is the marginal cost of cellulosic ethanol production (\$ gal^{-1}).

A cellulosic waiver credit (CWC) is a credit that blenders can purchase to comply with the current year's EPA requirement. CWC price is set to be the greater value of \$0.25 or \$3.00 minus the wholesale price of gasoline, where both \$0.25 and \$3.00 are adjusted for inflation [134]. The RIN price of cellulosic biofuel production is affected by the dynamic changes of the RIN price of advanced biofuels and CWC. The RIN price of cellulosic biofuel production is the sum of the RIN price of advanced biofuels and CWC [133]. The RIN price of advanced biofuels is estimated by following a distribution of *N* (0.68, 0.2) within the range from 0.15 to 1.50.

In the sub-model for cellulosic biofuel price and profit, the key variables in the feedstock supply chain and technological process are incorporated as shown in Fig. 5.3. The unit cost of cellulosic biofuel is comprised of the feedstock cost, transportation cost, fixed cost, and variable operating cost. The feedstock price of the energy crop is uncertain since there is no large-scale commercial market for cellulosic biomass. The feedstock price of the energy crop must be able to compete with other crops in order for land owners to be willing to produce an energy crop. Therefore, the minimum feedstock farm gate price is the price where the profit of growing the energy crop is equal to the maximum value between the profit of growing a food crop and the cash rent of cropland. The feedstock cost includes grower payments, harvest costs, and storage and handling costs. Corn is used as the comparison food crop in this study. The calculation of corn profit is based on the historical data of the corn cost, yield, and price.

The biorefinery is set to produce cellulosic ethanol via biochemical conversion associated with a feedstock processing capacity of 2000 dry tonnes per day [135]. The capital investment for construction and equipment installation is obtained from the Jobs and Economic Development Impact (JEDI) models developed by the NREL (National Renewable Energy Laboratory, 2015). Net cash flow is calculated (see Eq. (3)) to provide the annual net present value (NPV) for the cellulosic ethanol facility and the internal rate of return (IRR). The revenue of a cellulosic ethanol facility includes the sale of cellulosic ethanol and byproducts (e.g., electricity and biochemicals) [137]. Policy incentives, such as government subsidies, can also contribute to the revenue. The NPV is a net cash return of a biofuel facility (see Eq. (4)) and the IRR is usually a metric for investors to estimate the profitability of potential investments (calculated as Eq. (5.5)).

$$NCF_t = Cap \cdot (P_c - MC_c) \tag{5.3}$$

$$NPV = -I_0 + \sum_{t=1}^{N} \frac{NCF_t}{(1+r)^t} \tag{5.4}$$

$$0 = NPV = -I_0 + \sum_{t=1}^{N} \frac{NCF_t}{(1+IRR)^t} \tag{5.5}$$

where *Cap* is the biofuel capacity of a facility (Million gallons), I_0 is the capital investment (Million dollars), and r is the discount rate (10%).

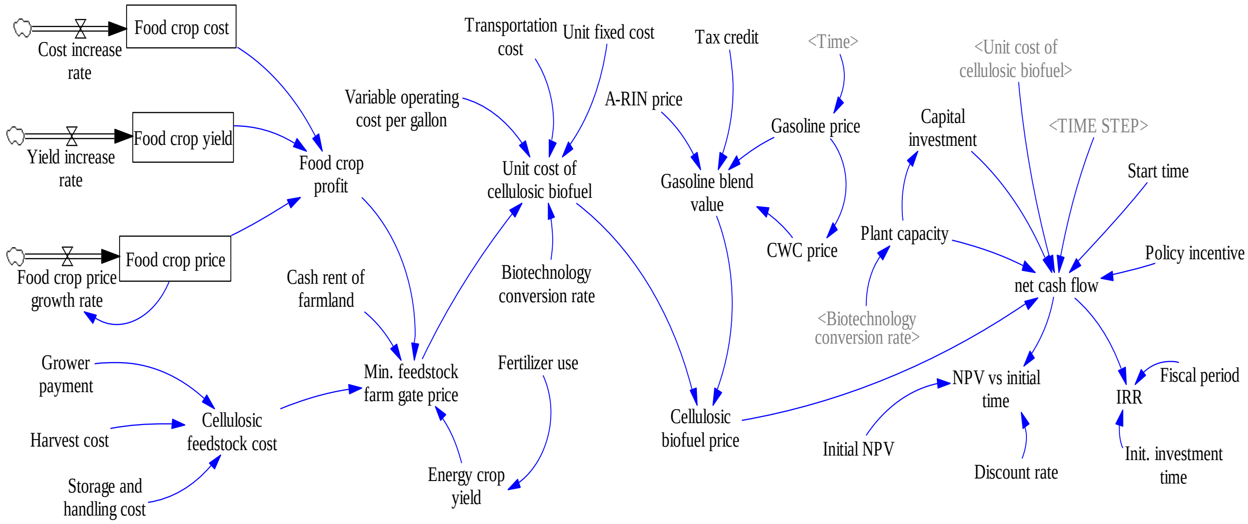

Figure 5.3. Stock and flow diagram of the cellulosic biofuel price and biorefinery economic performance sub-models

5.4.3 *Land-use change for energy crops*

A sub-model is developed for land use change between marginal land, pasture, and cropland (see Fig. 5.4). Land-use change plays a key role in the supply of cellulosic feedstock for biofuels, and uncertain land availability for growing energy crops is a critical issue for cellulosic biofuel development.

In this study, marginal land, pasture, and cropland are potential alternatives for land dedicated to energy crops. In the U.S. Midwest, cropland accounts for 52% of the total rural land, while the remaining 48% of rural lands include forest land, rangeland, and pasture. According to historical LUC trend, 77% of all new croplands were converted from pasture from 2008 to 2012 in the U.S.[138]. Table 5.1 shows the net average change rate for the U.S. Midwest cropland and pasture in 1982 and 2015. The acreage of marginal lands was estimated to be 11.36 million hectares in 10 states of the U.S. Midwest by Environmental Policy Integrated Climate (EPIC) model [139].

Table 5.1. Annual net change rate for each type of land in the U.S. Midwest [140]

	Cropland (Mha)	Pasture (Mha)
1982	75.1	11.6
2015	71.8	10.1
Annual net change rate (Mha yr^{-1})	-0.1	-0.05

To mitigate land competition between food crops and energy crops, it is assumed that converting marginal land to energy crop land is the preferred option. Pasture and cropland will be converted to energy crop land after all available marginal lands are converted. The marginal land change rate depends on the feedstock demand for cellulosic ethanol and energy crop productivity. In addition, cropland and pastureland will be converted to energy crop land only if the land profit for growing an energy crop is higher than profits for growing agricultural crops or rent value for other land-uses. This assumption indicates that the land owners are profit driven when deciding whether pasture, marginal land, or cropland is converted to energy crop land. The rent value of marginal land is neglected in this study due to the lack of available information. The maximum change rates for lands (excluding marginal land) are based on the data in Table 2 in order to reflect practical land change behaviors. Annual desired energy crop land is mathematically expressed as Eq. (5.6):

$$L_D = \frac{D_e}{Y_E} - L_E \tag{5.6}$$

where D_e is the feedstock demand for biofuels (Mha); Y_E is the yield of switchgrass (t ha^{-1}); and L_E is the existing land dedicated to switchgrass (Mha).

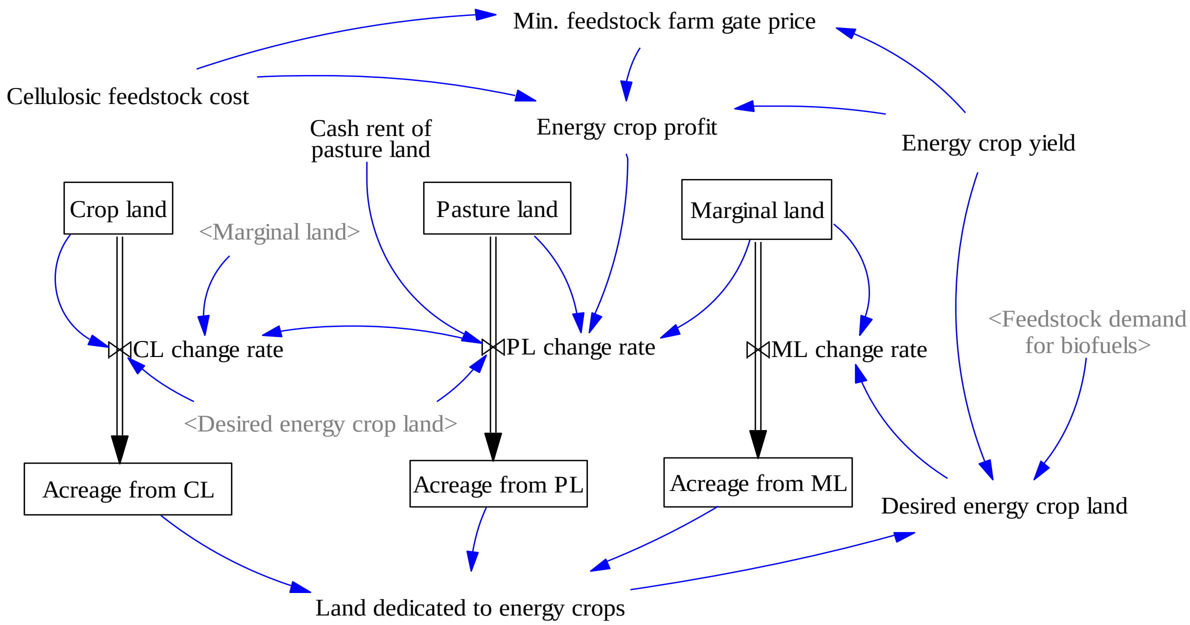

Figure 5.4. Stock and flow diagram for the land-use change for energy crop sub-model

5.4.4 *Environmental impact assessments*

The sub-models of cellulosic biofuel production and land-use change can be used as inputs to quantify the environmental impacts. The predicted environmental impacts are GHG emissions, soil carbon storage, nitrate leaching, water consumption, and biodiversity change (see Fig. 5.5). The GHG emission of cellulosic biofuel is estimated based on a life cycle analysis of cellulosic ethanol using feedstock to fuel product as system boundaries. The scenario of a biorefinery with an annual capacity of 60 million gallon analyzed in Murphy and Kendall (2015) is practical for producing cellulosic biofuels using a dilute acid pretreatment with the bioconversion technologies, where cellulosic ethanol production has a GHG emission of 46.3 g $CO_{2\text{-eq}}$ MJ^{-1} [66].

GHG emissions from LUC for energy crops are considered in this system. Besides cropland, marginal lands or poor grasslands are potential lands for cultivating energy crops with GHG benefits through soil carbon sequestration. However, direct and indirect changes of land can lead to nitrous oxide (N_2O) emissions from the use of nitrogen-based fertilizers for energy crops. Nocentini et al. (2018) analyzed the soil GHG emissions including soil organic carbon (SOC) change and N_2O emissions caused by the conversion of different land types to switchgrass land. This study uses the results estimated in Nocentini et al. (2018) to calculate the GHG emissions from SOC storage and N_2O emissions (see Table 5.2). As shown in Table 5.2, an increase of soil carbon storage will occur when cropland is converted to switchgrass land. In contrast, converting pasture to switchgrass land will result in a loss of SOC. Converting land into energy crop lands can cause an increase in N_2O emissions due to the use of nitrogen fertilizer. In general, the GHG emissions from direct and indirect LUC cannot be ignored.

Table 5.2. Mean SOC change and mean N_2O emissions for different LUC scenarios [132]

LUC scenarios	Mean SOC change (Mg ha^{-1} $year^{-1}$)	Mean N_2O emissions (kg ha^{-1} $year^{-1}$)
Marginal land to switchgrass	0.014	1.94
Cropland to switchgrass	0.27	1.7
Pasture to switchgrass	-0.23*	1.9

*Negative value indicates a loss of SOC

Nitrate leaching can be reduced by converting cropland to switchgrass land. Preventing nutrient loss from soil to water can also reduce the cost of crop production. However, growing switchgrass on other types of land leads to nitrate leaching due to the use of fertilizers. The nitrate leaching of LUC for switchgrass is taken into account for GHG emissions (see Eq. (5.7)). The total reduction in GHG emissions of cellulosic biofuel is calculated by comparison with the GHG emissions of gasoline [132].

$$\vartriangle CO_2 = (E_g - E_c) \cdot R_c \cdot H_c + \vartriangle SOC \cdot 3.67 + \vartriangle Nitrate \cdot 0.0075 \cdot 298 - \vartriangle N_2O \cdot 298 \quad (5.7)$$

where E_g and E_c are the GHG emissions of gasoline and cellulosic ethanol (gCO_2 MJ^{-1}), respectively. R_c is the annual RINs of cellulosic ethanol (Million gallons) and H_c is the energy content of cellulosic ethanol (MJ gal^{-1}).

The water consumption of cellulosic biofuels is caused by the irrigation of the feedstock crops and the water used in the bioconversion process. Energy crops such as switchgrass require much less water to grow and are more tolerant to water shortage compared to food crops [141]. The estimations of water use in the production of cellulosic ethanol, conventional ethanol, and gasoline are derived from the study conducted by Argonne National Laboratory [142].

A sub-model is developed to estimate the impacts of cellulosic biofuels on biodiversity. Biodiversity change is mainly affected by LUC. Bird species richness is widely used as a proxy for biodiversity and is used here to of biodiversity change. The bird species richness is related to the acreage converted from cropland and encountered at-risk species are related to the acreage converted from cropland and pastureland. The calculations of bird species richness and encountered at-risk species are expressed as Eq. (5.8) and Eq. (5.9), respectively.

$$BSR(t) = BSR(0) + \int r_{bs}\, dt \tag{5.8}$$

$$ERS(t) = ERS(0) + \int [r_{CL} \cdot l_{CL} + r_{PL} \cdot l_{PL} + r_{CPL} \cdot (l_{CL} + l_{PL})] dt \tag{5.9}$$

where *BSR* is bird species richness and *ERS* is the encountered at-risk species; r_{bs} is the bird species increase when cropland is converted to energy crop land; r_{CL} and r_{PL} are the at-risk species that can be affected by LUC in cropland only and pasture only, respectively (species Mha^{-1}), and r_{CPL} is the at-risk species encountered by LUC in either cropland or pasture (species Mha^{-1}); l_{CL} and l_{PL} are the annual acreage change in cropland and pasture, respectively (Mha yr^{-1}).

5.4.5 *Social benefits*

The sub-model of social benefits is developed to measure the SCC savings from reductions in GHG emissions (see Fig. 5.5). The average SCC of the U.S. were estimated by the EPA from 2010-2050 (see Table 5.3). These SCCs are estimated based on different discount rates at 2%, 3%, and 5%. The sub-model of the SCC uses the value of the SCC at a 3% discount rate to predict the potential economic benefits from CO_2 reduction caused by the utilization of cellulosic biofuels. The savings of SCC is calculated as Eq. (5.10).

$$\triangle SCC_t = SCC_t \cdot \triangle CO_2 \tag{5.10}$$

Table 5.3. Social cost of CO_2 in the U.S., 2010-2030 ($ tCO_2^{-1}) [143]

Year	5% Average	3% Average	2% Average
2010	10	31	50
2015	11	36	56
2020	12	42	62
2025	14	46	68
2030	16	50	73

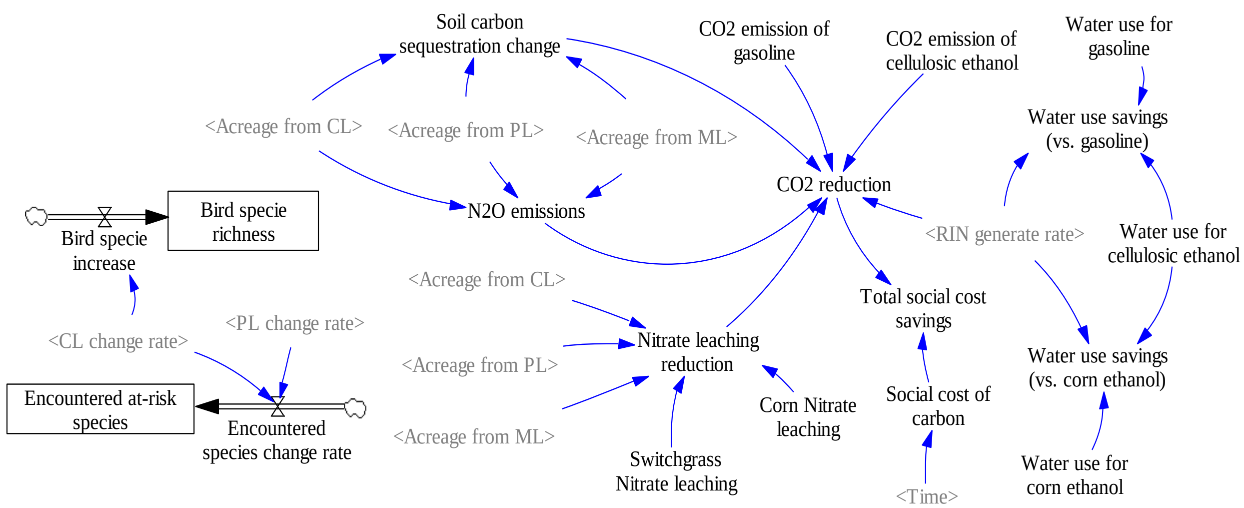

Figure 5.5. Stock and flow diagram of environmental and social impact sub-models

5.4.6 *Economic analysis*

The sub-model for economic analysis is shown in Fig. 5.6. The economic contribution of the cellulosic biofuel system is related to the cellulosic biofuel industry and market. The increasing demand for cellulosic biofuel drives the expansion of biorefineries with an economically viable production capacity. The construction and operation of a biorefinery can offer job opportunities for local people and the sale of cellulosic biofuel can increase the gross domestic product. The economic impact of a cellulosic ethanol biorefinery is analyzed by using an economic input-output (EIO) model created by NREL (National Renewable Energy Laboratory, 2015). The EIO model can estimate the economic impacts associated with the construction and operating expenditures of a new cellulosic ethanol facility. Table 5.4 quantifies the economic impacts of a cellulosic ethanol biorefinery with two different plant sizes during the construction and operation periods. The economic impact indicators include employment, gross output, and earnings. The multiplier of each economic impact indicator is provided to estimate the total changes in that economic impact due to an additional final demand.

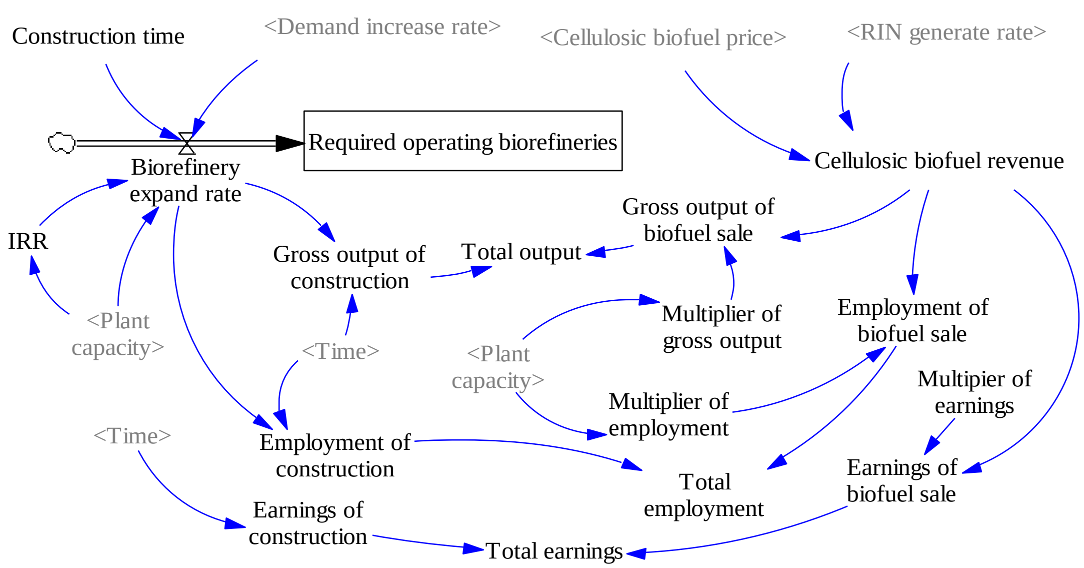

Figure 5.6. Stock and flow diagram of economic impact sub-model

Table 5.4. Economic impacts for a cellulosic ethanol biorefinery

		Plant capacity (million gallons)	
		54	75.6
Construction	Gross output (M$)	1,878.57	2,629.99
	Earnings (M$)	619.97	876.97
	Employment (jobs)	8,261	11,566
Multipliers for operation	Gross output (M$/M$)	2.34	2.34
	Earnings (M$/M$)	0.49	0.47
	Employment (jobs/M$)	7.74	7.27

The timeline of the simulation is from 2015 to 2030. The key simulation parameters are listed in Table A4 in the Appendix and the data are derived from relevant pilot-scale studies. 2015 data is used for the initial values. Both current and future bioconversion technologies are examined in the base scenario and make projections using the current trends in annual cellulosic biofuel production and compliance rates. The RFS2 scenario is conducted based on the requirement of cellulosic biofuel in the RFS2 program.

5.5 Model Validation

Validation of the system dynamics model aims to assess divergence between the dynamic model prediction and actual behaviors [77]. The validation includes structural and behavioral tests. The structural test verified the relationship among parameters and the consistency of units. The behavioral test was performed by comparing the projected behaviors with historical data and sensitivity analysis. The historical data of cellulosic biofuel RIN price (C-RIN) is used to validate the model's behavior. Figure 5.7 shows the comparison between predicted C-RIN and its historical data. The projected C-RIN has a similar behavior with the historical data. The sensitivity analyses for key uncertain parameters have been conducted in Section 5.6.1.

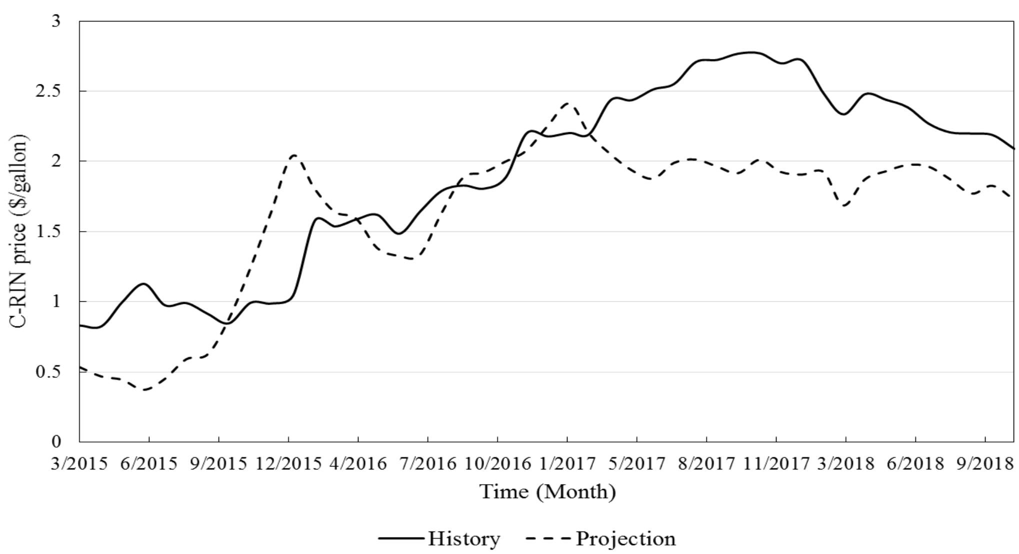

Figure 5.7. Comparison of the projected and historical C-RIN prices

5.6 Results and Discussion

There will be a huge demand for cellulosic biofuel due to the RFS2 mandate. However, the expansion of cellulosic biofuel use is determined by the economic viability of cellulosic biofuel commercialization. One of the key factors in the commercialization of cellulosic biofuel is the market price of cellulosic biomass, which affects the decision of investors to produce cellulosic biofuel. The biorefineries utilizing current and future bioconversion technologies are assumed to have an annual production capacity of 54 and 75.6 million gallons, respectively. Figure 5.8 includes the projected prices of cellulosic ethanol, the annual IRRs, and the net present value of return for two biorefineries with different capacities. The average biofuel price (\$3.22 gal^{-1}) for a biorefinery with an annual capacity of 75.6 million gallons is lower than the price (\$3.35 gal^{-1}) for a biorefinery with an annual capacity of 54 million gallons. When the gasoline price is consistent for both cases, the biorefinery with a lower marginal cost of cellulosic ethanol production has a lower selling price of cellulosic ethanol. Biorefineries utilizing more efficient bioconversion technologies can increase capacity with the same feedstock inputs. The IRR for a biorefinery with a 75.6 million gallon capacity is 13.5% and the IRR for a biorefinery with a 54 million gallon capacity is 8.1% for a 15-year investment period. Therefore, a biorefinery with a 54 million gallon capacity is not a strong investment opportunity since it has an IRR that is lower than 10%. A simulation is used to identify that for an IRR of 10%, the minimum viable capacity of a biorefinery is 60 million gallons with a bioconversion efficiency of 83 gallons t^{-1}. These values indicate the efficiency required for the biorefinery to be a cost-effective investment. Moreover, the payback period for a large capacity biorefinery is 10 years and a relatively small sized biorefinery will not be profitable by the end of 2030 (see Figure 5.8c). Since a biorefinery with a 54 million gallon capacity is not worth the investment, the rest of the discussion will focus on the results from a biorefinery with a 75 million gallon capacity.

