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Exploring the feasibility of bioenergy crop production with a multi-analytical approach: a case study from Kentucky

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I am submitting herewith a dissertation written by Sandhya Nepal entitled "Exploring the feasibility of bioenergy crop production with a multi-analytical approach: a case study from Kentucky." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

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DEDICATION

This dissertation is dedicated to my parents, Thakur Nath Nepal and Tara Devi Nepal, who believed in the value of education and motivated me to succeed academically. Without you, dada and mamu, I would not be where I am today.

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ABSTRACT

Bioenergy crops can provide a reliable and adequate supply of biomass feedstocks to support the bioenergy industry. However, commercial scale production of bioenergy crops has not been established to meet the increasing energy demand for the bioenergy industry. Thus, there is a need to explore the full potential of bioenergy crop production to support energy generation. This dissertation examined the feasibility of bioenergy crop production in the southern United States with a case study from Kentucky. For the feasibility of bioenergy crop production, I (1) analyzed trade-offs among the major components of bioenergy crop production, (2) assessed landowners' willingness to promote bioenergy crops and, (3) evaluated potential bioenergy policies and prioritized them based on their effectiveness to support the promotion of sustainable bioenergy production. I used multiple approaches including a multi-objective optimization model, a questionnaire survey, and an analytic hierarchy process (AHP) model, to examine the feasibility of bioenergy production. The trade-off analysis highlighted potential opportunities and risks in bioenergy production. Even though there were suitable lands for growing bioenergy crops, the production was not economically beneficial. Further, higher bioenergy production generated concerns for negative impact on the environment. Thus, results from the trade-off analysis showed a need to find the best balance among the trade-offs for better production decisions. The landowner survey indicated that they were relatively more willing to grow bioenergy crops themselves than rent their land to others. Current land management practices and socio-economic and environmental factors affected their land use decisions about bioenergy crop production. Finally, my policy analysis highlighted that policies that incorporate environmental conservation are key to establishing bioenergy crops. In addition, consideration should also be given to efficient technological support while designing specific policy to promote bioenergy production. Overall, results from the whole study can be useful to design effective policies, develop outreach activities, and support technological investments that would promote bioenergy crop production in ways that are economically efficient as well as compatible with social, and environmental factors.

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CHAPTER 1

INTRODUCTION

Renewable energy sources such as energy from biomass (bioenergy) is a key to address concerns for energy security and climate change. Even though bioenergy is supported by various policies and incentives in the United States (US), commercial scale production of bioenergy has not been established to meet the increasing energy demand. There are challenges for bioenergy production in terms of various socio-economic and environmental factors that must be addressed before bioenergy could be sustainable. Thus, there is a need to explore different aspects of bioenergy production to support energy generation. In this dissertation, I assessed the feasibility of bioenergy crop production with a case study from Kentucky. This chapter provides a background on bioenergy research, including current developments, opportunities and challenges. It describes specific research questions for three manuscript chapters and lays out foundation to show how the chapters link together. In addition, it also summarizes the potential contributions of the study in the context of broader bioenergy research. Finally, this chapter outlines how the dissertation is organized into various chapters.

1.1 Background

1.1.1 Biomass for energy

Current energy consumption in the US is dependent on fossil fuels, mainly, coal, petroleum, and natural gas. Fossil fuels are non-renewable energy sources which deplete over time. Further, they are harmful to the environment as they emit greenhouse gases (GHGs) that contribute to global warming and climate change. In addition, fossil fuels currently in operation in the US are not enough to meet the increasing energy demand. As a result, there is a huge reliance on petroleum fuels from foreign countries, especially from oil producing regions in the Middle East that has unstable political regimes causing an unsustainable energy supply and fuel price volatility. Diversifying the current energy supply with alternative renewable energy sources is crucial to reducing our long-term dependence on fossil fuels and addressing environmental concerns about greenhouse gas emissions and global climate change. Wind, solar, hydropower, geothermal, and biomass are some of the renewable energy sources that can potentially replace existing fossil fuels. However, economic development in the US is primarily dependent on fossil fuels - coal for electricity generation that makes the shift to renewable energy costly and time consuming (US DOE, 2010). Nevertheless, the US government is committed to promoting renewable, potentially carbon neutral energy sources. While renewable energy sources such as solar, wind, and hydropower technologies are evident, biomass has become one of the most promising renewable energy sources in the US (Rousseau, 2010). Biomass energy (or bioenergy) simply refers to the generation of energy from plants or plant-based materials. Generating energy from biomass has been established for centuries (mainly for cooking food and keeping warm) but biomass prices have not been competitive with existing fossil fuels. Consequently, energy production from biomass has not been adopted on a commercial basis (White, 2010). However, projections of future energy demand and climate change legislations suggest an increase in the use of biomass for energy generation in the near future. In addition, the demand for bioenergy (biomass energy) is likely to increase to achieve emission reduction goals in the energy and transportation sectors (IEA 2011, 2012).

1.1.2 Bioenergy policies and incentives

Bioenergy has been promoted by various policies over several decades. The Energy Policy Act (EPAct) of 1992 aimed at improving energy independence and enhancing environmental quality by acknowledging different aspects of energy demand and supply, including alternative renewable energy and energy efficiency (EPAct, 1992). The act provided incentives for development and commercialization of renewable energy technologies that are clean and cost-efficient (NRRI, 1993). The Biomass Research and Development Act 2000 identified the need of large research driven advancement in technology to support bioenergy industry (BRDA, 2000). The act established a Biomass Research and Development Board to coordinate research and developments activities between USDA and USDOE with other federal departments and agencies to promote the bioenergy industry and maximize the benefits from federal grants and assistance (ibid). Farm Bill 2002 supported bioenergy production through various research and cooperative extension programs. It provided grants and loans for various research, for risk sharing, and promoting the use of renewable energy (Bracmort, 2017). It also provided incentives to feedstock producers and education to farmers, local authorities and civil society to promote the benefits of bioenergy production and utilization (USDA, 2007). The Energy Policy Act of 2005 established Renewable Fuel Standards (RFS). Initially the RFS mandated a minimum of 4 billion gallons of renewable fuels to be blended into gasoline in 2006, raising that to 7.5 billion gallons by 2012 (Schnept and Yacobucci, 2013). The Energy Independence and Security Act of 2007 increased the mandate to 36 billion gallons by 2022 (EPA, 2017). The act also encouraged research and development for advanced biofuels including cellulosic fuels and set up cellulosic mandate at 16 billion gallons by 2022 (Bracmort, 2015). Farm Bill 2008 expanded bioenergy programs, emphasizing mainly those using biomass feedstocks to promote renewable energy. It authorized more than $1 billion mandatory funding for energy programs for FY2008-2012, $255 million of which was allocated to the Rural Energy for America Program (REAP) (Bracmort, 2017). REAP was initiated to assist landowners and rural entrepreneurs to conduct feasibility studies for renewable energy projects. In addition, the Biomass Crop Assistance Program (BCAP) that supports bioenergy feedstock production, collection, harvesting, storage and transportation, was authorized to receive funding under the Farm Bill 2008 (ibid). They highlighted the need to expand legislative initiatives to address concern for energy security and greenhouse gas emissions from fossil fuels. More recently, Farm Bill 2014, Title IX has continued to support the production of bioenergy. It extended the Biomass Research and Development Initiative (BRDI) with more funding for research within USDA and DOE (ibid). Similarly, it has extended the Bioenergy Crop Assistance Program (BCAP). In addition, many states have developed bioenergy incentives in the form of tax credits, grants, loan and cost-share programs.

1.1.3 Sources of bioenergy

Bioenergy can be produced from a variety of resources. First-generation sources that include food crops such as corn, soybean and sugarcane have not only raised questions about food versus fuel debate but also price volatility and adverse environmental impacts (Foley, 2011). On the other hand, non-food crops (bioenergy crops), agricultural residues, waste materials, and forest biomass have gained considerable attention mainly because they do not displace agriculture production or threaten the health of farms and forests. Bioenergy crops stand out as having the largest long-term opportunity to promote bioenergy production in the US. Bioenergy crops are fast-growing plant species with the ability to produce high yield biomass, they have high energy potential (generate energy directly by combustion or gasification and convert to liquid fuels such as ethanol) with less CO_2 emissions, they can be grown on less fertile soil, and they require less fertilizers and pesticides (Lemus and Lal, 2007; MBEP, 2002). Bioenergy crops can be herbaceous or woody crops. Herbaceous crops are mostly perennial grasses that can be harvested as hay. Switchgrass, miscanthus, and wheatgrass are some of the important crops that can been grown mainly to produce energy. Woody crops are mainly tree species with short rotation. Fast growing hardwood species such as eastern cottonwood, sweetgum, American sycamore, willow and yellow poplar are potential species as woody crops. Those woody crops are native species with wider geographic distribution throughout the US and they can produce economically viable biomass feedstocks within short rotations (Rousseau, 2010). Further, the management and silvicultural operations for establishing and growing these crops are well understood. When compared to biomass supply from other sources such as agricultural residues, waste and forest biomass, biomass from energy crops are likely to be significant feedstock source for the bioenergy industry. It has been projected that more than 400 million tons of biomass could be produced each year by 2030 (UCS, 2012). Further, there are existing coal facilities that provide opportunity to co-fire biomass with coal for energy generation without significant capital investment for new bioenergy facilities.

1.1.4 Challenges for promoting bioenergy crop production

Bioenergy crops are fast growing species that are dedicated to the production of energy (Sartori et al., 2006). These crops can generate energy directly by combustion or gasification, and they can also be converted to liquid fuels such as ethanol (MBEP, 2002). Even though there is an increasing interest in bioenergy crop production throughout the United States (especially, in the southern US because of favorable climatic conditions for growing woody bioenergy crops), commercial production of bioenergy crops is still in its infancy. Studies have shown that sustainable bioenergy production can provide numerous socio-economic and environmental benefits (Souza et al., 2017; Hill et al., 2006), but how realistic these opportunities is questionable. Increasingly, various concerns have been expressed to promote the bioenergy industry. Even though they have been considered to have major environmental benefits such as improved soil and water quality, carbon sequestration, and improved biodiversity, the relative environmental impacts of land use conversion to bioenergy crops depend on previous land use. If bioenergy crops are displacing annual agricultural or marginal land, the ecological implications could be positive. When more natural land cover types such as forests are displaced with bioenergy crops, however the effects could be negative. In the latter case, land use change can be a potential risk exacerbated by bioenergy development. Similarly, the notion of bioenergy as a carbon-neutral source of energy is questionable. Even though bioenergy is considered carbon-neutral, fossil fuels is required for transporting feedstocks to bioenergy facility, processing and converting feedstocks to energy, and distributing bioenergy to end users (Hill et al., 2006). In addition, the net carbon balance can greatly vary depending on the type of crop species used as feedstock, and on where and how it is grown and used (Bracmort, 2016).

Bioenergy production also faces competition at various levels. There are competing uses for the biomass resource itself (for example, paper and pulp, lumber). There is also competition for existing land for food and fuel. Further, in the southern US, there are many factors that restrict the production of bioenergy from woody crops, for example, high pulpwood prices, low electricity prices, low coal prices and poorly understood environmental benefits of bioenergy crops (Badger, 1996). In addition, there is not enough energy production and distribution infrastructure for the bioenergy industry and it must rely on existing infrastructure designed for fossil fuel industries. Displacing a significant amount of existing use of fossil fuels is a long-term process and it will require technological advancement and major changes in economic, technical and social processes (NRC, 2011). Currently, technologies are available for bioenergy production, but they are not economically beneficial at a commercial scale, even with existing production subsidies and mandates (ibid).

There are also some social barriers to promoting bioenergy production. Biomass feedstocks for the bioenergy industry are likely to come from landowners as they own majority of land in the south (Leitch et al., 2013). However, whether these landowners are willing to harvest biomass feedstocks in their property is poorly understood (Cope et al., 2011). Studies have shown that there is a lack of information and awareness among landowners about potential opportunities to grow and harvest bioenergy crops. In addition, there is no proper infrastructure developed for bioenergy production and an efficient and economical transportation is lacking. Further, cultural barriers to converting existing land use practices to bioenergy crop production, insufficient economic and policy incentives, and uncertainty around biomass yield and market conditions make bioenergy crops less attractive to landowners (NRC, 2011). Although policy incentives would benefit landowners' desire to establish bioenergy crops, biomass market and government incentives change over time and it becomes hard to predict what policies would be favorable to promote energy crops.

1.2 Need for research

Sustainable production of bioenergy must address challenges related to balancing food and energy production, environmental sustainability, maintenance of biodiversity and ecosystem services, and various socio-economic factors. Marginal lands, lands with low productivity and poorly suited for food crops production, have recently been considered for producing feedstocks that could potentially avoid many problems associated with bioenergy production (Lewis and Kelly, 2014). Marginal lands are attractive for growing energy crops because they do not compete with food production or promote forest conversion or intervene with any existing management practices. Further, growing energy crops on marginal land will have positive ecological implications such as improved soil and water quality, carbon sequestration, and biodiversity. For example, growing bioenergy crops on marginal lands can help rebuild soil profile and increase soil organic matter content and increase carbon sequestration in the soil. Similarly, establishing bioenergy crops can provide a protective cover, help reduce runoffs and loss of sediments, and reduce the risk of water erosion (Blanco-Canqui, 2016). Further, growing bioenergy crops can improve biodiversity in terms of faunal diversity and abundance (ibid). However, several questions arise about how to grow bioenergy crops on such lands and whether these lands can produce abundant biomass feedstocks to support the bioenergy industry while providing environmental services (ibid). In addition, questions about economic and social implication of bioenergy crop production on marginal lands need careful analysis mainly because the production might not be economically beneficial unless a stable biomass market is established, and other ecosystem services are valued and incentivized (Blanco-Canqui, 2016; Kang et al., 2013). Therefore, it becomes imperative to explore high yielding bioenergy feedstock sources and plan a feasible biomass production system on the available marginal lands based on the interconnectedness between social, economic and environmental dimensions of sustainability. In addition, ensuring the broad potential of bioenergy as a sustainable energy source will require participation from landowners for producing bioenergy crops. Even though a large amount of marginal lands might be suitable for growing bioenergy crops, previously studies have shown that bioenergy crop production is less attractive to landowners and the actual land available for bioenergy crops could be significantly less than what is suitable for establishing bioenergy crop production (Braham et al., 2016; Skevas et al., 2016). Several factors, including marginal returns, familiarity about bioenergy crop production, perception and attitude towards bioenergy, environmental concerns, and amenity values (such as aesthetic and recreational values) may affect their view toward opportunities and challenges presented by bioenergy crop production (Caldes et al., 2014; Leitch et al., 2013; Qualls et al., 2012). It is therefore important to understand if and under what conditions landowners are willing to change their land use behavior to promote bioenergy crop production. Understanding people's view on bioenergy and their preferences for their land use decision can help identify whether suitable marginal lands are actually available for bioenergy production and what policies, technologies and investments they seek to ensure maximum potential of bioenergy crop production on their land. Furthermore, there is not a well-developed market for biomass and several uncertainties exist about the availability of feedstock sources, technologies to convert biomass to energy, political and regulatory environment for promoting bioenergy crop production (Dumortier, 2016; NRC, 2011). Thus, it is also important to evaluate what policies would be effective to ensure that bioenergy production is promoted in ways that are economically efficient as well as compatible with social, political and environmental concerns.

1.3 Case study: Kentucky

This research explores the potential of bioenergy crop production in the southern United States with a case study from Kentucky. Kentucky is the fifth largest coal producing state in the US and coal is the major source of energy in the state, accounting for approximately 79% of electricity generation (EIA, 2018). Even though the economy of the state is highly dependent on the coal industry, various efforts are underway to diversify away from coal with alternative renewable energy sources. Renewable energy sources such as solar, wind and hydropower are not feasible in Kentucky because of geographic limitations. However, energy from biomass can be a viable source to partially replace coal. Currently, bioenergy accounts for a small fraction of total energy produced in the state but efficient policy incentives can promote bioenergy in the long run. An energy plan developed by the Governor's office in 2008 has prioritized bioenergy production to meet the energy demand in the state. According to the plan, Kentucky will need to produce 25 million tons of biomass annually by 2025 to meet the federal and state fuel standards. Agriculture and forest resources could contribute to approximately 12 to 15 million tons of biomass per year but there will be a need to improve crop productivity, and farmland and forest management to meet the energy demand (Governor's office, 2009; Cowie et al., 2007). In this regard, energy crops have been identified as one of the important sources of bioenergy to supply adequate feedstock to sustain the bioenergy industry (Staudhammer et al., 2011). Previous studies in the state have identified 14 native Kentucky crop species that are suitable for biomass-based energy production and to make bioenergy production a feasible and clear alternative to fossil fuels (Governor's Office, 2009). Kentucky is also unique for its geographical location bordering northern and southern regions of the US. Further, there is a diverse land use with privately owned small parcels of lands. In addition, there are many coal plants in the state that provide opportunities to co-fire biomass with coal for energy generation without significant capital investment for establishing new bioenergy facilities. Further, co-firing has the potential to reduce emissions of GHGs. For example, Mann and Spath (2001) estimated that co-firing rates of 5 and 15% would reduce CO_2 emissions by 5.4 and 18.2 percent, respectively. Their study also showed reductions in the emissions of SO_2, NO_x and CO. Thus, Kentucky serves as a suitable location to analyze the potential of bioenergy crop production. The findings can be useful for other states in similar geographic locations where bioenergy crop production has been recommended. Bioenergy crop production in the state/region can promote renewable energy and diversify current coal-based energy generation. Additionally, it can provide opportunities to supply significant portion of the country's energy needs and achieve energy security, contribute to GHG emission reductions and transition to a more clean and sustainable energy. Further, as bioenergy production is more labor intensive (it requires site preparation, plantation and management, harvesting, storage, and transportation) than other energy resources, bioenergy production can provide opportunities for rural jobs and increase farm income of people who grow and harvest bioenergy resources. Lastly, this study uses marginal lands (lands with poor quality soil that are unfit for agricultural production) in Kentucky as potential sites for growing bioenergy crops. Establishing bioenergy crops on marginal lands can help improve environmental quality by restoring degraded lands. Growing tress help rebuild soil profile and provide a protective cover, thus they help reduce runoffs and reduce the risk of water erosion.

1.4 Research objectives

This study has three specific objectives as show below:

1. To identify trade-offs between socio-economic and environmental factors for bioenergy crop production
    a. Assess social, economic and environmental effects of bioenergy crop production
    b. Identify trade-offs between social, economic and environmental factors in bioenergy crop production

    c. Analyze shift in trade-offs when preferences for different factors change in the production decisions
2. To understand landowners' perceptions of bioenergy and their willingness to promote bioenergy crop production
    a. Understand landowners' perceptions about bioenergy
    b. Analyze how willing landowners are to supply their land for bioenergy crop production
    c. Identify how much of current land landowners are willing to make available for bioenergy crop production
    d. Identify factors that affect landowners' land use decisions for promoting bioenergy crop production
3. To evaluate potential bioenergy policies for promoting sustainable bioenergy crop production.

1.5 Theoretical framework

This research uses a sustainability concept that ensures simultaneous achievement of economic prosperity, a healthy environmental and social equity over the long term (Muralikrishna and Manickam, 2017). More recently, sustainable development has emerged as an integrated framework to achieve sustainability. Sustainable development has gained considerable attention at national and international levels due to challenges faced in the areas of rural development, environmental conservation, energy generation and climate change (Olawumi, 2018). The vision of sustainable development was first implemented by the Brundtland Commission in 1987 which defined sustainable development as "the development that meets the needs of the present generation without compromising ability of the future generation to meet their own needs" (WCED, 1987). This vision was refined by the UN General Assembly with the adoption of The 2030 Agenda for Sustainable Development that focused on coupled socio-environmental systems where social factors (human population, economies, technologies, intuitions) interact with the environment (climate, ecosystem, biochemical cycle) at various temporal and spatial scales (Clark et al., 2016; UN, 2015).

Over the years, several inter-disciplinary theories (with their own set of assumptions) have been used to interpret sustainable development and to study relationships between the environment and social factors (for example, landscape ecology, political ecology, political economics, etc.). Among them, there are two leading theories on sustainable development that integrate economic, social and environmental dimensions of development. These are ecological economics theory and environmental economics theory (Beder, 2011; Grainger, 2004; de Wit and Blignaut, 2000). Ecological economics theory considers economy as a subset of a global ecosystem. According to this theory, the flow of income and materials into the economic system is indeed, a part of transformation of energy and materials within the ecosystem (Grainger, 2004). Since the earth is finite, there should be limits to the physical growth of economy. Thus, long term economic viability is subject to how well we adhere to the rules governing the ecosystem (ibid). Environmental economics theory, on the other hand, is the most commonly used theory and it incorporates all three dimensions of development (economic, social and environmental dimensions) (ibid). Within this theory, the mainstream economic principles are applied to the environment (environmental issues) and development is considered as the accumulation of man-made capital at the expense of natural capital (Harris and Roach, 2018; Grainger, 2004). According to this theory, environmental problems arise because there is a lack of a proper mechanism to price the environment and, additionally, a lack of incentives to protect it. More recently, economists have provided ways to allocate market prices for environmental commodities under the demand and supply framework which enter into the market analysis for better decisions. Contingent valuation techniques are widely used to allocate prices for environmental commodities for which a market does not exist (Mulder and van den Bergh, 2001).

These theories have been used to address sustainable development issues. For example, there is a controversy between economic growth and environmental conservation. On the one hand, some argue that economic growth is a prerequisite to preserve environmental quality, but on the other hand, others argue that economic growth will create more pressure on the environment (ibid). Studies have suggested that environmental quality may decline in the early stages of economic development, but it will subsequently improve in the long-run. Similarly, studies have focused on technological improvement as an approach to dissociate economic growth from environmental pressure (ibid). In the context of material consumption, changing the current consumption pattern to a more sustainable direction would require integration of socio-cultural and psychological factors (need, opinion, preferences, lifestyle) into economic and technological solutions. Research has incorporated social and cultural theories into economic theory to understand such human behavior. More recently, economic analysis of climate change policies under uncertainty has been conducted. In addition, economic analysis has been used to provide policy suggestions for sustainable energy generation and to analyze whether policies are sensitive to social, economic and environmental changes(ibid). This dissertation adds to the existing literature by focusing specifically on bioenergy generation where analyses were performed for planning efficient energy production scenarios based on economic analysis and a consideration for social and environmental factors. I applied environmental economics theory as it focuses on market-based resource use and management and allocates resources more efficiently. It considers natural resources as scarce resources and applies the optimal allocation theories to those resources (van den Bergh, 2001). Since there is no well-defined market for biomass and there are so many uncertainties in the production process, I allocated prices for biomass produced in the biomass supply chain with an aim to produce sustainable feedstocks to meet the increasing energy demand. Using market-based instruments (biomass prices) also incentivized landowners to promote bioenergy. In addition, environmental economics provided a way to find the best balance between economic activities and environmental impacts in ways that considered all costs and benefits associated with bioenergy production.

In the context of bioenergy crop production, sustainability focuses on three components: energy production, income opportunities and environmental quality. Ensuring sustainable bioenergy crop production is a complex and multi-dimensional process that requires a careful assessment of various impacts at various temporal and spatial scales (Popp et al., 2014). Promoting bioenergy crop production would not only lead to change in physical/natural structure (change in soil and water quality, biodiversity, GHG emissions) but this shift would also generate political and economic interests, and social values are likely to be intertwined (Calvert et al., 2017). In addition, assessing sustainability of bioenergy must be evidence-based that needs to consider trade-offs among various production factors, landowners' opinions on production, and policies to support good practices in bioenergy production (FAO, 2018; FAO, 2016). Therefore, it is important to develop an integrated approach that addresses all the dimensions of sustainability given a set of constraints such as existing land management practices, energy demand, socio-economic and policy structures.

The goal of sustainability has been analyzed by diverse disciplines. Geographical scholars use a spatial perspective to understand human interactions with the-environment. Some of the key questions they ask about sustainability include the following: How do long-term global trends including material consumption and population growth reshape human-environment interactions in ways relevant to sustainability? (Parris and Kates, 2003) What determines vulnerability and resilience of particular places and people's livelihood to deal with changing environment? (NRC, 2010) What incentives can improve society's ability to guide human-environment interactions more sustainable? (Clark, 2007) How can participatory decision making be integrated in the planning process for sustainable natural resource management? How can research and development (R & D) and technological advancement be more efficiently used to gain sustainability goals? (ibid) As a geographer, I mainly focused on place-based energy production planning that can contribute to the sustainability studies in various ways. First, as most of the interferences on the natural system are primarily human choices (Davis et al., 2014), I used modeling tools to represent changes in the environment and to generate knowledge about the dynamic interaction between environment and society. This knowledge about human-environment interaction can support policy-making process for sustainable energy generation. Second, I studied how societies react to the opportunities and risks to the changing environment, and what incentives they seek to maintain a more sustainable interaction with the environment. Lastly, I focused on participatory planning (taking into consideration of various stakeholders in the policy process) for sustainable usage of natural resource management.

Specifically, in the context of sustainable energy generation, geographers have previously studied implications of energy transitions from fossil fuels to renewable energy (such as bioenergy) (Calvert, 2016). However, they have mainly focused on issues related to land-use change and resource management. More recently, scholars have focused on bioenergy research to explore potential environmental benefits to reduce GHG emissions (Fast et al., 2011). There is a lack of research that addresses issues related to biomass supply chain and bioenergy use in the context of existing socio-economic and political structure that could provide an insight into potential opportunities and risks for promoting a sustainable bioenergy production. Achieving sustainable bioenergy requires meeting the energy demand for an increasing population while protecting the natural environment. In this context, it is important to consider all aspects of sustainability (economic, social and political) and examine the relationship between them.

Drawing on the economics theories of sustainability, this research examined the feasibility of sustainable bioenergy crop production taking into consideration of various socio-economic, ecological and political factors. Bioenergy production in this study is portrayed as a link between human and physical environment fitting firmly within the geography's human-environment theme.