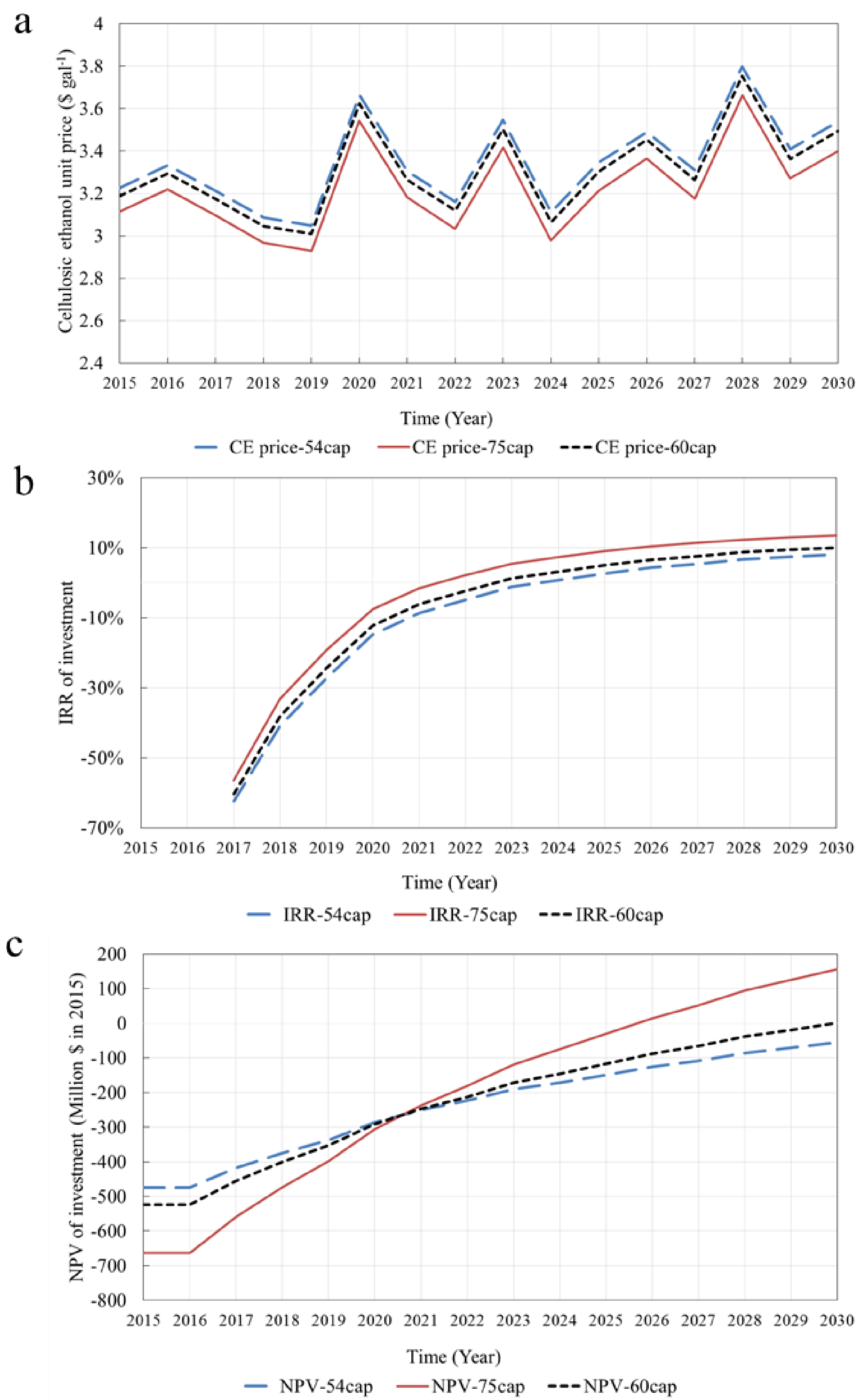

Figure 5.8. Projected behaviors of (a) cellulosic ethanol price (b) IRR of investment on a biorefinery (c) NPV of a biorefinery

The supply and demand for cellulosic ethanol are shown in Figure 5.9(a). The production of cellulosic ethanol will exceed the demand for complying with the projected RVOs in 2023. There will need to be 11 additional operating cellulosic ethanol biorefineries to meet the demand for cellulosic ethanol in that year. The annual production of cellulosic ethanol can meet demand from 2023 to 2030. The annual production of cellulosic ethanol is projected to be 1.36 billion gallons in 2030. The results shown in Figure 5.9(b) indicate that the feedstock supply is lower than the demand based on the expansion of cellulosic ethanol use before 2023. As annual cellulosic ethanol demand increases, the demand for switchgrass increases. Prior to 2023, the demand for switchgrass is driven by the cumulative deficit of RINs. After 2023, when the supply of cellulosic ethanol can meet demand, the demand for switchgrass is driven by the consumption of operating cellulosic ethanol biorefineries. The feedstock supply mainly depends on the land area for switchgrass and the yield of switchgrass. Land dedicated to energy crops is estimated to be 1.54 million hectares in order to meet the demand in 2030. The available marginal land in the Midwest can be used to grow switchgrass without LUC in other lands. Annual switchgrass production with a yield of 9 t ha^{-1} is projected to be 13.88 million tonnes in 2030. Under the conditions of the basic scenario, cellulosic ethanol can be produced stably from switchgrass grown on marginal land in order to meet the slowly increasing demand for cellulosic biofuels.

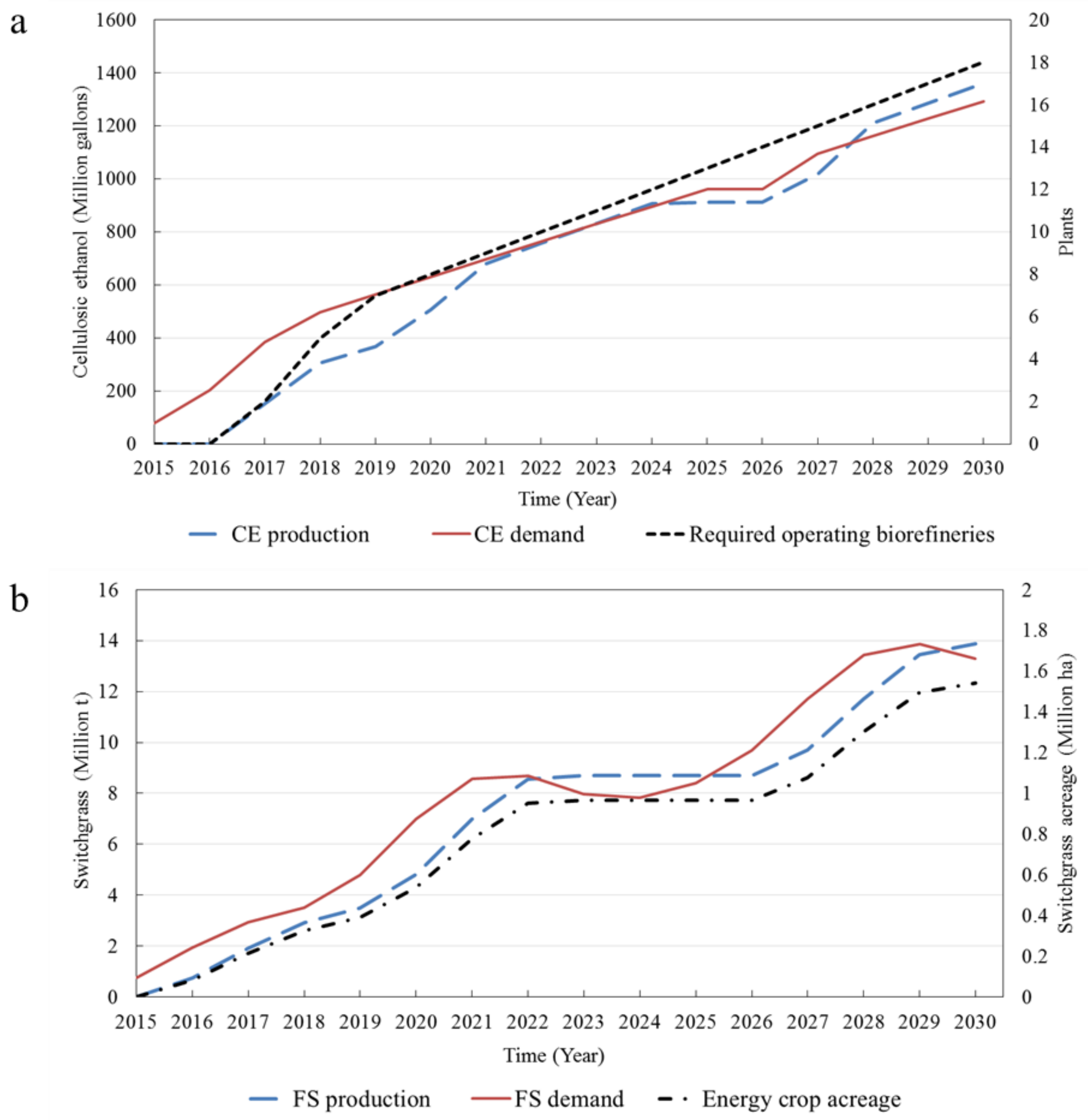

Figure 5.9. Projections of (a) cellulosic ethanol supply and demand (b) feedstock supply and demand

The soil carbon storage and nitrate leaching for switchgrass cultivation are shown in Figure 5.10. In this case, the soil carbon storage and nitrate leaching are caused by the LUC in marginal land for growing switchgrass. There will be an annual increase of 21.6 thousand tonnes of soil organic carbon sequestered in 2030. However, the total amount of nitrate leaching caused by growing switchgrass on marginal land will increase to 3,239 tonnes by the end of 2030. Meanwhile, the annual water use savings for cellulosic ethanol are estimated to be 8.85 and 1.13 billion gallons compared to the use of convention ethanol and gasoline, respectively. The GHG emissions will increase in the first two years due to the direct LUC for planting switchgrass. From the third year onward, the reduction in GHG emissions of cellulosic ethanol production can offset the increased GHG emissions from the LUC in marginal land. The total reduction in CO_2 emissions for cellulosic ethanol and LUC is projected to be 4.69 million tonnes (see Figure 5.10(a)) in 2030. Biodiversity in birds and other at-risk species will not change because no cropland and pasture will be converted to switchgrass land in the basic case.

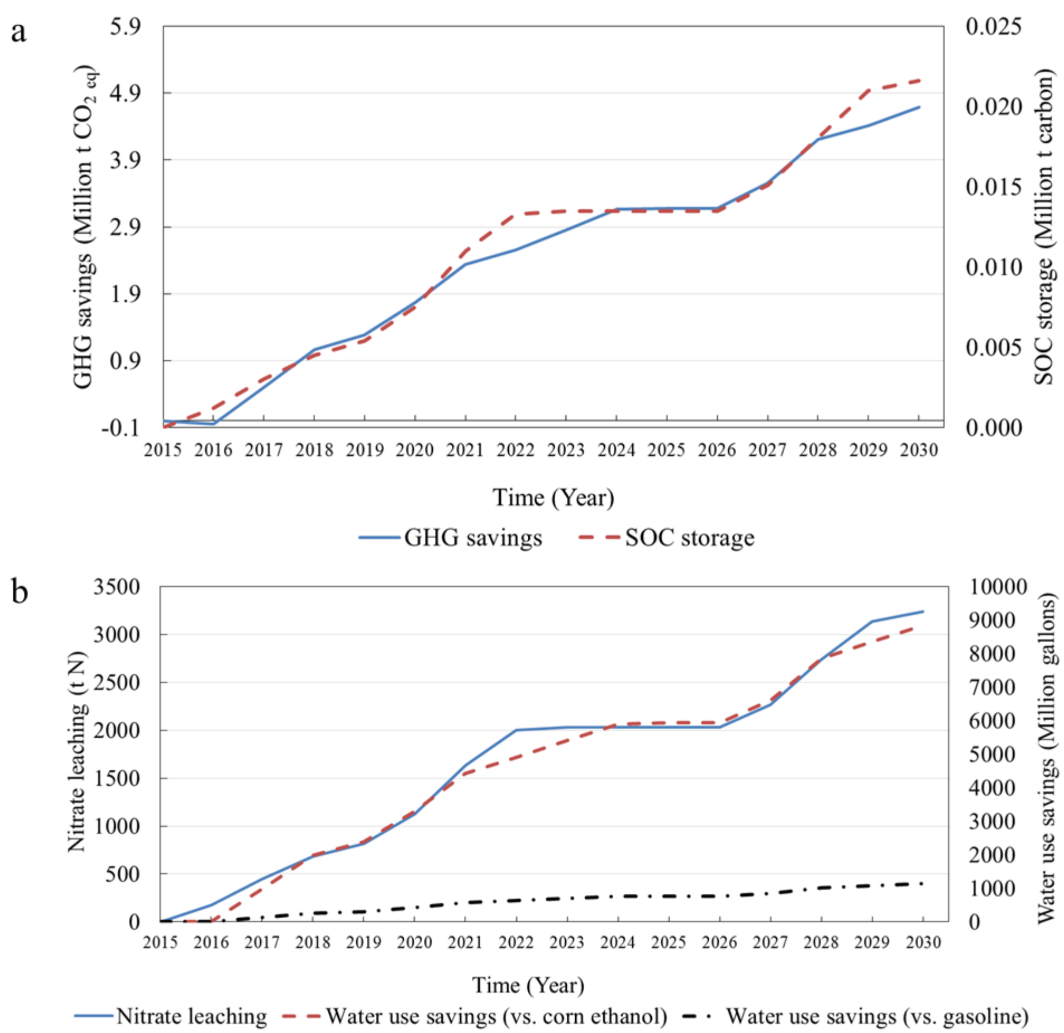

Figure 5.10. Projected environmental impacts of cellulosic ethanol system. (a) GHG reduction and SOC storage (b) Nitrate leaching and water use savings

Economic impacts for cellulosic ethanol production are simulated in terms of gross output and employment. The economic impacts are created during the facility construction period and during the sale of cellulosic ethanol. Figure 5.11(a) shows that the annual gross output and earnings are projected to be more than $113 billion and $2.9 billion in 2030, respectively. Moreover, the cellulosic ethanol industry can provide 44,099 jobs in the Midwest, especially for people living in rural areas. The average earnings per job is calculated to be $67,375 in 2030. The GHG reduction of cellulosic the ethanol system will generate a total saving of SCC by $234 million in 2030 (see Fig. 5.11(b)).

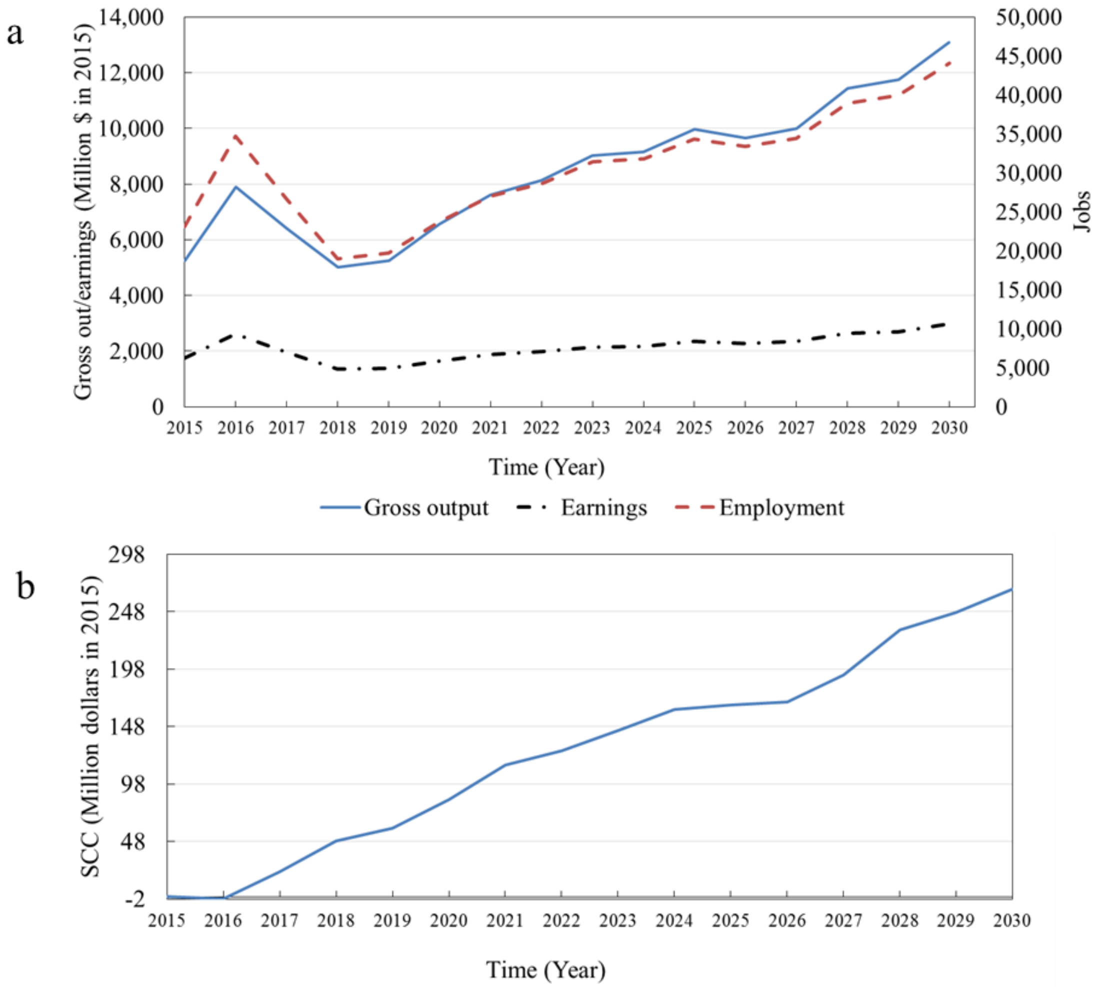

Figure 5.11. Projected (a) economic and (b) social impacts of the cellulosic ethanol system

5.6.1 *Sensitivity analysis*

Since cellulosic biofuel is not yet commercialized and all the related work is performed at pilot scale, there are many uncertainties in the cellulosic biomass supply chain and cellulosic biofuel production process. In this section, sensitivity analyses are conducted to examine the effects of uncertainties in several key variables on the cellulosic biofuel economics and environmental performance. The switchgrass productivity depends on the type of cultivator, fertilizer use, and location. The yield of switchgrass on marginal land ranges from 7.5 to 12 Mg ha^{-1} [132], [144], [145] and the bioconversion rate for cellulosic ethanol ranges from 289 to 399 L t^{-1} [127], [146]. The GHG emissions of the cellulosic ethanol system are also uncertain owing to a variety of bioconversion rates and switchgrass productivities. Table 5.5 shows the variation in life cycle GHG emissions of cellulosic ethanol production from different combinations of bioconversion rates and the yields of switchgrass. The results in Fig. 5.12(a) show that the changes in bioconversion rate and the yield of switchgrass can adjust the IRR of a biorefinery from 4.3% to 15.2% for a 15-year investment period. A high switchgrass yield enables a biorefinery using current bioconversion technology to be economically viable, because it increases the 15-year IRR to 11%. Figure 5.12(b) depicts the differences in total GHG reduction of the cellulosic ethanol system under different combinations. Under high yield conditions and high bioconversion rates for switchgrass, the cellulosic ethanol system has 16% more GHG savings than the baseline case by the end of 2030. Improving the efficiency of bioconversion technology and the productivity of switchgrass can make significant contributions to the growth of the cellulosic biofuel industry and the environmental performance of cellulosic biofuel production.

Table 5.5. GHG emissions of cellulosic ethanol under various conditions [66]

	GHG emission of cellulosic ethanol (t $CO_{2\text{-}eq}$ MJ^{-1})	
	High yield of switchgrass (12 t ha^{-1})	Low yield of switchgrass (7.5 t ha^{-1})
High bioconversion rate (399 L t^{-1})	41.8	46.6
Low bioconversion rate (289 L t^{-1})	50.8	61.2

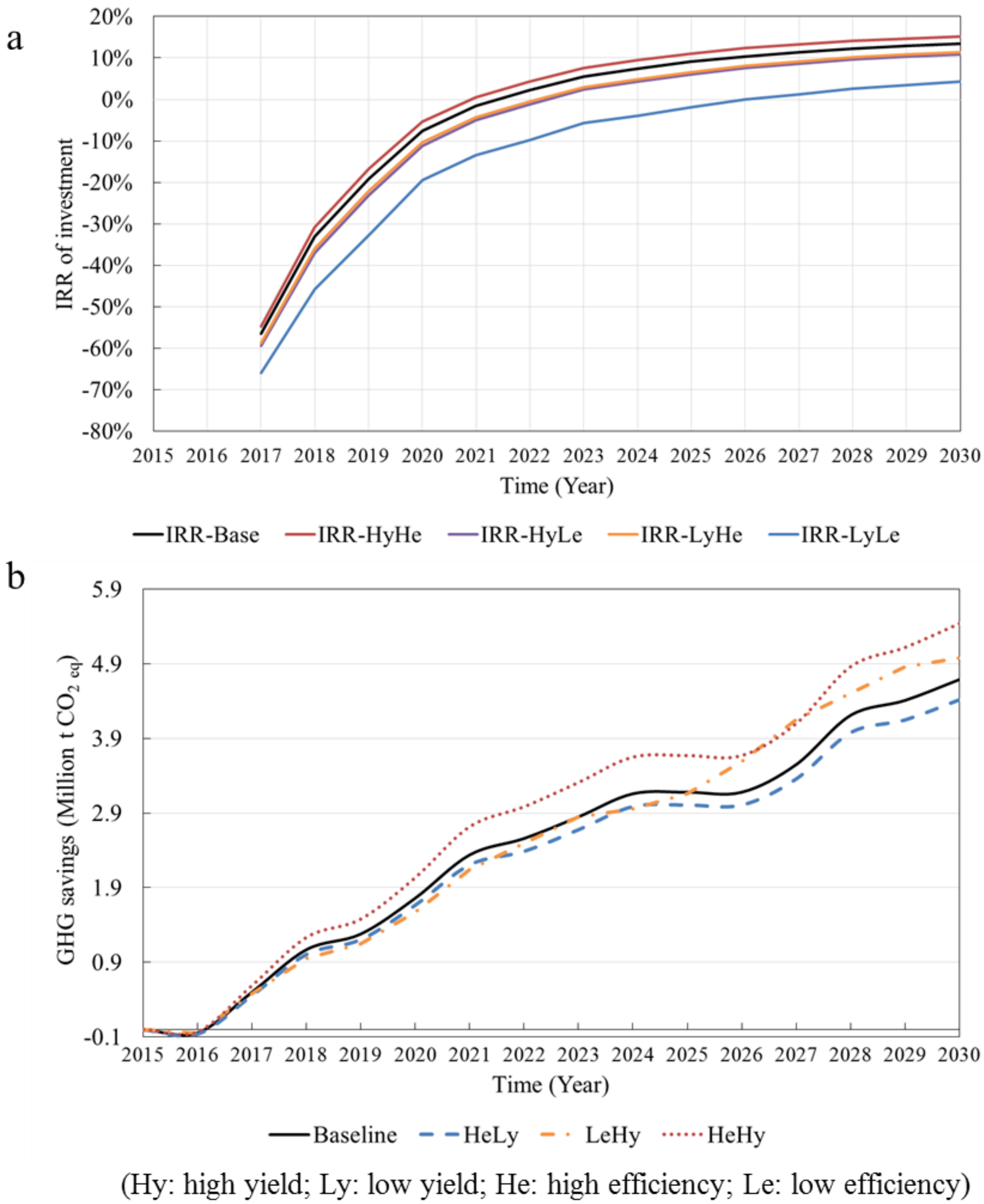

Figure 5.12. Sensitivity analysis for bioconversion rate and the yield of switchgrass (a) the IRR of a biorefinery and (b) GHG reduction of cellulosic ethanol system with different bioconversion rates and switchgrass yields

5.6.2 *Scenario analysis*

In the scenario analysis, various scenarios with different levels of subsidies are examined to understand how the governmental financial support affect the cellulosic biofuel industry. In addition, the cellulosic biofuel system is simulated using a scenario in which compliance with the RFS2 mandate is strictly achieved.

5.6.2.1 Subsidy scenarios

Policy incentives can significantly facilitate the commercialization of cellulosic biofuels [147]. A fixed subsidy of \$0.50 gal^{-1} to the cellulosic ethanol production is incorporated in the baseline as suggested by Clark et al. (2013). The scenarios of no economic support and higher subsidy (\$1.00 gal^{-1}) for cellulosic ethanol are also analyzed in this section. The IRRs under different subsidy scenarios are shown in Fig. 5.13. The IRR of a biorefinery in the baseline with no economic support is reduced to less than 10%. In contrast, a higher subsidy scenario can create an IRR above the expected level so that the cellulosic biorefinery is worth investment. In the high subsidy scenario, the IRR of a biorefinery with low efficient biotechnologies (289 L t^{-1}) increases to 13.4%. In general, biorefineries with low efficiency biotechnology or a small capacity may become viable for production of cellulosic biofuels with favorable economic support.

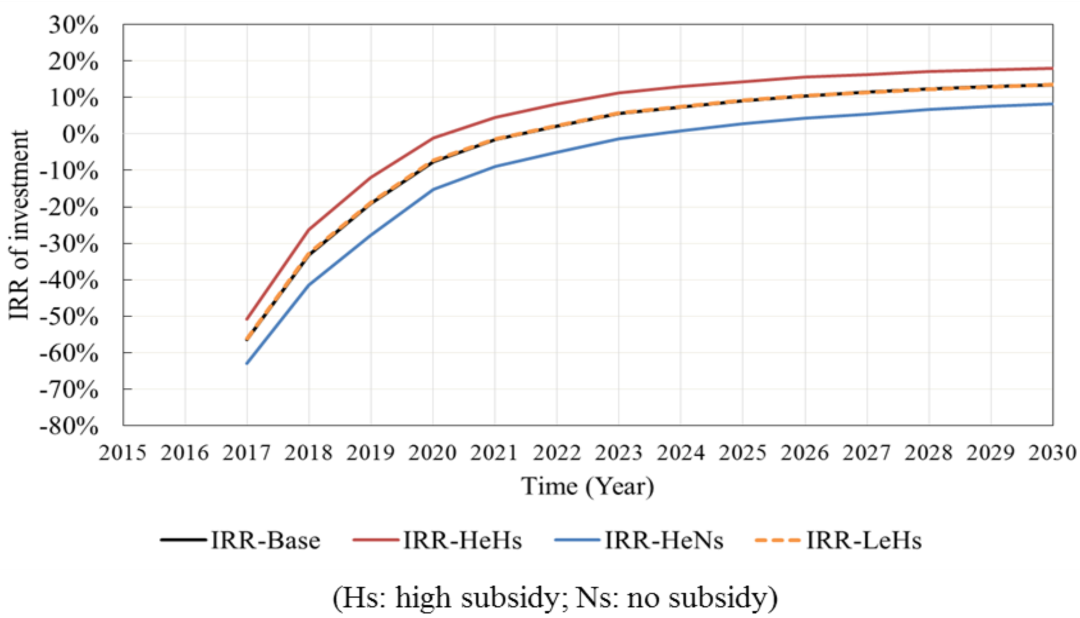

Figure 5.13. Variation in IRR under different subsidy scenarios

5.6.2.2 Compliance scenarios

In the basic scenario, the demand for cellulosic biofuels is assumed to grow linearly, in accordance with EPA projections, which is far behind the required volume of cellulosic biofuel in RFS2 mandate. The RFS2 scenario simulates the behavior of a system in which obligated refiners strictly comply with the cellulosic biofuel consumption requirements in the RFS2 program. The details of RFS2 program are listed in Table 5.6. It is assumed that the annual requirement of cellulosic biofuel from 2023 to 2030 remains the same as the volume in 2022.