Assessing sustainability for a bioenergy production system requires careful consideration of various socio-economic and environmental impacts. It is a step-wise decision-making process where we first set up a goal for production, create scenarios based on available data, identify and measure different indicators related to the scenarios, and identify the scenario that provides the most efficient solution (Rathore et al., 2017). Some of the most widely used assessment methods for bioenergy production include life cycle analysis, environmental impact assessment (EIA), and strategic environmental assessment (SEA) (Wu et al., 2018; de Carvalho, 2011; Fernando et al., 2010). While these methods are important, they limit environmental performances of bioenergy systems and ignore the fact that bioenergy systems consider social and economic factors as well. To address this limitation and to incorporate all dimensions of sustainability, methods such as multi-criteria decision analysis (MCDA) can be used. MCDA is a decision support system that can address multiple and conflicting criteria. For sustainable bioenergy production, some of the most common criteria include energy production, investment costs, GHG emissions, land use change and social acceptance. Thus, MCDA is an applicable tool to address sustainability. MCDA can provide a structured representation of various criteria that are relevant to sustainable bioenergy production and identify the most critical criterion for sustainability assessment. In addition, MCDA can integrate stakeholders' participation and evidence-based information throughout the entire decision-making process. This cooperation ensures all the components of socio-economic and ecological components and their relationships are identified and investigated (Haywood et al., 2009). Various MCDA methods have been recorded in literature that support decision-making in a more transparent and structured way with underlying assumptions of sustainability. For example, in analytic hierarchy process (AHP), the decision problem is structured as a simple hierarchy, weights are assigned for each element within the hierarchy and pairwise comparisons are performed to evaluate the overall ranking of different alternatives. In addition, AHP considers qualitative and quantitative aspects of a decision problem and facilitates communication among different stakeholders for better decision making. Even though MCDA is certainly applicable, there has not been substantial use of MCDA in bioenergy research especially, on a local or regional scale. This study uses MCDA for a comprehensive analysis on the planning of sustainable bioenergy crop production at a regional scale.

1.6 Significance of research

Renewable energy sources such as energy from biomass will be a key to realize the goal of energy independence through domestic energy production. This research assessed the feasibility of producing biomass for energy in the southeastern US with a case study from Kentucky. First, the study assessed the interconnected/trade-offs between socio-economic and environmental aspects of bioenergy crop production on marginal lands. Proper knowledge of the trade-offs between various sustainability dimensions can be helpful for effective planning for the establishment of bioenergy crops and for assisting in other sustainability goals such an economic growth, environmental conservation and rural development. This study also integrated knowledge from landowners and examined their preferences for land use decisions. Individual landowner's decision to convert existing land use to bioenergy crops was affected not only by biomass markets and policies but also by various socio-cultural factors. This study also provided insights into the barriers to landowners' engagement in the bioenergy production process. This information will be useful in understanding the factors affecting the adoption rate and to plan for a policy that is effective and acceptable for landowners to encourage bioenergy feedstock production. Lastly, this study integrated quantitative and qualitative information to evaluate common bioenergy policies to promote a sustainable bioenergy production. Results from the study can be used for regional planning of bioenergy crop production, developing outreach activities for landowners in the study area (and beyond) and assisting state agencies in selecting and implementing suitable bioenergy policies to promote the bioenergy industry.

Additionally, a major focus of this study was place-based bioenergy production planning with a consideration of various dimensions of sustainability into one integrated approach. While it is common in bioenergy research that economists, natural resource scientists and social scientists work and collect data differently at various spatial scales, there is limited research to combine the data and integrate them into one methodological framework. This study used an integrated approach that was inclusive to different stakeholders in the production process and the different dimensions of sustainability was preciously included at the same spatial scale. This strengthens the idea that during planning for effective policies, bioenergy production should not be viewed in an isolated fashion rather a part of integrated system that would require policies that support use of bioenergy in the framework of larger land use and market policies. Further, this study evaluated the role of bioenergy under different existing and potential policy incentives to scale up the bioenergy industry to address the concerns for energy security. Lastly, this study provided spatial perspective on bioenergy production at a regional level which can be linked to other regions or national system to explore how investment on small-scale bioenergy systems can be developed to address increasing energy demands.

1.7 Organization of the dissertation

This dissertation is organized in five chapters. Chapter 1 provides a general background and impetus for this study. Chapters 2 -4 are prepared as individual manuscripts for submission to peer-reviewed journals. These manuscripts address the three objectives of my research. Chapter 2 focusses on identifying trade-offs between various sustainability dimensions for bioenergy crop production. In Chapter 3, I analyzed landowners' perception on bioenergy and their willingness to promote bioenergy crops on their land through a questionnaire survey. For Chapter 4, I evaluated potential bioenergy policies for sustainable bioenergy crop production. Chapter 5 summarizes the findings of Chapters 2 through 4 and discusses the overall implication/contribution of the dissertation and provides suggestions for future research.

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CHAPTER 2

IDENTIFYING TRADE-OFFS BETWEEN SOCIO-ECONOMIC AND ENVIRONMENTAL FACTORS FOR BIOENERGY PRODUCTION: A CASE STUDY FROM NORTHERN KENTUCKY

This chapter is prepared for journal submission. The use of “we” in this chapter refers to co-author, Dr. Liem T. Tran, and me. I am the first author, and my contribution to this project include model development, data analysis, and writing the manuscript.

Abstract

Bioenergy crops can provide a reliable and adequate supply of biomass feedstocks to support the bioenergy industry. However, promoting bioenergy crops would require major changes in land use and management practices that can have long term socio-economic and environmental impacts. Therefore, it is important to have a careful evaluation of potential opportunities and challenges presented by bioenergy crop production. We developed a multi-objective optimization model to analyze trade-offs among various components of bioenergy crop production to help make better production decisions. Our model integrated sustainability dimensions including social, economic, and environmental factors for bioenergy crop production. As bioenergy crop production may incorporate various objectives, we ran the model by optimizing one objective at a time to measure the magnitude of change in one objective with respect to change in other objectives given a set of constraints. In addition, our model had the ability to assess how trade-offs would be affected by chancing preferences for different factors in the production decisions. The model was applied for a four-county study area in northern Kentucky and it provided a regional examination for the potential of bioenergy crops for energy production. The model can serve as an effective tool for making bioenergy production planning and management decisions.

Key words: bioenergy, trade-offs, optimization, sustainability, decisions, Kentucky

2.1 Introduction

The increasing demand for bioenergy in the United States, driven by concerns for energy security and climate change, creates both opportunities and risks. Bioenergy development has the potential to promote rural economy by improving land productivity, creating employment opportunities, and improving access to renewable energy services in rural areas (FAO, 2012). However, if poorly managed, bioenergy development can generate serious environmental impacts such as excessive pressure on land and water resources, greenhouse gas (GHG) emissions, wildlife habitat loss, reduced biodiversity, and soil degradation. For example, growing crops for energy puts pressure on land use, exacerbating land use change such as deforestation and driving up the food vs. fuelwood debate. Similarly, when bioenergy crops replace existing forests, and when they are grown in monoculture, there could be loss of habitat and biodiversity (Bookhout, 2012). In addition, many of the potential bioenergy crops could have relatively higher water requirements thus, making water a major limiting factor (Caldwell et al., 2018). Developing a sustainable bioenergy sector is therefore a challenge because it must be evaluated in terms of both its potential socio-economic and environmental impacts. The result of this evaluation is largely dependent on how the interconnectedness between social, economic, and environmental dimensions of sustainability are framed (Acosta et al., 2014). Properly understanding and assessing the potential trade-offs between socio-economic and environmental outcomes is thus crucial for promoting beneficial bioenergy production.

Planning for sustainable bioenergy production must address multiple, and often conflicting, objectives as obtaining a certain outcome for one particular objective can require sacrificing or trading-off another objective. For example, ensuring long-term high biomass productivity can have negative consequences on environmental conditions such as water and soil quality. Therefore, a trade-off analysis is required to analyze the compromises implicit in different objectives and identifying an acceptable balance in order to make better decisions (Parnell et al., 2016). A trade-off analysis can provide a large systemwide view for bioenergy production that includes relationships between various socio-economic and environmental factors. When potential changes in preferences for these factors are analyzed, the shift in trade-offs provide insight into how different outcomes may be sensitive to such changes. Thus, trade-off analysis can be useful in identifying problems and/or opportunities and characterizing solutions for a holistic decision-making process that considers all factors of the bioenergy production system (ibid). If trade-offs are not emphasized during the planning for bioenergy production, conflicts among various objectives may arise leading to outcomes that have a lower probability of meeting the sustainability goals of bioenergy production (Madni and Ross, 2016).

Various methods have been used for trade-off analysis. For example, empirical or experimental approaches have been used to identify a set of meaningful quantitative relationships among different input variables and outcomes based on a dataset generated within a system. By contrast, simulation models can explore relationships among input variables and outcomes not generated (or observed) within a system (Klapwijk et al., 2013). Optimization approaches, specifically, multi-objective optimization approaches can be used to study trade-offs in biomass supply chains (Zhang et al., 2017; Bonsch et al., 2014; Lautenback, 2013). A multi-objective optimization approach can incorporate various and often conflicting objectives and when each objective is optimized with respect to other objectives, trade-offs among the objectives can provide an understanding of how a system works. Trade-off analysis can be the foundation for setting up a multi-objective optimization model that searches for a feasible solution to provide the best compromise among various conflicting objectives where the values of different objective functions are optimized considering the tradeoffs with other objectives (Mousa and Elattar, 2014; Ferrucci, 2013). In other words, quantitative assessment of various trade-offs among different dimensions of sustainability can affirm that each individual objective is optimized according to the overall multi-objective goal in a multi-objective optimization problem.

Various studies have used a multi-objective approach to include environmental and social dimensions in addition to economic criteria to analyze sustainable production of biomass. El-Halwagi et al. (2013) used a mixed integer linear programming (MILP) model to consider cost and safely dimensions of a biomass supply chain and found contradictions between economic and safety objectives. You and Wang (2011) developed an optimization model for the design and planning of a biomass supply chain in Iowa under economic and environmental criteria. Their aim was to minimize total cost of production and GHG emissions. Their model revealed a trade-off between economic and environmental factors and showed that higher GHG emissions occurred with lower cost. You et al. (2012) proposed a similar model in Illinois with an added social objective to maximize the potential for employment generation. Their study also found that there were tradeoffs between economic and environmental factors of the bioenergy supply chain. Similarly, Bernadi et al. (2012) considered multiple objectives when optimizing the biomass supply chain and they suggested that net present value (NPV) was positively related to both carbon emissions and water consumption. Although the aforementioned studies are helpful in understanding the relevance of incorporating different objectives for the planning of bioenergy production, there is a lack of comprehensive analyses on biomass supply chains that focus on all the key dimensions of a sustainable biomass production including the economic, environmental, and social factors specific to the southern US. Further, analysis of potential trade-offs between economic, environmental, and social factors for converting specific land use types (such as marginal land) to bioenergy plantations is still lacking in the multi-objective optimization of the biomass supply chain literature.

In this study, we analyzed the trade-offs among the major components of a bioenergy crop production system using an optimization approach to make better production decisions at a sub-regional level (e.g., multiple counties in a state). A mixed-integer linear programming (MILP) model was developed that considered the main characteristics of the biomass supply chain, including the spatial diversity and availability of biomass feedstock resources, infrastructure compatibility, and economic structure. As bioenergy production may incorporate various objectives, we ran the model by optimizing one objective at a time to measure the magnitude of a change in one objective with respect to changes in other objectives given a set of constraints. The model was applied to a four-county study area in northern Kentucky. The model allowed us to integrate sustainability dimensions including social, economic, and environmental factors for bioenergy production decisions, and to examine trade-offs between these factors for bioenergy production in a systematic way for the study area. In addition, the model allowed us to assess how bioenergy production decisions could be affected by uncertainties.

2.2 Methodology

2.2.1 Model formulation

For this study, we integrated economic, environmental, and social objectives in the optimization of the biomass supply chain for bioenergy production. We used a mixed integer linear program (MILP) to model the relationship among various factors in the production system. The optimization model in the study had four specific objective functions:

1. Production Objective: The production objective emphasized maximizing total biomass yield from different bioenergy crops (P).
2. Economic Objective: The economic objective maximized total net revenue from the production of bioenergy crops (E). The net revenue accounted for revenues earned from the sale of biomass and the costs for production, harvesting, and transportation of biomass feedstocks.
3. Environmental Objective: The environmental objective captured soil quality loss (S) and water use efficiency (W) from the production of bioenergy crops.

4. Social Objective: The social benefits of bioenergy production were measured in terms of potential job creation (J). For this study, we only considered jobs that support biomass production. The number of feedstock production jobs created was assumed to be linear and depend on the acreage available for establishing bioenergy crops and the potential yield from plantations.

Constraints:

1. Land constraint: The total amount of land that could be used for bioenergy crop production for a crop from a particular site was not allowed to exceed the available land in terms of area. The geographic availability and site conditions of different biomass feedstocks were considered through different values of the parameters (e.g. yield, costs, etc.)
2. Species constraint: We tested the effectiveness of different species using three bioenergy crops that were suited for the study area. The species constraint implied that only one species could be grown in each potential site.

Each individual optimization model for the specific objective functions are presented in the equations 2.1 to 2.5.1 in the Appendix of this chapter. We ran the MILP model by optimizing each objective at a time. The LPSolve IDE – 5.5.2.5 was used to solve the model. All simulations were performed on a desktop computer with an Intel® Core ™ i5 2.71 GHz CPU and 8 GB RAM on a windows operating system.

2.2.2 Uncertainty analysis

Uncertainty exists in bioenergy production systems. Some of the uncertainties relate to biomass production logistics and transportation, bioenergy markets and economic fluctuations, governmental and regulatory policies, etc. In addition, uncertainties related to natural conditions such as weather and natural disasters are also present. In the optimization model discussed above, uncertainty in the parameters was not considered however, large or small variations in parameter values is inevitable and such variations could potentially affect the results. For example, fluctuation in biomass prices and demand may pose obstacles during the planning phase for bioenergy production. Thus, uncertainty (e.g. market uncertainty) should be incorporated into the optimization framework for better decision-making. Previous studies have also emphasized the need to investigate uncertainty in terms of demand/supply fluctuations, biomass yield, and government incentives (You et al., 2012; You and Wang, 2011). Different methods have been used to address uncertainty in wood-based biomass systems. They include scenario-based optimization (stochastic programming and robust optimization), simulation, and hybrid models (Holm-Nielsen and Ehimen, 2016). Stochastic programming and simulation models have been the most widely used tools to address market and yield uncertainties in woody biomass systems. A simulation model is based on an existing system and helps evaluate the system performance based on various what-if scenarios and allows for system improvements. For instance, Mahmaudi et al. (2009) developed a discrete event simulation model to assess the logistics of supplying biomass feedstocks to a power plant in British Columbia, Canada. Mobini et al. (2011) also used a simulation model to account for variability in forest biomass availability. In contrast to simulation models, a stochastic programming model considers the probability of occurrence for uncertain parameters. It allows decision makers to build scenarios that can provide more accurate representations. You et al. (2012) used a two-stage stochastic programming approach to address uncertainty in a biomass supply chain in Illinois. Similarly, Gebreslassie et al. (2012) developed a stochastic model to address optimal design of a bio-refinery supply chain with demand and supply uncertainties. In this study, we used simulation models to address uncertainties of different parameter estimates. Data from the existing literature was used to run the simulations to develop different scenarios to address uncertainties.

2.2.3 Setting spatial unit for bioenergy crop production

Precise spatial information is important in assessing the socio-economic and environmental dimensions of a bioenergy supply system (Yu et al., 2014). Production costs of bioenergy feedstocks is highly sensitive to spatial diversity of the amount and site-specific conditions of available land. In addition, the quality of local transportation networks greatly affects the transportation cost and emissions of GHG. Spatial factors such as the conversion of a particular land cover type to bioenergy crops can have various implications on the socio-economic and environmental performances of the biomass supply chain. As a result, the integration of critical spatial information into multi-objective optimization frameworks has recently emerged in the bioenergy literature. For instance, You et al. (2012) conducted a county-level multi-objective study for a biomass feedstock supply chain for the entire state of Illinois to examine the tradeoffs between various economic and environmental factors. Their study considered all of the state’s 102 counties as potential harvesting sites for bioenergy feedstocks. Another county-level study was conducted for a biomass feedstock supply chain in North Dakota (Osmani and Zhang, 2013). This study considered all 53 counties in that state as potential biorefinery locations and biomass supply and demand zones. Finally, higher resolution spatial data was used in a study in Tennessee to develop a multi-objective optimization model used to examine the tradeoffs between GHG emissions and feedstocks costs (Yu et al., 2014). In the study, authors decomposed all the land area into five square mile hexagons to define land resource units. They assumed that biomass can be transported from each of the land resource units to the nearest facility. For the four-county area in this study, we considered soil units (map units) from the SSURGO Database within each county as potential land resource units. Each soil unit describes various components of soil that have unique characteristics, interpretations, and productivity. These soil units are used for planning and management by the counties (www.nrcs.usda.gov) and thus were ideal for this study.

2.2.4 Study area and input data

Four counties in northern Kentucky (Trimble, Carroll, Gallatin and Boone) were selected as the study area to grow bioenergy crops (Figure 2.1). The study area is unique for its geographic location bordering the northern and southern regions of the US. Further, there are three coal plants within the study area that provide an opportunity to co-fire biomass with coal for energy generation without significant capital investment for establishing new energy facilities.

We selected sweetgum, sycamore and cottonwood as three potential bioenergy crops in the study area. These are short rotation crops with a rotation age between 8 to 12 years and are the most widely adapted hardwood species that can grow on a variety of soil and site conditions (Nepal et al., 2014). Even though perennial grasses such as switchgrass have also been widely used for bioenergy production, we focused only on woody crops mainly because they are fast growing tree species with a potential for higher yield. In addition, management practices for these crops are well understood (Pleguezuelo et al., 2015). Further, they have been recommended as potential bioenergy crops for the southeastern US including Kentucky (UK Cooperative Extension Service, 2012; Kline and Coleman, 2010).

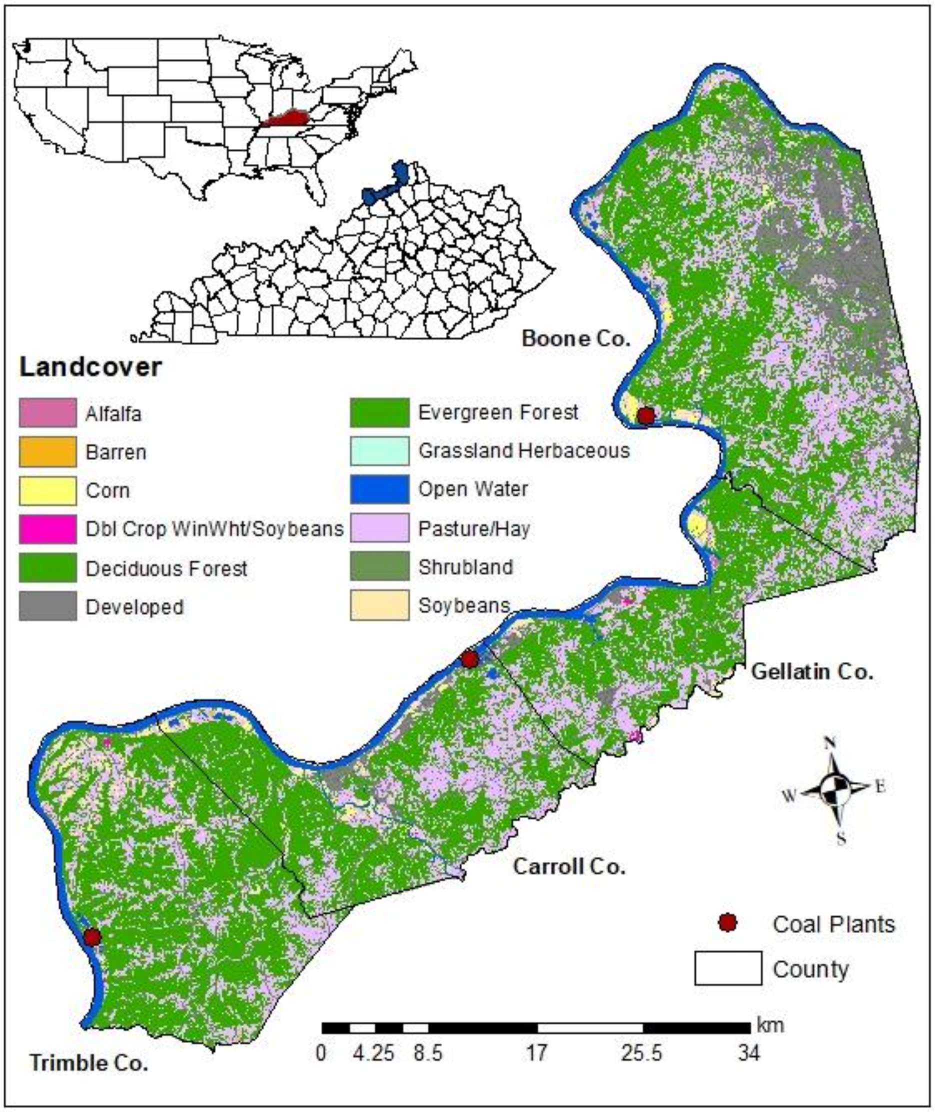

Figure 2.1: Four-county study area with different land cover types

Potential yield

Land cover data for the study area was obtained in a 30-m resolution from the USDA National Agricultural Statistics Services (2012). We focused on marginal lands as potential sites for promoting bioenergy crops in the study area because they do not compete with food production, promote forest conversion, or intervene with any existing management practices. Thus, we extracted marginal lands from the land cover data for analysis. Potential yield for each species within the marginal lands was estimated based on site conditions obtained from SSURGO soil data. Soil conditions were based on site index values that were previously calculated using the procedure developed by Baker and Broadfoot (1979). Based on the site index values, we categorized existing soil types into suitable and unsuitable. Within the suitable class, we further classified the sites into poor, medium and high site conditions. Potential biomass yield within the poor, medium and high site conditions were then estimated based on the yield values proposed by Kline and Coleman (2010).

Costs and revenue

The costs of bioenergy production from the three species included costs of establishment and management. We used information obtained from the literature that reported costs based on treatments including site preparation, planting, herbicides, pesticides and fertilizers incurred at different years throughout the rotation. Harvesting costs and transportation costs were based on a previous study conducted on the same study area (Nepal et al., 2014). The revenue from bioenergy production is influenced by market conditions and feedstock availability. For this study, we assumed a delivered biomass process at the conversion facilities based on price ranges reported in the literature (US DOE, 2016; Skog et al., 2012; Kline and Coleman, 2010).

Soil loss

The potential soil loss values across the study area was calculated using the Revised Universal Soil Loss Equation (RUSLE). The RUSLE uses the expression below:

$$A = R * K * LS * C * P$$

where, A is the average annual potential soil loss, R is the rainfall-runoff erosivity factor (affected by storm intensity, duration, and potential obtained from USDA's soil erosion dataset for each county using RUSLE software), K is the soil erodibility factor (based on soil texture, structure, organic matter, and permeability obtained from SSURGO soil data), LS is the slope length and degree factor (based on digital elevation model and slope), C is land-cover management factor (the C factor for individual species was based on canopy cover where the leaf area index was used as a proxy), and P is conservation factor which was held constant.

Water use efficiency

Water use efficiency is the amount of water consumed for growing a particular crop. Water use data is hard to gather without field experiments. For this study, we obtained information on average annual evapotranspiration (based on leaf area index) and average annual production to calculate water use efficiency for the three bioenergy crop species from previous studies (Kline and Coleman, 2010; Nagler et al., 2007; Murthy et al., 2005; Wullschleger and Norby, 2001; Wittwer and Stringer, 1985).

Jobs/employment

Bioenergy production can promote jobs within the bioenergy facility and jobs related to feedstock production, collection, handling, and transportation. This study assumed that biomass produced in the study area will be co-fired in existing coal plants, we therefore only focused on the potential job creation for biomass feedstock production, storage, handling, and transportation. We made projections for potential jobs based on previous regional studies conducted on bioenergy production (English et al., 2013). The number of feedstock production jobs created was assumed to be linear and depend on acreage available for establishing bioenergy crops and the potential yield from plantations.

2.3 Results

2.3.1 Trade-off analysis

Table 2.1 shows the results from the optimization model. Each column represents the output when individual objective function was optimized. The numbers along the diagonal shows the optimal values for individual objective function.

As expected, the model provided the highest yield when the production function was maximized. The model indicated that there was the possibility to provide jobs in this scenario as well. In contrast, there was very little or no economic benefit that could be obtained while maximizing

Table 2.1: Trade-offs among different objectives

	Max Production	Max Revenue	Max Jobs	Max Water use Efficiency	Min Soil Loss
Yield (tons)	**39192.57**	16710.77	39174.89	27824.46	3565.718
Revenue ($)	0	**8763.36**	0	0	2.67
Jobs (#)	155.546	64.76	**155.667**	109.81	14.67
Water use Efficiency (tons/mm)	40.49	20.28	35.748	**65.688**	3.24
Soil Loss (tons)	2694.50	1148.56	2715.002	2426.92	**1148**

yield (we got 0 rather than negative values for economic returns mainly because of the way we set up non-negative constraint in the optimization model). Thus, even though there is a potential for high yield bioenergy crop production in the study area, this production would produce negligible economic benefits. Poor market conditions with low biomass prices and high costs associated with establishment and management, harvesting and transportation of biomass could have accounted for the lack of economic benefits in this scenario. The production objective was also less favorable for environmental aspects of bioenergy production because the model provided less efficient water use (water efficiency reduced by 38%) and more soil loss. Water use by bioenergy crops is relatively high (in other words, water could be a limiting factor for producing bioenergy crops) indicating a need for irrigation in the study area to achieve higher yields. Although, there is a potential for an increase in production; decreasing crop prices, low profitability, and potential negative implications on the environment might trigger a decrease in the amount of land that is suitable to produce bioenergy crops.

Similar trends were obtained when we maximized economic benefits. Even though higher benefits were expected in this scenario, the solution produced 57% less biomass yield, created fewer jobs, and reduced water efficiency by 69%. As mentioned earlier, producing biomass requires a substantial capital investment to make available lands more productive. And since the biomass market is not well developed, producing bioenergy crops on all available land might not generate economic returns. Marginal lands for this study were categorized as poor, medium and high-quality sites based on existing soil conditions. Thus, it may be more beneficial to promote bioenergy crops only on high quality sites that could potentially provide high yield and generate more income. Since job creation is a direct function of how much land is available for production, lower acreage and less production in this scenario explains why there was low potential for job creation. In addition to fewer jobs, low production accounted for lower soil loss in this scenario.

The maximum social benefit scenario provided results similar the maximum production scenario. As mentioned previously, job creation is directly related to amount of land available for promoting bioenergy crops. In our model, more land would produce greater yield and support more jobs.

When the focus was on maximizing water efficiency, the model provided a solution that was the most water efficient. This scenario produced 29% less yield and there were no economic benefits. Soil quality also degraded with soil loss almost doubling. Introducing water saving plants in the future as bioenergy crops could effectively increase water efficiency as recent studies have shown that the metabolic mechanisms of such plants conserve more water (DOE/ORNL, 2016).