Table 5.6. Volume standards for cellulosic biofuel as set forth in RFS2 mandate [123]

Year	Cellulosic Biofuel (billion gallons)
2015	3.0
2016	4.25
2017	5.5
2018	7.0
2019	8.5
2020	10.5
2021	13.5
2022	16.0

Figure 5.14 depicts the behaviors of cellulosic ethanol supply and demand under the compliance for RFS2. Due to increased demand for cellulosic ethanol, a shortage of cellulosic ethanol will emerge by 2022. The supply of feedstock is constrained by limited land-use changes in pasture and cropland. The RIN deficit under RFS2 scenario will be 32 billion gallons in 2030, which is caused by a low switchgrass expansion rate. To prevent this shortage, it is essential to improve the availability of feedstock in order to meet the required volume of cellulosic biofuels in the RFS2 scenario. This may require a large conversion of cropland and pastureland to energy crop land. Due to the expansion of energy crops on pasture and cropland, the plantation of switchgrass will increase number of bird species by 36 by 2030. It is should be noted that 23 at-risk species may be encountered and their living habitats could be disturbed by the expansion of switchgrass as shown

in Fig. 5.14(e). The expansion of switchgrass cropland will be necessary for the improved commercialization of cellulosic biofuels, but some environmental damages may be incurred.

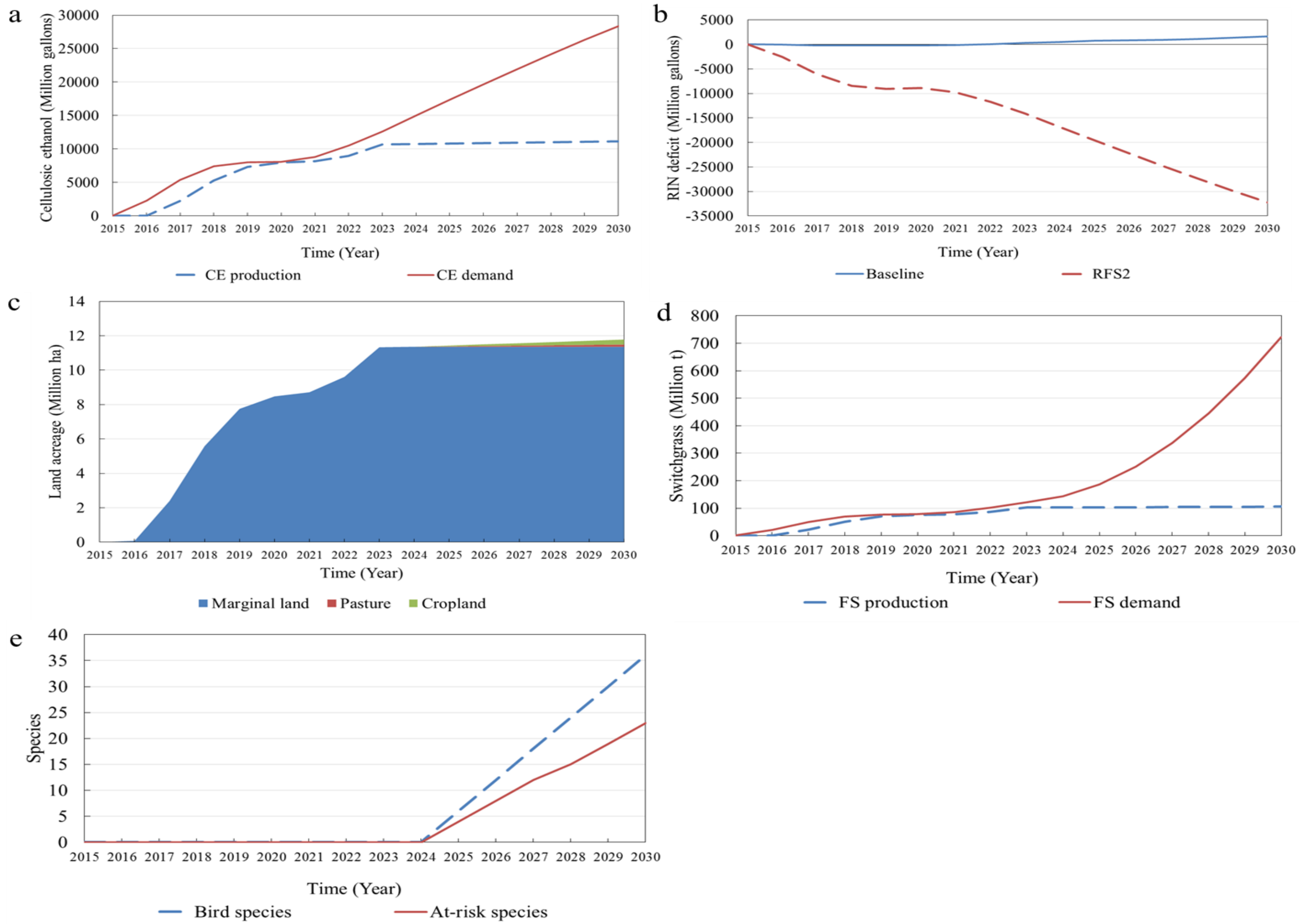

Figure 5.14. Projected behaviors of cellulosic ethanol systems under the RFS2 scenario. (a) Cellulosic ethanol supply and demand (b) RIN deficit (c) Land allocation for switchgrass (d) Feedstock supply and demand (e) Biodiversity change

The basic and RFS2 scenarios are associated with the constraints of practical LUC rates for different types of land. Figure 5.15 shows the supply and demand for cellulosic ethanol and the acreage of land dedicated to switchgrass without LUC constraints. The production of cellulosic ethanol will be sufficient for demand and remain at a stable level from 2026 to 2030. The total acreage of switchgrass land is projected to reach 21 million hectares by 2030. During the first ten years, all available marginal lands will be converted to switchgrass land and the remaining switchgrass land will be converted from pasture. After 2024, no croplands will be converted to energy crop land and SOC will be lost during the conversion from pasture to switchgrass land. Overall, the total savings of CO_2 emissions will increase since more cellulosic ethanol will be produced to achieve compliance with the RFS2 mandate. Nitrate leaching will increase to 44 thousand tonnes N in 2030, which is 13.6 times as much as the amount of nitrate leaching in the basic scenario. When land use constraints are not imposed in the RFS2 scenario, increased cellulosic ethanol production will result in 12 times greater water use savings (when compared to gasoline) than the basic scenario. The RFS2 scenario without land-use constraints leads to significantly lowered water use and GHG emissions than the basic scenario, but may cause higher nitrate leaching.

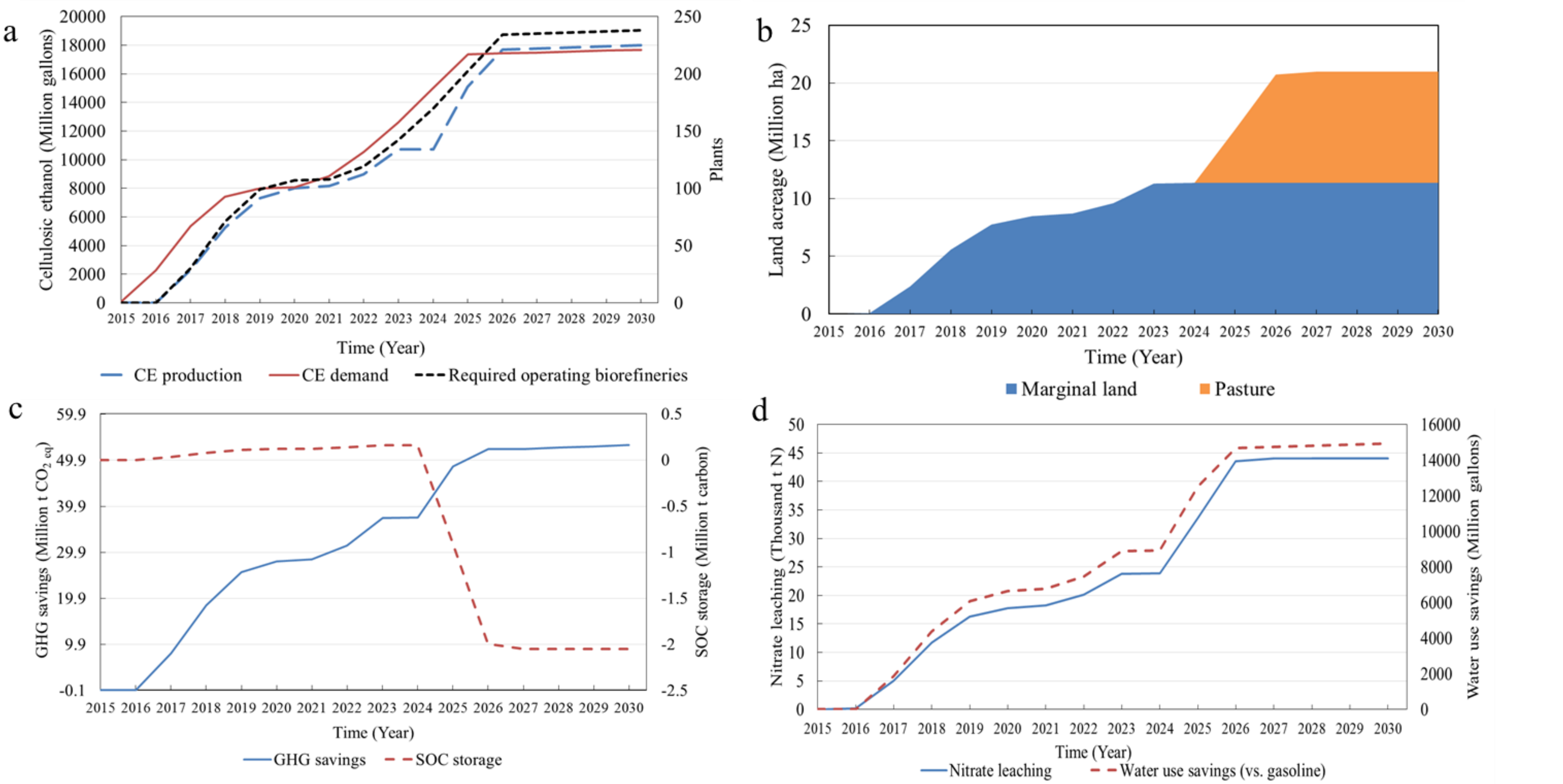

Figure 5.15. Projected behaviors of cellulosic ethanol systems under the RFS2 scenario without LUC constraints. (a) Cellulosic ethanol supply and demand and (b) Land allocation for switchgrass (c) GHG reduction and SOC storage (d) Nitrate leaching and water use

Generally, the viability of producing cellulosic ethanol at a large-scale significantly relies on advanced bioconversion technologies. More efficient bioconversion technologies enable biorefineries to expand the capacity of cellulosic biofuel production. Although a biorefinery with larger capacity needs higher initial capital investment, it provides an attractive investment with a higher IRR and shorter payback period. Moreover, a larger scale biorefinery can produce cellulosic biofuels with a lower cost, which results in a lower market price. The projected price of cellulosic ethanol from switchgrass is in line with the estimated selling price of cellulosic ethanol by NREL [148]. However, the projected price of cellulosic ethanol may not be competitive with conventional ethanol ($1.39 gal^{-1} in 2018) [149]. Therefore, more advanced bioconversion technologies for cellulosic ethanol need to be developed to support the commercialization of cellulosic biofuels on a large scale. Cellulosic ethanol biorefineries need policy incentives to maintain the operation, especially for plants with small capacities. Dumortier (2016) argued that cellulosic ethanol may not be competitive with conventional ethanol without government subsidies. This study also finds that appropriate economic supports (e.g., a fixed subsidy of $1.00 gal^{-1}) for cellulosic ethanol production can encourage stakeholders to invest in biorefineries and facilitate the commercialization of cellulosic biofuels.

In the baseline case, the annual required volume of cellulosic biofuel is assumed to follow the slow growth rate of cellulosic biofuel production instead of the required volume in the RFS2 program. The biorefineries in the Midwest can generate enough RINs of cellulosic biofuels for obligated parties to comply with these current low volume requirements. The available marginal land is sufficient for meeting the switchgrass feedstock needs for cellulosic ethanol based on projected demands. However, marginal lands are not sufficient to grow energy crops for cellulosic biofuels to achieve the compliance with the RFS2 mandate. An alternative solution could be to utilize other cellulosic biomass, such as corn stover and woody crops. Although the land area is sufficient for energy crops without the land-use change constraints, it is still unclear whether this LUC pattern is practical and efficient. It is difficult to predict whether landowners will adopt energy crops or whether a robust feedstock market will emerge. Furthermore, the EPA has adjusted the total cellulosic biofuel mandate (8.5 billion gallons) down to 418 million gallons for compliance year 2019 since the RFS2 implementation experienced slower development of cellulosic biofuels than what was expected [151]. The CWC will continue to be used to comply with the mandate facing a shortfall in cellulosic biofuels.

The utilization of cellulosic biofuels can significantly reduce GHG emissions even when including the indirect LUC effects. The most significant environmental concern is that growing energy crops on marginal land will lead to nitrate runoff due to the use of fertilizers. LUC of pastures for energy crops may have negative impacts on the at-risk species living in the pasture. However, the cellulosic biofuel industry can increase economic output and job opportunities, especially in rural areas. The earnings from the cellulosic biofuel industry can increase the income level of people living in the Midwest. The cellulosic biofuel system can avoid significant costs of damages associated with increased GHG emissions.

CHAPTER 6. AGENT-BASED MODELING FOR ENERGY CROP ADOPTION AND CELLULOSIC BIOFUEL COMMERCIALIZATION

6.1 Introduction

The utilization of dedicated energy crops for cellulosic biofuels is still in the early stage or pilot scale, and cellulosic biofuel production has yet to be widely commercialized. There were only 5 commercial-scale cellulosic ethanol plants in operation in the U.S. by the end of 2016, with a total capacity of 61.6 million gallons per year [130]. However, only two cellulosic ethanol biorefineries in Iowa are still operating in 2018. There are many economic risks in the biofuel supply chain and many technical barriers to efficient biological conversion which limit the commercial development of cellulosic biofuels. The risks in the biofuel supply chain include feedstock availability, collectability, and high capital investment in new technologies [152]. Kim and Kim [28] indicated that the main technical issues in the bioconversion process occurred in the pretreatment process, and high costs of pretreatment and enzymes can increase the price of cellulosic ethanol. Therefore, to facilitate the commercialization of cellulosic biofuels, it is essential to ensure the stable availability of feedstock and to determine the conditions under which cellulosic biofuel production is economically viable. Farmers and biorefineries play important roles in overcoming these challenges in the biofuel supply chain. Since the dedicated energy crops and conversion technologies for cellulosic biofuel have many associated uncertainties, understanding the behaviors of farmers and biorefineries is crucial to assess the stability of the cellulosic biofuel market.

Several studies have investigated the patterns of land-use change and the potential supply of dedicated energy crops based on the adoption behavior of farmers. Many studies have used agent-based modeling (ABM) to analyze how farmers make decisions about their land management and to indicate which factors affect the adoption of bioenergy crops of farmers. Agent-based modeling is an approach that has been utilized in recent years for land-use modeling because it offers a method to model an individual farmer’s behavior by incorporating social interactions and the influences of economic and environmental factors on human decision making. Agent-based modeling can identify the heterogeneity of agents in different spatial regions. Brown et al. [153] integrated socio-economic rationalization to indicate that the willingness of Scottish farmers to adopt dedicated energy crops is associated with their willingness to compromise their profits. Bichraoui-Draper et al. [122] employed ABM to estimate the adoption rate of dedicated energy crops based on the levels of familiarity and risk-aversion of individual farmers. Alexander et al. [154] applied ABM to understand the spatial dynamic adoption rate of dedicated energy crops in the UK, based on the feedstock market price as determined by feedstock supply and demand.

Other efforts combined agent-based modeling with economic return optimization to simulate the decision-making of farmers. Huang et al. [155] conducted an agent-based simulation to analyze the decision-making of farmers in switchgrass adoption scenarios in Iowa. The authors used tradeoff optimization and incorporated neighborhood influences on the behaviors of individual farmers as constraints to quantify the amount of land area that was changed to grow switchgrass. Li and Ross [156] utilized ABM to determine the optimal contract configuration between farmers and a single biorefinery and considered the risks in farming and contract hold-up. However, the previous studies assumed that the biorefineries were inherently willing to contract with farmers in order to reduce the risks for farmers who adopted the dedicated energy crops. A major risk in investing in a biorefinery is feedstock supply uncertainty, which can lead to a biorefinery making contracts which secure more feedstock than is demanded by the biorefinery [157]. It is not clear what biorefineries will pay for switchgrass as a cellulosic feedstock. Paying higher prices due to contractual obligations may lead an economic loss for a biorefinery and this risk has not been considered in other literature. The biorefinery does not necessarily need to make contracts with farmers if the potential supply of feedstock is sufficient for the demand for biofuel production. In addition, the spatial pattern of adopting the dedicated energy crops is not discussed and the spatial heterogeneity of each agent (e.g., cost of crop production and transportation cost of feedstock) is neglected in most previous studies.

This work uses spatial agent-based modeling of switchgrass adoption by farmers to understand the farmers' willingness to adopt dedicated energy crops and the potential supply of feedstock for cellulosic ethanol. A case study of this system is presented using Indiana as an example. A geographic information system (GIS), including data from the Indiana agricultural census and from biofuel facilities, is inserted into the ABM to simulate the spatial diffusion of switchgrass adoption. In addition, this study identifies the viability of commercialization of cellulosic biofuels in Indiana by assessing whether biorefineries can produce cellulosic ethanol without a supply shortage and/or an economic loss. The model incorporates economic return optimization and the influence of neighbors on the diffusion of switchgrass adoption to simulate the decision-making of farmers. Governmental subsidies for cellulosic biofuel production are introduced to the agent-based system to understand how policy implementation can facilitate the commercialization of cellulosic biofuels.

6.2 Agent-based Modeling for Energy Crop Adoption

In the ABM of cellulosic biofuel systems, biorefineries and farmers are two agent groups. Figure 6.1 shows the decision-making processes of two agents and their interactions. Biorefineries generally acquire cellulosic feedstocks from farmers and produce cellulosic biofuels. A biorefinery needs to make sure that its operation is profitable based on capital investment, variable operating cost, transport cost, feedstock cost, and biofuel production capacity. In addition, the demand for biofuels should be satisfied by a stable feedstock supply. Farmers that own cropland need to decide which crops to grow to maximize the profit of their land, based on different crop market conditions. When allocating crops to land, farmers are likely to consider the cost of environmental damages, such as soil erosion and fertilizer leaching. A farmer will only adopt a dedicated energy crop if it is more profitable than conventional crops, based on the maximum farm gate price of feedstock offered by a biorefinery. If the price is too low, this farmer will not switch from the current crop to the dedicated energy crops. Adopters will transition back to a conventional crop and will not adopt a dedicated energy crop, if they perceive that growing a dedicated energy crop is less profitable than growing a conventional crop in the coming year. Farmers that have a history of not adopting energy crops may be willing to shift to energy crops, based on the influence of neighbors that have adopted dedicated energy crops. It should be noted that for the purpose of this paper, the dedicated energy crop is assumed to be switchgrass, but this approach could be used for other energy crops, such as miscanthus.

Once farmers adopt and allocate land for the dedicated energy crop, a biorefinery will have a feedstock supply for producing biofuels. If the amount of harvested feedstock can meet the demand for generating biofuels, it is viable to operate a biorefinery to produce biofuels. Otherwise, a biorefinery needs to make contracts with farmers that are willing to adopt the dedicated energy crops to close the gap between feedstock supply and demand. A biorefinery with a supply shortage will incur an economic loss by paying higher prices for the contract than what it can afford. It is still possible that the harvested feedstock from adopters and contracts cannot meet the demand for biofuel production. In both situations, it is not economically viable to produce cellulosic biofuels at a biorefinery with a supply shortage.

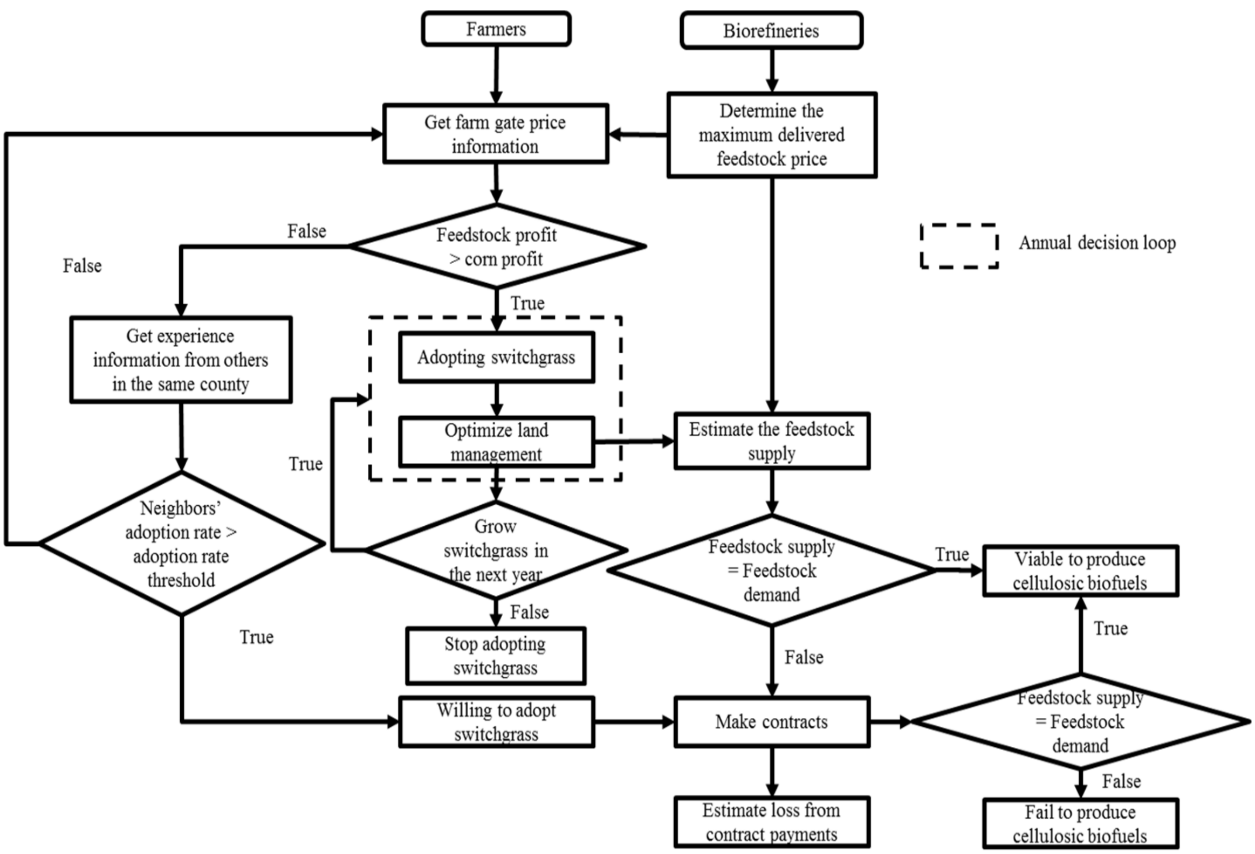

Figure 6.1. Decision-making processes of the agents

6.2.1 *Agents*

The biorefinery agents were assumed to be profit driven, meaning that they pursue a positive net present value of cash flows for a given interest rate. The net present value depends on the capital investment cost, operational cost, feedstock cost, and biofuel revenues. The total capital investment varies based on conversion processes and capacities for utilized for the biorefinery. The U.S. National Renewable Energy Laboratory (NREL) used techno-economic analysis to estimate the economics of biofuel production using various pretreatment technologies. A pretreatment with dilute acid was identified to have the lowest production cost [158]. In this study, biorefineries with a dilute acid pretreatment are used as the base case. Besides biofuel, a biorefinery can generate electricity from biological conversion processes. Therefore, the revenue of a biorefinery includes the sales of biofuels and electricity.

Biorefinery revenues can be combined with its fixed and variable operating costs to estimate the minimum selling price of a biofuel; this is commonly done using a zero net present value calculation. Therefore, given the selling price of biofuels, the maximum delivered feedstock price that is paid by a biorefinery can be estimated. Biorefineries can either obtain the dedicated energy crops from the open market or can secure the supply of feedstock through contracts with farmers. In the open market for dedicated energy crops, the feedstock price offered by a biorefinery to a farmer is determined by the breakeven cost of biofuel production and transportation cost; the transportation cost varies according to different transport distances. When the supply of switchgrass on the open market cannot meet demand, a biorefinery needs to make contracts with farmers to sustain the production of feedstock for cellulosic biofuels. Farmers that are willing to adopt switchgrass will make contracts with a biorefinery only if the expected profit of the contract is higher than the expected profit from growing corn. However, the payments of the contract are higher than the maximum feedstock prices that biorefineries can afford. Therefore, a biorefinery will incur a loss due to contract payments.

Farmers are agents who decide which crops to grow on their land. The major factor affecting their decisions is the profit per unit land area. Land area, crop productivity, and feedstock cost differ among farmers located in different regions. Farmers will compare the profit from growing conventional crops with the profit from growing dedicated energy crops each year, based on the prices and costs for that year. Then, farmers that are willing to adopt a dedicated energy crop will optimize their land area allocation to grow the new adopted crops.

6.2.2 *Feedstock price*

The breakeven feedstock price offered by a biorefinery is estimated by the net present value (NPV), which is the present value of t future cash flows (C_t) generated by a capital investment over its life (n). The NPV depends on the interest rate (i). The utilization period of a biorefinery (n) is assumed to be 20 years and an interest rate of 10% is used in the cash flow analysis. The NPV and cash flow are calculated via Eqs. (6.1) and (6.2), respectively.

$$NPV = -I_0 + \sum_{t=1}^{n} \frac{C_t}{(1+i)^t} \quad (6.1)$$

$$C_t = P_e Cap + R_{elec} - (C_{fixed} + C_{var})Cap - C_f N_s \quad (6.2)$$

$$P_{gate} = C_f - C_{trans} \quad (6.3)$$

where:

I_0 - total capital investment

P_e - price of cellulosic ethanol

Cap – production capacity of a biorefinery

R_{elec} - revenue from electricity export

C_{fixed} - fixed operating cost

C_{var} - variable operating cost

C_f - cost of delivered feedstock

P_{gate} – maximum farm gate price of feedstock

C_{trans} - cost of transportation

The maximum delivered feedstock price (paid by the biorefinery) is equal to the breakeven cost (incurred by the farmer) of the delivered feedstock which includes production cost and transportation cost of switchgrass. This study assumes that the biorefinery covers the transportation cost of feedstock. From the perspective of the biorefinery, the price paid by the biorefinery to a farmer is viewed as the production cost of feedstock. The maximum production cost of feedstock is calculated based on zero net present value of return. This means that this maximum feedstock cost is the maximum price the biorefinery can afford to purchase the feedstock from farmers. If the price of the feedstock paid by the biorefinery is higher, the biorefinery will have a negative net present value. Therefore, the maximum farm gate price paid by the biorefinery to a farmer is equal to the production cost of the feedstock. The farm gate price of the feedstock is calculated from Eq. (3), which is the maximum delivered feedstock price minus the transportation cost. The transportation cost is related to the distance between the farm and a biorefinery.

6.2.3 *Profit optimization for the adoption of dedicated energy crops*

A farmer that is willing to adopt a dedicated energy crop will allocate the cropland between conventional crops and dedicated energy crops in order to optimize annual profit. The total annual profit per unit land area is calculated with Eq. (6.4). Switchgrass is selected as the adopted dedicated energy crop and corn is used as the major conventional crop grown by farmers in Indiana. Total land area owned by a farmer can be allocated to corn and switchgrass. In reality, it is unlikely for farmers to change all conventional cropland to a dedicated energy crop. Therefore, a rational constraint for switchgrass land area is imposed on the land profit optimization. The maximum ratio of switchgrass area to the total cropland area is assumed to be equal to the historical ratio of corn area to the total cropland area.

$$R_T = R_c A_c + R_s A_s \tag{6.4}$$

$$A_T = A_c + A_s \tag{6.5}$$

$$0 \leq A_c \leq A_T \tag{6.6}$$

$$0 \leq A_s \leq A_T p_c \tag{6.7}$$

$$R_c = P_c Y_c - C_c - E_c \tag{6.8}$$

$$R_s = P_s Y_s - C_s - E_s \tag{6.9}$$

where:

R_T - total profit from adopting switchgrass

R_c - profit of corn per unit land area

R_s - profit of switchgrass per unit land area

A_c - corn land area

A_s - switchgrass land area

A_T - total land area

p_c - proportion of historical corn land area

P_c - price of corn

P_s - price of switchgrass

C_c - cost of corn production

C_s - cost of switchgrass production

Y_c - yield of corn

Y_s - yield of switchgrass

E_c - environmental cost of corn

E_s - environmental cost of switchgrass

The revenue of each crop is related to the farm price of the feedstock and the yield. The farm price of corn, as shown in Table A5, is projected by the U.S. Department of Agriculture (USDA) from 2017 to 2026. The farm prices of corn in 2015 and 2016 are $3.64 per bushel and $3.28 per bushel, respectively. The farm price of corn in the previous year is used to estimate the revenue from corn products in this year. For this case, the variable cost of corn production is estimated based on costs of seed, fertilizer, pesticides, machinery fuel and repair, hauling, and insurance associated with the yield of corn in Indiana. The farm gate price of switchgrass is determined by biorefineries. The price that a farmer receives for switchgrass depends on the breakeven cost of the biorefinery, which includes the cost to transport the switchgrass from a given farmer to the biorefinery. The production cost and yield of switchgrass are estimated from other studies. More details of the data will be discussed in the case study.

The ‘cost’ of each crop is considered to have economic and environmental costs. Switchgrass has a lower environmental cost than corn. The environmental cost for both crops is attributed to the damage from soil erosion and nutrient leaching. Soil erosion and water quality are two of the most concerning environmental impacts associated with agricultural production. According to a report from the USDA [159], each tonne of eroded soil contains 1.05 kg of nitrogen and 0.45 kg of phosphorus. The soil erosion rate for cropland in Indiana was estimated by the National Resources Inventory [160] to be 7.66 tonnes ha^{-1} yr^{-1}. The cost of soil erosion for corn land is estimated to be $24.50 ha^{-1} based on the prices of nitrogen and phosphorus fertilizers in Indiana. Switchgrass does not cause significant soil erosion due to its deep-rooted growth form [161]. The amount of nitrogen leaching into the groundwater from corn and from switchgrass are reported to be 39.5 kg nitrogen ha^{-1} yr^{-1} and 2.1 kg nitrogen ha^{-1} yr^{-1}, respectively [162]. The costs of nutrients leaching from corn and switchgrass production are estimated to be \$86.90 ha^{-1} and \$5.54 ha^{-1}, respectively. In general, the costs of environmental damage from corn production are higher than those for the production of switchgrass; these costs directly affect the adoptability of both crops.

6.2.4 *Diffusion of dedicated energy crop adoption*

Adopting dedicated energy crops as feedstocks for cellulosic biofuels is a relatively new experience for farmers in the region (Indiana). Therefore, the cumulative adoption of a dedicated energy crop is analogous to new technology diffusion, which will empirically follow an S-shaped curve [154], [156]. The diffusion rate is slow at early stages, as a small number of risk-tolerant innovators adopt the technology. Then, the number of adopters increases as success influences neighbors to adopt the technology. Finally, the technology becomes widely used and the number of adopters stabilizes. In this study, an adoption threshold approach was implemented to reflect the influence of neighbor-adoption on the willingness of farmers to adopt the dedicated energy crop [154]. Farmer agents are initially assigned an adoption threshold from a normal distribution with a mean adoption rate of 20% and a standard deviation of 10.2% [154]. Farmers will adopt the dedicated energy crops if growing dedicated energy crops is more profitable than growing conventional crops. Farmers that do not perceive that they will earn more profit from growing dedicated energy crops will maintain their decisions to grow conventional crops. However, these farmers can be affected by decisions made by their neighbors. If the proportion of neighbors with a net positive experience of adoption is greater than their adoption threshold, a farmer will adopt the dedicated energy crop. Farmers that continually adopt the dedicated energy crop each year are regarded to have had a positive experience of adoption. On the other hand, if farmers change their cropland from dedicated energy crop-use to conventional crop-use, based on an economic return comparison, they are regarded to have had a negative adoption experience and will not adopt dedicated energy crops. The neighbors of a farmer are defined as the other farmers in the same county. The adoption rate was set to be the net proportion of positive experiences minus negative experiences of the farmers which planted dedicated energy crops in the same neighborhood [154].

6.3 Case Study: Switchgrass Adoption in Indiana

Indiana is one of the largest corn production states in the U.S., with an annual production of over 934 million bushels of corn in 2017. Indiana farmers planted 2,442,970 hectares of corn, which occupied approximately 47% of the total cropland. According to U.S. bioenergy statistics [163], corn production for fuel ethanol use accounts for 37% of the total use under the RFS2 mandate. Currently, Indiana has 14 corn-based ethanol plants with a total corn ethanol production of 1.1 billion gallons (4.2 billion liters) in 2017 [164].

Indiana has 92 counties and 58,695 farms with an average farm size of 251 acres (101.6 hectares) [165]. The farmland in the northern region of the State is more productive than the farmland in the south, due to different soil qualities [166]. Therefore, crop productivity varies across the counties. In this study, the corn productivity is classified into three yield levels: low, average, and high. Each level of productivity is associated with relevant variable costs of corn production. The details of the corn yields and variable costs are shown in Table A6.

Switchgrass, which is a warm-season perennial crop that grows across the U.S., is one alternative to the use of corn as a dedicated energy crop. Switchgrass has been identified as a second-generation feedstock that can be used for the production of cellulosic biofuels, given its high productivity and low nutrient input requirements. Currently, the use of switchgrass as a bioenergy feedstock is only being considered in some pilot scale experiments that are being conducted by universities and government agencies. The productivity of switchgrass varies depending on nitrogen fertilization, soil type, precipitation, and cultivar. Liu et al. [167] assessed the economic and environmental performances of switchgrass utilization for bioenergy products associated with a range of yields from 6.6 – 12.6 t ha^{-1}. Wullschleger et al. [168] conducted a statistical analysis to identify the switchgrass yield responses to two ecotypes. That study revealed that the upland ecotypes had an average yield of 8.7 Mg ha^{-1} and the lowland ecotypes had an average yield of 12.9 Mg ha^{-1}. Fike et al. [169] investigated the switchgrass yield responses to nitrogen and the estimated production cost on a set of diverse sites over multiple years. This study implied that the average yield of switchgrass is 6.3 Mg ha^{-1}, which was lower than the yields reported in other research. The authors also found that the addition of nitrogen increased yields significantly in the well-drained soils of Iowa, South Dakota, and Virginia. Sanford et al. [170] indicated similar switchgrass yields in southcentral Wisconsin and southwest Michigan, with an average yield rate of 6.9 t ha^{-1} and 6.0 t ha^{-1}, respectively.

In this study, the cost of switchgrass production is based on the Iowa cost estimated by Fike et al. [169]. This assumption is realistic since Indiana has similar soil, precipitation, and climate conditions to those in Iowa (no switchgrass yield data currently exists for Indiana). The average cost of switchgrass production is estimated to be \$694.5 ± 48.2 ha^{-1} at a nitrogen fertilization rate of 112 kg ha^{-1} [169]. The corresponding average yield of switchgrass is calculated to be 9.0 t ha^{-1}. [169] The transportation cost for the switchgrass is estimated to be \$0.2 t^{-1} km^{-1}, assuming a hauling rate of \$2.24 per load-kilometer [171] and 11.8 tonnes per load [172]. In general, switchgrass yields are uncertain. Therefore, a sensitivity analysis of various switchgrass yields will be performed in this study to understand how switchgrass yield affects the cellulosic biofuel market.

The spatial data on the location of cropland and ethanol plants in Indiana are adopted from the GIS data of the Indiana agricultural census and Indiana biofuel facilities, respectively. Calculations are performed with the GIS data using the ArcGIS® Pro software [173] and the spatial ABM uses these data to simulate the model in the Netlogo® software [174]. The ABM was run at least five times to observe the influence of parameters for which there is uncertainty (e.g., corn production cost, farm size, and adoption threshold) on overall model performance. There were no significant differences between results of multiple runs for the same combinations of variables. Simulation results are expressed using the average value of multiple runs.

6.3.1 *Biorefinery data*

The number and location of cellulosic biofuel plants are assumed to be the same as the existing corn ethanol plants in Indiana. Table A7 shows the location and production capacity of each current operating biofuel facility in Indiana. The capacity of each cellulosic biofuel plant is simulated with a capacity equal to the capacity of each existing corn ethanol plant (in 2017), and the total capacity of cellulosic biofuels is assumed to be 1.1 billion gallons (4.2 billion liters) per year. A biorefinery can produce cellulosic ethanol for transport fuels and electricity that is exported to the electric grid. Table 6.1 shows the parameters of a cellulosic biorefinery with a capacity of 202.2 million liters per year, considering a capacity factor of 96%, these parameters will be used in the cash flow analysis. Since the capacities of the cellulosic biorefineries differ from the reference capacity, this study assumes that the installed equipment costs and electricity export revenue scale linearly with the capacity, with a scaling coefficient of 1. Other parameters of the cash flow analysis remain the same.

Table 6.1. Biorefinery parameters

Parameters	Value
Biofuel production capacity (million liters)	202.2 [158]
Biomass treatment capacity (t)	643,744
Conversion efficiency (liters t^{-1})	314.1 [30]
Total capital investment ($M in 2015)	423 [158]
Installed equipment cost ($M in 2015)	187 [158]
Scaling coefficient of equipment cost	1
Electricity export ($M in 2015)	13.37 [158]
Discount rate	10%
Plant life (years)	20
Fixed operating cost ($ $liter^{-1}$)	0.05 [30]
Variable operating cost ($ $liter^{-1}$)	0.03 [30]
Transport cost ($ t^{-1} km^{-1})	0.2 [171], [172]
Loading rate ($ t^{-1})	1.52 [171]

In this study, the price of cellulosic ethanol is assumed to be the same as corn ethanol. The projection of corn ethanol prices, shown in Table A8, was published by the U.S. Energy Information Administration (EIA) in the Annual Energy Outlook 2017 [175]. Although the price projections for cellulosic ethanol and corn are out of the scope of this research, it should be noted that the prices of both products of play a significant role in decision making processes of biorefineries and farmers. The price of each product is projected based on the rational market behaviors and published data sources. The corn market is stable for a long term and it is expected no extreme changes in the future price. The fluctuation of ethanol market price could be affected by extreme price changes in the gasoline market or consumer perception, either for or against ethanol. The assumption used to determine the cellulosic ethanol price is conservative at the current stage, but the farmers and biorefineries are assumed to make decisions rationally based on their profits in the open market.

6.3.2 *Farm data*

The number of farms and farm size in each county are based on county level data from the 2012 Agricultural Census in Indiana [165]. The land acreage of farms is assumed to follow an exponential distribution ($P = \lambda e^{-\lambda x}$) with a mean (1/λ) of 251 acres (101.6 hectares). Such a distribution well describes the sizes of Indiana farms [165]. The adoption rate of farmers is assumed to follow a normal distribution with a mean adoption rate of 20% and a standard deviation of 10.2%. The standard deviation was calculated based on the diffusion of innovation theory and the number of initial adopters was assumed to be 2.5% of the farmer population [154]. The corn productivity of each farm is represented as the average yield from its respective county, as reported by the USDA [176]. The variable cost of corn production of each farm is determined by the productivity of the farm, as found in Table S2. For instance, the cost of corn production for a farm with a corn yield of 400 bushels ha^{-1} is \$1,063 ha^{-1}. The corn production cost was initialized for each farmer at the beginning of the simulation and was updated for the next iteration/year based on the yield of corn from the past year.

6.4 Model Initialization

At the beginning of the simulation, the geographic map of Indiana is loaded into the system. Meanwhile, 14 biorefineries are established at the locations of the existing ethanol plants. The model initially generates 58,695 farmers with attributes such as the county of origin, farm size, corn productivity, proportion of corn land to total land, and adoption rate threshold. These farmers in each county are assumed to be evenly distributed in the parts of the county with cropland. The model was allowed to simulate the actions of agents from 2015 to 2027. Biorefineries were assumed to be under construction for two years, beginning in 2015 and reach 50% of their cellulosic biofuel production capacity in 2016 startup year. The key model parameters are listed in Table 6.2.

Table 6.2. Simulation parameters

Parameter	Value
Farm size	Exponential (0.004)
Adoption threshold	N (0.2, 0.102)
Corn production cost	\$959 ha^{-1}(low)
	\$1063 ha^{-1}(average)
	\$1114 ha^{-1}(high)
Switchgrass yield	9.0 t ha^{-1}
Switchgrass production cost	N (\$694.5 ha^{-1}, 48.2)
Soil erosion from corn land	7.66 t ha^{-1} yr^{-1}
Nitrate leaching from corn land	39.5 kg N ha^{-1} yr^{-1}
Nitrate leaching from switchgrass land	2.1 kg N ha^{-1} yr^{-1}
Scaling coefficient	1

6.5 Model Comparison

It is generally recognized that the validation of ABMs is challenging. Historical data is usually used for the model validation. However, the lack of historical production data for switchgrass and cellulosic ethanol production makes validation of the developed ABM of switchgrass adoption difficult. Model-to-model comparison is a validation technique that compares the outputs between two different simulation models with the same input data [177]. In this study, the results were compared against projected data for switchgrass adoption in Indiana, as published by the U.S. Department of Energy in the 2016 Billion-ton Report. The purpose of model comparison is to examine the differences and similarities between two different trends in switchgrass supply.

This study applied the same yields of switchgrass used in the 2016 Billion-ton Report to the ABM to simulate the adoption of switchgrass in Indiana. The projected data of the switchgrass acreage is based on the baseline scenario associated with a delivered feedstock price of \$100 t^{-1} in the 2016 Billion-ton Report. Figure 6.2 shows the trends of switchgrass adoption from this model simulation and the projected data for the 12 years since the base year in the 2016 Billion-ton Report. Since the feedstocks for biofuels in the 2016 Billion-ton Report include a mix of biomass, e.g., miscanthus, energy cane, and agricultural residue, and the constraints of the available cropland that can be converted to dedicated energy crops are different [157], the scale of the projected data from the Billion-ton Report is significantly smaller than the ABM projection. The major difference between the two projected behaviors of switchgrass acreage occurs in the first four years. The behavior of switchgrass acreage, as modeled by ABM, shows a huge increase in the second year due to the assumption that the biorefineries start to produce cellulosic biofuels at full capacity in that year. Then, the acreage of switchgrass decreases in the third year because the yield of switchgrass increases, while the demand for switchgrass remains the same. In contrast, the behavior of the switchgrass acreage in the Billion-ton Report continues increasing until the fourth year. The two projections of switchgrass acreage have similar trends from the fifth year to the eighth year. The switchgrass acreage simulated by ABM drops in the ninth year and then rises until the end. The different trends between the two projections are mainly due to different assumptions and scenarios (e.g., land allocation and yields of bioenergy crops). For example, the switchgrass acreage projected by the 2016 Billion-ton Report is driven by an increasing demand for switchgrass. The switchgrass acreage, simulated by the ABM, is affected by the switchgrass yield under a stable demand projection.

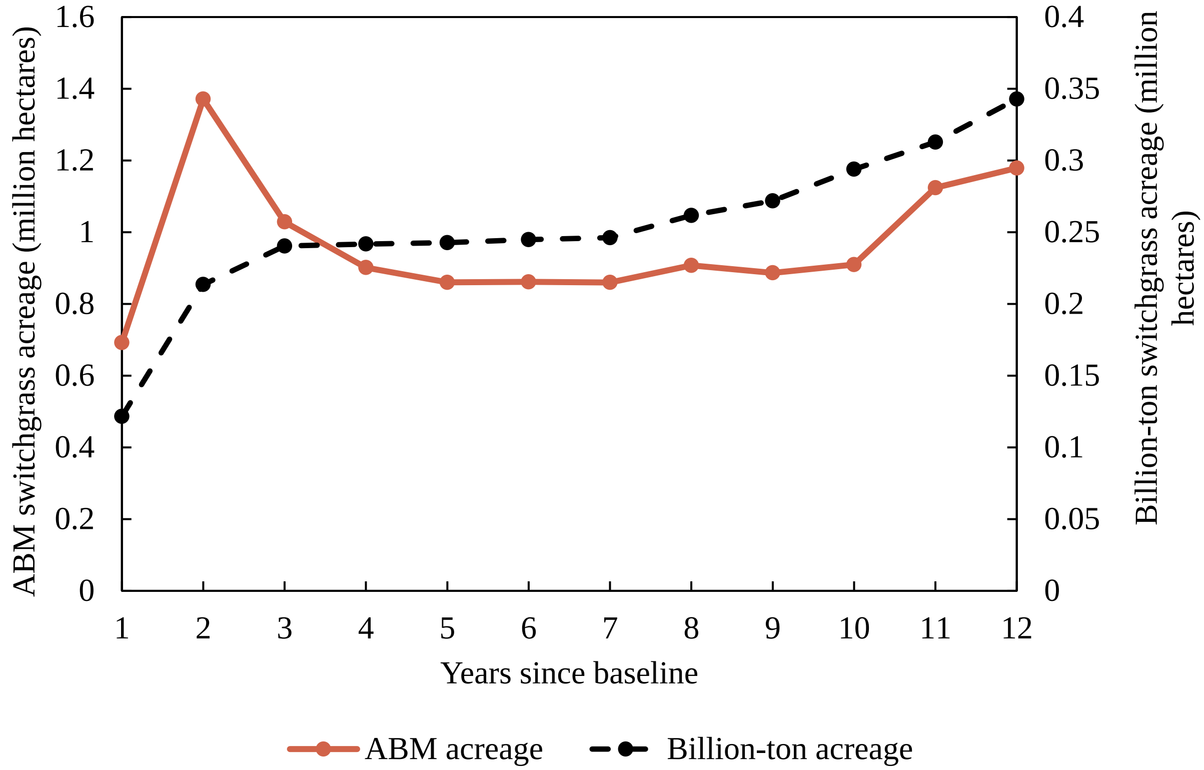

Figure 6.2. The 2016 Billion-ton projection of switchgrass acreage in Indiana with a baseline year of 2018 is plotted with simulated switchgrass acreage from the ABM in Indiana using a baseline year of 2015

6.6 Results and Discussion

6.6.1 *Potential adopters and supply of cellulosic biofuel*

In the basic case, the total capacity of Indiana cellulosic biofuel production is 4.2 billion liters per year. The annual demand for switchgrass in Indiana is estimated to be 13.4 million tonnes, which requires at least 1.49 million hectares of switchgrass land with a yield of 9 t ha^{-1}. The estimated adopters of switchgrass and the total acreage of switchgrass grown by adopters are shown in Fig. 3. Given specific farm gate prices, the supply of switchgrass provided by adopters can only meet the demand for cellulosic biofuels from 2016 to 2023. During this period, the maximum acreage of switchgrass is simulated to be 1.6 million hectares grown by 37,337 farmers, and the minimum acreage of switchgrass, as grown by 37,289 farmers, is estimated to be 1.5 million hectares. The behavior of the total acreage of switchgrass corresponds to the number of adopters. In 2016, there is not a strong demand for switchgrass since there is a small demand for switchgrass. In the subsequent year, the number of adopters doubles and the number of adopters remains stable from 2017 to 2023 with an average number of 37,330 farmers per year, which accounts 63.6% of the total farmers in Indiana.

The supply of switchgrass is not able to meet demand beginning in 2024 due to a decreasing number of adopters. The supply shortage is caused by adopters who stop growing switchgrass in 2024 (see Fig. 6.3). The number of farmers that earned a lower profit from growing switchgrass compared to growing corn continues to increase over the simulation period. There are 25,666 farmers who had negative experiences attributed to their adoption of switchgrass in 2027. As the number of farmers with negative experience increases, the positive influence of neighbors on farmers with no experience decreases. Therefore, the number of potential adopters that are willing to adopt switchgrass decreases to 1,545 farmers in year 12. The average farm gate price of switchgrass among adopters is shown in Fig. 4. The maximum average farm gate price of switchgrass is observed to be \$126.36 t^{-1} in 2016 and then continues falling to \$122.63 t^{-1} in 2024. This is because increasing numbers of farmers close to biorefineries have negative experiences when growing switchgrass, and biorefineries need to obtain feedstock from farmers located further away. Then, the farm gate price rises to \$123.68 t^{-1} in the final year due to fewer adopters. The average annual farm gate price for the period without a supply shortage is estimated to be \$124.30 t^{-1}.

Adopters in Indiana are able to meet the demand for switchgrass, given farm gate prices paid by 14 biorefineries from 2016 to 2023. With a sufficient supply of switchgrass, no biorefineries have economic losses from additional contract payments. This implies that the commercialization of cellulosic biofuels is economically viable during this period.