Minimizing the soil loss objective provided solutions with zero value (indicating that zero soil loss could only be attained when leaving the existing land use as it is). However, soil erosion is a naturally occurring process and soil loss would still exist in marginal lands that have poor quality soil and rough topographic features (Pimentel, 2006). Thus, we chose to reduce soil loss to a minimal level and set a constraint on soil loss based on other individual objectives presented above. This provided a solution with the least yield, no economic benefits, fewer jobs, and less efficient water use.

These results indicate that a multi-objective optimization model can clearly depict trade-offs between production, socio-economic, and environmental factors for bioenergy production. Understanding the links among the various factors is very important for planning or designing a sustainable bioenergy crop production system that incorporates various stakeholders with diverse and often conflicting interests. In addition to the trade-offs analysis, our results were also able to show how distribution of suitable areas are dispersed in space when we prioritized different objectives in the study area. For instance, maximizing the production objective showed 613 ha of marginal lands that were suitable for growing bioenergy crops (Table 2.2). From Figure 2.2, it can be seen that almost all the available locations were suitable for sycamore plantations while there are only traces of areas where sweetgum was suitable. Cottonwood was not suitable on any land.

When maximizing economic returns, 255.7 ha was available for growing bioenergy crops. Similarly, incorporating environmental factors for bioenergy production in terms of maximizing water use efficiency and minimizing soil loss resulted in 437.51 ha (436 ha for sycamore and 1.04 ha for sweetgum) and 55.35 ha being available, respectively. It should be noted that 2.07 ha were available for cottonwood plantations when minimizing soil loss was the major focus (Table 2.2).

The distribution of areas available for the three species under different objectives reveal that the

Table 2.2: Areas of land available under different objectives

Objectives	**Cottonwood (ha)**	**Sweetgum (ha)**	**Sycamore (ha)**
Max. Production	0	0.000138	613.17
Max. Revenue	0	0	255.70
Max. Jobs	0	0	613.12
Max. Water use efficiency	0	1.04	436.47
Min. Soil loss	2.07	2.3	50.98

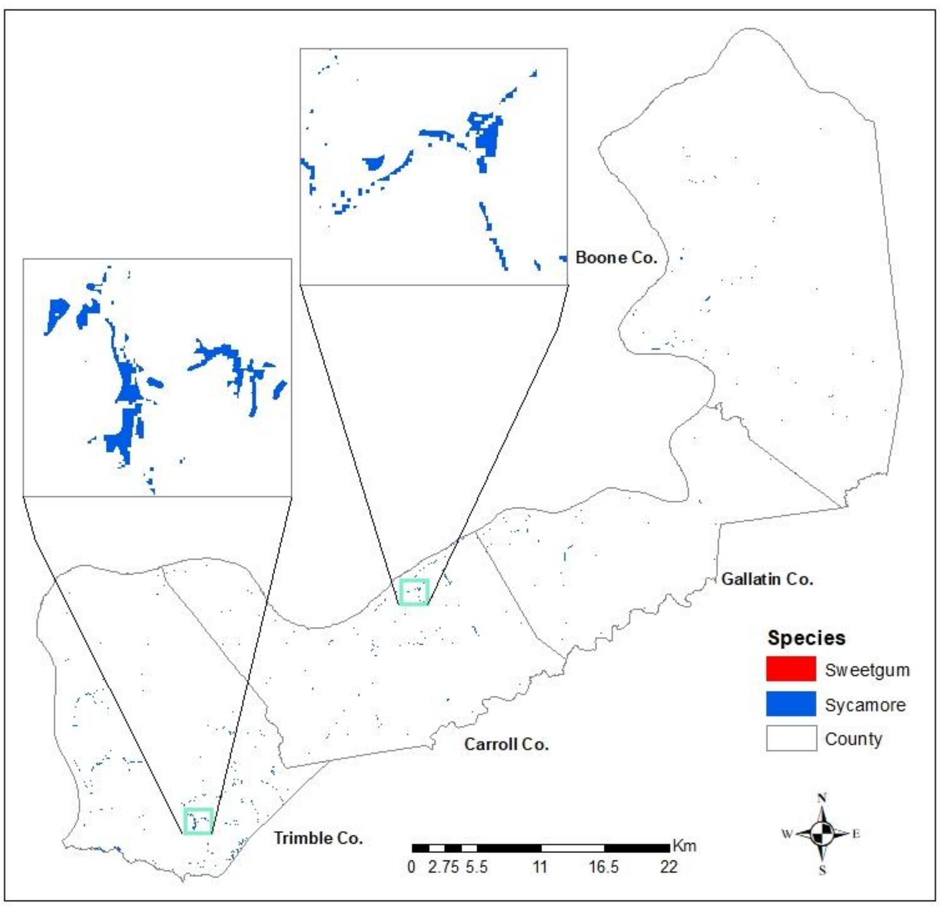

Figure 2.2: Suitable locations for growing bioenergy crops under production objective

choice of species for bioenergy production is sensitive to the objectives that are prioritized. When production and socio- economic gain were prioritized, our results showed sycamore was the most favorable species, however, when environmental factors were prioritized, sweetgum and cottonwood were also favorable. Even though, sycamore may have the potential for higher biomass yield with a shorter rotation period, existing site conditions including soil quality and water requirements may be favorable for the other two species.

It is important to highlight that the total amount of land available for bioenergy crops differed depending on the objective(s) prioritized. Existing site condition/qualities can have important implications for which areas are suitable for growing the three crops used in this study. For this study, our biomass yield value was based on site qualities obtained from SSURGO database and the potential biomass yield values were based on experts' opinions as reported by Kline and Coleman (2010). Our baseline yield values did not account for possible management changes to improve productivity. However, additional management options such as promoting hybrid bioenergy species (such as hybrid cottonwood) and GMOs can improve productivity and potentially make more lands suitable for plantations. In addition, we focused on hardwood species that are common to the study area that have been recommended by previous studies. However, species like loblolly pine and perennial grasses such as switchgrass have also been identified (and widely grown) as potential species for bioenergy production in the southern US. Inclusion of these species could produce different results. In addition, other factors such as relatively poor biomass market conditions and uncertainty in other parameter estimates could have resulted in less areas suitable for growing bioenergy crops.

2.3.2 Uncertainty analysis results

Relationship between parameters and outcomes are not known a priori. We used "lp_solve", specifically the "lpsolveAPI" in the R statistical computing program, to generate simulations to address how changes in each of the parameter estimates would affect the trade-offs among various objectives. We generated models to reflect different biomass market conditions, biomass productivities, different job creation assumptions, water use efficiencies, and soil loss functions for the three species under consideration to identify critical input parameters and understand how model outputs were sensitive to changing parameter values.

Figures 2.3 and 2.4 show the distribution of trade-offs among different objectives from the

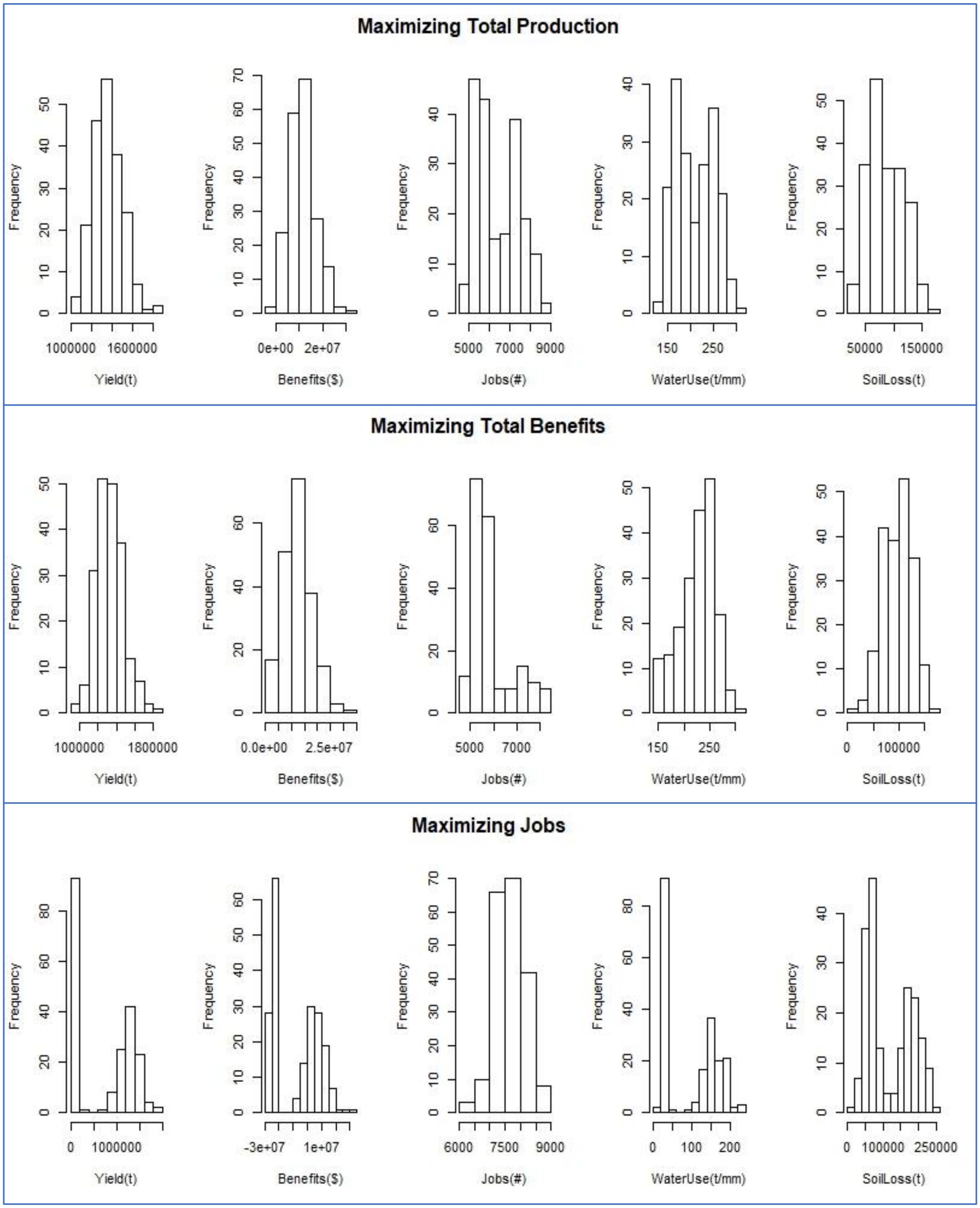

Figure 2.3: Histograms to display trade-offs among various factors for bioenergy production (maximizing production, maximizing benefits, and maximizing jobs)

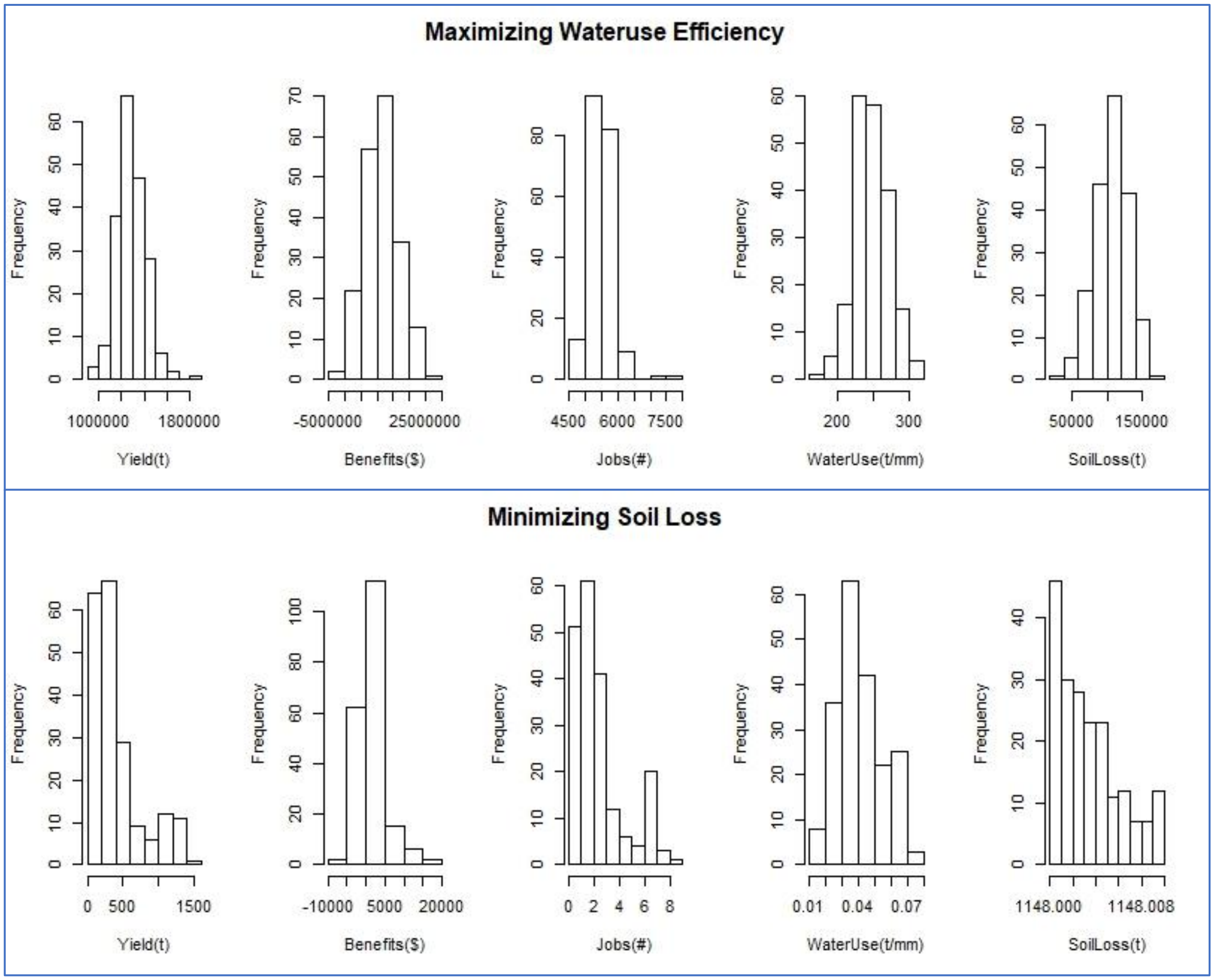

Figure 2.4: Histograms to display trade-offs among various factors for bioenergy production (maximizing water use efficiency and minimizing soil loss)

uncertainty analysis. We ran one objective at a time and generated five histograms for all five objectives. In the maximizing production scenario, the simulations with improved productivity values for each bioenergy crop showed an increase in total yield for the study area. As expected, better market conditions with higher biomass prices provided greater economic benefits from the biomass produced. A positive correlation was observed for the two parameters (total yield and expected benefits) implying that better market incentives would promote more production and generate more benefits. The histogram for total jobs in this scenario showed two distinct peaks. With increasing yield, the total number of jobs increased in the beginning however, they declined and peaked again. Thus, there is not a strict linear relation between the total number of jobs and total yield. Since we made choices among the crop types while designing the optimization model, our model switched crop types and the output for total jobs was dependent on the range of values provided for different crop types that were the most favorable with the set objectives. Figure 2.5 shows the distribution of total number of jobs w.r.t the potential job creation assigned in the model for two different crop types. When the potential jobs for both crops were small (towards the left), the distributions for total jobs were similar however, as we increase the potential job creation for sweetgum (along the x-axis), we observed a higher value of total jobs clustered for sweetgum, irrespective of the values for American sycamore. This distribution provides a plausible explanation for the shift in the histogram as our model had the ability to switch crop types to generate efficient results. The histogram for water use efficiency showed similar pattern as the jobs. With increasing yield, the water use efficiency peaked at a lower value (which could imply that water is a limiting factor for producing higher yield), declined and peaked again. Since water use efficiency is related to the potential production values associated with each crop type, we plotted scatter plots for total water use efficiency and potential yield for each crop. Figure 2.6 shows two scatter plots for cottonwood and American sycamore. Increasing potential yield value for cottonwood did not improve the total water use efficiency however, when the potential yield for American sycamore was increased, the water use efficiency improved. Thus, productivity/yield and water use efficiency were not correlated in a similar way for each of the three species. Providing choices for the crop types for each site switched the crop types in the final model resulting in output values that were most efficient. In the case of soil loss, histogram showed that increasing productivity was associated with higher soil loss.

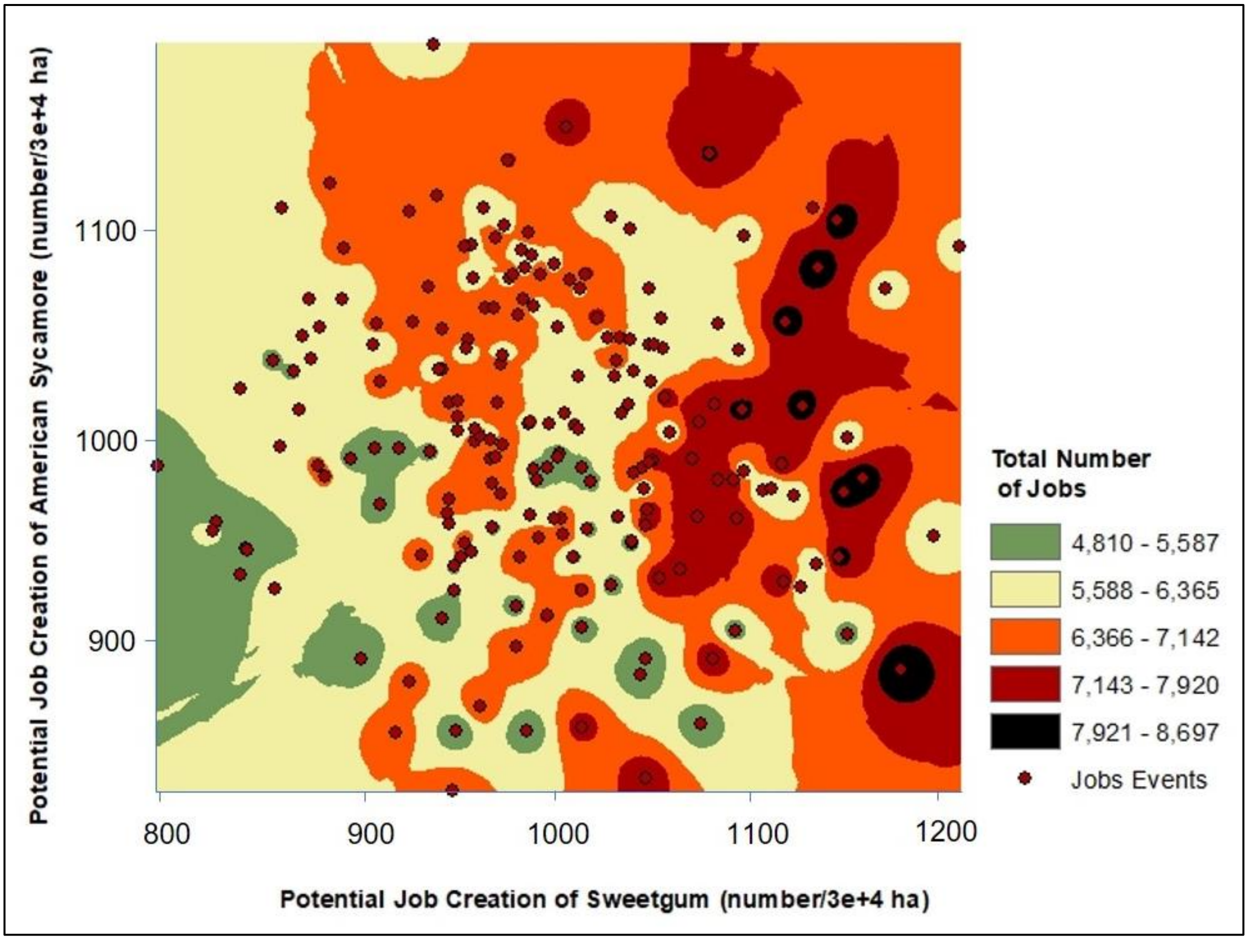

Figure 2.5: Variation of total number jobs with respect to uncertainty in potential job creation of two crops, sweetgum and American sycamore

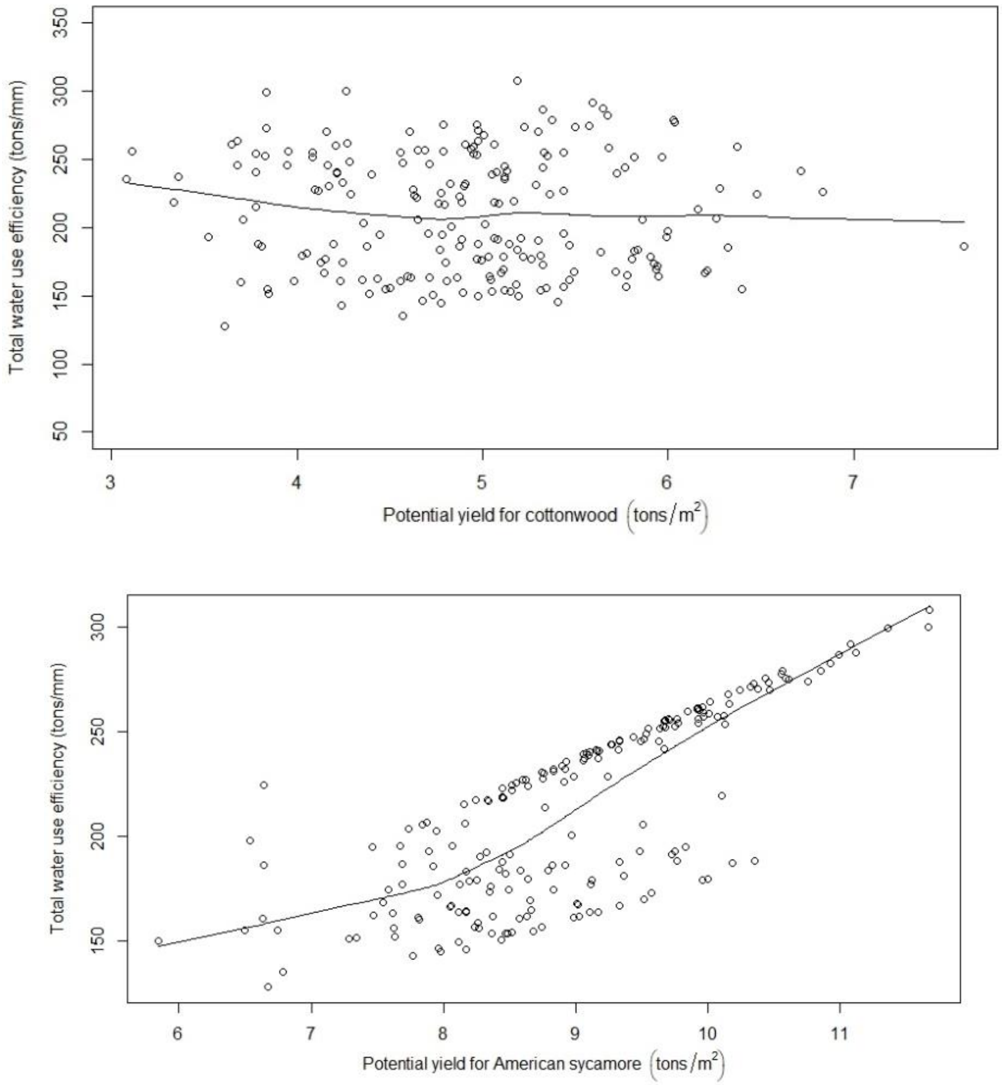

Figure 2.6: Scatterplots for total water use efficiency and potential yields for cottonwood and American sycamore

In the maximizing revenue scenario, the histograms showed similar patterns for yield, revenue, and jobs to the maximizing production scenario. This implies that in better biomass market conditions, maximum revenue can only be generated when the full potential yield is obtained. As job creation was directly related to the amount of land available for growing bioenergy crops and the potential yield, more yield would support more jobs. Water use efficiency had a slightly negative skew while maximizing the revenue indicating that water could be a limiting factor. In the maximizing jobs scenario, the histogram showed two distinct peaks in the distribution of yield. Around half of the yield values were centered around 90,000 to 200,000 tons. In addition, there was another smaller peak around 1,300,000 tons. Similar patterns were observed for the distribution of economic benefits, water use efficiency, and soil loss.

When jobs were maximized, the lower yield was correlated with negative economic benefits (e.g. a higher cost to produce bioenergy crops when compared to potential revenues), lower water use efficiency, and higher potential soil loss. One possible explanation for the gaps in the histograms is the spatial units considered in the study. The spatial units, in other words, soil map units from SSURGO database were non-uniform and they were defined by site qualities (into poor, medium and high-quality sites). Biomass production on larger areas would require more labor (with the potential for more employment opportunities) but when the larger areas fall within the poor-quality soil, the total yield from those sites may be less and the production may not be economically beneficial because of the high costs of establishment and management. Furthermore, since these areas could be environmentally sensitive, production without careful planning may lead to more environment degradation instead reclaiming poor quality marginal lands from bioenergy crop production. A further look at the histograms under the job maximization scenario for example, for total yield, shows a smaller peak after the gap. Since total yield obtained was a function of potential yield values associated with each crop, we examined if the choice of crop species has any influence in the distribution of yield in the simulation results. Figure 2.7 shows the distribution of yield for two crop types. The x and y axes represent the increasing values for potential yield for sweetgum and American sycamore, respectively. At a lower value of potential yield for the two crop types, the total yield value is minimum (which could relate to poor-quality site). Even though American sycamore has higher potential yield than sweetgum in general, increasing potential yield for American sycamore did not show strong pattern (influence) on the total yield and the distribution was rather random.