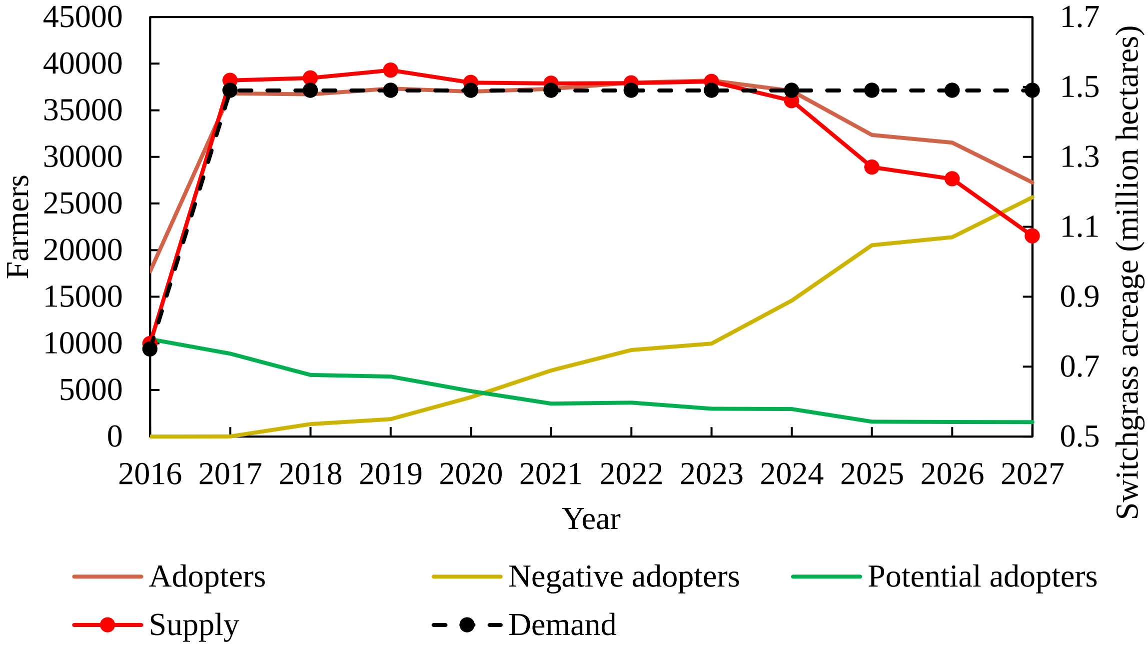

Figure 6.3. Switchgrass adopters, potential adopters, negative adopters, and acreage

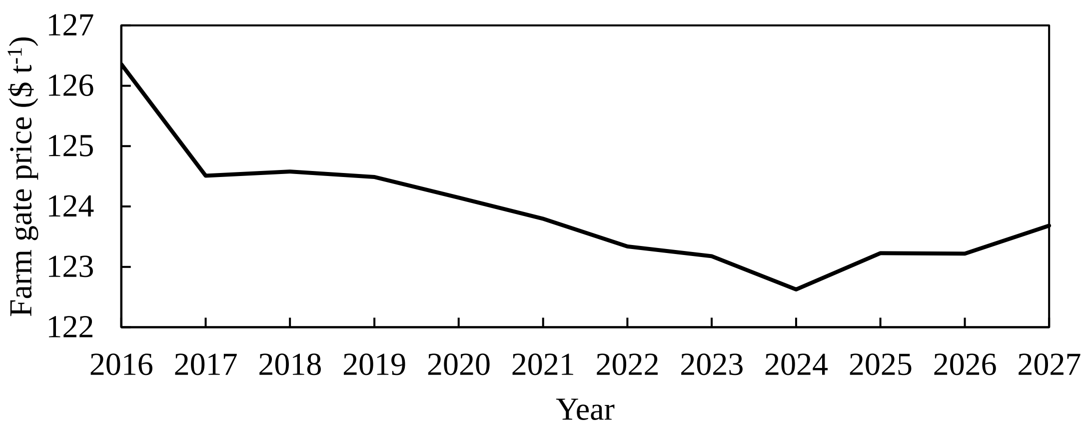

Figure 6.4. Annual farm gate price of switchgrass

6.6.2 *Economic loss of biorefineries incurred by contracts*

Although demand for switchgrass is met from 2017-2023, some biorefineries need to make contracts with farmers to secure enough supply of switchgrass between 2024 and 2027. Since the price of a contract is higher than the farm gate price that a biorefinery can afford to profitably pay, the biorefinery will incur an economic loss. Figure 6.4 shows that there are 1,385 and 1,545 contractors in 2024 and 2027, respectively. Table 6.3 gives the estimated economic loss of each biorefinery. It is only economically viable for 7 biorefineries to produce cellulosic biofuels from 2016 to 2027. Biorefinery 3 and 12 (with a supply shortage) have an economic loss of $0.2 million and $14.9 million, respectively. Other refineries that operate with a supply shortage cannot secure additional supply by making contracts with farmers, since no additional farmers are willing to adopt switchgrass. However, this model only considers farmers and cropland in Indiana as potential adopters of switchgrass. In reality, some biorefineries can secure feedstock from farmers in neighboring states (e.g., Illinois, Michigan, and Ohio), assuming they are close enough to these states to keep transportation costs low.

Table 6.3. Economic losses of biorefineries

Biorefinery ID	Years without supply shortages and contracts	Years without supply shortages	Maximum economic loss (million $)
1	12	12	0
2	12	12	0
3	9	10	0.2
4	12	12	0
5	9	9	N/A*
6	9	9	N/A
7	11	11	N/A
8	12	12	0
9	9	9	N/A
10	12	12	0
11	12	12	0
12	8	9	14.9
13	11	11	N/A
14	12	12	0

*The biorefinery has a supply shortage, but no farmers are willing to make contracts with this biorefinery.

6.6.3 *Sensitivity analyses*

Several sensitivity analyses were conducted to understand the influences of technical and economic uncertainties in the production of switchgrass and cellulosic biofuels on the commercialization of advanced biofuels. The ABM examines the simulation results, based on variabilities in the yield of switchgrass, operating cost of cellulosic biofuel production, and scaling coefficient of the equipment cost.

The yield of switchgrass is highly variable between different locations and ecotypes, and large uncertainties exist related to the commercialization of cellulosic biofuels. Therefore, understanding how the variation in switchgrass yield affects the adoption behaviors of farmers is important in the commercialization of cellulosic biofuels. In this sensitivity analysis, the yield of switchgrass is varied from 7.5 t ha^{-1} to 12 t ha^{-1} and is compared with the baseline of 9 t ha^{-1}. The number of adopters and the switchgrass production under different yield scenarios are shown in Fig. 6.5 & 6.6, respectively. For switchgrass yields of 10 t ha^{-1} and 12 t ha^{-1}, adopters are able to provide sufficient switchgrass production to biorefineries over the entire simulation period. When the minimum yield of switchgrass is set to 7.5 t ha^{-1}, the supply of switchgrass is less than the demand for the entire simulation. With a lower switchgrass yield, biorefineries will experience a supply shortage earlier. A higher switchgrass yield can maintain the number of adopters at a more stable level. In general, increasing the yield of switchgrass can significantly stimulate farmers to adopt switchgrass and provide more available cellulosic biomass for biofuels.

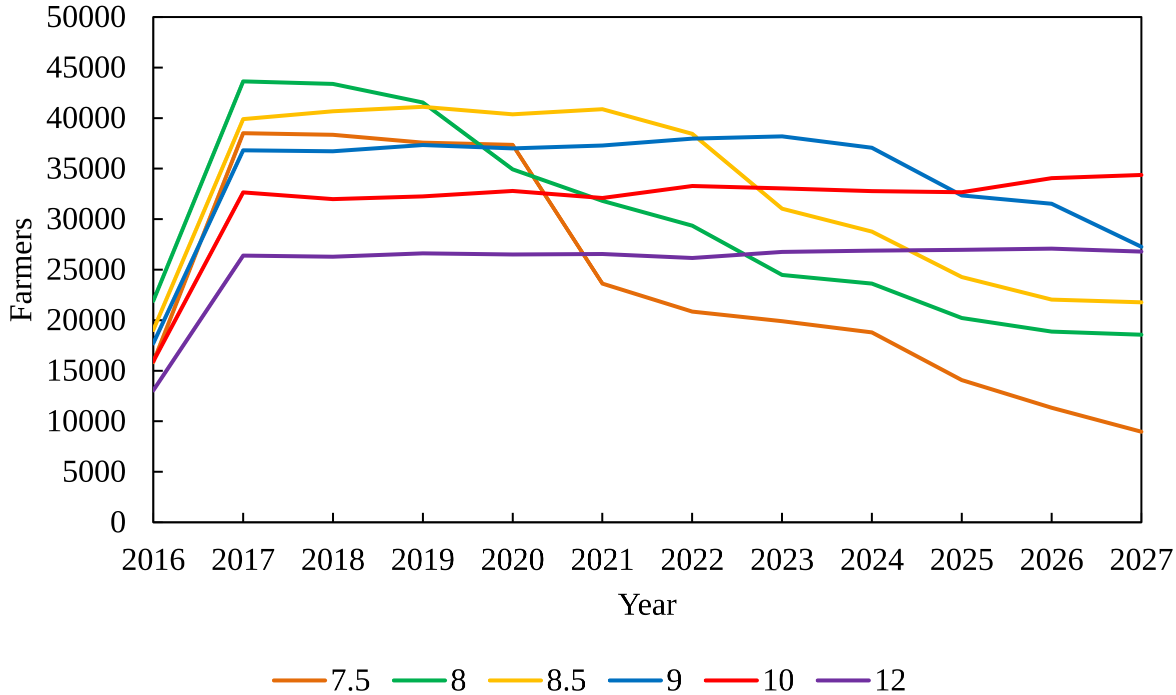

Figure 6.5. The number of switchgrass adopters under different switchgrass yield scenarios

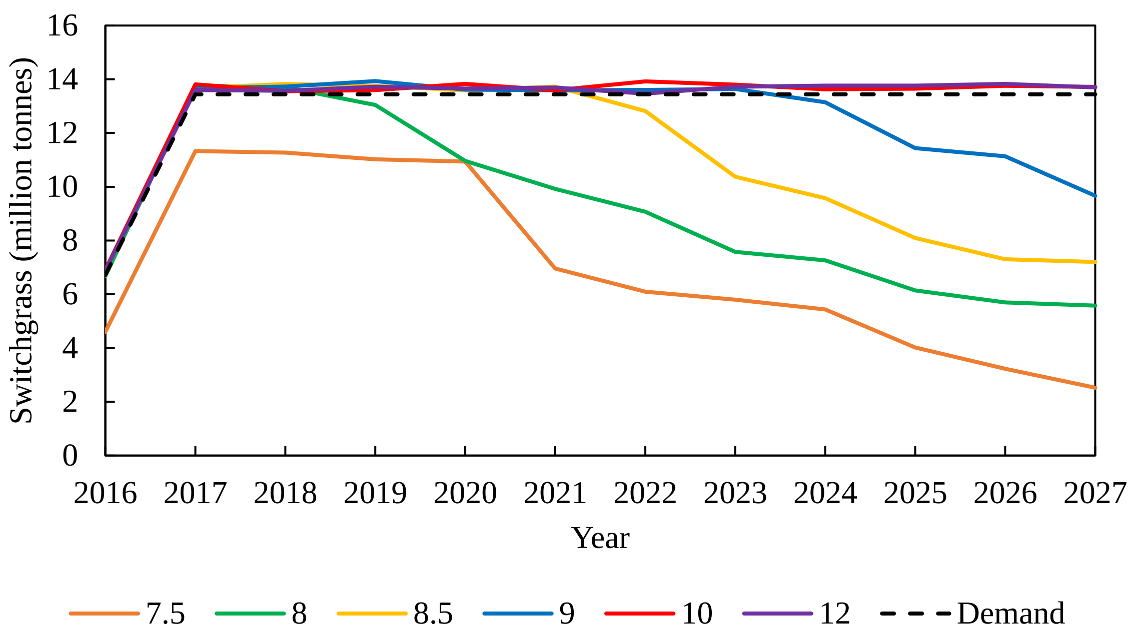

Figure 6.6. Switchgrass production under different switchgrass yield scenarios

The variable operating cost of cellulosic biofuel production mainly depends on the pretreatment costs and enzyme costs used in the fermentation step. Costs of pretreatment and enzyme materials heavily affect the selling price of cellulosic biofuels, reducing pretreatment and enzyme costs remains a challenge in developing a cost-effective bioconversion technology. This study assumes that the variable operating cost is \$0.03 per liter, which is lower than the estimated values (\$0.10-\$0.20 per liter) in other studies [135], [158], [178]. Figure 6.7 shows the changes in the amount of switchgrass acreage and the farm gate price associated with the variable operating costs of \$0.03 L^{-1} (base), \$0.05 L^{-1}, and \$0.10 L^{-1}. For the scenario with a variable operating cost of \$0.05 L^{-1}, a switchgrass supply shortage occurs in 2021, and the adoption of switchgrass decreases from 2021 until the end of the simulation. For the scenario with a variable operating cost of \$0.10 L^{-1}, the supply of switchgrass cannot meet the demand in the first year, which implies that biorefineries have to initiate contracts with farmers in order to secure enough feedstock supply. The average annual farm gate prices with variable operating costs of \$0.05 L^{-1} and \$0.10 L^{-1} are 5% and 17.7% lower than the price in the basic case, respectively. Given a constant breakeven price for cellulosic ethanol, higher variable operating costs limit the price that a biorefinery can afford to pay for feedstock. As a result, farmers will not adopt switchgrass at the lower price. It turns out that the variable operating cost of cellulosic biofuel production has a significant influence on the viability of cellulosic biofuel commercialization.

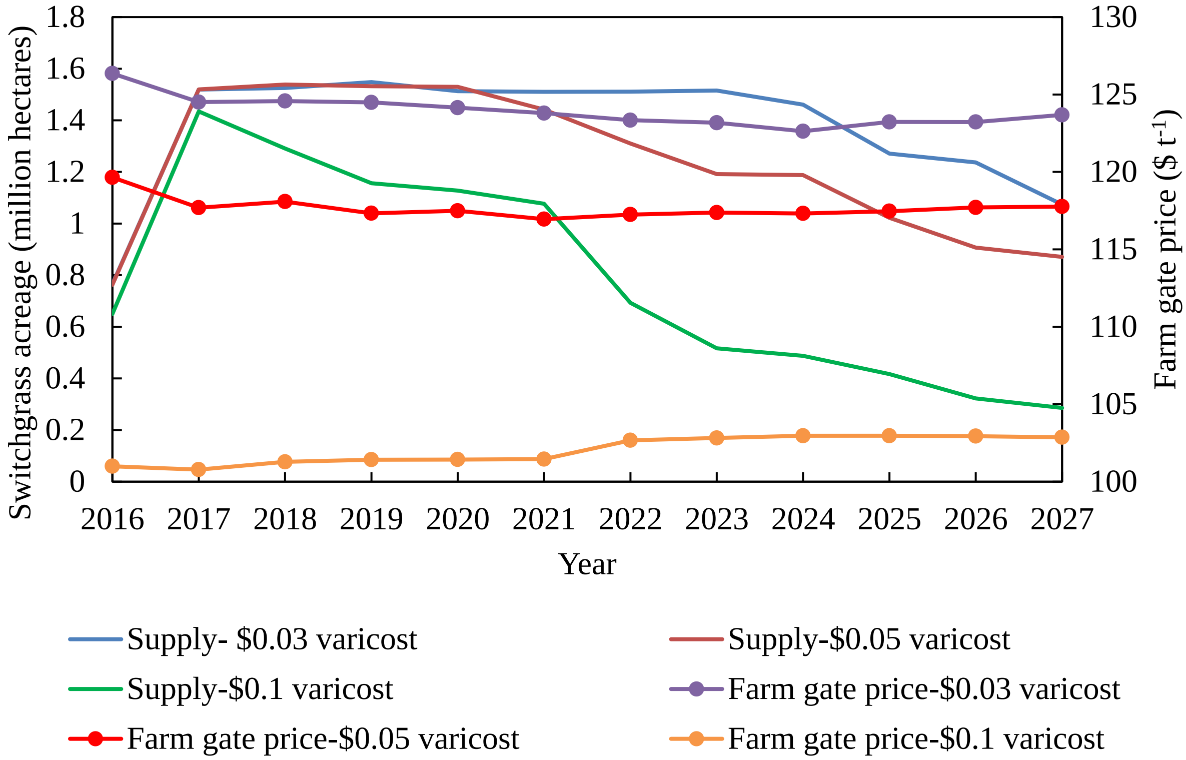

Figure 6.7. Comparisons of switchgrass acreage and farm gate price for different variable operating cost scenarios

High capital investment, including facility construction cost, equipment costs, and working capital, is another concern for biorefinery investors. A technical report on the techno-economic analysis of cellulosic ethanol production from NREL indicated that if the equipment size changes, the equipment cost will scale exponentially, based on ratio of the new equipment size to the original equipment size. However, the value of the scaling exponent was not available in the technical report. This sensitivity analysis differentiates the scaling coefficient of the equipment cost into values of 0.8, 1, and 1.2. A scaling coefficient of less than 1 indicates that the marginal equipment cost reduces with increased output of a product. When a scaling coefficient is greater than 1, the marginal equipment cost increases with additional output. As shown in Fig. 6.8, the scenario with a scaling coefficient of 0.8 has a stable switchgrass supply that can meet the annual demand for cellulosic biofuels. The switchgrass supply of the scenario with a scaling coefficient of larger than 1 is below the supply in the basic case. The average annual farm gate price, when the scaling coefficient is set to be 1.2, is estimated to be \$112.04 t^{-1}, which is 7% lower than the price in the basic case. When scaling coefficients increase over the basic case, the farm gate price for feedstock offered by the biorefineries decreases significantly, so it is unlikely that farmers would adopt dedicated energy crops in these circumstances.

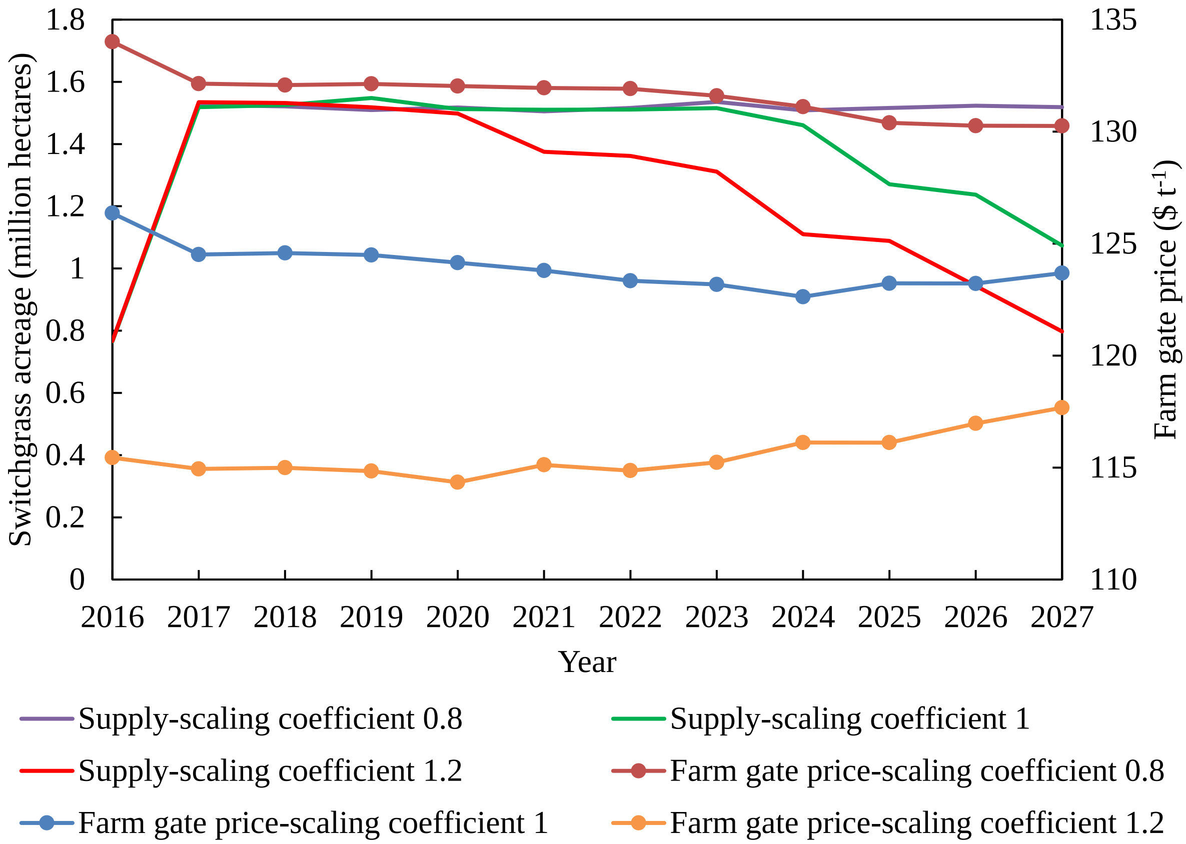

Figure 6.8. Comparisons of switchgrass acreage and farm gate price for different scaling coefficient scenarios

6.6.4 *Subsidy for cellulosic biofuel production*

Bioenergy policy is one of the most important drivers that can expand the market for second generation biofuels. Besides the RFS2 mandates, governmental subsidies or federal tax incentives can play a significant role in promoting regional bioenergy development. Significant research has indicated that a fixed subsidy for bioenergy production (e.g., bioethanol and bioelectricity) improves both the supply of dedicated energy crops and the consumption of bioenergy [179], [180]. However, in reality, the subsidy or tax credit was paid to biofuel blenders (petroleum companies) rather than biorefineries [152]. To simplify the implementation of the subsidy, this study assumes that the government will provide a fixed subsidy up to $1.0 per gallon ($0.26 per liter) for cellulosic biofuels. The additional subsidy will be a part of the revenue generated from cellulosic biofuel production. A comparison between subsidized and un-subsidized biofuel production scenarios are shown for both switchgrass adopters and switchgrass acreage in Fig. 6.9 (a) and (b), respectively. In the subsidy scenario, the supply of switchgrass is stable and sufficient for the required amount of cellulosic biofuels over the entire simulation period. In addition, the average annual farm gate price of switchgrass production increases to \$207.63 t^{-1} (see Fig. 6.10) and the subsidy is paid to the cellulosic biofuel plants.

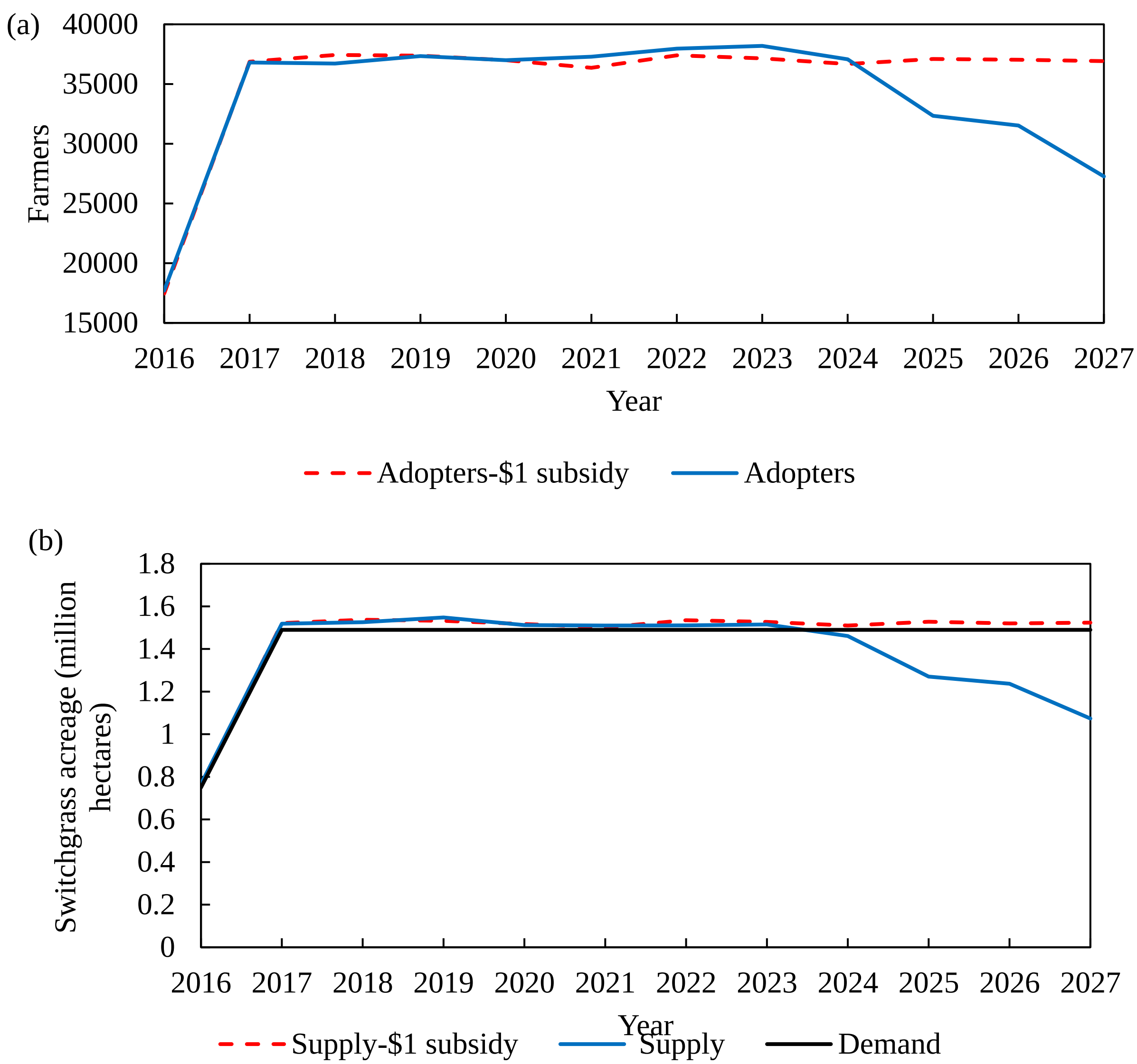

Figure 6.9. Comparisons of switchgrass adopters (a) and switchgrass acreage (b) between basic and subsidy scenarios

This study further examines different values of the subsidy at $0.01, $0.10, and $0.50 to identify the optimal magnitude of the subsidy to boost the commercialization of cellulosic biofuels. As the results show in Fig. 6.11, a subsidy below $0.10 per gallon cannot stabilize the supply of switchgrass and biorefineries will have a supply shortage in the last three years of the simulation. Therefore, a minimum subsidy of $0.10 per gallon is the optimal support strategy for facilitating the commercialization of cellulosic biofuels in Indiana.

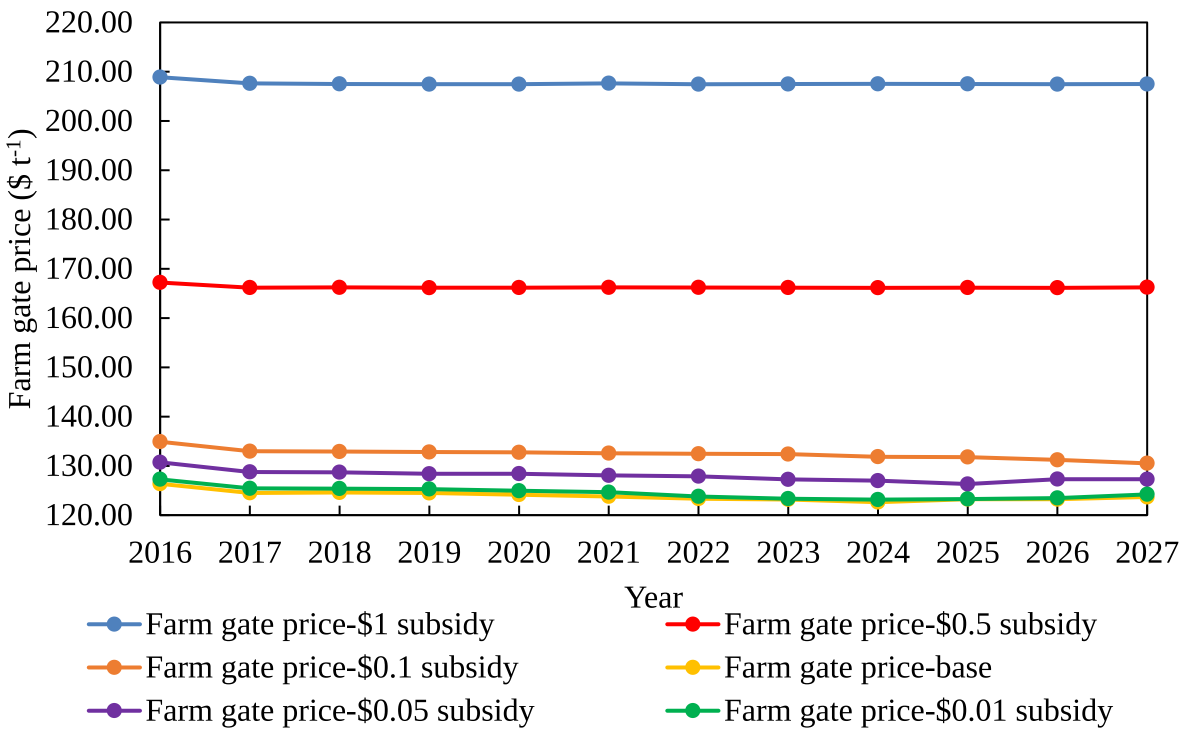

Figure 6.10. Comparisons of switchgrass farm gate price under different subsidy scenarios

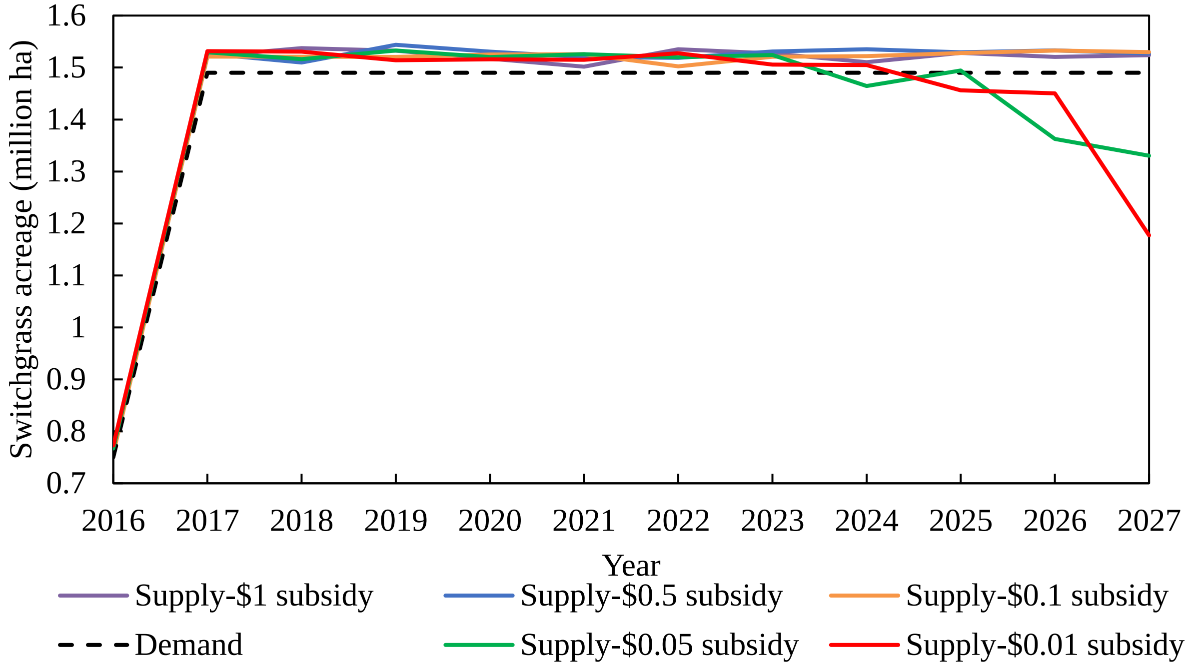

Figure 6.11. Comparisons of switchgrass acreage under different subsidy scenarios

6.6.5 *Spatial diffusion of switchgrass adoption*

In order to understand the spatial diffusion pattern of switchgrass adoption, the distribution of adopters is mapped based on the numbers of adopters in different counties in 2017 and 2023, as shown in Fig. 6.12(a) and (b), respectively. The red plant symbols represent the cellulosic biofuel facilities in Indiana. Most adopters are located in the same (or adjacent counties) where biorefineries are built at the beginning of adoption timeline (2017). Figure 6.12(b) depicts the adopters from different counties in 2023 with the same annual cellulosic biofuel production capacity. The red arrows indicate the directions and flows of adoption diffusion for a selected subset of counties. Comparing the number of adopters in 2017 with the results in 2023, it is found that the number of adopters in counties that are nearby biorefineries decrease and more adopters diffuse to some counties that are farther away from the biorefineries after 6 years. Moreover, the diffusion pattern for the adoption of switchgrass is found to be related to the corn productivity of the county. The corn yield of the county is given in Fig. 6.12(c). In general, more switchgrass adopters diffuse to the counties with lower corn yield than the counties with higher corn yield. For example (see the red circle area), the number of adopters in Cass County decreases in 2023 and more adoption occurs in Pulaski County, and Tippecanoe County, rather than other nearby counties, such as White County, Carroll County, and Fulton County, with relatively high corn yields. This implies that farmers in a lower corn-yield county are more likely to adopt switchgrass than farmers in a higher corn-yield county.

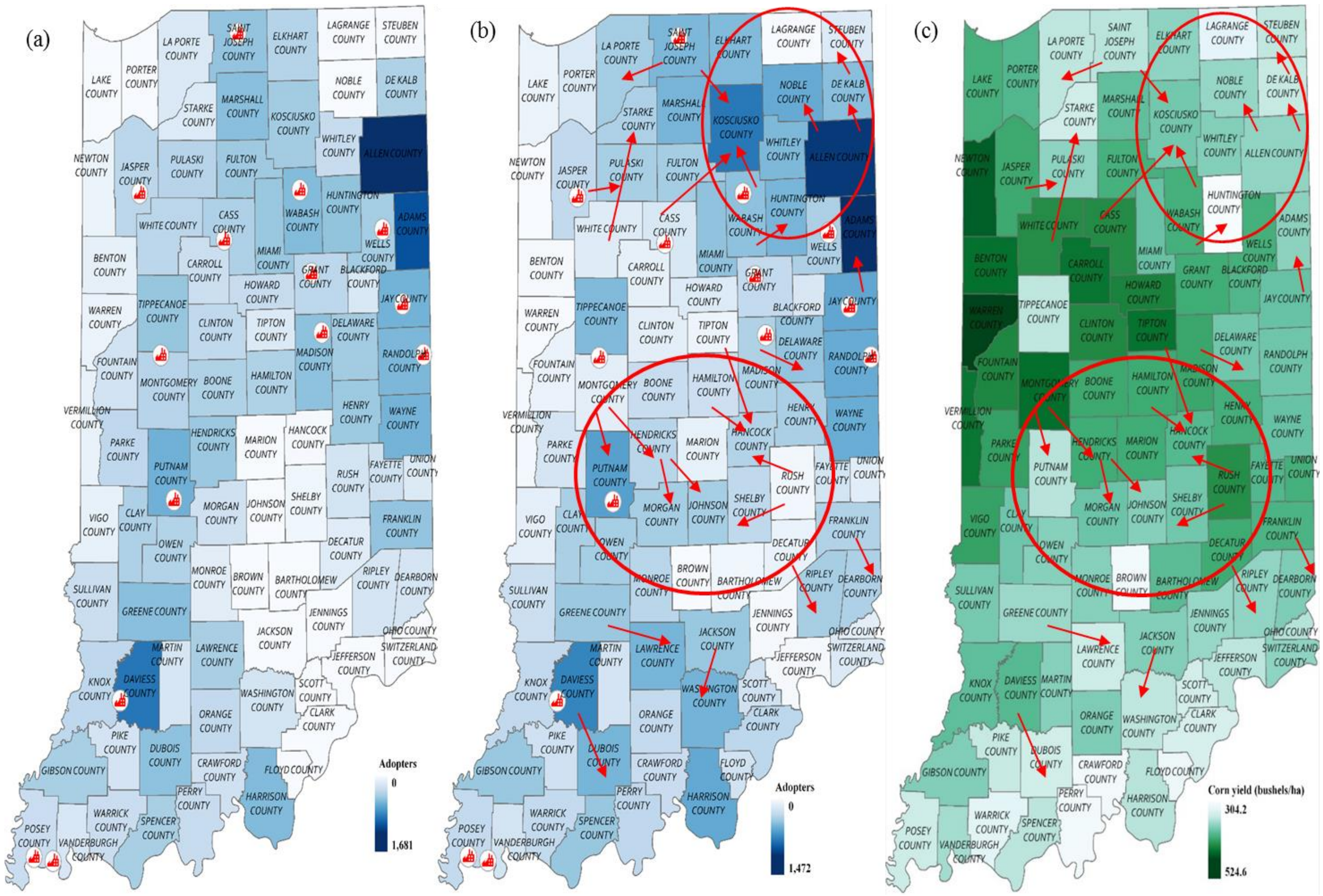

Figure 6.12. The number of switchgrass adopters in 2017(a) and in 2023 (b) and corn yields of the county (c).

6.6.6 *Viability of cellulosic biofuel commercialization in Indiana*

The viability of cellulosic biofuel commercialization in Indiana is simply identified by comparing the potential supply of switchgrass with the demand for cellulosic biofuels. Based on the simulated results, the commercialization of cellulosic biofuels has not proved to be viable in Indiana under the current situation. From the perspective of biorefineries, producing cellulosic biofuels from switchgrass is not economically viable when the supply of feedstock does not meet the demand for cellulosic biofuels. From the perspective of farmers, adopting switchgrass is not profitable compared to producing corn for a large range of farm gate prices. Biorefineries can secure a sufficient supply of feedstock by making contracts with farmers but it is likely that only a small proportion of farmers are willing to accept the contracts. The commercialization of cellulosic biofuels is likely to be economically viable at a higher price point than that used in this study for cellulosic ethanol. Gnansounou and Dauriat [30] concluded that the minimum selling price of cellulosic ethanol ranged from \$1.23 gal^{-1} (\$0.32 L^{-1}) to \$3.50 gal^{-1} (\$0.92 L^{-1})based on different feedstocks and the minimum selling price of cellulosic biofuel from corn stover was estimated to be \$3.40 gal^{-1} (\$0.90 L^{-1}) in the NREL technical report. [158] However, cellulosic biofuels with a higher selling price will not be competitive with conventional biofuels in the biofuel market and this issue will inhibit the commercialization of cellulosic biofuels.

The commercialization of cellulosic biofuels can be achieved by improving the yield of switchgrass production and reducing the production costs of cellulosic biofuels. Adopting high productivity strains of switchgrass generates higher profits for farmers, especially for locations with low production costs. A switchgrass yield of 10 t ha^{-1} or higher can provide a stable supply of switchgrass for cellulosic biofuels from Indiana farmers. Evidence has shown that yields of switchgrass can be as high as 10.7 t ha^{-1} in Indiana. [181] Higher yields of switchgrass also require lower land area conversion from cropland or marginal land. Reducing the variable operating cost of cellulosic biofuel production enables biorefineries to pay higher prices for feedstock and enhances the willingness of farmers to adopt switchgrass. In addition, a low variable operating cost can improve the competitiveness of cellulosic biofuels over conventional biofuels. Biorefineries may utilize new technologies to improve the conversion efficiency of cellulosic biomass into biofuels to reduce the variable operating cost. It is not economically viable to scale up the production capacity of a biorefinery if the cost to scale up the equipment is too high (e.g., the scaling coefficient of the equipment cost is more than 1). Investors are suggested to assess the optimal production capacity of a biorefinery in order to avoid economic losses. Government subsidies for bioenergy products are effective strategies to promote switchgrass adoption. A subsidy for cellulosic biofuel production will reduce economic risks for biorefineries to a certain degree and help secure a stable supply of feedstock.

6.6.7 *Social attributes related to the willingness of farmers*

In this model, the adoption threshold is employed as a social factor which influences whether farmers are willing to adopt the dedicated energy crops based on the average adoption rate of their neighbors. The distribution of the adoption threshold is assumed to follow the theory of innovation diffusion as mentioned in Section 6.2.4. Alexander et al. [154] found that the estimated total dedicated energy crop area was much higher when farmers had a high initial willingness (25% initial innovators) to adopt energy crops than the basic case (2.5% initial innovators). Brown et al. [153] incorporated mitigation willingness factors that represent the willingness of farmers to compromise revenue in order to reduce environmental impacts into an ABM to model bioenergy crop adoption. Risk aversion, education level, and familiarity with bioenergy crops were utilized as social attributes to reflect the willingness of farmers to adopt energy crops in the previous studies. For example, the risk of adopting energy crops could be alleviated by establishing contracts between farmers and biorefinery [156]. In reality, contracts are commonly used in existing biorefineries to procure switchgrass from farmers. However, biorefineries may experience an economic loss when offering a high contract payment for farmers. Due to the lack of survey data and limited information about the willingness of farmer to adopt dedicated energy crops in Indiana, other social attributes are not investigated in this study. Understanding the opinions and perceptions of farmers about dedicated energy crops is useful to predict their adoption behaviors more accurately.

6.6.8 *Influences of spatial heterogeneity on the diffusion of switchgrass adoption*

The effects of the spatial heterogeneity of farmers is included in the transportation distance to biorefineries, corn yield and production cost parameters. For instance, farm gate prices paid by biorefineries for feedstock are different for farmers due to different transportation distances of the feedstock. Farmers make different switchgrass adoption decisions based on their corresponding spatial attributes. Incorporating the spatial heterogeneity of farmers into the ABM enables an understanding of how switchgrass adoption can diffuse spatially. This study finds that the geographic location of switchgrass cultivation diffuses from counties with high corn productivity to counties with low corn productivity, because farmers in lower corn-yield counties may be able to realize higher profits by growing switchgrass rather than corn. Farmers that have a lower corn productivity are more likely to earn more money by adopting switchgrass than farmers that have a higher corn productivity. Biorefineries located near the counties with higher corn productivity can be provided feedstock by adopters from counties farther away with lower corn productivity. The diffusion pattern of switchgrass adoption could be an important factor for identifying the optimal location of a cellulosic biofuel facility. To ensure a stable supply of feedstock, biorefineries are suggested to be built in the center of a lower corn-productivity region. Moreover, cellulosic biofuel facilities must be located near switchgrass farms to reduce the cost of transportation and offer an acceptable price for farmers to adopt switchgrass.

CHAPTER 7. SUMMARY AND CONCLUSION

This dissertation developed an integrated sustainability model for assessing the sustainability performance regarding the expansion of bioenergy production. The ISM can simulate the dynamic behaviors of the bioenergy market so that it can capture the changes in environmental and socio-economic impacts caused by the bioenergy production in a given temporal and spatial scale. First, the ISM has been applied to the corn ethanol system. The demand for corn ethanol production is projected to increase in the short-term to meet the growing need for fuel (gasoline blended with ethanol), which is in turn driven by the economic and population growth in the U.S. It should be noted that the projected supply and demand of corn ethanol is based on recent historical data and the fuel ethanol price could be influenced by other factors such as feedstock price and regulatory incentives. In spite of the increased demand, the price of corn ethanol is expected to increase only slightly, with advanced biofuels addressing some portion of future needs. The reduction in GHG emissions due to biofuels (relative to gasoline) will continue owing to advancements in corn ethanol (and other biofuels) processing technology. The corn ethanol industry adds to the U.S. economy and it can create additional employment opportunities for involved sectors with stable labor income, especially when the demand for biofuels continues to rise. Tax revenue generated by the biofuel industry should serve to increase societal benefit.

Second, the ISM has been used for a forest biomass system for electricity generation to forecast environmental and socio-economic impacts. The model addresses dynamic changes in forest residue supply and demand. The projected results reveal that the available amount of forest residue can completely satisfy the demand for forest biomass for electricity generation associated with the current consumption level of bioenergy. The projected market price of forest residue production is consistent with the delivered cost estimated by others in the literature. An increase from 0.3% to 0.5% in the bioenergy share level of the total electricity demand will stimulate the bioenergy market for electricity generation. The utilization of forest residues can enhance soil carbon sequestration due to LUC from cropland to timberland; the consequence of this change is the avoidance of substantial GHG emissions, and a reduction of CO_2 emissions in the biomass co-firing system. The gross output and employment generated by the logging residue recovery and bio-power operation sectors have a significant contribution to the regional economy and society, especially for rural areas. In conclusion, forest residues are a promising alternative biomass for displacing coal in a co-firing system while reducing GHG emissions and generating socio-economic benefits in local communities.

Finally, this study has investigated a cellulosic biofuel system that produces cellulosic ethanol from switchgrass to achieve compliance with the RFS2 mandate. The results show that the demand for cellulosic biofuels in the lower volume requirement scenario can be met with the expansion of energy crops on marginal land and the development of biorefineries with advanced bioconversion technologies. Moreover, the growth of the cellulosic biofuel industry is expected to create significant benefits for the environment, the economy, and society, by increasing soil carbon storage, reducing GHG emissions, creating water use savings, improving gross economic output and job opportunities from cellulosic biofuel production, and reducing the social cost of carbon. However, the environmental damage from energy crop land expansion on marginal land (e.g., nitrate leaching) cannot be ignored. Given the land expansion constraints, the RFS2 volumetric requirements for cellulosic biofuels cannot be met when supply of energy crops is constrained by LUC. More lands need to be converted from cropland or pasture into energy crop land in order to comply with the RFS2 mandate. Governments should provide supportive policies for landowners and investors to improve the LUC for energy crops and the growth of the cellulosic biofuel industry. Developing more efficient bioconversion technologies of cellulosic biofuels and improving the productivity of energy crops can not only increase the profits for biorefineries but also reduce the GHG emissions in the life cycle of cellulosic biofuel production. However, a large expansion in energy crop land may increase nitrate leaching and affect the habitat of at-risk species living in cropland and pasture.

In addition, this study developed a spatial agent-based model to determine how decision-making processes of farmers effect the adoption of dedicated energy crops. The model is compared with the projection of switchgrass production from the 2016 Billion-ton Report. The simulation results indicate that the commercialization of cellulosic biofuels is not viable in Indiana in the long term, based on an expected demand for cellulosic biofuels of 1,115 million gallons. In the basic case, the supply of switchgrass provided by adopters can only meet the demand for cellulosic biofuels from 2016 to 2023. The maximum total supply of switchgrass as a feedstock for cellulosic biofuels is estimated to be 13.9 million tonnes with a yield of 9 t ha^{-1}. Only 7 biorefineries can produce cellulosic biofuels under current economic conditions in the long term. The ABM simulation indicates that increasing numbers of adopters in the counties with a high corn yield stop growing switchgrass and that the adoption of switchgrass diffuses to counties with a low corn yield. Improving the productivity of the switchgrass strain is an effective way to increase the adoption of dedicated energy crops. The high scaling equipment cost and variable operating cost for cellulosic biofuel production can dramatically reduce the market potential of cellulosic biofuels. In addition, governments can implement some supportive policies such as subsidies or tax credits for bioenergy producers to facilitate the commercialization of advanced biofuels. Some other actions, such as educational programs provided by universities and non-profit organizations will also increase the willingness of farmers to adopt dedicated energy crops. The approach of this study is intended to be informative rather than predictive, since only limited information about the perceptions of farmers for dedicated energy crops are included. To make the ABM more comprehensive and empirical, land allocation of a variety of crops and the availability of other land types (e.g., pasture and marginal land) can be included into the decision-making mechanisms of farmers.

In terms of future work, the developed ISM may be extended to include more advanced and complex sub-models to minimize the uncertainty in model projections. It should be noted that the model projections provide an informative implication (e.g., the trend of cellulosic ethanol production) rather than a deterministic solution, because external factors that can significantly alter the results are difficult to be controlled or prevented. While environmental and economic impacts are addressed in the current version of the ISM, additional social impacts and other performance measures may be added to the ISM in future research. The ISM is applicable for other complex bioenergy systems as an overall sustainability assessment tool. Both the ISM and agent-based modeling can provide comprehensive insights for stakeholders and policy makers to establish and implement favorable strategies for facilitating bioenergy sustainability development. The agent-based modeling can be incorporated into the ISM to understand how individual stakeholder's behaviors affect the sustainability performance of bioenergy systems.

REFERENCES

[1] M. Balat, "Global status of biomass energy use," *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 31, no. 13, pp. 1160–1173, 2009.

[2] E. M. W. Smeets, A. P. C. Faaij, I. M. Lewandowski, and W. C. Turkenburg, "A bottom-up assessment and review of global bio-energy potentials to 2050," *Prog. Energy Combust. Sci.*, vol. 33, no. 1, pp. 56–106, 2007.

[3] A. Eisentraut, A. Brown, and L. Fulton, "Technology Roadmap: Biofuels for Transport," *Int. Energy Agency, Paris, Fr.*, pp. 1–56, 2011.

[4] J. L. Sawin, K. Seyboth, and F. Sverrisson, *Renewables 2016: Global Status Report*. 2016.

[5] U.S. Department of Energy, "Global Ethanol Production," 2016. [Online]. Available: https://www.afdc.energy.gov/data/categories/biofuels-production.

[6] U.S. Energy Information Administration, "Monthly Energy Review December 2014," 2014.

[7] M. Downing, L. M. Eaton, R. L. Graham, M. H. Langholtz, R. D. Perlack, A. F. Turhollow Jr, B. Stokes, and C. C. Brandt, "U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry," no. August, 2011.

[8] C. Hitaj and S. Suttles, "Trends in U.S. Agriculture's Consumption and Production of Energy: Renewable Power, Shale Energy, and Cellulosic Biomass," no. 159, p. 47, 2016.

[9] R. Schnepf and B. D. Yacobucci, "Renewable Fuel Standard (RFS): Overview and Issues," 2011.

[10] EIA, "Monthly Energy Review," 2016.

[11] EIA, "Electric Power Annual," *Eia.Doe.Gov*, vol. 348, no. January, p. 2, 2016.

[12] C. Galik, R. Abt, and Y. Wu, "Forest Biomass Supply in the Southeastern United States—Implications for Industrial Roundwood and Bioenergy Production," *J. For.*, vol. 107, no. 2, p. 8, 2009.

[13] Jaya Shankar Tumuluru, Christopher T Wright, Richard D Boardman, Neal A Yancey, and Shahab Sokhansanj, "A review on biomass classification and composition, co-firing issues and pretreatment methods," *2011 Louisville, Kentucky, August 7 - August 10, 2011*, vol. 7004, no. 11, pp. 1–31, 2011.

[14] E. Agbor, X. Zhang, and A. Kumar, "A review of biomass co-firing in North America," *Renew. Sustain. Energy Rev.*, vol. 40, pp. 930–943, 2014.

[15] W. M. Post and K. C. Kwon, "Soil carbon sequestration and land-use change: Processes and potential," *Glob. Chang. Biol.*, vol. 6, no. 3, pp. 317–327, 2000.

[16] L. Vesterdal and J. Leifeld, "Land-use change and management effects on soil carbon sequestration: Forestry and agriculture," *Greenhouse-gas Budg. soils under Chang. Clim. L. use (BurnOut)• COST*, vol. 639, pp. 2006–2010, 2010.

[17] D. Nicholls and J. Zerbe, "Cofiring biomass and coal for fossil fuel reduction and other benefits-status of North American facilities in 2010," *USDA For. Serv. - Gen. Tech. Rep. PNW-GTR*, no. 867, pp. 1–22, 2012.

[18] D. Loeffler and N. Anderson, "Emissions tradeoffs associated with cofiring forest biomass with coal: A case study in Colorado, USA," *Appl. Energy*, vol. 113, pp. 67–77, 2014.

[19] N. Kaliyan, R. V. Morey, and D. G. Tiffany, "Reducing life cycle greenhouse gas emissions of corn ethanol by integrating biomass to produce heat and power at ethanol plants," *Biomass and Bioenergy*, vol. 35, no. 3, pp. 1103–1113, 2011.

[20] B. D. Solomon, "Biofuels and sustainability," *Ann. N. Y. Acad. Sci.*, vol. 1185, pp. 119–134, 2010.

[21] J. Domac, K. Richards, and S. Risovic, "Socio-economic drivers in implementing bioenergy projects," *Biomass and Bioenergy*, vol. 28, no. 2, pp. 97–106, 2005.

[22] F. Neuwahl, A. Löschel, I. Mongelli, and L. Delgado, "Employment impacts of EU biofuels policy: Combining bottom-up technology information and sectoral market simulations in an input-output framework," *Ecol. Econ.*, vol. 68, no. 1–2, pp. 447–460, 2008.

[23] D. Timmons, D. Damery, and G. Allen, "Energy from forest biomass: Potential economic impacts in Massachusetts," *for Massachusetts*, no. December, p. 30, 2007.

[24] B. C. English, K. Jensen, J. Menard, M. Walsh, C. Brandt, J. Van Dyke, and S. Hadley, "Economic Impacts Resulting from Co-firing Biomass Feedstocks in Southeastern United States Coal-Fired Plants," *Am. J. Agric. Econ.*, pp. 1–22, 2005.