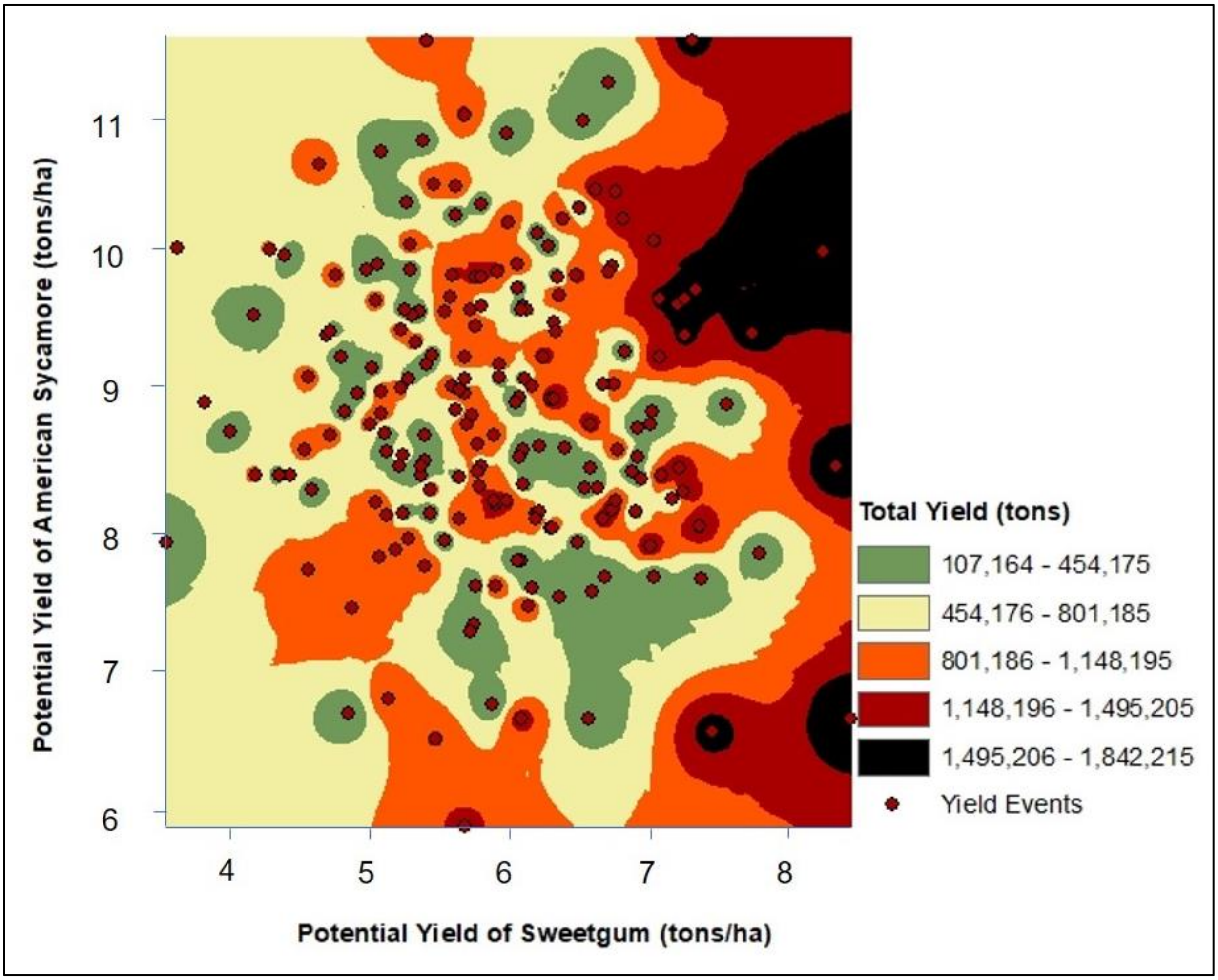

Figure 2.7: Variation of total yield with respect to uncertainty in potential yield of two crops, sweetgum and American sycamore

However, a higher value of potential yield for sweetgum, irrespective of the values for American sycamore, showed more of a linear relationship with the total yield. Since we had discrete choices in the model, our model had the ability to switch crop types to generate efficient results.

When water use efficiency was maximized, the histograms showed water use efficiency was rightly skewed indicating a more water efficient scenario with a mean value around 250. As expected, water use efficiency had a strong positive correlation with potential yield (r=0.89). The higher yield in the scenario generated economic benefits and provided some opportunities for employment (not as strong as in the job maximization scenario) however, higher production was associated with higher soil loss as well. Lastly, when minimizing soil loss, the histogram shows a small range for potential soil loss. However, this scenario generated the least yield, lowest economic benefits, very few jobs, and the least water use efficiency. Thus, the overall simulation results indicate that the optimization model developed for this study is robust.

It is evident from the histograms that the distribution of parameters under different scenarios did not behave in a similar pattern. The distribution of the parameters under uncertainty provides better information about the system that was modeled. The range of values observed for each objective in all the scenarios provided an insight on how strange the system may behave under uncertainties. In addition, the choice of different crop types in the optimization model had different influence on the outcome and it showed how bioenergy production system could be sensitive to the choice of bioenergy crops for production decisions. The range of values obtained from the simulation analysis can be the first and the most important step in designing a multi-objective model just as a goal programming (GP) model where the extreme values can use used as aspiration levels or target values. In GP model that considers multiple objectives, instead of optimizing all the objectives directly, achievement of the aspiration levels helps measure the achievement of objectives. Since decision makers in multi-objective optimization problems must chose targets or aspiration levels that are realistic based on proper understanding of how the system under study works, our simulation results can be helpful to identify optimal scenarios for bioenergy production decisions.

Even though our uncertainty analysis provided a system overview for bioenergy production, it must be noted that we only considered uncertainty of parameters while running the simulations. However, in practice there could be uncertainty about the model itself. There could be several other models that might work to understand how a system works. For this study, we used a linear programming approach that allowed us to examine the trade-offs among different factors of production where relations among all the variables corresponding to bioenergy resources were considered linear.

2.4 Discussion

Making bioenergy production decisions are difficult as decision-makers have to consider multiple and competing objectives (e.g., often there are tradeoffs among different objectives). In addition, uncertainty of circumstances (such as substantial production and market uncertainties) could impact these tradeoffs. The trade-off analysis in this study provided an integrated approach to highlight potential opportunities and risks in bioenergy production. The analysis considered all aspects of bioenergy production including socio-economic and environmental factors and examined whether bioenergy crops would be feasible in northern Kentucky. By quantifying the inter-relationships among the different factors, our analysis revealed that northern Kentucky can be a suitable area to promote bioenergy crop production. This production can support the state's energy plan which focuses on developing a sustainable biofuels industry in Kentucky with an aim to produce 25 million tons of biomass every year by 2025 to meet the energy demand with the potential to contribute $3.4 billion and 10,000 jobs to the state's economy (Governor, 2009). However, our results clearly show that there are trade-offs among various objectives that should be considered.

For instance, maximizing biomass yield provides no economic return, implying that production is not economically beneficial. This could result from poor market conditions due to low demand of bioenergy, high costs associated with production and management, lack of proper infrastructure, and the viability of cost competitive fossil fuels such as coal for electricity generation. This trade-off highlights the need for better economic incentives to ensure production is economically beneficial. One possible way for the state to do this would be to implement policies that focus on incentivizing landowners for growing bioenergy crops. In addition, encouraging private sector investment, better infrastructure for energy generation, and creating new opportunities for better markets could increase the economic benefit of bioenergy production. This trade-off analysis also suggested that higher bioenergy production generates concerns for water availability and soil erosion. In other words, higher production may come at the cost of greater environmental degradation. Thus, there is a need to take environmental impacts into consideration when promoting bioenergy crop production in the state. In addition, the potential yield values across all the objectives varies substantially. The highest yield is obtained while maximizing production while the least yield is obtained when minimizing potential soil erosion. Since this study mainly focused on marginal lands as potential sites for growing bioenergy crops, minimum soil erosion on such lands could only be attained when much of the existing land was not brought under production and the bioenergy crop was produced on a relatively small amount of the available land. Since higher production resulted in greater environmental degradation in terms of soil loss from poor quality marginal lands, this result highlights the need to explore other land use types such as land currently in agriculture and forests as potential sites for bioenergy production because they are more productive and have better site conditions.

When economic returns were maximized, the potential yield was reduced by 57% which implies that generating economic benefits would not require establishing bioenergy crops on all available land. The spatial units for this study consisted of soil units that were categorized as poor, medium and high quality based on existing site conditions. Establishing bioenergy crops on low quality sites could incur higher costs. Thus, to generate higher economic gains in bioenergy production, the focus must be on high quality sites. In addition, this scenario also results in less soil erosion. Thus, lower production could yield substantially lower soil erosion values. This tradeoff also highlights the need to consider high quality sites for bioenergy crops. Thus, again, other land use types such as agriculture and forests should be studied in the future.

Since, there are no existing policies specific to bioenergy crop production in Kentucky, results from this study highlight the opportunity to design policies that would generate economic returns and promote environmental conservation while establishing bioenergy crops on good quality sites by explicitly considering the trade-offs among various objectives. Specifically, policies that incentivize landowners to grow bioenergy crops, develop larger markets with higher biomass prices, and support infrastructure would likely be effective in promoting bioenergy crop production. While our trade-off analysis showed higher production may come at the cost of environmental degradation, policy support for improved technologies to promote better soil and water management strategies can help reduce some of the negative impacts of bioenergy production on soil and water resources. While marginal lands have been an attractive option to promote bioenergy crop production, the results here show that these lands might not be an attractive source of biomass because of concerns for the environment such as potential soil erosion. Thus, again future studies should also focus on other more productive lands such as agricultural lands and forests to explore the full potential of bioenergy crop production in the study area. Overall, integrated policies for bioenergy, land use, soil and water management are likely required to make bioenergy crops a sustainable feedstock source for the bioenergy industry.

2.5 Conclusions

Trade-off analysis can be a very effective tool to assess the potential of biomass production from a multidimensional perspective. In this study, we presented a multi-objective optimization approach to analyze trade-offs between social, economic, and environmental factors for bioenergy production. The economic factor incorporated production and management costs and revenues generated from the sale of biomass. The environmental factor captured soil quality and water loss due to the establishment of bioenergy crops. Lastly, the social factor represented the number of potential new jobs created related to biomass feedstock production. The results clearly show that there are trade-offs among these factors.

Results from this analysis showed that forests and agricultural lands in addition to marginal lands can be a valuable for establishing bioenergy plantations. However, the choice of energy crops to be grown on such lands will substantially depend on regional conditions including site quality, water requirements, landcover types and biomass market conditions. The trade-offs among the various factors highlight the need for systematic planning to promote bioenergy crop production. With effective planning, establishment of bioenergy crops on marginal lands and/or forests and agricultural lands can promote biomass for bioenergy and assist in other sustainability goals such an economic growth, environmental conservation, and rural development. Finally, this study suggests that an integrated approach such as multi-objective optimization with a variety of objectives for bioenergy production can reveal important trade-offs and enhance decision making for sustainable bioenergy production.

Although the model used in this study was specifically applied to decision making related to bioenergy production in northern Kentucky, it can potentially be applied to a larger or different geographic area where bioenergy plantations have been recommended. All the data used in this study were publicly available, thus the results from this study can be easily compared to other regions using the same technique. This would be helpful to policy makers or planners in designing effective policies to support bioenergy production.

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Appendix

Mathematic formulation for optimization models

Model 1: Maximizing economic benefits

$$\text{Max E}= \sum_{j=1}^{n} a_jX_j+b_jY_j+c_jZ_j \qquad (2.1)$$

subject to

$$X_j + Y_j + Z_j = 1 \quad \forall j \qquad (2.1.1)$$

$$\sum_{j=1}^{n} s_jK_j \leq \Omega \qquad (2.1.2)$$

$$X_j \geq 0 \quad \forall j \qquad (2.1.3)$$

$$Y_j \geq 0 \quad \forall j \qquad (2.1.4)$$

$$Z_j \geq 0 \quad \forall j \qquad (2.1.5)$$

$$X \in \{0,1\} \qquad (2.1.6)$$

$$Y \in \{0,1\} \qquad (2.1.7)$$

$$Z \in \{0,1\} \qquad (2.1.8)$$

$$K \in \{0,1\} \qquad (2.1.9)$$

where,

$$a_j = f(P_{jx}, C_{jx}) \quad \forall j \qquad (2.1.10)$$

$$b_j = f(P_{jy}, C_{jy}) \quad \forall j \qquad (2.1.11)$$

$$c_j = f(P_{jz}, C_{jz}) \quad \forall j \qquad (2.1.12)$$

Model 2: Maximizing total yield

$$\text{Max P} = \sum_{j=1}^{n} d_jx_j + e_jy_j + f_jz_j \qquad (2.2)$$

subject to equations (1.1) to (1.9)

Model 3: Maximizing job creation

$$\text{Max J} = \sum_{j=1}^{n} g_j x_j + h_j y_j + i_j z_j \qquad (2.3)$$

subject to equations (1.1) to (1.9)

Model 4: Maximizing water use efficiency

$$\text{Max W} = \sum_{j=1}^{n} m_j x_j + n_j y_j + o_j z_j \qquad (2.4)$$

subject to equations (1.1) to (1.9)

Model 5: Minimizing soil loss

$$\text{Min S} = \sum_{j=1}^{n} p_j x_j + q_j x_j + r_j x_j \qquad (2.5)$$

subject to equations (1.1) to (1.9) and

$$\sum_{j=1}^{n} S_j \geq \Omega' \qquad (2.5.1)$$

Indices

j=spatial unit (site)

jx= crop type x grown in site j

Parameters

X, Y, Z= three species (cottonwood, sweetgum and American sycamore) considered in the study area

s_j = area of site j

K = binary variable, 1 if site j is selected; 0 otherwise

Ω = total available area

P_{jx} = revenue generated from biomass produced from crop type x in site j

C_{jx} = cost of producing x crop in site j

P_{jy} = revenue generated from biomass produced from crop type y in site j

C_{jy} = cost of producing y crop in site j

P_{jz} = revenue generated from biomass produced from crop type z in site j

C_{jz} = cost of producing z crop in site j

a_j = total benefits from producing crop x in site j

b_j = total benefits from producing crop y in site j

c_j = total benefits from producing crop x in site j

d_j = total yield produced from crop type x in site j

e_j = total yield produced from crop type y in site j

f_j = total yield produced from crop type z in site j

g_j = total number of jobs created by producing crop type x in site j

h_j = total number of jobs created by producing crop type y in site j

i_j = total number of jobs created by producing crop type y in site j

m_j = total wateruse efficiency for producing crop type x in site j

n_j = total wateruse efficiency for producing crop type y in site j

o_j = total wateruse efficiency for producing crop type z in site j

p_j = total soil loss by producing crop type x in site j

q_j = total soil loss by producing crop type x in site j

r_j = total soil loss by producing crop type x in site j

S_j = soil loss in site j

Ω' = minimum soil loss value assigned based on previous models

CHAPTER 3

DETERMINANTS OF LANDOWNERS' WILLINGNESS TO PROMOTE BIOENERGY CROP PRODUCTION: A CASE STUDY FROM NORTHERN KENTUCKY

This chapter is in preparation for journal submission. The use of "we" in this chapter refers to co-authors, Dr. Donald G. Hodges, Dr. Liem T. Tran, and me. I am the first author, and my contribution to this project include survey design and administration, data analysis, and writing the manuscript.

Abstract

There is an increasing interest in bioenergy in the southern US, mainly because of the favorable climatic conditions to grow highly productive bioenergy crops. Establishing bioenergy crops in this region requires participation from landowners as they own the majority of land. It is crucial to understand whether landowners intend to harvest bioenergy feedstocks from their property and to explore how they view and react to both the opportunities and challenges presented by bioenergy crops. We administered a quantitative survey for landowners in a four-county study area in northern Kentucky to evaluate their perception of bioenergy and their willingness to promote bioenergy crop production. Results indicated that current land management practices, socio-economic, and environmental factors affected the landowners' land use decisions about bioenergy crop production. The study revealed landowners' intent for bioenergy production, which would be helpful for estimating the potential of large-scale bioenergy expansion in the study area and beyond. Further, landowners' opinions on bioenergy and their preferences for land use decisions would be helpful to identify barriers to their engagement in the bioenergy production process. This information could be useful to plan for policies, and technological investments that would be effective for landowners to encourage bioenergy feedstock production. Lastly, the results could also be used to develop outreach programs to increase adoption of bioenergy crops in the study area.

Key words: bioenergy, willingness, landowners, land use, decision-making, Kentucky

3.1 Introduction

There is a substantial demand for bioenergy in the United States (US) for its potential to displace fossil fuels, enhance energy security, promote environmental benefits, and provide opportunities for economic development. Bioenergy has been promoted by federal policies, including the most recent Energy Independence and Security Act (EISA) of 2007 that set a mandatory Renewable Fuel Standard (RFS) requiring energy producers to use at least 36 billion gallons of biofuels in 2022 (EPA, 2013). Similarly, the Food Conservation and Energy Act has provided various provisions and incentives to promote biomass and bioenergy. Recently, policies have promoted improvements in crop productivity as well as farmland, forest, and land management to support the bioenergy industry. As a result, establishing bioenergy crops has been identified as a significant source of bioenergy with the potential to supply adequate feedstock to sustain the bioenergy industry (Staudhammer et al., 2011).

Interest in bioenergy has increased in the southern US as well, mainly because of a warm and wet climate that is conducive to highly productive bioenergy crops (Brosius et al., 2013). However, establishing bioenergy crops in this region will require participation from private landowners as they own most of the land (Leitch et al., 2013). It is crucial, therefore, to estimate the availability of biomass feedstocks from private land by understanding to what extent and under which conditions landowners intend to harvest bioenergy feedstocks from their property. Even though bioenergy crops can potentially provide a sustainable feedstock to support the bioenergy industry, commercial scale production of bioenergy crops (especially short rotation woody crops) has not been established yet (Nepal et al., 2015). Further complicating the issue, introducing bioenergy crops to conventional farming practices will require major changes in land use and management practices, and it is currently restricted by several factors such as uncertain economic returns for landowners, inadequate knowledge/awareness about bioenergy and their willingness to promote bioenergy crops, and low cost fossil fuels such as natural gas and coal (Leitch et al., 2013; Tyndall et al., 2011; Jessup, 2009). Finally, insufficient economic and policy incentives along with uncertainty in the biomass market, make bioenergy crops less attractive to landowners. Since there is not a well-defined market for biomass, determining landowner willingness to produce bioenergy crops is a challenge.

Basic decision-making models suggest that landowners make land use decisions in relation to available human, natural and capital resources, potential opportunities against constraints, and careful examination of uncertainty and risk (Caldas et al., 2014). Several studies have been conducted in the past to understand factors that affect landowners' decisions for adopting a bioenergy crop production system. Caldas et al. (2014) assessed farmers' willingness to produce biomass feedstocks from crop residues, dedicated annual crops, and perennial crops for three regions in Kansas. Their study found that farmers' lack of familiarity with producing bioenergy crops and their perception play a key role in their willingness to plant bioenergy crops. Leitch et al. (2013) studied private landowners' intent to supply forest biomass for energy in Kentucky based on the theory of planned behavior. Their study highlighted that respondent attitudes, perceived subjective norms, and perceived control are significantly related to their intent to harvest woody biomass for bioenergy production. In another study in the southeastern US, farmers were asked to indicate their willingness to plant switchgrass (Qualls et al., 2012). The results showed that many nonfinancial factors such as perceived environmental benefits, reduced crop inputs, contribution to national energy security, and diversification of farm incomes significantly increase landowner willingness to produce energy crops.

The aforementioned studies mainly focused on how landowner knowledge and attitudes toward bioenergy influence their willingness to promote bioenergy production overall. There is a limited research on potential biomass crop production focusing specifically on marginal lands -lands with poor quality soil and lower productivity including grasslands, shrubland, fallow cropland, and hay/pasture. Marginal lands are attractive options for growing energy crops because they do not compete with food production or promote forest conversion and are less likely to intervene with existing management practices. Further, growing energy crops on marginal lands can provide positive ecological benefits such as improved soil and water quality, carbon sequestration, and biodiversity. Finally, previous research also suggests that bioenergy crops grown on marginal lands require less fertilizer and are more flood and drought tolerant than conventional crops (Blanco-Canqui, 2016; McLaughlin and Walsh, 1998)**.** The few studies on marginal lands for bioenergy production mainly focused on suitability analyses without assessing the social availability of such lands (Nepal et al., 2015; Nepal et al., 2014). Even though a substantial amount of marginal lands may be suitable for growing energy crops, it is important to understand if landowners are willing to change their land-use behavior to make those lands available for bioenergy crop production.

This study evaluated landowners' perceptions of bioenergy and their willingness to utilize marginal lands for bioenergy production in northern Kentucky. It collected information on landowners' existing land management practices, knowledge and understanding of bioenergy crops, key price variables (biomass prices and rental rates), landowner perceptions of bioenergy, and key socio-demographic information (such as age, sex, education, income) to examine if and under what conditions landowners would make their land available for growing bioenergy crops. The study contributes to the existing literature in several ways. First and foremost, it is one of the first studies to investigate the social availability of marginal land for bioenergy production.

Second, even though the study is limited to northern Kentucky, landowner intent to harvest energy crops or rent their land for bioenergy crop production in this region may also apply to private landowners in similar geographic locations where bioenergy crop production has been recommended. The results of this study should be useful for policy makers trying to promote effective biomass supply chain strategies and future renewable energy production.

3.2 Methodology

3.2.1 Methodological approach

Since there is no existing market for biomass, landowner decisions cannot be observed directly. However, it is possible to estimate landowners' preferences for different bioenergy crops based on a contingent valuation survey. Contingent valuation (CV) surveys are often used to estimate willingness to pay for environmental goods and services for which a market does not exist. For example, the cost people pay for a visit to a national park is the price of access to the park and its environmental services. It can be measured in terms of the number of times people visit the park at different costs. This gives the economic values of recreation sites, in other words, the value of recreational sites is related to the costs people are willing to pay for the use of recreation (Pirikiya et al., 2016). Contingent valuation surveys can also be used to estimate willingness to accept payments to supply goods and services that are not currently sold in the market (Swinton et al., 2007).

In contingent valuation, all attributes of the environmental resource are first described and then survey respondents are asked whether they would pay (or accept) a specific amount to access (or provide) the resource. In general, CV generates a scenario like that encountered in typical market transactions (Cameron and James, 1987). Respondents are given a hypothetical price (payment) for a resource and they decide to accept the price (payment) or not. Generally, they are not required to suggest a specific price - that they are willing to accept if they deny the offer (ibid). If the attributes of environmental resources are described precisely, CV techniques can provide valuable information about the demand and supply of non-marketed resources.

For this study, we used a contingent valuation survey to assess landowners' willingness to accept a payment for biomass production. Specifically, we assessed their willingness to accept a direct payment for producing bioenergy crops on their land, as well as their willingness to accept a payment for renting their land to someone for bioenergy crop production. The main reason for assessing the rental payment option was that many rural landowners might not be currently engaged in farming activities and they may not have the capabilities and interest in growing energy crops on their land. In addition, a rental payment is an easy, certain and secure income source for the landowner. Finally, they would be able to avoid some of the risks associated with bioenergy crop production. The survey also collected data on landowners' perceptions of bioenergy. Surveys have long been a useful tool to gather information about people's attitudes and opinions regarding certain phenomena (Parfitt, 2005; McLafferty, 2003).

3.2.2. Study area and data collection

The study focused on four counties (Trimble, Gallatin, Carroll, and Boone) in northern Kentucky. This area is unique for its geographical location bordering northern and southern regions of the US. It is also representative of Ohio River basin. There is a diverse land use with small, privately-owned, parcels of land. Further, there are three coal plants within the four-county area that provide opportunities to co-fire biomass with coal for energy generation without the need of significant capital investment for establishing new bioenergy facilities (Figure 3.1).

As discussed previously this study examined only marginal lands. However, identifying the subset of landowners who have marginal land and obtaining their information is challenging. Many previous studies focused on all or most existing forest or cropland, making identifying respondents relatively easier by using existing publicly available information such as county tax records or landowner association membership lists. To overcome this difficulty, we used a private vendor, listGIANT to identify landowners who have at least 10 acres of marginal land. Previous studies have also proposed 10 acres as a minimum viable area for bioenergy production due to production logistics such as storage, transportation etc. (Hayden, 2013). listGIANT defined 10 acres of marginal lands by aggregated land use identified as fallow cropland, shrubland, grassland, hay/pasture and barren land. Other researchers have used listGIANT in similar studies (Adjoyi and Ellene, 2017; Khanal and Grebner, 2014). Based on available tax records and other information, listGIANT provided information on 1,544 landowners who satisfy the requirement for the survey within our study area. Of the 1,544 landowners, 522 had valid email addresses.

Prior to contacting respondents, we conducted a pilot study with local landowners in

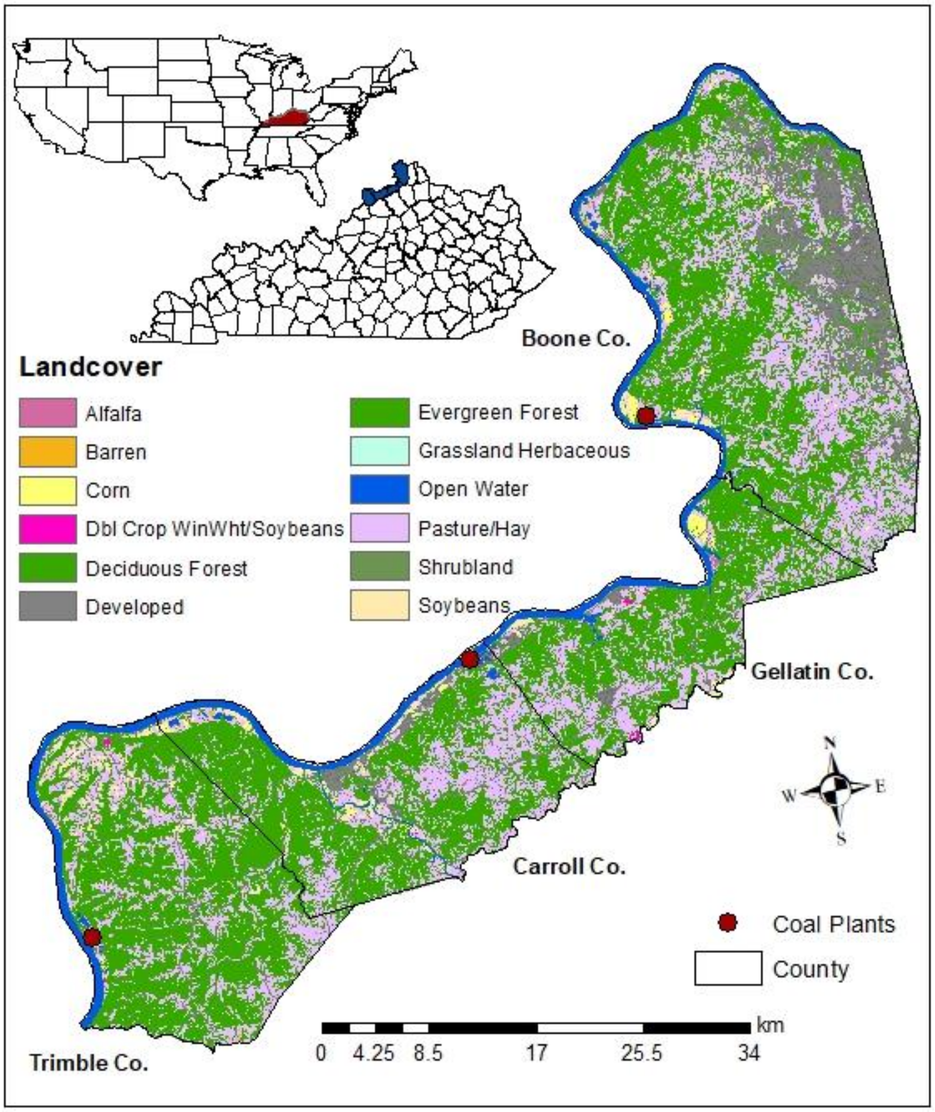

Figure 3.1: Four-county study area with different land cover types

collaboration with University of Tennessee Extension to check the effectiveness of the question wording, the flow of questions, and survey length. Based on the input from the pilot survey minor changes were made to the survey to improve clarity. After finalizing the questionnaire, surveys were sent to 1,544 landowners, 522 via email and the rest through traditional mail.