[25] G. Perez-Verdin, D. L. Grebner, I. A. Munn, C. Sun, and S. C. Grado, "Economic impacts of woody biomass utilization for bioenergy in Mississippi.," *For. Prod. J.*, vol. 58, no. 11, pp. 75–83, 2008.

[26] N. Scarlat and J. F. Dallemand, "Recent developments of biofuels/bioenergy sustainability certification: A global overview," *Energy Policy*, vol. 39, no. 3, pp. 1630–1646, 2011.

[27] BirdLife International, "A NEW EU SUSTAINABLE BIOENERGY POLICY," 2016.

[28] T. H. Kim and T. H. Kim, “Overview of technical barriers and implementation of cellulosic ethanol in the U.S.,” *Energy*, vol. 66, pp. 13–19, 2014.

[29] A. Welfle, P. Gilbert, P. Thornley, and A. Stephenson, “Generating low-carbon heat from biomass: Life cycle assessment of bioenergy scenarios,” *J. Clean. Prod.*, vol. 149, pp. 448–460, 2017.

[30] E. Gnansounou and A. Dauriat, “Technoeconomic analysis of lignocellulosic ethanol,” *Biofuels*, vol. 101, no. 13, pp. 123–148, 2011.

[31] UNEP, “Technologies for Converting Waste Agricultural Biomass To Energy,” pp. 1–229, 2013.

[32] D. Carpenter, T. L. Westover, S. Czernik, and W. Jablonski, “Biomass feedstocks for renewable fuel production: a review of the impacts of feedstock and pretreatment on the yield and product distribution of fast pyrolysis bio-oils and vapors,” *Green Chem.*, vol. 16, no. 2, pp. 384–406, 2014.

[33] N. Springer, N. Kaliyan, B. Bobick, and J. Hill, “Seeing the forest for the trees: How much woody biomass can the Midwest United States sustainably produce?,” *Biomass and Bioenergy*, vol. 105, pp. 266–277, 2017.

[34] B. T. Office, “BIOENERGY TECHNOLOGIES OFFICE Forest Biomass and Wood Wastes *,” 2011.

[35] S. N. Naik, V. V. Goud, P. K. Rout, and A. K. Dalai, “Production of first and second generation biofuels: A comprehensive review,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 2, pp. 578–597, 2010.

[36] R. B. Mitchell, M. R. Schmer, W. F. Anderson, V. Jin, K. S. Balkcom, J. Kiniry, A. Coffin, and P. White, “Dedicated Energy Crops and Crop Residues for Bioenergy Feedstocks in the Central and Eastern USA,” *Bioenergy Res.*, vol. 9, no. 2, pp. 384–398, 2016.

[37] N. S. Margaris, “Agricultural residues and energy crops,” *Energy from Biomass*, 1981.

[38] U. S. E. P. A. USEPA, “Advancing sustainable materials management: 2014 Fact Sheet,” *United States Environ. Prot. Agency, Off. L. Emerg. Manag. Washington, DC 20460*, no. November, p. 22, 2016.

[39] C. Dong and X. Hu, “CHAPTER 4 Co-combustion coal and bioenergy and biomass gasification : Chinese experiences,” vol. 2010, 2010, pp. 97–128.

[40] E. Kantarelis, W. Yang, and W. Blasiak, “Biomass pyrolysis for energy and fuel production,” in *Technologies for converting biomass to useful energy – Combustion, Gasification, Pyrolysis, Torrefaction andFermentation*, 2013, pp. 245–271.

[41] J. L. Carrasco, S. Gunukula, A. A. Boateng, C. A. Mullen, W. J. DeSisto, and M. C. Wheeler, “Pyrolysis of forest residues: An approach to techno-economics for bio-fuel production,” *Fuel*, vol. 193, pp. 477–484, 2017.

[42] M. F. Demirbas, M. Balat, and H. Balat, “Potential contribution of biomass to the sustainable energy development,” *Energy Convers. Manag.*, vol. 50, no. 7, pp. 1746–1760, 2009.

[43] D. J. Stevens, “Hot Gas Conditioning: Recent Progress with Larger-Scale Biomass Gasification Systems; Update and Summary of Recent Progress,” 2001.

[44] N. Rader and S. Hempling, “The renewables portfolio standard: A practical guide,” *Natl. Assoc. Regul. Util. Comm.*, no. February, 2001.

[45] F. J. Rossi, D. R. Carter, and R. C. Abt, “Woody Biomass for Electricity Generation in Florida : Bioeconomic Impacts under a Proposed Renewable Portfolio Standard (RPS) Mandate Final Report,” *Florida Derartment Agric. Consum. Serv.*, 2010.

[46] S. Carley, “State renewable energy electricity policies: An empirical evaluation of effectiveness,” *Energy Policy*, vol. 37, no. 8, pp. 3071–3081, 2009.

[47] F. C. Menz, “Green electricity policies in the United States: Case study,” *Energy Policy*, vol. 33, no. 18, pp. 2398–2410, 2005.

[48] L. Bird, M. Bolinger, T. Gagliano, R. Wiser, M. Brown, and B. Parsons, “Policies and market factors driving wind power development in the United States,” *Energy Policy*, vol. 33, no. 11, pp. 1397–1407, 2005.

[49] E. Blank, L. Bird, and B. Swezey, “A certificate-based approach to marketing green power and constructing new wind energy facilities,” *Wind Eng.*, vol. 26, no. 2, pp. 63–70, 2002.

[50] J. H. Stock, “The Renewable Fuel Standard: A Path Fow,” 2015.

[51] T. J. Lark, J. Meghan Salmon, and H. K. Gibbs, “Cropland expansion outpaces agricultural and biofuel policies in the United States,” *Environ. Res. Lett.*, vol. 10, no. 4, p. 44003, 2015.

[52] R. S. Dodder, A. Elobeid, T. L. Johnson, P. O. Kaplan, L. A. Kurkalova, S. Secchi, and S. Tokgoz, “Environmental Impacts of Emerging Biomass Feedstock Markets: Energy, Agriculture, and the Farmer,” no. 919, pp. 1–12, 2011.

[53] J. M. Melillo, J. M. Reilly, D. W. Kicklighter, A. C. Gurgel, T. W. Cronin, S. Paltsev, B. S. Felzer, X. Wang, A. P. Sokolov, and C. A. Schlosser, "Indirect Emissions from Biofuels: How Important?," *Science (80-.).*, vol. 326, no. 5958, pp. 1397–1399, 2009.

[54] D. Rutz, "Biofuel Technology Handbook," *Contract*, p. 152, 2008.

[55] E. Cushion, A. Whiteman, and G. Dieterle, *Bioenergy Development*. 2009.

[56] A. Rossi and Y. Lambrou, "Gender and equity issues in liquid biofuels production: Minimizing the risks to maximize the opportunities," *East*, 2008.

[57] N. Goad and S. Vermeulen, *Towards Better Practice in Smallholder Palm Oil Production*, vol. 43, no. 4. 2006.

[58] L. V. Rasmussen, R. Bierbaum, J. A. Oldekop, and A. Agrawal, "Bridging the practitioner-researcher divide: Indicators to track environmental, economic, and sociocultural sustainability of agricultural commodity production," *Glob. Environ. Chang.*, vol. 42, pp. 33–46, 2017.

[59] B. Hickman, "Environmental and Socioeconomic Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States Field to Market : The Alliance for Sustainable Agriculture," 2016.

[60] A. C. McBride, V. H. Dale, L. M. Baskaran, M. E. Downing, L. M. Eaton, R. A. Efroymson, C. T. Garten, K. L. Kline, H. I. Jager, P. J. Mulholland, E. S. Parish, P. E. Schweizer, and J. M. Storey, "Indicators to support environmental sustainability of bioenergy systems," *Ecol. Indic.*, vol. 11, no. 5, pp. 1277–1289, 2011.

[61] V. H. Dale, M. H. Langholtz, B. M. Wesh, and L. M. Eaton, "Environmental and Socioeconomic Indicators for Bioenergy Sustainability as Applied to *Eucalyptus*," *Int. J. For. Res.*, vol. 2013, pp. 1–10, 2013.

[62] R. A. Efroymson, V. H. Dale, K. L. Kline, A. C. McBride, J. M. Bielicki, R. L. Smith, E. S. Parish, P. E. Schweizer, and D. M. Shaw, "Environmental indicators of biofuel sustainability: What about context?," *Environ. Manage.*, vol. 51, no. 2, pp. 291–306, 2013.

[63] F. Cherubini and A. H. Strømman, "Life cycle assessment of bioenergy systems: State of the art and future challenges," *Bioresour. Technol.*, vol. 102, no. 2, pp. 437–451, 2011.

[64] E. Gnansounou, A. Dauriat, J. Villegas, and L. Panichelli, "Life cycle assessment of biofuels: Energy and greenhouse gas balances," *Bioresour. Technol.*, vol. 100, no. 21, pp. 4919–4930, 2009.

[65] F. Cherubini, N. D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, and S. Woess-Gallasch, “Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations,” *Resour. Conserv. Recycl.*, vol. 53, no. 8, pp. 434–447, 2009.

[66] C. W. Murphy and A. Kendall, “Life cycle analysis of biochemical cellulosic ethanol under multiple scenarios,” *GCB Bioenergy*, vol. 7, no. 5, pp. 1019–1033, 2015.

[67] S. Chovau, D. Degrauwe, and B. Van Der Bruggen, “Critical analysis of techno-economic estimates for the production cost of lignocellulosic bio-ethanol,” *Renew. Sustain. Energy Rev.*, vol. 26, pp. 307–321, 2013.

[68] R. Bess and Z. O. Ambargis, “Input-Output Models for Impact Analysis: Suggestions for Practitioners Using RIMS II Multipliers,” *50th South. Reg. Sci. Assoc. Conf.*, pp. 1–28, 2011.

[69] D. Conley, K. Brooks, C. Walters, and E. Thompson, “Economic Impacts of the Ethanol Industry in Nebraska Department of Agricultural Economics Bureau of Business Research,” no. March, 2015.

[70] N. Onat, M. Kucukvar, A. Halog, and S. Cloutier, “Systems Thinking for Life Cycle Sustainability Assessment: A Review of Recent Developments, Applications, and Future Perspectives,” *Sustainability*, vol. 9, no. 5, p. 706, 2017.

[71] L. Elghali, R. Clift, P. Sinclair, C. Panoutsou, and A. Bauen, “Developing a sustainability framework for the assessment of bioenergy systems,” *Energy Policy*, vol. 35, no. 12, pp. 6075–6083, 2007.

[72] T. S. Buchholz, T. A. Volk, and V. A. Luzadis, “A participatory systems approach to modeling social, economic, and ecological components of bioenergy,” *Energy Policy*, vol. 35, no. 12, pp. 6084–6094, 2007.

[73] J. J. Wang, Y. Y. Jing, C. F. Zhang, and J. H. Zhao, “Review on multi-criteria decision analysis aid in sustainable energy decision-making,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2263–2278, 2009.

[74] D. Thrän, R. Schaldach, M. Millinger, V. Wolf, O. Arendt, J. Ponitka, S. Gärtner, N. Rettenmaier, K. Hennenberg, and J. Schüngel, “The MILESTONES modeling framework: An integrated analysis of national bioenergy strategies and their global environmental impacts,” *Environ. Model. Softw.*, vol. 86, pp. 14–29, 2016.

[75] S. Peterson, B. Bush, E. Newes, D. Inman, D. Hsu, L. Vimmerstedt, and D. Stright, "An Overview of the Biomass Scenario Model," *Proc. 31st Int. Conf. Syst. Dyn. Soc.*, vol. Biofuels a, no. July 2011, 2013.

[76] A. Barisa, F. Romagnoli, A. Blumberga, and D. Blumberga, "Future biodiesel policy designs and consumption patterns in Latvia: A system dynamics model," *J. Clean. Prod.*, vol. 88, pp. 71–82, 2015.

[77] A. Blumberga, G. Bazbauers, P. I. Davidsen, D. Blumberga, A. Gravelsins, and T. Prodanuks, "System dynamics model of a biotechonomy," *J. Clean. Prod.*, vol. 172, pp. 4018–4032, 2018.

[78] J. K. Musango, A. C. Brent, B. Amigun, L. Pretorius, and H. Müller, "Technology sustainability assessment of biodiesel development in South Africa: A system dynamics approach," *Energy*, vol. 36, no. 12, pp. 6922–6940, 2011.

[79] E. Jin and J. W. Sutherland, "A Proposed Integrated Sustainability Model for a Bioenergy System," *Procedia CIRP*, vol. 48, pp. 358–363, 2016.

[80] R. F. Jeffers, J. J. Jacobson, and E. M. Searcy, "Dynamic analysis of policy drivers for bioenergy commodity markets," *Energy Policy*, vol. 52, pp. 249–263, 2013.

[81] L. J. Vimmerstedt, B. Bush, and S. Peterson, "Ethanol distribution, dispensing, and use: Analysis of a portion of the biomass-to-biofuels supply chain using system dynamics," *PLoS One*, vol. 7, no. 5, 2012.

[82] C. Lin, "A generic methodology that aids the application of system dynamics to manufacturing system modelling," *Int. Conf. Simul.*, vol. 1998, no. October, pp. 344–349, 1998.

[83] J. D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*. 2000.

[84] C. June, S. E. E. L. Page, and D. M. Kammen, "Ethanol can contribute to energy and environmental Goals," *Science (80-.).*, vol. 311, no. January, pp. 506–509, 2006.

[85] U. S. D. of A. Economic Research Service (ERS) and (USDA)., "Bioenergy Statistics. Table 14 Fuel ethanol, corn and gasoline prices, by month," 2016. [Online]. Available: http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx.

[86] E. Zafeiriou, G. Arabatzis, P. Karanikola, S. Tampakis, and S. Tsiantikoudis, "Agricultural commodity and crude oil prices: An empirical investigation of their relationship," *Sustain.*, vol. 10, no. 4, pp. 1–11, 2018.

[87] A. Dutta, E. Bouri, J. Junttila, and G. S. Uddin, "Does corn market uncertainty impact the US ethanol prices?," *GCB Bioenergy*, vol. 10, no. 9, pp. 683–693, 2018.

[88] M. Wang, M. Wu, and H. Huo, "Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types," *Environ. Res. Lett.*, vol. 2, no. 2, p. 24001, 2007.

[89] J. M. Urbanchuk, "Contribution of the Ethanol Industry to the Economy of the United States," no. 2, pp. 1–10, 2010.

[90] Cardno Entrix, "Current state of the US ethanol industry," 2011.

[91] B. S. W, "GHG EMISSION REDUCTIONS FROM WORLD BIOFUEL PRODUCTION AND USE -2015 Global Renewable Fuels Alliance," 2015.

[92] J. I. Briedis, J. S. Wilson, J. G. Benjamin, and R. G. Wagner, "Logging Residue Volumes and Characteristics following Integrated Roundwood and Energy-Wood Whole-Tree Harvesting in Central Maine," *North. J. Appl. For.*, vol. 28, no. 2, pp. 66–71, 2011.

[93] J. Gan and C. T. Smith, "Availability of logging residues and potential for electricity production and carbon displacement in the USA," *Biomass and Bioenergy*, vol. 30, no. 12, pp. 1011–1020, 2006.

[94] W. B. Smith, J. S. Vissage, D. R. Darr, and R. M. Sheffield, "Forest Resources of the United States, 1997," *Distribution*, p. 127, 1997.

[95] U.S. Energy Information Administration, "Short-Term Energy Outlook (STEO)," no. July 2017, 2018.

[96] P. Stewart, "Wood Supply Market Trends in the US South Wood Supply Trends in the US South: 1995-2015," 2015.

[97] J. L. Howard, "U . S . Timber Production , Trade , Consumption , and Price Statistics , 1965 – 2013," no. February, pp. 1965–2013, 2016.

[98] M. a Bernstein and J. Griffin, "Regional differences in the price-elasticity of demand for energy," *Distribution*, no. February, p. 122, 2005.

[99] International Energy Agency, "International Energy Agency Statistics." [Online]. Available: http://www.iea.org/statistics/statisticssearch. [Accessed: 10-Mar-2017].

[100] Z. Haq, "Biomass for Electricity Generation," no. June 1999, pp. 1–18, 2001.

[101] E. M. White, G. Latta, R. J. Alig, K. E. Skog, and D. M. Adams, "Biomass production from the U.S. forest and agriculture sectors in support of a renewable electricity standard," *Energy Policy*, vol. 58, pp. 64–74, 2013.

[102] S. De and M. Assadi, "Impact of cofiring biomass with coal in power plants - A techno-economic assessment," *Biomass and Bioenergy*, vol. 33, no. 2, pp. 283–293, 2009.

[103] D. Yemshanov, D. W. McKenney, S. Fraleigh, B. McConkey, T. Huffman, and S. Smith, "Cost estimates of post harvest forest biomass supply for Canada," *Biomass and Bioenergy*, vol. 69, pp. 80–94, 2014.

[104] J. Gan and C. T. Smith, "A comparative analysis of woody biomass and coal for electricity generation under various CO2 emission reductions and taxes," *Biomass and Bioenergy*, vol. 30, no. 4, pp. 296–303, 2006.

[105] J. Wang, "Woody Biomass Sustainability for Bioenergy Production in West Virginia," *Citeseer*, pp. 1–10, 2008.

[106] B. D. . b Solomon and V. A. . Luzadis, *Renewable energy from forest resources in the United States*. 2008.

[107] S. N. Oswalt, W. B. Smith, P. D. Miles, and S. A. Pugh, "Forest Resources of the United States, 2012: a technical document supporting the Forest Service 2015. Update of the 2010 RPA Assessment Forest Resources of the United States , 2012 :," no. October, p. 228, 2014.

[108] D. G. Kim and M. U. F. Kirschbaum, "The effect of land-use change on the net exchange rates of greenhouse gases: A compilation of estimates," *Agric. Ecosyst. Environ.*, vol. 208, pp. 114–126, 2015.

[109] Y. Zhang, J. McKechnie, D. Cormier, R. Lyng, W. Mabee, A. Ogino, and H. Maclean, "Life Cycle Emissions and Cost of Producing Electricity from Coal, Natural Gas, and Wood Pellets in Ontario, Canada Life Cycle Emissions and Cost of Producing Electricity from Coal , Natural Gas , and Wood Pellets in Ontario , Canada," *Environ. Sci. Technol.*, vol. 44, no. 1, pp. 538–544, 2010.

[110] A. Femp, "Biomass Cofiring in Coal-Fired Boilers," *Management*, pp. 1–40, 2004.

[111] R. N. Lubowski, M. Vesterby, S. Bucholtz, A. Baez, and M. J. Roberts, "Major Uses of Land in the United States, 2007," *Econ. Inf. Bull.*, vol. 77, no. May, p. 47, 2006.

[112] C. Gutzler, K. Helming, D. Balla, R. Dannowski, D. Deumlich, M. Glemnitz, A. Knierim, W. Mirschel, C. Nendel, C. Paul, S. Sieber, U. Stachow, A. Starick, R. Wieland, A. Wurbs, and P. Zander, "Agricultural land use changes - A scenario-based sustainability impact assessment for Brandenburg, Germany," *Ecol. Indic.*, vol. 48, pp. 505–517, 2015.

[113] T. T. Liu, B. G. McConkey, Z. Y. Ma, Z. G. Liu, X. Li, and L. L. Cheng, "Strengths, weaknessness, opportunities and threats analysis of bioenergy production on Marginal Land," *Energy Procedia*, vol. 5, pp. 2378–2386, 2011.

[114] G. Papachristos and E. Adamides, "System dynamics modelling for assessing promotion strategies of biofuels used in land transportation," *30th Int. Conf. Syst. Dyn. Soc.*, pp. 1–25, 2012.

[115] D. Dickens, D. Moorhead, C. Dangerfield, U. G. A. Wsfr, and S. C. Gfc, "Thinning Pine Plantations."

[116] N. C. Hanzelka, M. C. Bolding, J. Sullivan, and S. M. Barrett, "Productivity and costs of utilizing small-diameter stems in a biomass-only harvest," *Int. J. For. Eng.*, vol. 27, no. 1, pp. 43–52, 2016.

[117] C. Demers, A. Long, and J. Nowak, "EDIS Thinning Southern Pines - A Key to Greater Returns," no. January 2010, pp. 1–6, 2010.

[118] T. R. Fox, E. J. Jokela, and H. L. Allen, "Pine Plantation Silviculture," *Gen. Tech. Rep. SRS–75. Asheville, NC U.S. Dep. Agric. For. Serv. South. Res. Station.*, pp. 63–82, 2004.

[119] R. L. Eberlein and D. W. Peterson, "Understanding models with Vensim," *Eur. J. Oper. Res.*, vol. 59, no. 1, pp. 216–219, 1992.

[120] A. Lebedys and Y. Li, "Contribution of the Forestry Sector to National Economies, 1990-2011," *FAO Rep.*, p. 168, 2014.

[121] J. P. Prestemon, D. N. Wear, and M. O. Foster, "The global position of the U.S. forest products industry," *U.S. Dep. Agric. For. Serv. South. Res. Stn. e-General Tech. Rep.*, vol. SRS-204, no. March, pp. 1–24, 2015.

[122] N. Bichraoui-Draper, M. Xu, S. A. Miller, and B. Guillaume, "Agent-based life cycle assessment for switchgrass-based bioenergy systems," *Resour. Conserv. Recycl.*, vol. 103, pp. 171–178, 2015.

[123] Environmental Protection Agency, "Environmental Protection Agency 40 CFR Part 80 Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule / Rules and Regulations," 2010.

[124] U. S. E. P. A. USEPA, "EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels," 2009.

[125] D. Burkholder, "A Preliminary Assessment of RIN Market Dynamics, RIN Prices, and Their Effects," pp. 1–31, 2015.

[126] T. A. Lloyd and C. E. Wyman, "Combined sugar yields for dilute sulfuric acid pretreatment of corn stover followed by enzymatic hydrolysis of the remaining solids," *Bioresour. Technol.*, vol. 96, no. 18 SPEC. ISS., pp. 1967–1977, 2005.

[127] F. K. Kazi, J. A. Fortman, R. P. Anex, D. D. Hsu, A. Aden, A. Dutta, and G. Kothandaraman, "Techno-economic comparison of process technologies for biochemical ethanol production from corn stover," *Fuel*, vol. 89, no. SUPPL. 1, pp. S20–S28, 2010.

[128] H. M. Zabed, S. Akter, J. Yun, G. Zhang, F. N. Awad, X. Qi, and J. N. Sahu, "Recent advances in biological pretreatment of microalgae and lignocellulosic biomass for biofuel production," *Renew. Sustain. Energy Rev.*, vol. 105, no. June 2018, pp. 105–128, 2019.

[129] U.S. Energy Information Administration, "State Energy Production Estimates 1960 Through 2011," pp. 1–16, 2011.

[130] K. Moriarty, A. Milbrandt, E. Warner, J. Lewis, and A. Schwab, "2016 Bioenergy Industry Status Report," no. March, 2018.

[131] U. S. E. P. A. USEPA, "Table 2: Total RVO for Each Compliance Year." [Online]. Available: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/annual-compliance-data-obligated-parties-and#total-rvo. [Accessed: 10-Jan-2019].

[132] A. Nocentini, J. Field, A. Monti, and K. Paustian, "Biofuel production and soil GHG emissions after land-use change to switchgrass and giant reed in the U.S. Southeast," *Food Energy Secur.*, vol. 7, no. 1, 2018.

[133] Biotechnology Industry Organization (BIO), "The value proposition for cellulosic and advanced biofuels under the US federal renewable fuel standard," vol. 7, no. 2, pp. 111–117, 2011.

[134] U. S. E. P. A. USEPA, "Cellulosic Waiver Credit Price Calculation for 2016," vol. 211, no. November 2015, pp. 2015–2016, 2016.

[135] Y. Zhang, M. Goldberg, E. Tan, and P. A. Meyer, "Estimation of economic impacts of cellulosic biofuel production: a comparative analysis of three biofuel pathways," *Biofuels, Bioprod. Biorefining*, vol. 10, no. 3, pp. 281–298, 2016.

[136] National Renewable Energy Laboratory (NREL), "JEDI : Jobs and Economic Development Impact Model," 2015.

[137] D. Bbosa, M. Mba-Wright, and R. C. Brown, "More than ethanol: a techno-economic analysis of a corn stover-ethanol biorefinery integrated with a hydrothermal liquefaction process to convert lignin into biochemicals," *Biofuels, Bioprod. Biorefining*, vol. 12, no. 3, pp. 497–509, 2018.

[138] T. J. Lark, J. Meghan Salmon, and H. K. Gibbs, "Cropland expansion outpaces agricultural and biofuel policies in the United States," *Environ. Res. Lett.*, vol. 10, no. 4, 2015.

[139] I. Gelfand, R. Sahajpal, X. Zhang, R. C. Izaurralde, K. L. Gross, and G. P. Robertson, "Sustainable bioenergy production from marginal lands in the US Midwest," *Nature*, vol. 493, no. 7433, pp. 514–517, 2013.

[140] USDA NRCS, "National Resources Inventory Summary Report," no. August 2015, 2012.

[141] R. Li and J. Chen, "Planning the next-generation biofuel crops based on soil-water constraints," *Biomass and Bioenergy*, vol. 115, no. March, pp. 19–26, 2018.

[142] M. Wu and Y. Chiu, "Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline 2011 update," 2011.

[143] U. S. G. Interagency Working Group on Social Cost of Carbon, "Technical Support Document: - Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866 -- July 2015 Revision," no. May 2013, pp. 1–21, 2013.

[144] Q. Feng, I. Chaubey, R. Cibin, B. Engel, K. P. Sudheer, J. Volenec, and N. Omani, "Perennial biomass production from marginal land in the Upper Mississippi River Basin," *L. Degrad. Dev.*, vol. 29, no. 6, pp. 1748–1755, 2018.

[145] E. Brandes, G. S. McNunn, L. A. Schulte, D. J. Muth, A. VanLoocke, and E. A. Heaton, "Targeted subfield switchgrass integration could improve the farm economy, water quality, and bioenergy feedstock production," *GCB Bioenergy*, vol. 10, no. 3, pp. 199–212, 2018.