The survey was administered between August 2017 to December 2017. Three mailings were sent: 1) a first questionnaire mailing accompanied by a cover letter explaining the purpose of the survey and a business reply envelop 2) a reminder/thank you post-card was sent one week after the first questionnaire mailing to express appreciation for responding as well as a request that if not completed, to do so, and 3) a final questionnaire mailing along with an updated cover letter and a business reply envelope after four weeks to non-respondents from the first round.

3.2.3 Survey design

The survey had several sections. Before asking questions in each section, a brief overview and introduction of the section was provided. The first section queried respondents on their current land management practices. In the second section, a series of questions asked landowners about their knowledge and understanding of bioenergy crops. In the following section, the contingent valuation part of the survey, we assessed landowners' willingness to grow bioenergy crops on their land and their willingness to rent their land to others for bioenergy crop production. This section also asked landowners about their opinions and attitudes towards bioenergy. Finally, the last section of the questionnaire asked general socio-demographic questions such as age, income, and education. The questionnaire is provided in the Appendix.

The questions for the contingent valuation section were separated into two sub-sections. The first sub-section assessed landowners' willingness to supply biomass from their land by growing short rotation woody bioenergy crops such as sweetgum, sycamore, and cottonwood. Since landowners with marginal lands may have limited information on specific bioenergy crops, survey respondents were provided a hypothetical scenario for a bioenergy crop with attributes similar to the three bioenergy crops. Information about this hypothetical scenario included detailed descriptions of production costs, potential yield, fertilization and irrigation requirements, and soil erosion potential. to help the survey respondent make an informed decision. Respondents were then asked if they would be willing to grow that crop on their marginal land.

If they indicated yes, they were asked how much of their existing marginal land were they willing to grow this crop and at what price would they be willing to sell its biomass.

As mentioned earlier, rural landowners might not be currently engaged in farming activities and therefore, they may not have the capabilities and interest in growing energy crops on their land. However, they might be willing to accept a rental payment for their land as a secured income source without actually engaging in any of the costs or risks associated with bioenergy crop production. Therefore, in the second sub-section, landowners were queried about their willingness to rent their land for biomass production. Detailed information about renting their land was provided to help them make an informed decision. They were then asked if they were willing to rent their land for bioenergy production. If they responded yes, they were asked how much of their existing marginal land they were willing to rent and at what rate. Finally, landowners were also asked about concerns they may have about renting their land for bioenergy production.

3.2.4 Boosted regression tree analysis

Landowner willingness to supply bioenergy was modeled as a two-step decision process. The first decision was whether they would be willing to grow bioenergy crops on their marginal land (or rent out their land to grow bioenergy crops) and if yes, the second decision was how much of their land they would be willing to put into bioenergy production (or how much to rent out for production). Boosted regression tree (BRT) analysis was used to model the two decisions separately.

Boosted regression trees (BRT) incorporate techniques from both statistics and machine learning (Elith et al., 2008). It uses two algorithms: decision tree algorithms (classification and regression trees) and boosting methods for combining several simple models. Decision trees are non-parametric supervised learning methods aimed at creating a model that predicts the value of a target variable based on the values of several input variables (Geurts et al., 2009). In classification trees, the target variable is categorical, and the tree is used to identify the “class” within which the target variable would likely fall (e.g., Yes/No, 0/1 etc.). In regression trees, the target variable is continuous, and the tree is used to predict its value (Pour et al., 2016). The boosting method is used to increase model accuracy based on the idea that final predictions are made by combining predictions from several individual models. In other words, boosting is a sequential method where one model is fitted after the other with the later model trying to reduce residuals weighted by the previous model's error (Kanamori, 2002). This technique optimizes predictive performance to provide better predictions than traditional regression methods that give one single best model (Elith et al., 2008). In addition, BRT identifies relevant variables and interactions without the need to explicitly specify them. Further, since boosting uses trees as a base learner, it is a better fit for this study which has ordered variables (Schonlau, 2005). BRT deals well with ordinal data (e.g., Likert scale values to understand what factors were more important in landowners' decision to promote bioenergy crops and their opinion about bioenergy crops), while such variables are often difficult to deal with in regular parametric regression. Lastly, this study has many predictor variables with relatively few observations, thus regular regression methods are more difficult to use.

For the first decision, two BRT models were developed to analyze whether landowners were willing to participate in bioenergy crop production (equation 3.1). The first model (BRTM 1) analyzed whether landowners would participate by growing bioenergy crops on their land. The second model (BRTM2) analyzed whether landowners would be willing to rent out their lands to others. For the second decision, two additional models were developed to analyze the amount of land that landowners were willing to commit to bioenergy crop production (equation 3.2). BRTM3 was used to estimate the number of acres landowners were willing to commit to growing and producing bioenergy crops themselves and BRTM4 was used to estimate the number of acres they were willing to rent out to others. Since some landowners did not specify how much they were willing to commit for bioenergy production, though they were willing to enter into the biomass production system, some of the observations were omitted. Thus, only observations with potential acreage commitment greater than zero were used.

The dependent variable for the first decision indicated whether a landowner was willing to grow or rent out their land. If they were, the variable was set to 1, if not 0. The dependent variable in the second part was a continuous variable equal to the number of acres that the landowner was willing to grow or rent out.

The explanatory variables for the models included current land management practices, knowledge and understanding of bioenergy crops, perceptions of bioenergy, and various demographic metrics. In addition, concerns about renting out land for bioenergy production were included.

Willingness to grow/rent = f (current land management practices, knowledge and understanding of bioenergy crops, perception of bioenergy, demographics, rental concerns) (3.1)

Acreage commitment= f (current land management practices, knowledge and understanding of bioenergy crops, perception of bioenergy, demographics, rental concerns) (3.2)

All the models were fitted using the software R Project for Statistical Computing with the **gbm** boosting package version developed by Ridgeway 2006. Since there was not a large amount of data, the cross-validation (CV) method was used for model development and identification of optimal settings for the models.

3.3 Results

Of the 522 email requests, only 17 people responded (3.25% response rate); and of the 1,022 mailed surveys, 148 were returned (14.48%), 18 were returned as undeliverable. We assumed that no significant variation was present in either of the two modes of survey administrations (Gigliotti, 2011; Yetter and Capaccioli, 2010; McCabe et al., 2006), implying the absence of bias across responses. Thus, we combined the responses for data analysis. After eliminating incomplete surveys and those where the respondents did not meet the criteria for participation or were simply not interested, 103 observations were used for data analysis. It is important to highlight that the response rate for this study was lower than expected, which is usually 20-30% for landowners' survey (Hiesl, 2018; Joshi et al., 2013). However, similar response rates have been reported in some other studies (Gowan et al., 2018; Thompson and Hansem, 2012). A lower response rate can affect the reliability and validity of the survey findings, but we used boosted regression tree (BRT) in this study which is capable of handling low observations. In BRT, we split the data into training and test datasets, fit the model to the training dataset, make predictions based on it and evaluate the predictions on the test dataset. To avoid overfitting of the model, we used cross-validation approach that splits the data into various subsets of training and test data (Schonlau, 2005). The model is then repetitively trained and validated on these different subsets.

3.3.1 Descriptive statistics

A majority of respondents **(79.01%)** were male with an average age of **68.03** years. Most had a median annual income between **$60,000 to 89,000**. Approximately, **75.30 %** had at least some college education. Out of all respondents, **43.37**% indicated they were retired.

Respondents on average owned **82.74** acres of marginal land, with the majority of the land in one county. Only **11%** landowners were currently renting their land, with an average rental rate of **$40.83/acre**. Only **7%** indicated that they were currently growing commercial crops. The majority of marginal lands in the study area was currently used for hay or pasture (**59.10 acres on average**). However, a substantial number of landowners indicated other land cover types such as woody and agricultural crops, lake, residential area, yard were present.

Concerning existing knowledge, **65.43%** indicated they had heard about bioenergy, **50 %** indicated they had knowledge of crops for energy production, and about same proportion of landowners **(47.56%)** indicated that they were aware that bioenergy crops can be grown on marginal lands. Even though about **23.75%** landowners indicated that they were familiar with existing technologies relevant to growing bioenergy crops, only **4.93%** of them indicated that they were currently growing them.

With regards to willingness to grow bioenergy crops, **45.23%** were willing to produce and harvest bioenergy crops on their property if markets existed for biomass. These landowners were willing to devote an average of **25.49 acres** of land to bioenergy crops. Landowners indicated that a steady biomass market and low investment costs were the most important factors for their decision to produce and sell bioenergy crops (Figure 3.2).

On the other hand, lack of interest in bioenergy, time, and lack of knowledge of how to effectively harvest bioenergy crops were the major reasons expressed by landowners for their reluctance to produce and harvest them **(53.08%)** (Figure 3.3).

For landowners who were willing to produce and harvest biomass, we asked them to indicate what price they were willing to accept and the number of acres of land they were willing to commit. Figure 3.4 shows the percentage of landowners willing to accept five different prices and their average acreage commitment. For a biomass price of $40/ton, 28.57% indicated that they were willing to produce and the average amount of land available at this price was 19.71

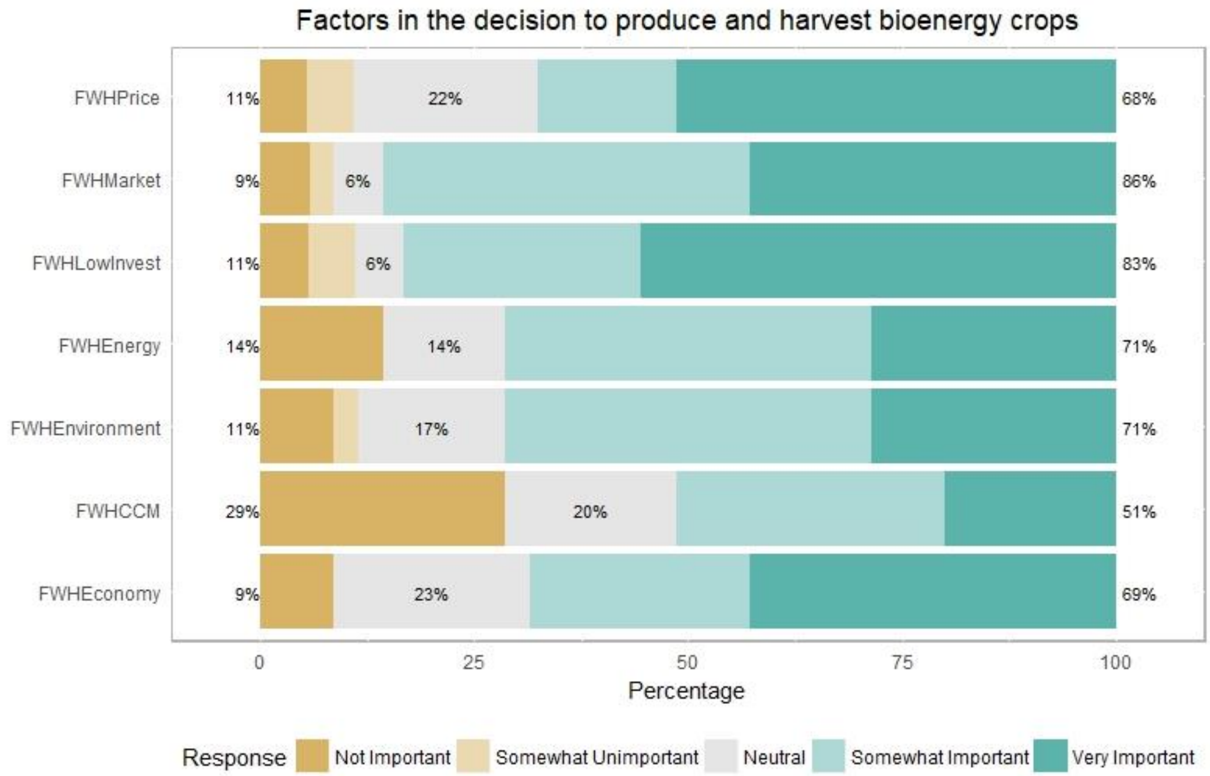

Figure 3.2: Factors influencing landowners' decision to produce and harvest bioenergy crops

(FWH: Factors for willing to produce/harvest)

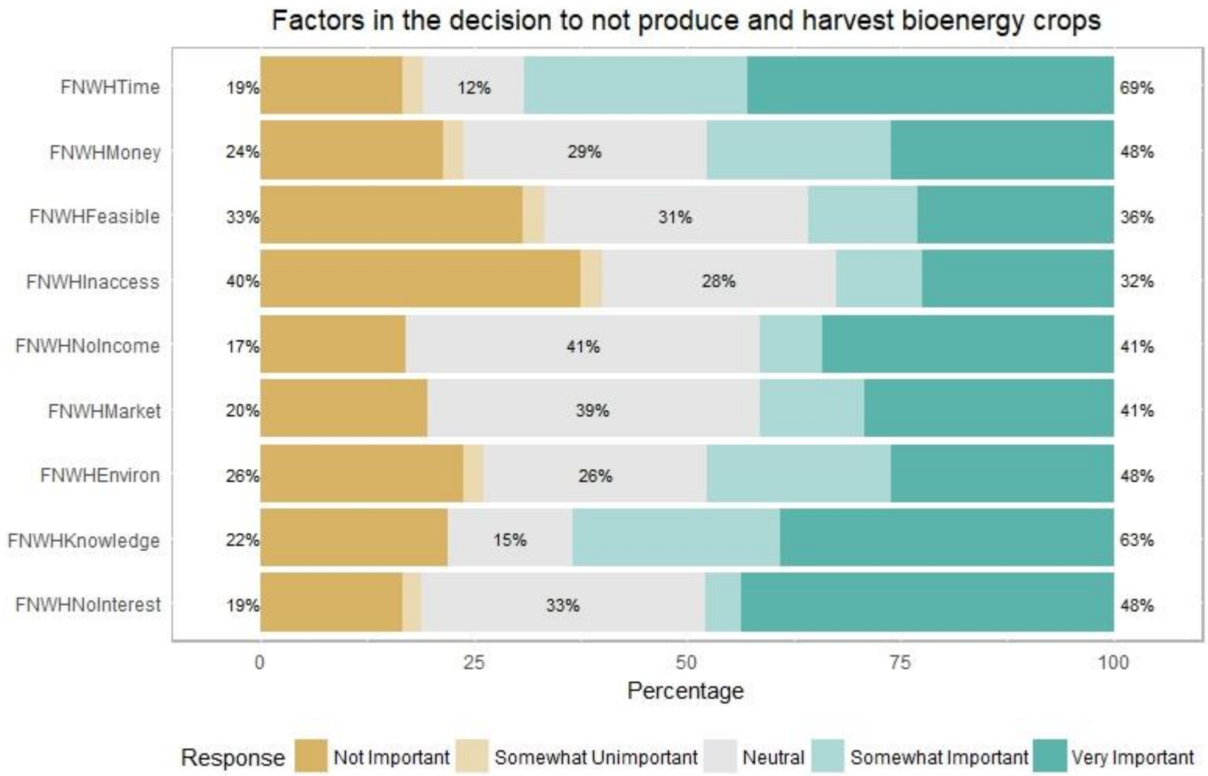

Figure 3.3: Factors influencing landowners' decision to not produce and harvest bioenergy crops

(FNWH: Factors for not willing to produce/harvest)

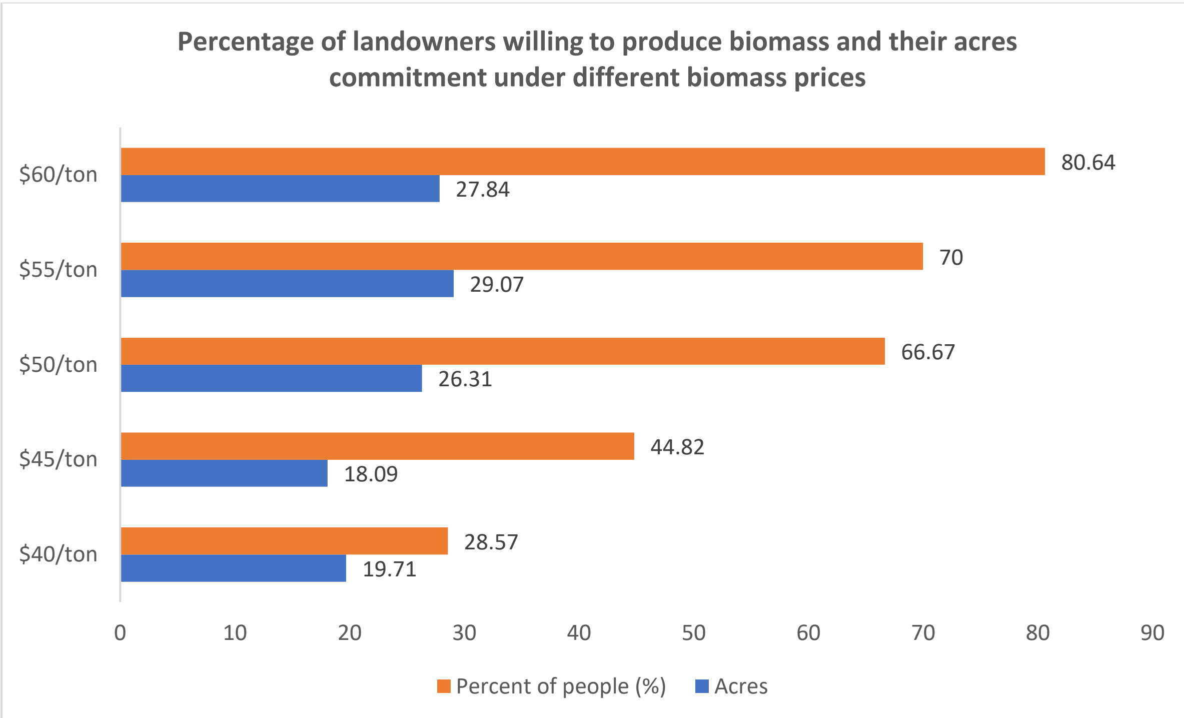

Figure 3.4: Percentage of landowners willing to produce biomass at different biomass prices and their acreage commitment

acres. When the price was $60/ton, 80.64% were willing to produce/harvest and the average land available increased to 27.84 acres.

Regarding landowners' willingness to rent, only **28.21 %** were willing to rent **(71.79%** preferred not to rent). Landowners indicated that the possible need for insurance, length of contract and legal cost of contracting were major impediments to renting (Figure 3.5).

Of the respondents who indicated no interest in renting, **91 %** said they would never rent their land for bioenergy production regardless of the rental rate. These respondents indicated that privacy, old age, and self-control were the major factors for their decision.

Landowners who were willing to rent their land for bioenergy production were asked to indicate the rental rate they were willing to accept. Figure 3.6 shows the percentage of landowners willing to rent and the acres they were willing to commit under four different rental rates. None of the respondents indicated that $25/acre was an acceptable rental rate. However, when the rental rate increased to $100/acre, 95.23% indicated they were willing to rent an average of 62.22 acres.

With regard to landowners' opinions on bioenergy (Figure 3.7), about 55% agreed that using domestic energy sources such as wood will reduce dependence on foreign energy sources. Similarly, more than 50% agreed that producing bioenergy crops can provide economic opportunities and improve the rural economy. Even though they expressed a concern that bioenergy markets are not sufficiently developed they said that the government should not be involved in bioenergy development.

3.3.2 Influence of measured variables on landowners' willingness to participate in bioenergy crop production

Optimal settings

Using the cross-validation method optimal settings were generated for all the decision models. The optimal number of trees for the four decision models are shown in Figure 3.8.

Willingness to participate in bioenergy crop production

Results of the boosted regression models (BRTM1 and BRTM2) are presented in Tables 3.1 and 3.2. Landowner age had the highest influence on both land use decisions. Younger landowners were more willing to participate in bioenergy crop production. In addition, landowners' positive

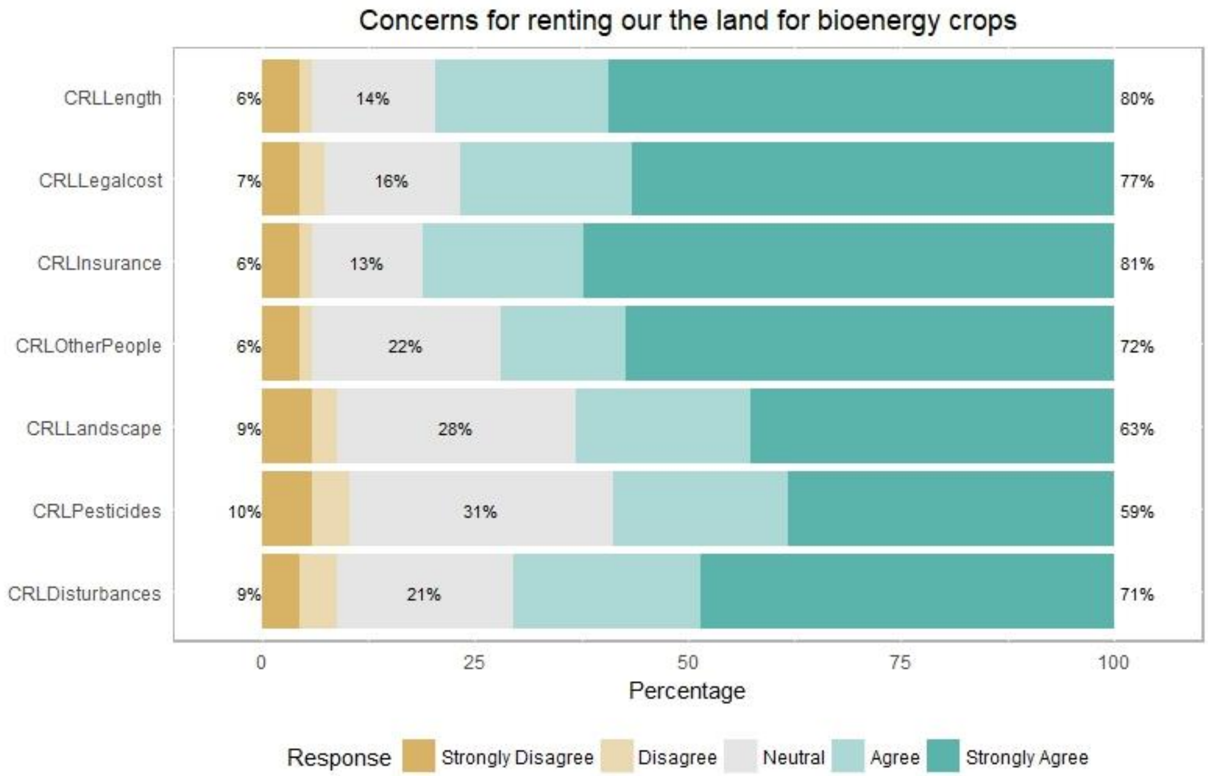

Figure 3.5: Landowners concerns for renting out their land for bioenergy crop production

(CRL: Concerns for renting land)

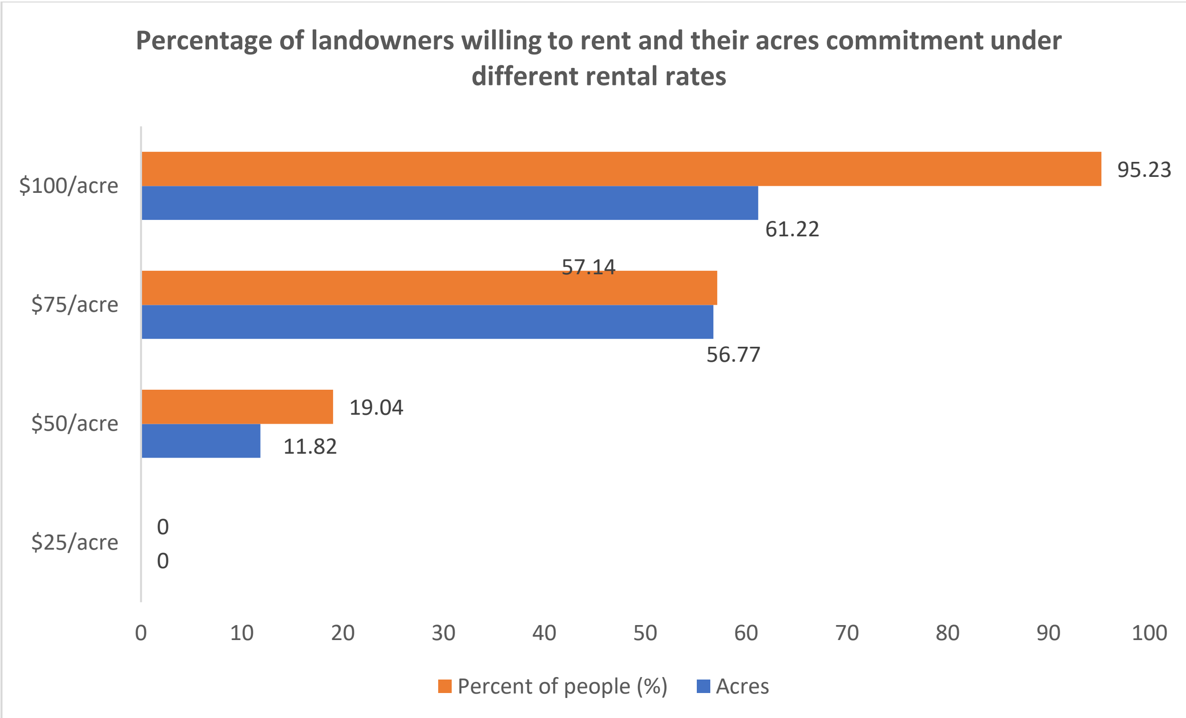

Figure 3.6: Percentage of landowners willing to rent their land and their acres commitment

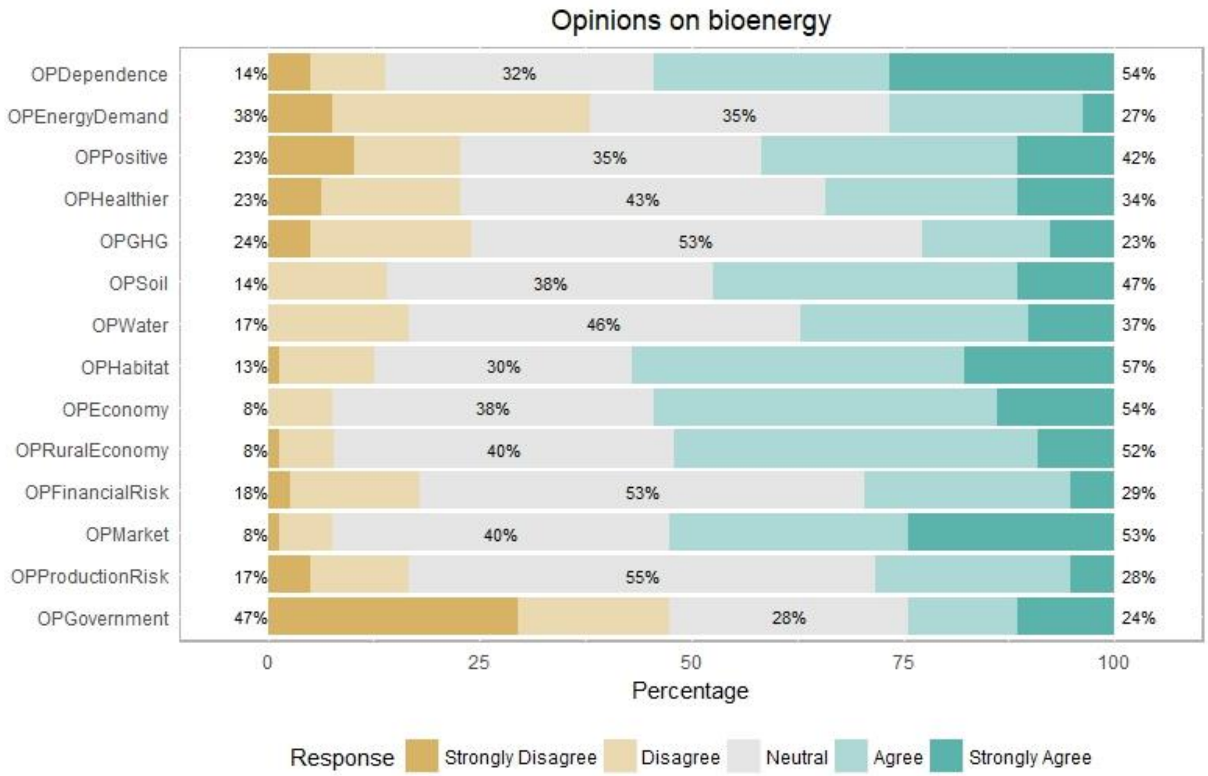

Figure 3.7: Landowners' opinions on bioenergy (OP: Opinion)

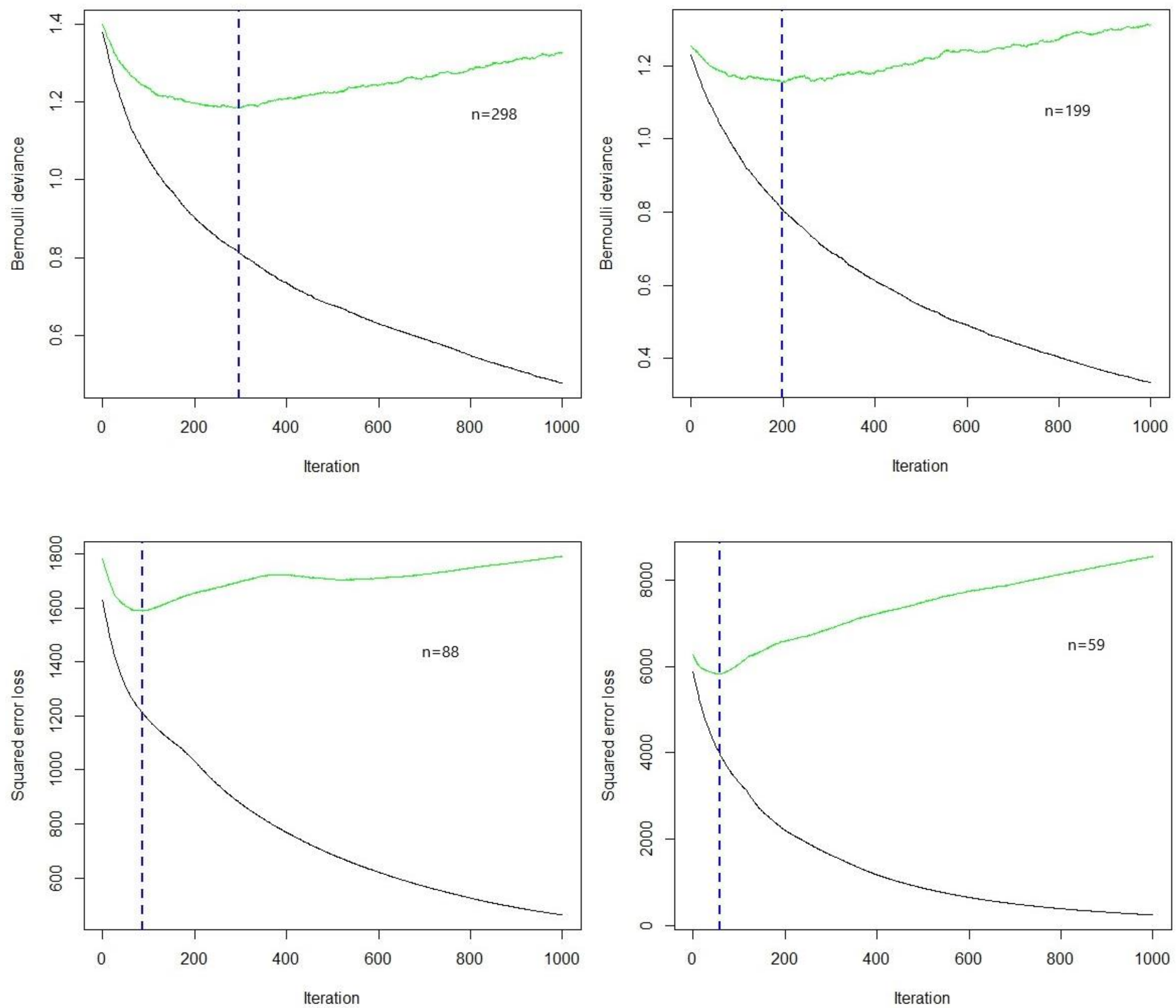

Figure 3.8: Example of cross-validation model fitting with initial number of trees=1000, interaction depth=5, shrinkage=0.01, and bag fraction=0.5 for willingness to produce (top left), willingness to rent (top right), acreage commitment to produce (bottom left) and acreage commitment to rent (bottom right).

Table 3.1: Variables and their relative influence on landowners' willingness to produce/harvest

Variables	**Relative Influence (%)**
Age	26.76
Positive opinion on creating energy from trees	18.11
Opinion that bioenergy crops can provide more habitat	9.16
Acres	5.55
Opinion that bioenergy crops improves rural economy	5.16
Opinion that electricity from wood contributes to a healthier planet	4.98
Opinion that biomass markets are not sufficiently developed	3.99
Opinion that bioenergy will meet energy demand	3.49
Opinion that bioenergy production creates more economic opportunities	2.50
Income	2.42
Household	2.38
Knowledge that crops can be growing for bioenergy production	2.35
Education	1.76
Opinion that government should be involved in bioenergy development	1.72
Heard of bioenergy	1.70
Opinion that energy from wood reduces dependence on foreign energy sources	1.69
Occupation	1.32
Opinion that bioenergy crops improves water quality	1.22
Opinion that diversifying production reduces financial risk on the farm	1.08
Opinion that bioenergy crops controls soil erosion	0.96
Gender	0.73
Opinion that production risk for bioenergy is lower than other crops	0.48
Opinion that bioenergy is effective to control GHG	0.27
Knowledge that bioenergy crops can be grown in marginal lands	0.21

Table 3.2: Variables and their relative influence on landowners' willingness to rent

Variables	**Relative Influence (%)**
Age	22.79
Positive opinion on creating energy from trees	13.95
Acres	11.65
Concerned with having other people on the land	5.89
Income	4.76
Concerned with the length of contract	4.25
Concerned with the need for insurance	4.10
Concerned with the changing landscape	3.78
Occupation	3.47
Opinion that electricity from wood contributes to a healthier planet	3.36
Opinion that bioenergy production creates more economic opportunities	2.81
Concerned with the potential legal cost of contract	2.67
Opinion that bioenergy crops controls soil erosion	2.38
Opinion that energy from wood reduces dependence on foreign energy sources	2.07
Concerned with the use of pesticides and fertilizers	2.03
Opinion that biomass markets are not sufficiently developed	1.88
Opinion that bioenergy will meet energy demand	1.40
Knowledge that bioenergy crops can be grown in marginal lands	1.32
Opinion that government should be involved in bioenergy development	1.31
Opinion that bioenergy crops can provide more habitat	0.99
Concerned with the disturbance from planting, harvesting, and other activities	0.85
Opinion that bioenergy crops improves water quality	0.80
Opinion that bioenergy crops improves rural economy	0.69
Knowledge that crops can be growing for bioenergy production	0.60
Education	0.20

perceptions about the idea of creating energy from trees on their property had a positive influence on their decision to promote bioenergy crop production. Further, the amount of existing land acreage also had a substantial influence on landowner willingness to rent their land: the more land they had, the more willing they were to rent their land for bioenergy production. Additionally, results showed that landowners' concern of having other people on their land had some influence on their willingness to rent out their land.

Partial dependence plots of the three most influential variables are presented in Figure 3.9. These plots show the effect of a variable on the response after accounting for the average effects of all other variables in the model. For example, in the willingness to produce model, landowners' production decisions changed with their age, with distinct observation after age 60 when an increasing age showed low willingness to produce.

In addition to the effect of a single variable on the response, the partial dependence plots show important interactions between variables. For both the willingness to produce/harvest and willingness to rent models, three of the six most important pairwise interactions included the most influential predictors, age and a positive perception about the idea of creating energy from trees (Figures 3.10 and 3.11). Allowing interactions reinforced the effect that younger landowners with a positive perception about generating bioenergy were more willing to participate in bioenergy crop production.

Acreage commitment

Results of the boosted regression models developed to analyze landowner acreage commitment for producing/harvesting bioenergy crops (BRTM3) and renting their lands (BRTM4) are presented in Tables 3.3 and 3.4. Results from both models show that total acres of current land ownership had the biggest influence on the amount of land landowners were willing to commit for bioenergy production. Age was also influential in landowner rental decisions. Many variables were omitted from the acreage commitment models because they had no detectable influence on the response variable.

Partial dependence plots of the most influential variable (total acres) along with the interaction effects are presented in Figure 3.12.

Again, in addition to the effect of a single variable on the response, the partial dependence plots

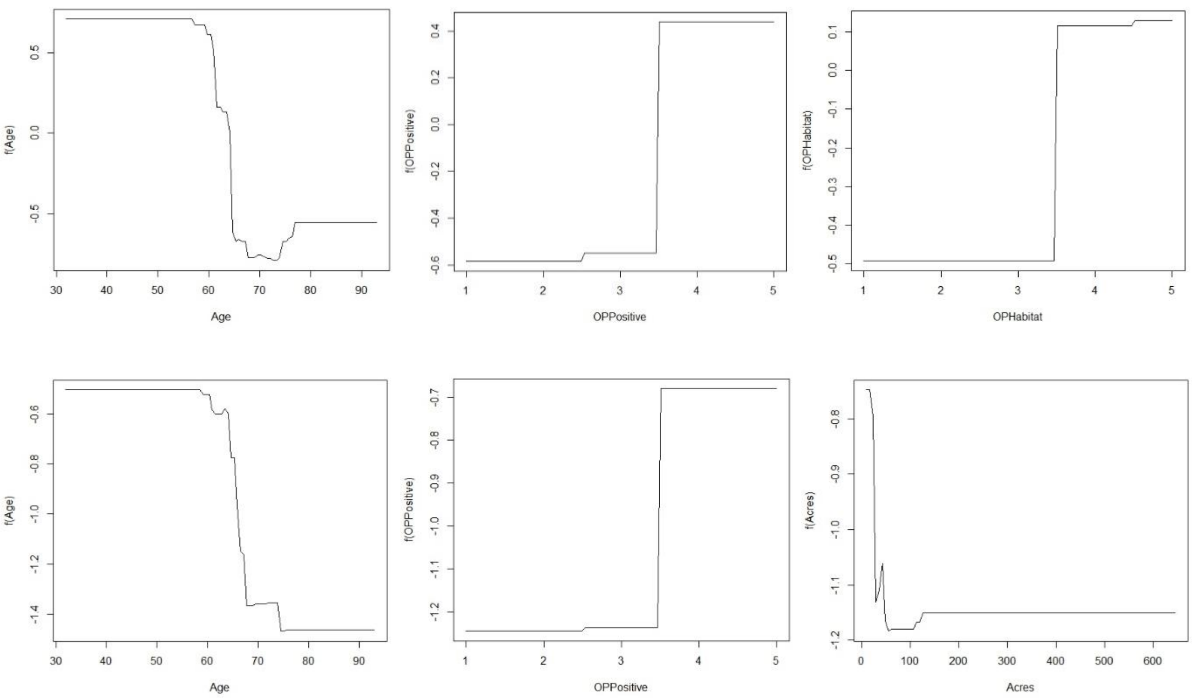

Figure 3.9: Partial dependence plots for the three most influential variables for the two models; willingness to produce (top) & willingness to rent (bottom)

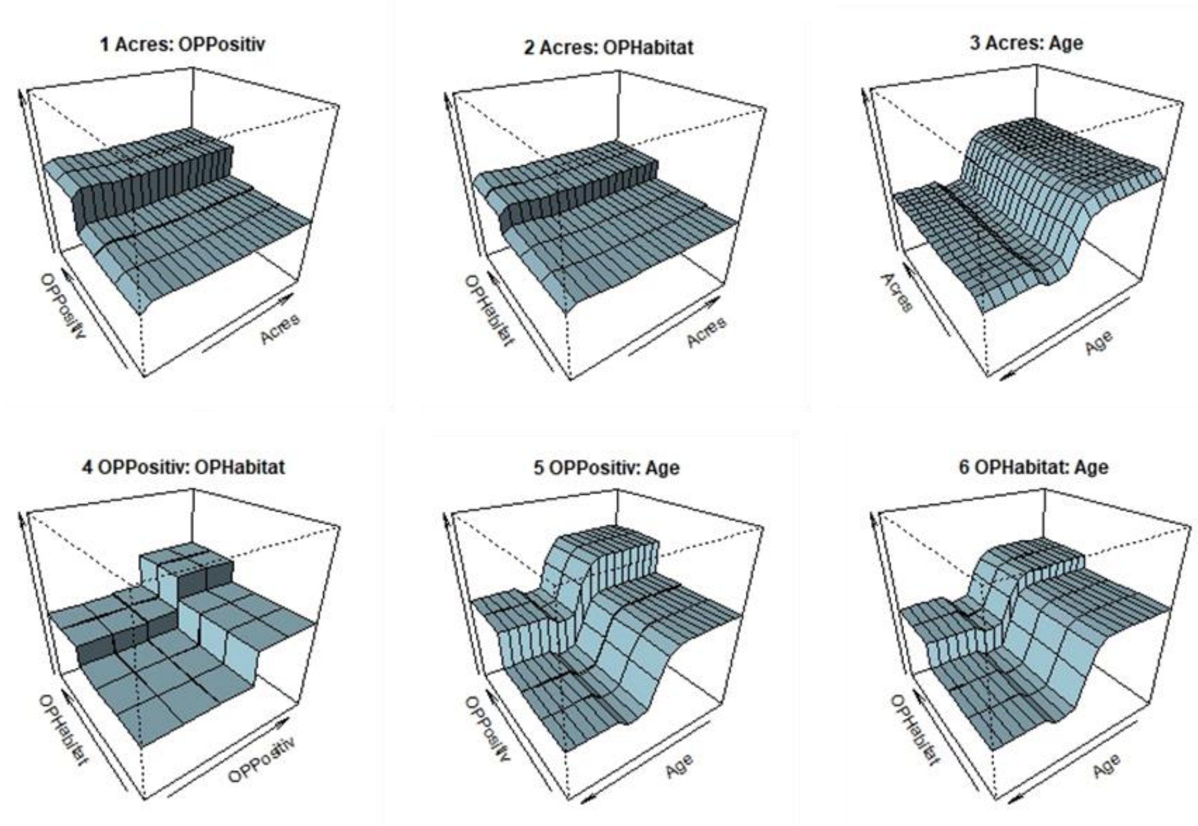

Figure 3.10: Interactions of the variables for the willingness to produce/harvest model

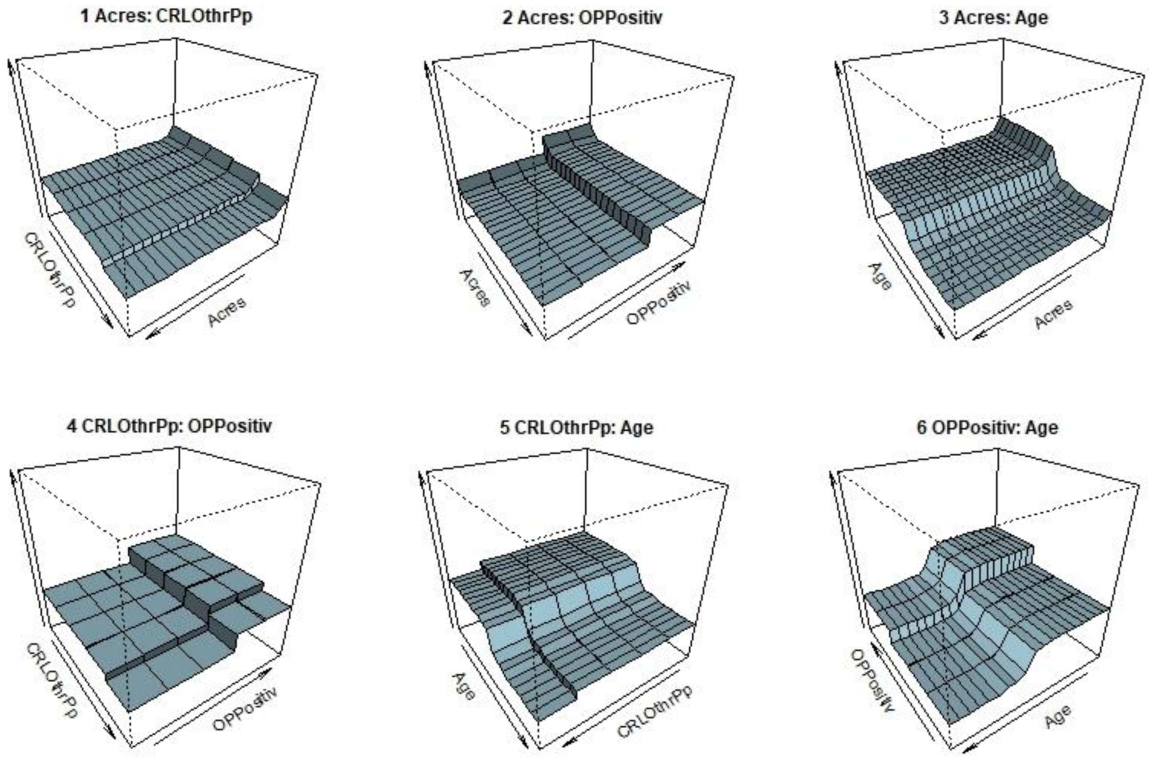

Figure 3.11: Interaction of variables for the willingness to rent model

Table 3.3: Variables and their relative influence on landowners' acreage commitment to produce

Variables	Relative Influence (%)
Acres	95.39
Opinion that electricity from wood contributes to a healthier planet	2.97
Age	1.63
Opinion that government should be involved in bioenergy development	0.01

Table 3.4: Variables and their relative influence on landowners' acreage commitment to rent

Variables	Relative Influence (%)
Acres	85.38
Age	14.34
Opinion that bioenergy will meet energy demand	0.17
Household	0.07
Concerned with the use of pesticides and fertilizers	0.04

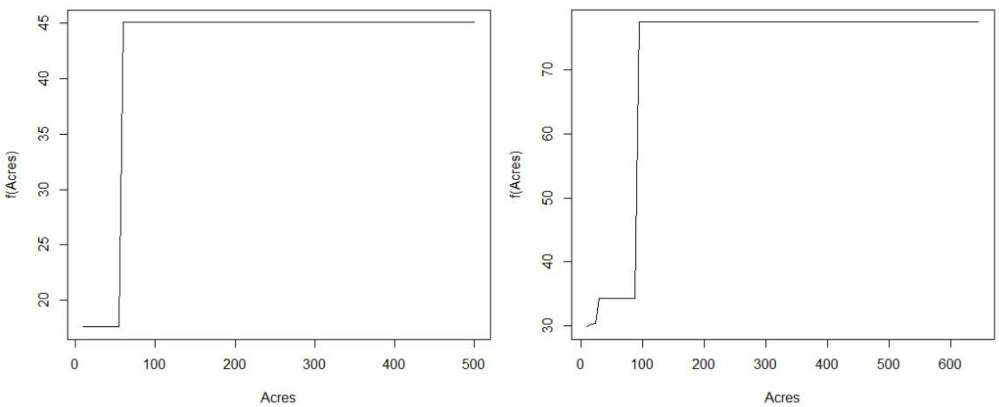

Figure 3.12: Partial dependence plots for acres for the two models; acres to produce (left) & acres to rent (right)

show important interactions between the variables. For both acreage commitment models, the variable acres was prominently visible in the pairwise interactions reinforcing the acreage decisions that landowners with large acres are more willing to commit to bioenergy production (Figures 3.13 and 3.14).

3.4 Discussions

3.4.1 Overall willingness

Survey responses aimed at understanding landowner willingness to promote bioenergy crop production in a four-county study area in northern Kentucky revealed a low willingness of landowners to participate in bioenergy production systems. The results prompt several observations. First, rural landowners who were willing to produce/harvest bioenergy crops indicated that a high biomass price was required to prompt them to produce bioenergy crops on their land. At a typical biomass price ($40/dry ton), the proportion of landowners' willing to produce bioenergy crops fell substantially relative to higher prices. Similar results were obtained for landowners' willingness to rent. Many landowners were simply not interested in renting their land regardless of the price offered. Thus, money was not the driving factor for these landowners. Loss of privacy, old age, loss of self-control, and potential disturbance from producing and harvesting energy crops were major factors in their decisions. In addition, previous studies have shown that non-market objectives such as wildlife habitat, aesthetics, and recreation could impact landowners' decision to never rent their land (Barham et al., 2016; Swinton et al., 2016; G.C. and Mehmood, 2012). Further, Kentucky is well known for horses. Thirteen counties in northern Kentucky (including the four counties considered in this study) make up the Bluegrass region that has pasture lands favorable horse farming (Stephanie, 2016). The equine industry has an important contribution for the culture and economic structure of the state. The direct economic benefits from the industry and other benefits such as recreational, environmental and aesthetic have thrived the industry since time immemorial. In this context, landowners with existing horse farms (which could be a potential site for growing bioenergy crops) may not be interested in converting their land to bioenergy crop production. Therefore, the overall availability of rural land for energy crops is likely lower than anticipated, even at relatively high biomass prices or rental rates. This could possibly make the feedstock supply scarce.

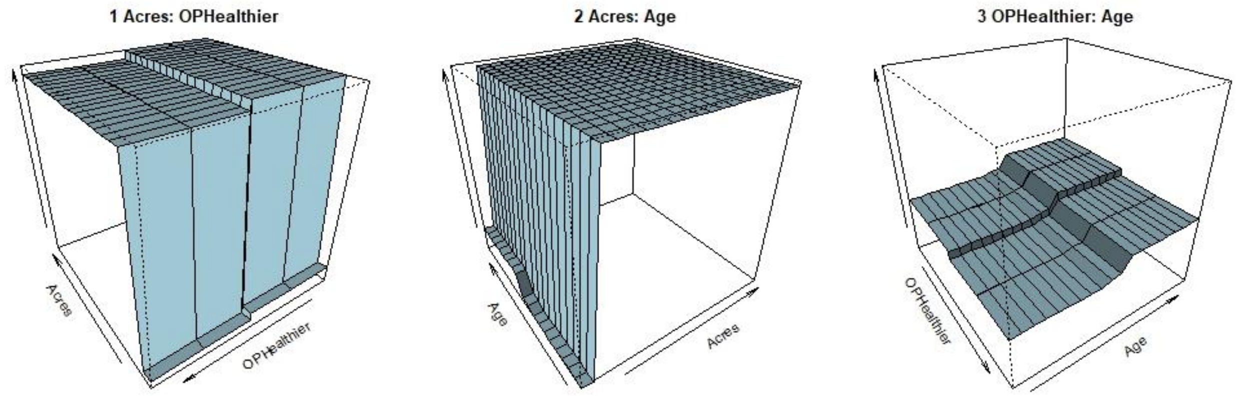

Figure 3.13: Interaction of variables for acres commitment model to produce

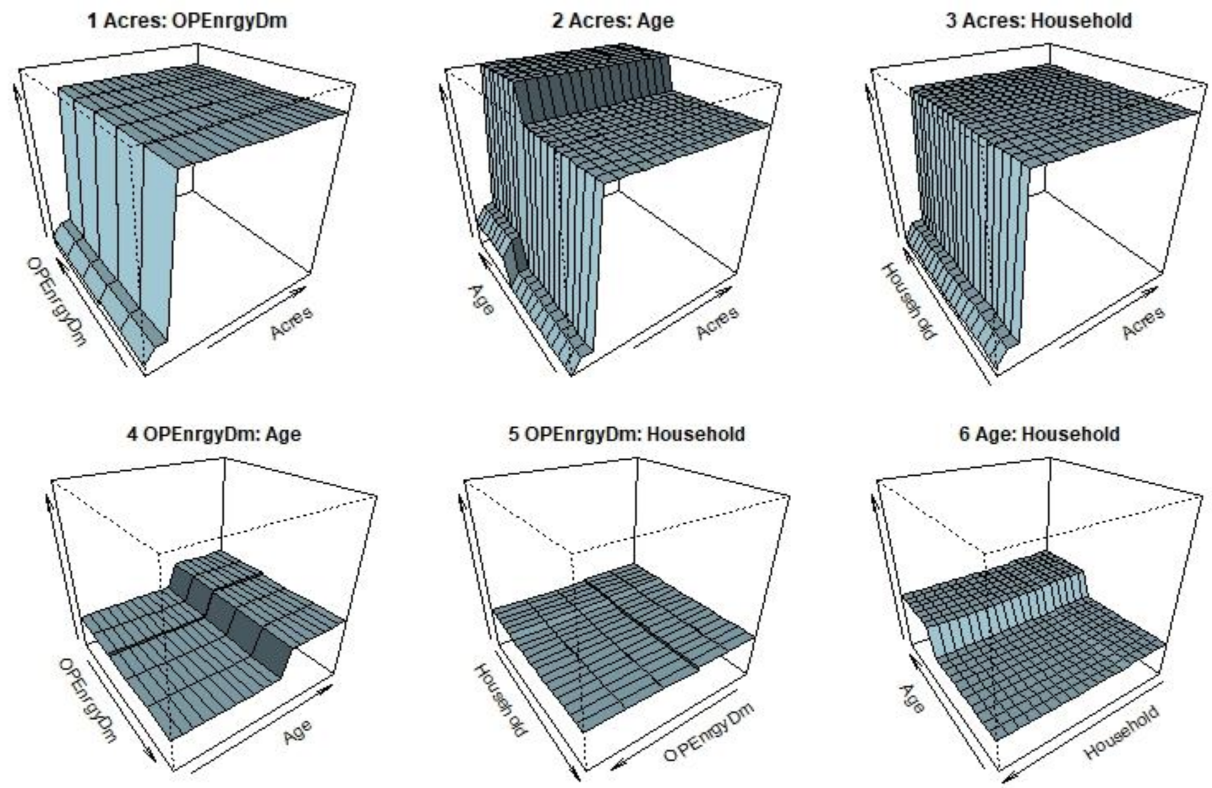

Figure 3.14: Interaction of variables for acres commitment model to rent

Recent studies on bioenergy production suggest the use of marginal lands for promoting bioenergy crop production. To explore this issue, the focus of this study was restricted to marginal lands as well. Since landowners who own marginal lands also own farmland, their willingness to participate in bioenergy crop production could have been different if they were asked to indicate their preference for different land use types. A recent study by Skevas et al. (2016) indicated that when landowners were asked to indicate what land they would be willing to rent for bioenergy crops, they were willing to provide more cropland than marginal land for bioenergy production. Thus, it is possible that the potential of marginal lands is less than what has been projected. Since landowners are reluctant to promote bioenergy crops on marginal lands, larger areas of marginal land may be needed to supply bioenergy feedstocks. Marginal lands are usually much smaller and spatially dispersed than traditional farmlands and forestlands (which are clustered) and supplying biomass feedstocks from these spatially dispersed/fragmented areas would likely trigger higher costs of bioenergy production, especially the transportation costs to processing facilities. In addition to increasing transportation costs, longer hauls of transporting feedstocks may trigger more GHG emissions.