[146] Q. Zhuang, Z. Qin, and M. Chen, "Biofuel, land and water: Maize, switchgrass or Miscanthus?," *Environ. Res. Lett.*, vol. 8, no. 1, 2013.

[147] C. M. Clark, Y. Lin, B. G. Bierwagen, L. M. Eaton, M. H. Langholtz, P. E. Morefield, C. E. Ridley, L. Vimmerstedt, S. Peterson, and B. W. Bush, "Growing a sustainable biofuels industry: Economics, environmental considerations, and the role of the Conservation Reserve Program," *Environ. Res. Lett.*, vol. 8, no. 2, 2013.

[148] F. K. Kazi, J. Fortman, R. Anex, and G. Kothandaraman, "Techno-economic analysis of biochemical scenarios for production of cellulosic ethanol," *Nrel*, no. June, 2010.

[149] U.S. EIA, "Annual Energy Outlook 2018 with projections to 2050," *Annu. Energy Outlook 2018 with Proj. to 2050*, vol. 44, no. 8, pp. 1–64, 2018.

[150] J. Dumortier, "Impact of agronomic uncertainty in biomass production and endogenous commodity prices on cellulosic biofuel feedstock composition," *GCB Bioenergy*, vol. 8, no. 1, pp. 35–50, 2016.

[151] U. S. E. P. A. USEPA, "Renewable Fuel Standard Program: Standards for 2019 and Biomass-Based Diesel Volume for 2020 - Final Rule (November 30, 2018)," 2019.

[152] U.S. Department of Energy's Bioenergy Technologies Office, "2015 Bioenergy Market Report," 2017.

[153] C. Brown, I. Bakam, P. Smith, and R. Matthews, "An agent-based modelling approach to evaluate factors influencing bioenergy crop adoption in north-east Scotland," *GCB Bioenergy*, vol. 8, no. 1, pp. 226–244, 2016.

[154] P. Alexander, D. Moran, M. D. A. Rounsevell, and P. Smith, "Modelling the perennial energy crop market: the role of spatial diffusion," *J. R. Soc. Interface*, vol. 10, no. 88, pp. 20130656–20130656, 2013.

[155] S. Huang, G. Hu, C. Chennault, L. Su, E. Brandes, E. Heaton, L. Schulte, L. Wang, and J. Tyndall, "Agent-based modeling of bioenergy crop adoption and farmer decision-making," *Energy*, vol. 115, pp. 1188–1201, 2016.

[156] H. Li and R. B. Ross, "Farmers' Switchgrass Adoption Decision Under A Single-Procurer Market: An Agent Based Simulation Approach," in *Agricultural & Applied Economics Association's 2014 AAEA Annual Meeting, Minneapolis, Minnesota*, 2013, no. June, pp. 1–27.

[157] U.S. Department of Energy, "2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks," 2016.

[158] F. K. Kazi, J. Fortman, and R. Anex, “Techno-Economic Analysis of Biochemical Scenarios for Production of Cellulosic Ethanol,” *Natl. Renew. Energy Lab.*, no. June, p. 102, 2010.

[159] M. Duffy, “Value of Soil Erosion to the Land Owner,” *Ag Decis. Mak.*, no. August, p. 10, 2012.

[160] U.S. Department of Agriculture, “2012 National Resources Inventory,” no. August 2015, p. 210, 2015.

[161] C. E. Stewart, R. F. Follett, and E. G. Pruessner, “Nitrogen and harvest effects on soil properties under rainfed switchgrass and no-till corn over 9 years : implications for soil quality,” *GCB Bioenergy*, vol. 7, no. 2, pp. 288–301, 2015.

[162] A. Monti, “Switchgrass: A valuable biomass crop for energy,” *Green Energy Technol.*, vol. 94, 2012.

[163] T. Capehart, A. Edward, and J. Bond, “Feed Outlook,” *United States Dep. Agric.*, pp. 1–21, 2018.

[164] U.S. Energy Information Administration, “U.S. Fuel Ethanol Plant Production Capacity,” 2017.

[165] United States Department of Agriculture, “Table 8 . Farms , Land in Farms , Value of Land and Buildings , and Land Use : 2012 and 2007 INDIANA 2012 CENSUS OF AGRICULTURE - COUNTY DATA,” 2012.

[166] A. N. Peterson, B. Rene, A. Garraghty, L. L. Miller, J. Lee, A. Michelle, R. Joseph, C. Mccants, A. Neil, L. Thomas, M. Lynn, E. Marie, M. Teresa, J. Ann, N. Roger, L. Ann, M. Alan, and T. Ryan, “Indiana Biofuels,” 2008.

[167] W. Liu, J. Wang, T. L. Richard, D. S. Hartley, S. Spatari, and T. A. Volk, “Economic and life cycle assessments of biomass utilization for bioenergy products,” *Biofuels, Bioprod. Biorefining*, vol. 11, no. 4, pp. 633–647, 2017.

[168] S. D. Wullschleger, E. B. Davis, M. E. Borsuk, C. A. Gunderson, and L. R. Lynd, “Biomass production in switchgrass across the United States: Database description and determinants of yield,” *Agron. J.*, vol. 102, no. 4, pp. 1158–1168, 2010.

[169] J. H. Fike, J. W. Pease, V. N. Owens, R. L. Farris, J. L. Hansen, E. A. Heaton, C. O. Hong, H. S. Mayton, R. B. Mitchell, and D. R. Viands, “Switchgrass nitrogen response and estimated production costs on diverse sites,” *GCB Bioenergy*, vol. 9, no. 10, pp. 1526–1542, 2017.

[170] G. R. Sanford, L. G. Oates, P. Jasrotia, K. D. Thelen, G. P. Robertson, and R. D. Jackson, "Comparative productivity of alternative cellulosic bioenergy cropping systems in the North Central USA," *Agric. Ecosyst. Environ.*, vol. 216, pp. 344–355, 2016.

[171] S. C. Brechbill, W. E. Tyner, and K. E. Ileleji, "The Economics of Biomass Collection and Transportation and Its Supply to Indiana Cellulosic and Electric Utility Facilities," *Bioenergy Res.*, vol. 4, no. 2, pp. 141–152, 2011.

[172] J. Zhang, A. Osmani, I. Awudu, and V. Gonela, "An integrated optimization model for switchgrass-based bioethanol supply chain," *Appl. Energy*, vol. 102, pp. 1205–1217, 2013.

[173] A. Stauffer, "Getting Started with ArcGIS Online," *ESRI Dev. Summit 2014*, pp. 3–26, 2014.

[174] U. Wilensky, "The NetLogo 6 . 0 . 2 User Manual Table of Contents Table of Contents What is NetLogo ?," *Northwest. Univ.*, 1999.

[175] U.S. Energy Information Administration, "Annual Energy Outlook 2017," 2017.

[176] United States Department of Agriculture, "Indiana Corn County Estimates 2016," 2016.

[177] X. Xiang, R. Kennedy, G. Madey, and S. Cabaniss, "Verification and Validation of Agent-based Scientific Simulation Models," *Proc. Spring Simul. Multiconference*, p. 11, 2005.

[178] T. Sanwal, "Economic Analysis of Biofuel Production From Switchgrass (Panicum virgatum) ans Sweet Sorghum (Sorghum bicolor) In The United States," 2016.

[179] F. Taheripour, J. Fiegel, and W. E. Tyner, "Development of Corn Stover Biofuel: Impacts on Corn and Soybean Markets and Crop Rotation," *Sustain. Agric. Res.*, vol. 5, no. 1, pp. 1–9, 2016.

[180] R. D. Sands, S. A. Malcolm, S. A. Suttles, and E. Marshall, "Dedicated energy crops and competition for agricultural land," 2017.

[181] J. J. Ojeda, J. J. Volenec, S. M. Brouder, O. P. Caviglia, and M. G. Agnusdei, "Evaluation of Agricultural Production Systems Simulator as yield predictor of Panicum virgatum and Miscanthus x giganteus in several US environments," *GCB Bioenergy*, vol. 9, no. 4, pp. 796–816, 2017.

[182] S. Boland and S. Unnasch, "Carbon Intensity of Marginal Petroleum and Corn Ethanol Fuels Prepared by :," no. January, 2014.

[183] A. J. Liska, H. S. Yang, V. R. Bremer, T. J. Klopfenstein, D. T. Walters, G. E. Erickson, and K. G. Cassman, "Improvements in life cycle energy efficiency and greenhouse gas emissions of corn-ethanol," *J. Ind. Ecol.*, vol. 13, no. 1, pp. 58–74, 2009.

[184] U.S. Department of Agriculture, “USDA Agricultural Projections to 2027,” *United States Dep. Agric.*, p. 97, 2018.

[185] M. Khanna, B. Dhungana, and J. Clifton-Brown, “Costs of producing miscanthus and switchgrass for bioenergy in Illinois,” *Biomass and Bioenergy*, vol. 32, no. 6, pp. 482–493, 2008.

[186] USDA Economic Research Service, “Farmland Values, Land Ownership, and Returns to Farmland, 2000-2016,” 2018.

[187] U. S. E. P. A. USEPA, “Emission Factors for Greenhouse Gas Inventories,” 2018.

[188] B. P. Werling, T. L. Dickson, R. Isaacs, H. Gaines, C. Gratton, K. L. Gross, H. Liere, C. M. Malmstrom, T. D. Meehan, L. Ruan, B. A. Robertson, G. P. Robertson, T. M. Schmidt, A. C. Schrotenboer, T. K. Teal, J. K. Wilson, and D. A. Landis, “Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes,” *Proc. Natl. Acad. Sci.*, vol. 111, no. 4, pp. 1652–1657, 2014.

[189] S. G. Evans, L. C. Kelley, and M. D. Potts, “The potential impact of second-generation biofuel landscapes on at-risk species in the US,” *GCB Bioenergy*, vol. 7, no. 2, pp. 337–348, 2015.

[190] U.S. Department of Agriculture, “USDA Agricultural Projections to 2026,” *United States Dep. Agric.*, no. February 2017, p. 106, 2017.

[191] C. L. Dobbins, M. R. Langemeier, B. Nielsen, T. J. Vyn, S. Casteel, and B. Johnson, “2018 Purdue Crop Cost & Return Guide,” *Purdue Agric. Econ. Rep.*, no. October, pp. 2008–2010, 2017.

APPENDIX

Table A1. GHG emissions of corn ethanol production by year

Year	GHG emissions (g $CO_{2\ eq}$ MJ^{-1})	Reduction relative to gasoline*	Source
2005	76.34	17%	[182]
2006	74.52	19%	[88]
2009	70.00	24%	[183]
2012	65.57	29%	[182]
2022	55.20	40%	[182]

*GHG emissions of gasoline is 92 g $CO_{2\ eq}$ MJ^{-1} [88]

Table A2. Economic impacts of corn ethanol industry by year

Year	2009	2010	2011	2012	2013	2014
GDP (bil $)	36.4	58.4	44.5	44.7	44.9	52.7
Labor income (bil $)	17.6	39.2	31.4	31.2	31.3	26.7
Employment (k jobs)	399	401	402	383	387	379
Federal tax (bil $)	8.4	8.6	4.3	4.6	4.5	5.7
State tax (bil $)	7.5	4.8	3.9	3.9	3.8	4.6

Table A3. Input-output multipliers of corn ethanol industry

Year	2009	2010	2011	2012	2013	2014
Ethanol revenue (bil $)	19.6	25.6	37.6	31.3	32.8	33.6
Multiplier of GDP	1.9	2.3	1.2	1.4	1.4	1.6
Multiplier of labor income	0.9	1.5	0.8	1.0	1.0	0.8
Multiplier of employment	20.4	15.6	10.7	12.2	11.8	11.3

Table A4. Simulation parameters for base scenario

Parameter	Value
Food crop (corn) cost	824.8 \$ ha^{-1} [184]
Crop cost increase rate	9.64 \$ ha^{-1} yr^{-1} [184]
Food crop (corn) yield	413 bushels ha^{-1} [184]
Crop yield increase rate	5 bushels ha^{-1} yr^{-1} [184]
Food crop price	3.64 \$ $bushel^{-1}$/143.30 \$ t^{-1} [184]
Food crop price growth rate	0.05 \$ $bushel^{-1}$ yr^{-1}/1.97 \$ t^{-1} yr^{-1} [184]
Cropland	71.85 Mha [140]
Cropland change rate	0.0475 Mha yr^{-1}
Pasture land	10.07 Mha [140]
Pasture land change rate	0.0216 Mha yr^{-1}
Marginal land	11.36 Mha [139]
Grower payment	36 \$ t^{-1} [135]
Harvest cost	17.4 \$ t^{-1} [135]
Storage and handling cost	6.8 \$ t^{-1} [135]
Transportation cost	9.5 \$ t^{-1} [135], [185]
Cash rent of farmland	499.2 \$ ha^{-1} [186]
Cash rent of pasture land	76.6 \$ ha^{-1} [186]
Switchgrass yield	9 t ha^{-1} [169]
Variable operating cost	0.35 \$ gal^{-1} [136]
Unit fixed cost	0.23 \$ gal^{-1} [136]
Feedstock capacity	0.72 million t yr^{-1} [135]
Conversion rate of current technology	289 L t^{-1} (76 gallons t^{-1})[127]
Conversion rate of future technology	399 L t^{-1} (105 gallons t^{-1})[146]
Plant capacity for current technology	54 million gallons
Plant capacity for future technology	75.6 million gallons
Capital investment for current technology	520.9 million \$
Capital investment for future technology	729.3 million \$
GHG emissions of cellulosic ethanol	46.3 g CO_{2-eq} MJ^{-1} [66]

Table A4 continued

GHG emissions of gasoline	92 g $CO_{2\text{-eq}}$ MJ^{-1} [183]
Heat content (HHV) of cellulosic ethanol	88.62 MJ gal^{-1} [187]
Nitrate leaching for corn	40 kg ha^{-1} [162]
Nitrate leaching for switchgrass	2.1 kg ha^{-1} [162]
Water use in cellulosic ethanol	4.5 gal gal^{-1} [142]
Water use in corn ethanol	11 gal gal^{-1} [142]
Water use in gasoline	8 gal gal^{-1} [142]
Bird species richness increase for switchgrass land	6 bird species [188]
At-risk species encountered in cropland only	57 species Mha^{-1} [189]
At-risk species encountered in pasture only	6 species Mha^{-1} [189]
At-risk species encountered in either cropland or pasture	14 species Mha^{-1} [189]

Table A5. U.S. corn price projections [190]

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Farm price ($ $bushel^{-1}$)	3.30	3.35	3.35	3.45	3.50	3.55	3.60	3.65	3.65	3.70

Table A6. Estimated corn variable cost for different levels of productivity [191]

	Corn productivity levels		
	Low	Average	High
Expected yield* (bushels ha^{-1})	316	395	474
Total variable cost ($ ha^{-1})	959	1063	1114
Yield improvement rate (bushels ha^{-1} $year^{-1}$)	7	8	10

* The expected yield is based on the yield of continuous corn system.

Table A7. Capacity and location of the corn ethanol plants in Indiana

Biorefinery ID	Facility	County	Production capacity, Mgal in 2017 (ML)
1	New Energy Corporation	Saint Joseph	65 (246)
2	Iroquois Bio-Energy Company, LLC	Jasper	40 (151)
3	The Andersons Clymers Ethanol, LLC	Cass	110 (416)
4	Central Indiana Ethanol, LLC	Grant	50 (189)
5	VeraSun Energy Corporation	Montgomery	110 (416)
6	POET Biorefining	Jay	73 (276)
7	POET Biorefining	Madison	65 (246)
8	POET Biorefining	Putnam	90 (341)
9	Cardinal Ethanol	Randolph	110 9416)
10	Indiana Bio-Energy, LLC	Wells	101 (382)
11	POET Biorefining	Wabash	68 (257)
12	Aventine Renewable Energy	Posey	110 (416)
13	Abengoa Bioenergy	Posey	110 (416)
14	Grain Processing Corporation	Daviess	35 (132)

Table A8. Projection of Ethanol Price

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Ethanol price, $/gal ($/L)	2.22 (0.59)	2.22 (0.59)	2.91 (0.77)	2.90 (0.77)	2.93 (0.77)	2.95 (0.78)	2.94 (0.78)	2.88 (0.76)	2.85 (0.75)	2.83 (0.75)
Year	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Ethanol price, $/gal ($/L)	2.73 (0.72)	2.72 (0.72)	2.68 (0.71)	2.66 (0.70)	2.61 (0.69)	2.48 (0.66)	2.50 (0.66)	2.50 (0.66)	2.51 (0.66)	2.51 (0.66)

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PUBLICATIONS

1. **Jin, E.**, and J. W. Sutherland, "A Proposed Integrated Sustainability Model for a Bioenergy System," *Procedia CIRP*, 48, 358-363, 2016.

2. **Jin, E.**, and J. W. Sutherland, "An Integrated Sustainability Model for a Bioenergy System: Forest Biomass for Electricity Generation", *Biomass & Bioenergy*, 119, 10-21, 2018.

3. **Jin, E.**, Mendis, G. P., and J. W. Sutherland, "Spatial Agent-based Modeling for Dedicated Energy Crop Adoption and Cellulosic Biofuel Commercialization", *Biofuels, Bioprod. & Biorefining*, February 09, 2019.

4. **Jin, E.**, Mendis, G. P., and J. W. Sutherland, "Integrated sustainability assessment for a bioenergy system: a system dynamics model of switchgrass for cellulosic ethanol production in the U.S. Midwest", *Journal of Cleaner Production*, March 08, 2019. (in review)

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A Proposed Integrated Sustainability Model for a Bioenergy System

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Abstract

The usage of bioenergy is expected to increase for at least ten more years in the U.S. owing to its environmental benefits relative to petroleum. Growing biomass, converting it to a biofuel (e.g., corn ethanol), and using the biofuel has consequences related to the three dimensions of sustainability: economy, environment, and society. An integrated sustainability model (ISM) using system dynamics is developed for bioenergy systems to understand how changes in bioenergy production influence environmental measures, economic development, and social impacts. Predictions, such as greenhouse gas emissions, biofuel price, and employment, can be made for a given temporal and spatial scale.

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Keywords: bioenergy production; integrated sustainability model (ISM); system dynamics modeling; corn ethanol

1. Introduction

Bioenergy, as an alternative energy resource for heating, electricity, and transportation fuel, provides about 10% of the current global energy demand and accounts for roughly 80% of renewable energy [1]. Smeets et al. [2] estimated the global potential of bioenergy production from agricultural and forestry residues and wastes as 76–96 EJ/year, and the total technical potential for biomass could be as high as 1500 EJ/year by 2050. The U.S. Department of Energy reports that the total projected consumption of biomass feedstocks may be roughly 330 million dry tons per year by 2030, a 54% increase over today [3]. The main reason for more biomass feedstock use is the increasing demand associated with biofuel production. Biofuels include ethanol, diesel, and methanol. The U.S. Energy Independence and Security Act of 2007 expanded the mandated use of biofuels based on the first Renewable Fuel Standard (RFS) that required the annual use of 9 billion gallons of biofuels in 2008, rising to 36 billion gallons in 2022 [4]. Global biofuel production has grown from 16 billion liters in 2000 to more than 100 billion liters in 2010. In the United States, the share of biofuels was 4% for road transport fuel and in the European Union (EU) around 3% in 2008 [5].

The use of fossil fuels for energy generation is widely linked to global warming. One of the advantages of bioenergy is that it reduces the greenhouse gas (GHG) emissions across the entire bioenergy life cycle. Using biomass to produce biofuels such as ethanol has already been proven that it can significantly mitigate CO_2 emissions when it is compared to gasoline production. For example, corn ethanol produced by a natural gas biorefinery can have a 38.9% reduction of GHG emissions relative to gasoline production and the reduction in GHG emissions could vary from 39.6–57.7% by integrating biomass to produce heat [6]. The International Energy Agency (IEA) reported that the projected use of biofuels could avoid around 2.1 gigatonnes (Gt) of CO_2 emissions per year by 2050 when produced sustainably [5].

Use of bioenergy is increasingly viewed as an opportunity, not only to enhance energy security and provide environmental benefits, but also to accelerate economic development, particularly in rural areas [7]. Solomon [8] found that existing biofuels industries have been a major contributor to rural economies and small farmers in several countries. Neuwahl et al. [9] also explored the employment impacts of biofuels development in the context of the Renewable Energy Roadmap for the European Union market and found that the biofuel

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Research paper

An integrated sustainability model for a bioenergy system: Forest residues for electricity generation

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A R T I C L E I N F O

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A B S T R A C T

In the U.S., bioenergy accounts for about 50% of the total renewable energy that is generated. Biomass may be used as a source of energy in a variety of ways. Using forest residues, which would normally be treated as waste, in a co-firing power plant application is one strategy for utilizing biomass. Every stage in the life cycle of using forest residues (e.g., growing biomass, harvesting biomass, transporting biomass, and co-firing with coal) has consequences in terms of the three dimensions of sustainability: economy, environment, and society. An integrated sustainability model (ISM) using system dynamics is developed for a bioenergy system to understand how changes in the bioenergy system influence environmental measures, economic development, and social impacts. Exogenous factors such as population growth, land-use change (LUC) patterns, and renewable energy policy are considered by the ISM. Predictions, such as soil carbon sequestration, greenhouse gas savings, monetary gain, and employment, can be made for a given temporal and spatial scale. Different policy scenarios varying the bioenergy share of the total electricity generation were identified and examined via the ISM. The results of the scenario analysis indicate that an increase in the bioenergy share of the total electricity generation will stimulate the bioenergy market for bio-power. Model projections provide comprehensive insights to key stakeholders and policy makers for supporting decision-making regarding bioenergy development.

1. Introduction

Renewable energy is receiving significant attention because of its ability to meet energy demands while supporting economic growth and reducing environmental impacts relative to fossil fuel extraction and use. Bioenergy represents a significant portion of the total renewable energy that is generated. Currently, 7–10% of global energy is provided by biomass energy production [1]. The U.S. Department of Energy reports that nearly 10% of energy consumption in the U.S. is derived from renewable energy sources and in 2014, biomass accounted for 50% of the renewable energy portfolio [2]. The most common biomass-based energy is from liquid transportation fuels, which includes bioethanol and biodiesel. Biomass co-firing is another attractive option of converting biomass into power and heat. In a co-firing power plant, biomass is simultaneously blended and combusted with other fuels such as coal or natural gas in a boiler for electricity generation [3]. According to the U.S. Energy Information Administration (EIA) [4], biomass and biomass-derived gases produced nearly 1.4×10^{12} MJ, and provided nearly 2.3×10^{11} MJ of electricity across all sectors in 2015. Sources of biomass include agricultural crops, grass, wood and wood residues, other wastes from wood production, and municipal solid waste. Types of biomass fuel and associated logistics can significantly affect the performance of biomass co-firing. Forest biomass has a unique advantage in reducing net carbon emissions compared to conventional fuels. Forest biomass is a less carbon-intensive energy source compared to coal as it captures and stores carbon during growth and releases it upon combustion, so no new carbon is released [5,6]. According to Galik et al. [7], forest biomass including marketable and non-marketable wood, is a potential source of biomass supply for electricity generation. Moreover, woody biomass such as forest residues is favorable for co-firing with coal owing to its low ash, sulfur and nitrogen content [8]. In both North American and Europe, many power plants have successfully used woody biomass in co-firing applications with coal [3].

The sustainability of a bioenergy system must address three dimensions: environment, economy, and society. One environmental advantage of using forest biomass for electricity generation is that it can enhance the soil carbon sink process when agricultural land is converted to forest land (afforestation). Post and Kwon [9] observed that the average accumulation rates of soil carbon were 33.8 g C m^{-2} yr^{-1} and 33.2 g C m^{-2} yr^{-1} in re-established forest land and grassland after agricultural use, respectively. Afforestation of former cropland was reported to increase total soil carbon stocks by 18% [10]. Moreover,

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Spatial agent-based modeling for dedicated energy crop adoption and cellulosic biofuel commercialization

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Abstract: Dedicated bioenergy crops, such as perennial grass and short rotation trees, qualify as cellulosic biofuel feedstocks to meet the requirements for advanced biofuel according to the expanded Renewable Fuel Standard. The utilization of dedicated energy crops for cellulosic biofuels is still in the early stage, at pilot scale, and the existing cellulosic biorefineries are yet to be commercialized. This study develops an agent-based model to simulate the spatial diffusion of switchgrass (*Panicum virgatum L.*) adoption in Indiana cropland from 2015 to 2027 under various biofuel market scenarios. Results indicate that it would be economically viable to produce 1.1 billion gallons (4.2 billion liters) cellulosic ethanol from switchgrass annually in Indiana until 2023, given an average annual farm-gate price of \$123.93 t^{-1} for the feedstock. This study also finds that the high productivity of switchgrass can increase the adoption rates of farmers and secure a stable feedstock supply. It also reveals that the high equipment costs required for scaling up production capacity and the high variable operating cost of cellulosic biofuel production will inhibit the viability of commercializing cellulosic biofuels with a stable supply of feedstock. Financial incentives for cellulosic biofuel production have a significant impact on promoting the adoption of dedicated energy crops in Indiana. This paper provides useful insights for biorefinery development and policy making to facilitate the commercialization of cellulosic biofuels by explaining the effects of the decisions of farmers on the adoption of dedicated energy crops.

Supporting information may be found in the online version of this article.

Keywords: agent-based modeling; dedicated energy crop; adoption; spatial diffusion; cellulosic biofuels; commercialization viability

Introduction

Bioenergy, as a renewable energy source, has contributed roughly 5% to the total primary energy supply in the USA since 2014.[1] The utilization of bioenergy is expected to expand, especially in the electricity and transportation sectors.[2] The federal Renewable Fuel Standard 2 (RFS2) mandates that 136 billion liters of biofuels need to be blended into transportation fuel by 2022. The total required renewable fuels include 79 billion liters of advanced fuel from cellulosic biomass and 57 billion liters of corn ethanol.[3] Corn ethanol, as a first-generation biofuel, has long been produced commercially, with approximately 13.4 million hectares of corn dedicated as

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