This study also focused on woody crops as potential bioenergy crops in the study area. Previous studies have included other bioenergy feedstock sources such as perennial grasses to understand people's willingness to promote bioenergy production (Skevas et al., 2016; Caldas et al., 2014; Timmons, 2014; Qualls et al., 2012). The main advantages of perennial crops are that they re-grow every year and do not need to be replanted annually. They also require fewer fertilizer and water inputs. In addition, they require lower production and management costs, thus, they could be attractive options for landowners to promote bioenergy crop production.

3.4.2 Methods discussion

An advantage of boosted regression tree (BRT) is that it combines the strength of regression trees and boosting methods to improve the predictive performance of a regression procedure. BRT boosts the predictive performance by fitting a series of models and then combine them into an ensemble to achieve better performance (Shin, 2015). BRT is flexible, it can handle several types of predictor variables, fit to non-linear relationships, and identify and handle interactions automatically. In our analysis, we had little control compared to a traditionally approach where we would be required to know and specifically indicate where interactions should be sorted for.

All the variables had a chance to predict the outcome and there was no need of data transformation or elimination of any outliers (Elith et al., 2008).

Boosted regression tree (BRT) builds an ensemble of trees and it is difficult to interpret when compared to individual decision trees. However, this often does not matter where improving the predictive accuracy is the most important goal (ibid). Another drawback of this method is that the output of the model does not generate confidence intervals or p-values to indicate relative significance of model coefficients as compared to traditional regression analysis (ibid). This makes interpretation of results and understanding of the model even more challenging (Lampa, et al., 2014). Partial dependence plots can be one way to visualize the level of dependence (ibid), and we were able to generate two-way interactions for important variables in our study.

3.5 Limitations

While this study contributes to a greater understanding of landowners' intent to enter into the bioenergy production system, there are a few limitations that should be noted. First, the response rate for survey was low. The study area could have been extended to include other adjacent counties in northern Kentucky, but due to budget and time constraints this was not possible. Second, only existing marginal lands were considered as potential sites for growing energy crops. As discussed previously, this might have had an impact on landowners' intent and commitment. It may be useful for future studies to focus on different land use types and/or include perennial grasses.

3.6 Conclusions

In conclusion, this study provides several insights into landowners' perceptions of bioenergy and their willingness to enter into the bioenergy crop production system. Overall, the results show that landowners are relatively more willing to grow bioenergy crops on their land than to rent their land to others for the same purpose. However, landowners are concerned about the uncertainty of the biomass market and the investment costs incurred in the production process. This information could be helpful in designing market protocols and incentive mechanisms to promote bioenergy production. In addition, results show that younger landowners, those with positive attitude towards bioenergy production, and those with large acres of land are more willing to promote bioenergy crop production. With this information, outreach programs focused on enhancing landowner awareness about the beneficial economic and environmental impacts could help promote their participation in bioenergy production in the long run.

3.7 Funding

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Appendix

Landowners' willingness questionnaire survey

Who Should Complete the Survey?

1. Do you own more than 10 acres of rural land, land that is grassland, shrubland, fallow cropland (unused cropland), hay/pasture or barren land?

   ☐ No (If you answered NO, please stop filling out the survey and return in the enclosed envelop. Thank You!)

   ☐ Yes

2. Are you the primary decision maker for management for your land?

   ☐ No (If you answered NO, please give this questionnaire to the person who makes land management decision for your land!)

   ☐ Yes

Section A: Current Land Management Practices

3. How many acres of rural land do you own? ____________ acres

4. Do you own rural land in more than one location?

   ☐ Yes ☐ No

5. In what county is most of your rural land located? _______________

6. Do you currently rent out any of your rural land to others?

   ☐ Yes ☐ No (Skip to Question 9)

7. If you answered yes to Q6, how many acres of your rural land did you rent out in 2016?

   __________ acres

8. What was the most common rental rate for your land? $______/ acre

9. Not including the land that you have rented out to others, did you grow any commercial crops on your rural land in 2016?

   ☐ Yes ☐ No

10. How would you describe what is on the rural land you own?

Description	**Acres**
Fallow cropland (unused cropland)	
Shrubland (land with shrubs, and small trees)	
Grassland	
Hay/pasture	
Barren	
Other (please specify)	

11. How do you and your family members use rural lands you own? Please check all that apply.

Recreational Activities	☐
Physical activities (walking, running, or sports)	☐
Livestock grazing	☐
Wildlife habitat	☐
Hunting	☐
Commercial crops	☐
Conservation Program	☐
Others (please specify)	☐

Section B: Bioenergy and Bioenergy Crops

Bioenergy is the energy that comes from a biological source, such as crops, grasses, or trees that can be burned to generate heat, electricity, and biofuels like ethanol. Fast growing tree species such as sycamore, sweetgum, and cottonwood can often be planted in 'bioenergy plantations' solely for being harvested for energy production. In this section, we would like to know your thoughts and perspectives on bioenergy plantation.

12. Have you heard of bioenergy?

☐ Yes ☐ No

13. Did you know that many crops can be grown for bioenergy production?

☐ Yes ☐ No

14. Did you know that many bioenergy crops can be grown on less fertile soil such as rural land (grassland, shrubland, fallow crop land, hay/pasture and barren land?

☐ Yes ☐ No

15. Are you currently growing bioenergy crops **on** your land?

☐ Yes ☐ No

16. Are you familiar that existing farming technologies work with bioenergy crops?

☐ Yes ☐ No

17. If a market existed for woody biomass, would you be willing to produce and sell biomass from your rural land?

☐ Yes ☐ No (Skip to Question 20)

18. If you answered **yes**, how much of your existing rural land will you be willing to harvest?

_______________ acres

19. How important would the following factors be in your decision to produce and harvest energy crops for bioenergy production? Choose one option in each row (and their level of importance) and Skip to Question 21.

	Not Important	Somewhat Unimportant	Neutral	Somewhat Important	Very Important
Price of timber	☐	☐	☐	☐	☐
Steady market condition	☐	☐	☐	☐	☐
Low investment cost	☐	☐	☐	☐	☐
Energy security benefits	☐	☐	☐	☐	☐
Environmental benefits	☐	☐	☐	☐	☐
Contribution to climate change mitigation	☐	☐	☐	☐	☐
Contribution to the local economy	☐	☐	☐	☐	☐
Others (please specify)	☐	☐	☐	☐	☐

20. If you answered **no** in Question 17, please indicate the importance of the following factors in your decision for not producing and harvesting energy crops for bioenergy production.

	Not at All Important	Somewhat Unimportant	Neutral	Somewhat Important	Very Important
Do not have time	☐	☐	☐	☐	☐
Do not have money and resources	☐	☐	☐	☐	☐
Harvesting is not feasible because of small area	☐	☐	☐	☐	☐
The land is not accessible for timber harvest	☐	☐	☐	☐	☐
Producing bioenergy crops would not generate adequate income	☐	☐	☐	☐	☐
Unsure about market conditions	☐	☐	☐	☐	☐
Concerned about the environmental impacts of producing and harvesting timber for energy	☐	☐	☐	☐	☐
Lack of knowledge to effectively harvest energy crops for bioenergy conversion	☐	☐	☐	☐	☐
Not interested	☐	☐	☐	☐	☐
Others (please specify)	☐	☐	☐	☐	☐

Section C: Specific Bioenergy Cropping Systems

Below is a hypothetical scenario, describing the process of growing a woody bioenergy crop such as sycamore, sweetgum, and cottonwood.

Planted: Spring
Harvested: 8 to 12 years
Fertilized: Every few years
Average number of farm visits: 1 per year
Maximum height: 20 to 30 feet
Production: Bioenergy
Average annual production: 2 to 4 dry tons/acre/year
Establishment and management costs: Average cost of $ 445 - 530/acre
Soil erosion: Low compared to other bioenergy crops
Carbon sequestration: Potential increase in carbon sequestration
Water contaminations: Less compared to other bioenergy crops

21. For each biomass price listed in the table below, please indicate whether you would sell the wood. For your reference, the current average biomass delivered price is $40/ dry ton. Also, please indicate how much of your rural land you would be willing to harvest at the specified biomass price.

Price levels for biomass	will not sell	will sell	Acres
$30/ dry ton	☐	☐	
$35/ dry ton	☐	☐	
$40/ dry ton	☐	☐	
$45/ dry ton	☐	☐	
$50/ dry ton	☐	☐	
$55/ dry ton	☐	☐	
$60/ dry ton	☐	☐	

Section D: Willingness to Rent Your Land for Bioenergy Production

Suppose that you have been approached to rent out your rural land to grow bioenergy crops (such as sweetgum, sycamore, and cottonwood) for 10 years.

22. Will you be willing to rent your rural land for a bioenergy plantation in the future?

    ☐ Yes ☐ No

23. If you said yes, how much of your existing rural land will you be willing to rent out?

    _______________ acres

24. In the following table, each row represents a rental rate for leasing your land for bioenergy plantation. For each of these price levels, please indicate your preferences of whether you will be willing to rent by checking a box. For your information, the current average rental rate is this region is approximately $40 to $50 per acre for pasture and hay. Also, please indicate how much of your rural land would you be willing to rent at the specified rental rate.

Price levels for rental	will not rent	will rent	Acres
$25/acre	☐	☐	
$50/acre	☐	☐	
$75/acre	☐	☐	
$100/acre	☐	☐	

25. If you would not rent your land for bioenergy for any price, please check here ☐

Explain WHY? ____

26. Please indicate your level of agreement or disagreement with the following statements regarding your concerns for renting out your land.

When I think about renting out my land for bioenergy crops, I am concerned with:	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The length of the contract	☐	☐	☐	☐	☐
Potential legal costs of contracting	☐	☐	☐	☐	☐
The possible need for insurance	☐	☐	☐	☐	☐
Having other people on my land	☐	☐	☐	☐	☐
The changing landscape	☐	☐	☐	☐	☐
The use of pesticides and fertilizers on my land	☐	☐	☐	☐	☐
Potential disturbance from planting, harvesting, and other activities	☐	☐	☐	☐	☐
Others (please specify)	☐	☐	☐	☐	☐

Section E: Opinions on Bioenergy

27. Please check the box that best represents your agreement with the following statements related to bioenergy.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Using domestic energy sources such as wood will reduce our dependence on foreign energy sources	☐	☐	☐	☐	☐
Generating energy from wood will meet our country’s energy demand	☐	☐	☐	☐	☐
I feel positive about the idea of creating energy from trees growing in my property	☐	☐	☐	☐	☐
Electricity and fuel made from wood, rather than fossil fuels, will contribute to a healthier planet	☐	☐	☐	☐	☐
Producing energy from biomass is an effective way to control atmospheric greenhouse gas emissions	☐	☐	☐	☐	☐
Bioenergy crops can help control soil erosion on my land	☐	☐	☐	☐	☐
Growing bioenergy crops can improve water quality on my land	☐	☐	☐	☐	☐
Bioenergy crops can help provide more habitat for wildlife species on my land	☐	☐	☐	☐	☐
Production of bioenergy can create economic opportunities for landowners like me in Kentucky	☐	☐	☐	☐	☐
Growing crops for energy is a promising local option to improve rural economy	☐	☐	☐	☐	☐
Diversifying my production will reduce financial risk on my farm	☐	☐	☐	☐	☐
I am concerned that biomass markets are not sufficiently developed	☐	☐	☐	☐	☐

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Production risk for bioenergy is lower than other crops	☐	☐	☐	☐	☐
Government should be involved in bioenergy development	☐	☐	☐	☐	☐

28. Please indicate your preferences for each of the following bioenergy policy options to your decision to promote bioenergy crop production by giving a score from 1 to 9. For your reference, a score of 3 indicates that a policy option is three times more preferred than a policy option with a score 1. Start by choosing the least preferred policy option among those on the list and give it a score of 1. Then score the remaining policies by comparing them one-by-one to the least preferred policy chosen earlier (use any number in between 1 to 9 for your scoring). Write the number in each box.

Policy Options	**Scoring**
I would prefer direct payments for producing bioenergy crops	
I would need capital support for initial stages of bioenergy crop production	
I would prefer cost share program (such as equipment and transportation) for promoting bioenergy crops in my property	
Federal and state governments should provide more tax incentives to promote investments in, and production of bioenergy crops	
I would need technical assistance to grow and harvest bioenergy crops	
I would prefer crop insurance for bioenergy crops	
I would consider signing long-term contracts (lease) to grow bioenergy crops	
The government should allow payments for ecosystem services such as carbon sequestration to promote bioenergy feedstock production	
The government should allow conservation programs such as Conservation Reserve Program (CRP) lands for bioenergy purposes	

Section F: Background Information

In this section, we would like to learn more about you. We stress that all your answers will remain strictly confidential and will only be used for group comparisons.

29. What is your age?

    ____________ Years

30. What is your gender?

    ☐ Male ☐ Female ☐ Do not want to disclose

31. Including yourself, how many members are in your household?

    ____

32. What is your current occupation? (Please check one)

    ☐ Owner of a business ☐ Government employee

    ☐ Professional/Management ☐ Retired

    ☐ Clerical or office worker ☐ Unemployed

    ☐ Farmer ☐ Seeking employment

    ☐ Forestry/Logging/Mining ☐ Homemaker

    ☐ Other ____________________

33. If you checked farmer in Q32 above, what percentage of your total 2016 income was from farming? (Please check one)

    ☐ None

    ☐ Less than 25 percent

    ☐ 25 – 49 percent

    ☐ 50 – 75 percent

    ☐ More than 75 percent

34. What is the highest level of education you have completed?

☐ Some school

☐ High school diploma

☐ Some college

☐ Bachelor’s degree or equivalent

☐ Advanced college degree

35. What was your approximate family income before taxes for 2016? Include net income from all sources (salary, wages, social security, rental properties, farming, and investment income). (Please check one).

☐ $30,000 or less	☐ $120,000 to $149,999
☐ $30,000 to $59,999	☐ $150,000 to $179,999
☐ $60,000 to $89,999	☐ $180,000 to $199,999
☐ $90,000 to $119,999	☐ $200,000 or more

Thank you for taking time to fill out our survey. Please feel free to write any comments you have in the space below.

CHAPTER 4

USING THE ANALYTIC HIERARCHY PROCESS (AHP) TO EVALUATE POTENTIAL BIOENERGY POLICIES FOR PROMOTING SUSTAINABLE BIOENERGY CROP PRODUCTION: A CASE STUDY FROM KENTUCKY

This chapter is in preparation for journal submission. The use of “we” in this chapter refers to co-author, Dr. Liem T. Tran, and me. I am the first author, and my contribution to this project include model development, data collection and analyses, and writing the manuscript.

Abstract

Bioenergy crops can provide a reliable and adequate supply of bioenergy feedstock to support the bioenergy industry. However, commercial scale production of bioenergy crops has not been established to support the increasing energy demand for the bioenergy industry. Even though a large amount of lands might be suitable for growing bioenergy crops, the actual lands available for bioenergy crops could be significantly less that what is suitable for establishing bioenergy crop production. Lack of a well-developed market for biomass, uncertainties about the availability of feedstock sources, technologies to convert biomass to bioenergy, and political and regulatory environment may hinder bioenergy crop production. Policy support can be crucial to address some of these uncertainties and promote bioenergy crop production in ways that are economically efficient as well as compatible with social, political and environmental factors. In this study, we evaluated bioenergy policies with respect to their effectiveness to support the promotion of sustainable bioenergy production. We developed an analytic hierarchy process (AHP) model that incorporated all the dimensions of sustainable bioenergy production including socio-economic, environmental and policy factors. The model was applied for a case study in Kentucky where various initiatives are underway to support bioenergy production. Results from the study showed conservation programs and technology support could be the most effective policy options to promote bioenergy crop production in the state. This information can help state governments to formulate policies that take environmental aspects into consideration and promote research and development to support technological advancement to promote a sustainable bioenergy production.

Key words: bioenergy, uncertainties, policy, AHP, Kentucky

4.1 Introduction

Bioenergy crops have the potential to supply sustainable feedstocks for the bioenergy industry and improve energy security, generate employment, promote local economic development, and address environmental issues such as climate change. Previous studies have mainly focused on the availability of land for growing bioenergy crops based on physical and socio-economic variables. Some studies have focused on identifying suitable and economically feasible locations to grow bioenergy crops while others have analyzed whether the feasible locations are socially available to promote bioenergy production (Aragon et al., 2017; KC et al., 2017; Swinton et al., 2016; Cladas et al., 2014; Nepal et al., 2014; G.C. and Mehmood, 2012; Hinchee et al. 2009). Since bioenergy feedstocks are likely to come from privately owned lands, landowners' reluctance to grow bioenergy crops has promoted observations that the actual land available for bioenergy crops could be significantly less that what is physically suitable (Skevas et al., 2016; Leitch et al., 2013). Thus, there is a clear gap between where we want to be in terms allocating lands to bioenergy crops and where we currently are in terms of how much land landowners are willing to put into production. Bioenergy policies that are well informed, effective, logical, and oriented towards providing socio-economic and environmental gains can bridge this gap and help make more physically suitable lands available for bioenergy crop production.

The federal government has enacted numerous laws and regulations, provided incentives, and made funding opportunities available to promote bioenergy production. Federal policies have also been essential for boosting state initiatives to develop the bioenergy industry. While there has been substantial federal involvement in promoting bioenergy, a national one size fits all approach may not work because federal policies cannot reflect state or region-specific conditions and circumstances (Patton-Mallory and Aguilar, 2010). Currently, there are various uncertainties in developing a sound strategy to promote the bioenergy industry. For instance, the availability of biomass feedstock sources is uncertain and the technologies for converting the feedstocks to bioenergy remain rudimentary. Further, studies have shown that landowners are in general risk averse, making them reluctant to change their current land management practices to bioenergy crops and invest in innovative technologies when the market is so uncertain (EESI, 2010). In addition, efficient bioenergy facilities are still in the planning and demonstration phase and not well established (EERE, 2016). Finally, the federal regulatory and political environment frequently changes over the time creating a hurdle for sustainable production of biomass feedstocks to meet the increasing demand of the bioenergy industry. Because of these technological, economic, political, and regulatory issues, advancing bioenergy production remains highly uncertain. Reducing these uncertainties is one of the most critical challenges for the bioenergy industry.

States can help address many of the uncertainties that the bioenergy industry faces. Many states have recognized the importance of bioenergy in their future economic development (EESI, 2010). Each state has its own unique natural resources, institutional capabilities, and human capital that can support the bioenergy industry. State and local governments are often in a better position to collaborate with diverse local stakeholders to create a common vision for a sustainable bioenergy industry (ibid). Their partnership with local communities, private industries, and the federal government in promoting the bioenergy industry can be effective in advancing the long-term developmental needs of local communities (ibid). States can also establish their own bioenergy industries and adopt their own policies and incentives to promote bioenergy production (Ashton et al., 2009). In addition, they can also support research and development to be in a better position to inform and restructure federal policies in the future.

Since existing bioenergy policies at the federal and state levels may not be synchronized with regard to incentivizing and regulating the bioenergy industry, it is important to have a comprehensive understanding of how these diverse programs may interact in advancing the growth of the bioenergy industry (Kaffka and Endres, 2011). In this study, we compared common bioenergy policies with respect to their effectiveness to support the promotion of sustainable bioenergy production at the state level. We developed an analytic hierarchy process (AHP) model that incorporated several important dimensions of sustainable bioenergy crop production including socio-economic, environmental, and political factors. The model was applied to a case study in Kentucky. The results from this model will help policy makers at the state level to design policies that are most likely accepted by the general public, implemented, and then evaluated if they attained their intended socio-economic and environmental outcomes. Although this study is specific for Kentucky, we developed a multi-criteria decision analysis model, AHP, to bring all relevant factors for decision making process for bioenergy crop production and ensured that objective decisions were made considering all the aspects (pros and cons) of the potential policy options to visualize the best policy for promoting bioenergy crop production. Thus, the outcome of the model can be used by other states as a reference in designing their own bioenergy policies to promote bioenergy crop production.

4.2 Methodology

Comparing various bioenergy policies and prioritizing them based on their effectiveness to promote the bioenergy industry is a multidimensional decision-making problem that requires the consideration of the complexity of the economic, environmental, technical, and social factors of bioenergy production (Taha and Daim, 2013). Thus, a multi-criteria analysis is a suitable approach to analyze the various factors important in evaluating different bioenergy policy options. A multi-criteria analysis is a formal approach that considers multiple criteria in helping individuals explore decisions that matter (Belton and Steward, 2002). It is considered one of the most promising frameworks for evaluation because of its potential to account for conflicting, multi-dimensional, incommensurable, and uncertain aspects of decision making (Ananda and Herath, 2003). Common multi-criteria analysis methods used in studies on renewable energy planning and policies include multi-attribute utility theory (MAUT), outranking, and the analytic hierarchy process (AHP) (Taha and Daim, 2013; Pohekar and Ramachandran, 2004). MAUT is an expected utility theory approach that determines the best alternative for a given problem by assigning a utility to every possible alternative and then calculating the best possible utility (Konidari and Mavrakis, 2007). The major strength of MAUT is its ability to take uncertainty into account and assign each alternative a utility. However, it requires an interactive decision environment to formulate the utility function. A large amount of input is required at each step to accurately record decision makers' preferences for different alternatives. Thus, this method is extremely data intensive (Velasquez and Hester, 2013). Outranking approach such as the Preference Ranking Organization Method or Enrichment Evaluations (PROMETHEE) uses a preference function to capture the differences between two alternatives for each criterion and comes up with a preferences index to rank all alternatives with respect to a number of criteria (Pohekar and Ramachandran, 2004). However, it does not provide a clear method to assign values/weights to each criterion (Murat et al., 2015). In addition to the MAUT and the outranking methods, AHP can facilitate multi-criteria decision making. AHP is the most widely used method in energy planning and have been applied to numerous (and complex) environmental and economic problems (Algarin et al., 2017; Hernandez et al., 2015; Ahmad and Tahar 2014; Berrittella et al., 2007). The wide applicability of AHP is mainly due to its ability to convert a complex decision problem into a simple hierarchical structure, its flexibility, and its ability to mix qualitative and quantitative information in the decision-making process (Wang et al., 2011). Further, it supports group decision making and provides opportunities to share information among stakeholders in the decision process. Lastly, AHP is a scientific method that has been validated, replicated and proven reliable in decision making (Whitaker, 2007; Saaty, 2005). As it has been widely applied for measuring preferences in complex, multi-attribute problems (Varis, 1989), we used AHP as the decision tool for this study.

4.2.1 Proposed model

To compare various bioenergy policies and prioritize the most effective ones to promote sustainable bioenergy production, we applied the analytic hierarchy process (AHP), developed by Saaty (1980). AHP establishes priorities and preferences in a decision-making process using a hierarchy of criteria, sub-criteria, attributes and alternatives. For this study, we applied a four-level AHP. The top-most level of the hierarchy is the ultimate goal (i.e., to identify the most effective bioenergy policy), the intermediate levels correspond to various criteria and sub-criteria and the lowest level represent various decision alternatives (Figure 1). We used the following criteria and sub-criteria to compare the policies.

- Economic Impact: Energy security, and economic viability (profitability)
- Environmental Impact: GHG emissions, biodiversity, soil quality, and water quality/quantity
- Social Impact: Social acceptability, and social wellbeing
- Governance: Legal feasibility, technical feasibility, administrative feasibility, and cost effectiveness

Based on these criteria and sub-criteria, we compared various policy alternatives. Most of the existing policies in the southern US focus on regulatory mechanisms, incentive-based policies, and support-based programs (SAFER, 2009). Since regulatory mechanisms focus on setting goals for renewable energy production or consumption, they might not directly address landowners' interest. Thus, we mainly focused on incentives-based and support-based policy alternatives as presented in Table 4.1.

We identified these policy alternatives based on some of the existing/potential bioenergy policies that directly address bioenergy feedstock production. For example, the Bioenergy Crop Assistance Program (BCAP) is one of the most popular federal policies to directly address landowners. The main goal of the BCAP is to promote cellulosic, non-food, biomass production

Table 4.1: Policy alternatives and their description

Policy Alternatives	**Description**
P1: Direct Payment	Payment to cover the cost of growing, harvesting, storing and transporting biomass feedstock
P2: Capital support for start-up	Payment to support establishment of bioenergy crops, including land preparation
P3: Cost support for equipment/transportation	Payment for harvesting equipment and for transporting biomass to the facility
P4: Tax incentives	Property tax exemptions for lands used for bioenergy crop production.
P5: Technology support	Technology support to • improve production and economic returns • promote precise farming techniques for soil and water conservation • promote R & D for a sustainable and ecologically compatible land use change for bioenergy production.
P6: Crop insurance	Premium subsides for landowners who comply with conservation provisions on their land
P7: Farm lease	Rental payment for supplying lands for growing bioenergy crops
P8: Payment for ecosystem services	Payment for ecosystem services such as carbon offset payments to acquire the value of carbon sequestration on plant biomass.
P9: Conservation programs such as CRP, CSP, EQIP, WHIP	Setting aside lands such as CRP land for bioenergy production that provide • environmental benefits like soil and water quality improvement • economic benefits in terms of additional farm income for landowners and annual rental payment for acreage commitment

on private lands by providing incentives such as subsidies for the establishment and management bioenergy crops and matching payments for collecting and harvesting existing biomass resources that currently lack an established market (Barham, et al., 2016). The most recent provision of BCAP includes a 50% cost share of establishment cost (not to exceed $500/acre) and an annual payment or rental payment for up to 15 years for woody crops paid to landowners who enter into contracts to produce bioenergy crops (McMinimy, 2015). The annual payment is on a per-acre basis and contingent upon market based rental rates regulated by Farm Service Agency (FSA). Similarly, the BCAP has a provision to provide matching funds of $20/dry ton of biomass collected, harvested, stored, and transported to the nearest facility. The BCAP is mainly designed to provide socio-economic incentives to landowners to promote bioenergy crop production. Some other federal policies such as the Conservation Reserve Program (CRP) and Environmental Quality Incentives Program (EQIP) address environmental concerns. The CRP and EQIP mainly focus on marginal lands by promoting long term production of bioenergy crops to improve water quality, control soil erosion, and enhance wildlife habitat. The average CRP rental rate in the US in the 2015 was $70/acre (FSA, 2017). In addition to federal policies, various states have their own policies to incentivize bioenergy production. Tax credits for growing bioenergy crops, grants, loans, and cost-supports are some of the common incentives provided by states throughout the US.

After establishing the structural hierarchy as shown in Figure 4.1, we performed pair-wise comparisons of relative importance between each of the elements of each level with respect to a specific element in the level immediately above it based on Saaty’s 1-9 scale (Table 4.2). In making the comparison between two elements, we specified which of the two elements was more important and how much more important. We expressed our intensity of preference on a nine-point scale as presented in Table 4.2. If two elements were of equal importance, 1 was given in the comparison while a 9 would indicate the absolute importance of one criterion over the other.

After the pair-wise comparisons, a comparison matrix was formed. The comparison matrix was used to compute the relate priority/weight attached to each of the elements being compared. Numerical priorities of each alternative were then calculated to determine the relative ability of the policy alternatives to achieve/support the overall goal. The policy alternative with the highest numerical priority was then selected as the most effective policy option to promote bioenergy

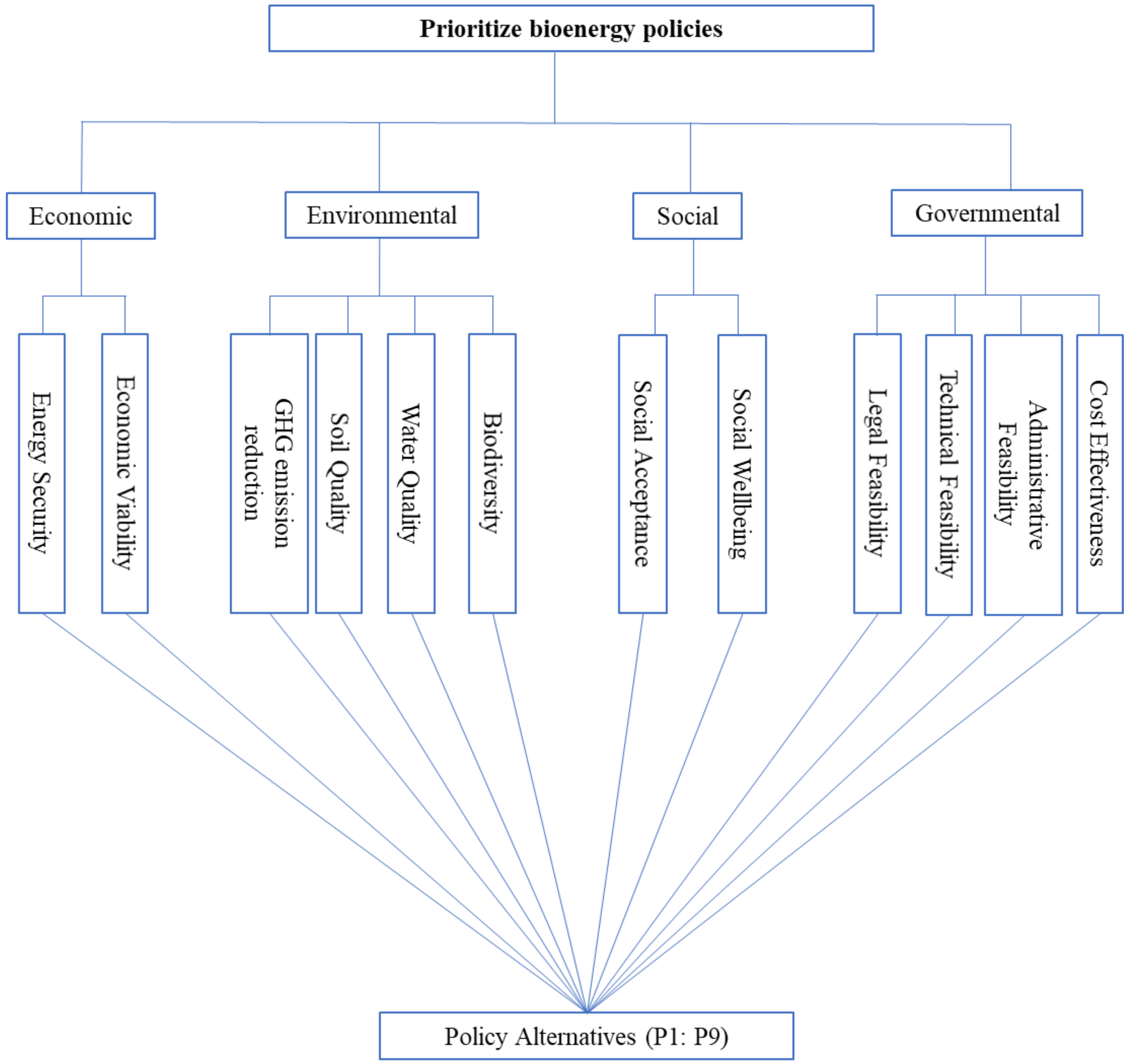

Figure 4.1: Analytic hierarchy process (AHP) model to evaluate bioenergy policies

Table 4.2: Saaty's pairwise comparison scale

Numerical Values	**Verbal Scale**	**Explanation**
1	Equal importance of both elements	Two elements contribute equally
3	Moderate importance of one element over another	Experience and judgement favor one element over another
5	Strong importance of one element over another	An element is strongly favored
7	Very strong importance of one element over another	An element is very strongly dominant
9	Extreme importance of one element over another	An element is favored by at least an order of magnitude
2,4,6,8	Intermediate values	Used to compromise between two judgements

production.

4.2.2 Study area and pairwise comparisons

Study area

For this study, we considered the state of Kentucky as a case study to evaluate various bioenergy policy options. Kentucky is a coal producing state, with 79% of the electricity generated in the state coming from coal (EIA, 2018). Even though the economy of the state is highly dependent on the coal industry, various efforts are underway to diversify with renewable energy sources such as bioenergy. The energy plan developed by the Governor's office (2009) requires 25 million tons of biomass to be produced annually by 2025 to meet federal and state standards. Thus, promoting bioenergy crops and the bioenergy industry is an important goal for the state. Previous studies in Kentucky have provided information on the availability of land for growing bioenergy crops. This study will be helpful by adding information about which policy would best promote bioenergy crops to fulfil the state's energy demands. This study specifically focuses on policies to promote bioenergy crops on marginal lands, i.e., low productive lands such as grasslands, shrubland, fallow cropland, and hay/pasture. Marginal lands do not compete with food production, promote forest conversion, or intervene with any existing management practices.

Pairwise comparisons

In this study we, as analysts, performed pairwise comparisons between each element at various levels based on objective data/information relevant for regional bioenergy production. We compared existing bioenergy policies based on economic, environmental, social, and governmental criteria using monetary, quantitative, and qualitative measures. We assumed that all criteria were equally important for the state government to promote sustainable bioenergy production. Thus, at the second level of the hierarchy, we assigned equal weights to each of the four criteria. The economic evaluation of the policies was based on regional data on potential yield, cost, and expected revenues (Halich, et al., 2018; FSA, 2017; Barham, et al., 2016; US DOE, 2016; Nepal et al., 2015; Skog et al., 2012; Kline and Coleman, 2010). For example, under the economic viability sub-criteria, net revenues were calculated from available data on costs and benefits for each policy option and our pairwise comparisons gave higher priority to policies that yielded higher revenues. Similarly, the environmental criterion was evaluated to assess how the policies would impact GHG emissions, biodiversity, and soil/water quality. For the environmental criterion, we gave a higher priority for soil quality than other sub-criteria. Even though reducing GHG emissions is one of the major focuses for promoting bioenergy, sustainable bioenergy production can only be attained when the land used for growing bioenergy crops can continuously produce as much biomass as is used for energy. This would require long-term soil fertility that can assure carbon neutrality from bioenergy production (WGBU, 2009). In addition to economic and environmental factors, it is important to evaluate policies based on how they can affect communities in which they are implemented because bioenergy production can affect agricultural productivity (in terms of the fuel vs. food debate), compete with land use, and impact the rural economy. Even though large-scale investment and governmental incentives are available, bioenergy production cannot be feasible without people's participation. Little is known about the public acceptance of bioenergy and its view on the opportunities and risks from bioenergy crop production. Local people may resist bioenergy crop production because of lack of awareness regarding the advantages of bioenergy and/or concerns over the socio-economic and environmental impacts of bioenergy crop production. People's perceptions and their acceptance is one of the major components of bioenergy production. Thus, for the social criterion, we focused on what policy characteristics people favor (accept) for bioenergy production and how bioenergy production can impact people's social welfare. In other words, what attributes of existing policies are most important to peoples' welfare in terms of bioenergy production. We gave the sub-criterion social acceptance more weight than social welfare mainly because opposition to certain bioenergy policies from the general public can thwart expansion of bioenergy crop production. Since the public does not have the power to make decisions about existing policies, information relevant to their policy preferences for promoting bioenergy crop production was obtained directly from a previous questionnaire survey that was primarily designed to evaluate landowners' willingness to make their land available for bioenergy crop production. In that survey, landowners were asked to rank different bioenergy policies based on their preferences. Landowners responses were combined using geometric means and entered directly into the AHP model.

Long term policy support can play a vital role in increasing stability in market conditions and reducing risk associated with establishing bioenergy crops (Nepal et al., 2015). For this study, we evaluated feasibility of the policy alternatives to determine whether they are viable for promoting bioenergy crop production. Feasibility for implementing policies depends on the availability of required resources such as human and capital resources, material resources, and technology. In addition, it is also important to understand whether policies conflict with existing legislation. Thus, we measured feasibility in terms of legal feasibility, technical feasibility, administrative feasibility, and cost effectiveness. For pair wise comparisons, we gave a slightly higher weight to cost effectiveness mainly because it explains the suitability of investment for the various policy options. In addition, policies that are not cost effective may cause unnecessary loss of economic welfare. Further, bioenergy policies that are most cost competitive and tailored to unique socio-economic, environmental and political circumstances would be most successful in the long-run. Thus, cost-effectiveness could be very important for encouraging bioenergy deployment.

4.3 Results

4.3.1 Ranking of policies

Local priorities obtained through pairwise comparisons over various levels of the hierarchy were synthesized to arrive at an overall priority for each policy alternative. The overall priority considers not only the performance of each policy alternative in terms of each criterion but also the different weight of each criterion. Results show that conservation programs, technology support, and tax incentives were the top three bioenergy policy alternatives in terms of their effectiveness for promoting bioenergy crops (Figure 4.2). Ranked as the most effective policy alternative, conservation programs, would be a better choice to promote regional sustainable bioenergy production. In addition, technology support and tax incentives were 87.3% and 69.78% as effective as conservation programs.

We then used a limiting matrix to display intermediate priorities under each node in the AHP model (Table (4.3) and Figure (4.3)). The limiting matrix here is a weighted supermatrix that shows how each criterion contributed to the overall effectiveness of each policy alternative. It must be noted that tax incentives, technology support, and conservation programs had higher priorities in the economic criterion. Similarly, conservation programs had a higher value in the environmental criterion. In addition, technology support and direct payments had higher priorities for governmental and social criteria respectively.

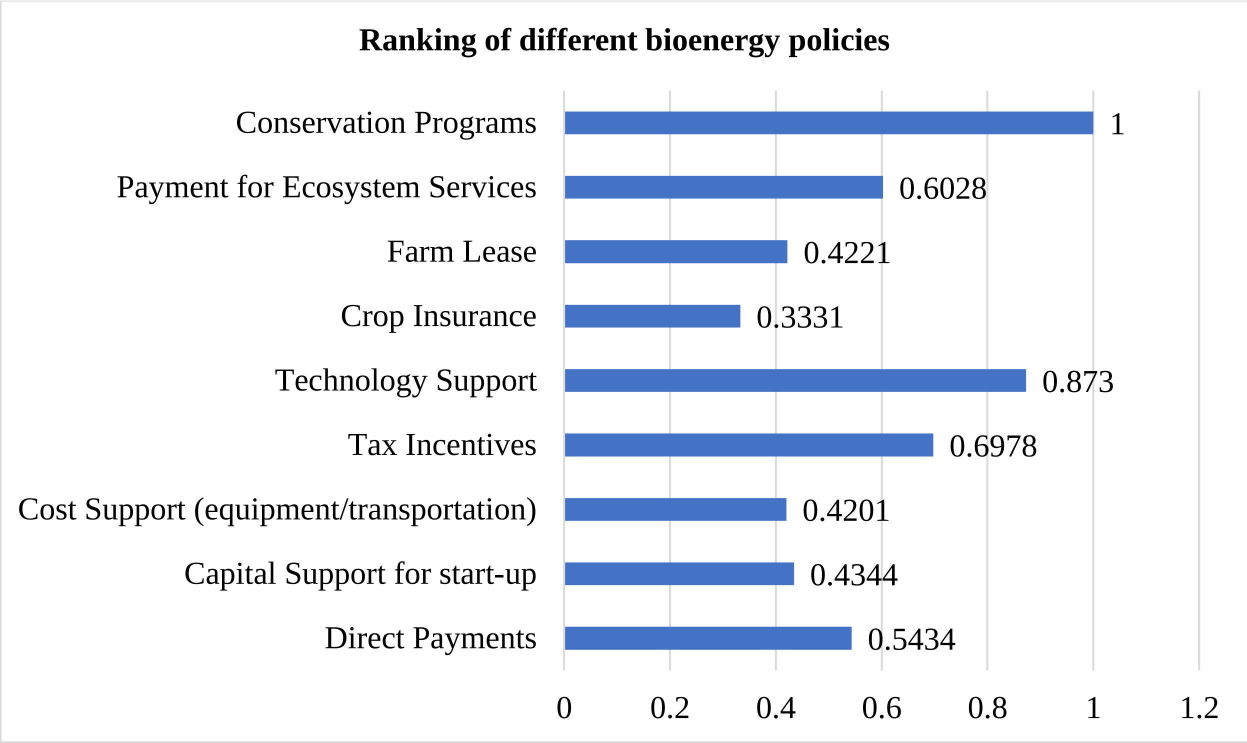

Figure 4.2: A graphical representation of ranking of different bioenergy policies

Table 4.3: Priority ratings for four different criteria

Alternatives	**Economic**	**Environmental**	**Governmental**	**Social**
Direct Payments	0.0275	0.0248	0.0537	0.0981
Capital Support for start-up	0.0358	0.0251	0.0551	0.0470
Cost Support (equipment/transportation)	0.0443	0.0258	0.0369	0.0506
Tax Incentives	0.0875	0.0584	0.0503	0.0657
Technology Support	0.1089	0.0832	0.0814	0.0542
Crop Insurance	0.0456	0.0251	0.0165	0.0379
Farm Lease	0.0276	0.0251	0.0721	0.0337
Payment for Ecosystem Services	0.0333	0.0615	0.0677	0.0638
Conservation Programs	0.0890	0.1711	0.0664	0.0489

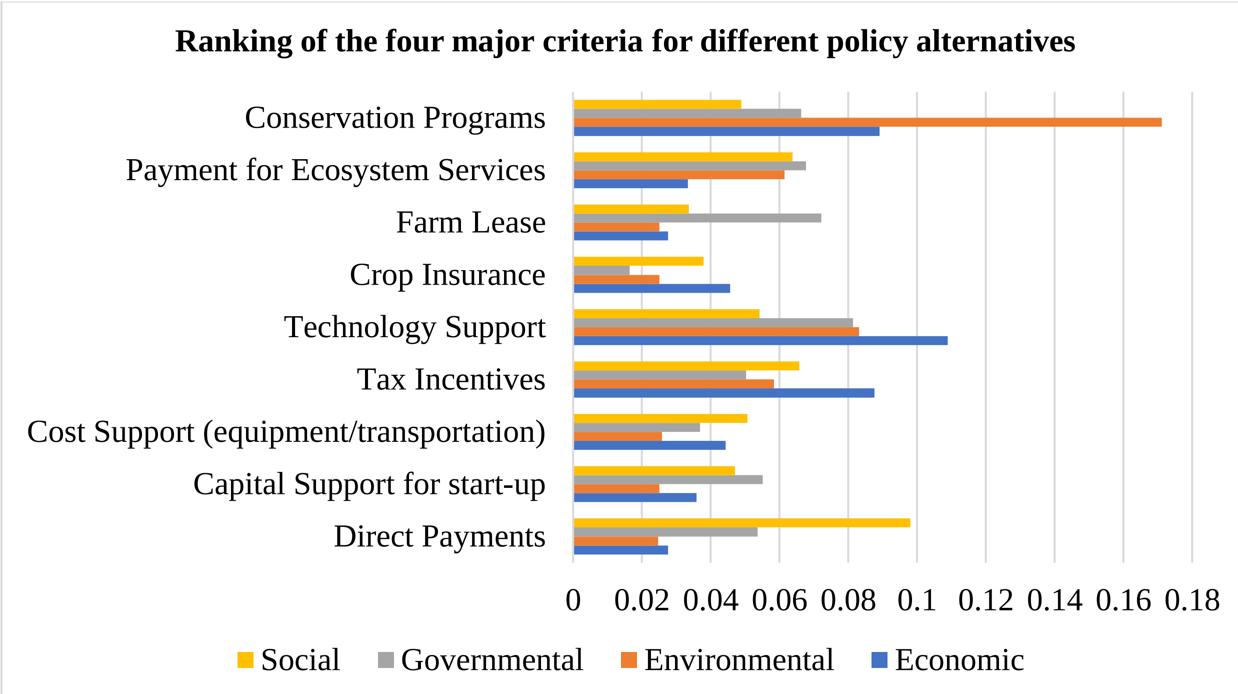

Figure 4.3: A graphical representation of different criteria for each policy alternative

4.3.2 Sensitivity analysis

The overall priorities for different policy alternatives obtained from the AHP model are highly contingent on the weights attached to criteria and sub-criteria. Thus, minor changes in the weights can cause major changes in the final rankings (Chang et al., 2007). Our analysis was based on objective data/information related to sustainable bioenergy production. However, any bioenergy production decision involves different stakeholders and weights attached to the main criteria are usually based on highly subjective judgements. Thus, it is important to test the stability of the ranking of the policy alternatives under varying criteria weights. To do this, we performed a sensitivity analysis to reflect different possible views/preferences of stakeholders on the relative importance of different criteria and examined how the overall priorities would change. Sensitivity analysis allowed us to examine which criterion/sub-criterion was the most critical to the final ranking. In terms of the main criteria the results are sensitive to changing the weights given to economic valuation, social impacts, and governmental feasibility in similar ways. For economic valuation, conservation programs stood out to be the favorable policy option when the weight was changed from 0.1 to 0.55. However, increasing the weight further made technology support a better option (Figure 4.4). Similarly, for governmental feasibility and social impacts, a weight from 0.6 onwards made technology support and direct payments better options, respectively (Figures 4.5 and 4.6). It must be noted that technology support had a higher priority for the economic and governmental criteria (Table 4.3), thus increasing the weight of economic and governmental criteria influenced the final results favorably for technology support. Similarly, the direct payments policy option had a higher priority within the social criterion (Table 4.3), undoubtedly favoring it when weight for the social criterion is increased.

The sub-criteria under the economic criterion (energy security, and economic benefits), environmental criterion (GHG, soil quality, water quality/quantity, and biodiversity), and social criterion (social acceptability, and social wellbeing) were not critical. However, for the governmental criterion with four factors (legal feasibility, technical feasibility, administrative feasibility, and cost effectiveness), only cost effectiveness was critical. Only when the weight for cost effectiveness was increased above 0.8 did the priorities of the different policy alternatives change, with technology support becoming the most preferred policy option to promote bioenergy crop production (Figure 4.7). This demonstrates that an increase in the weight for cost effectiveness would have to be very high to have an impact on the overall ranking.

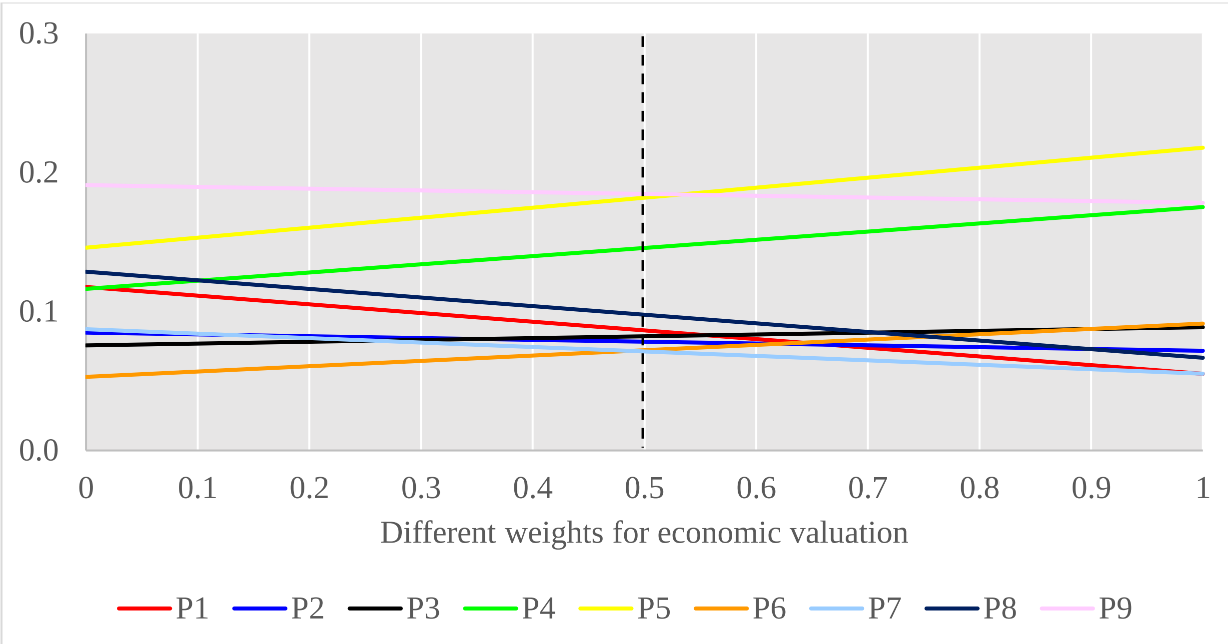

Figure 4.4: Sensitivity analysis at the second level of hierarchy with different weights for economic valuation

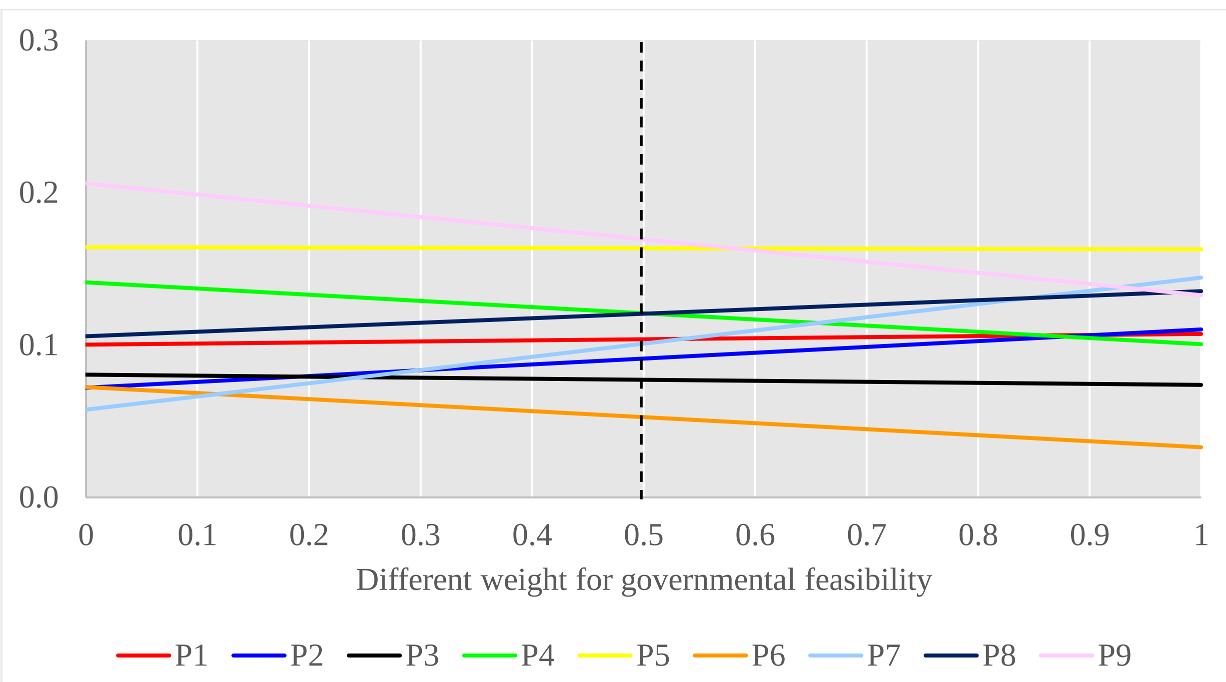

Figure 4.5: Sensitivity analysis at the second level of hierarchy with different weights for governmental feasibility

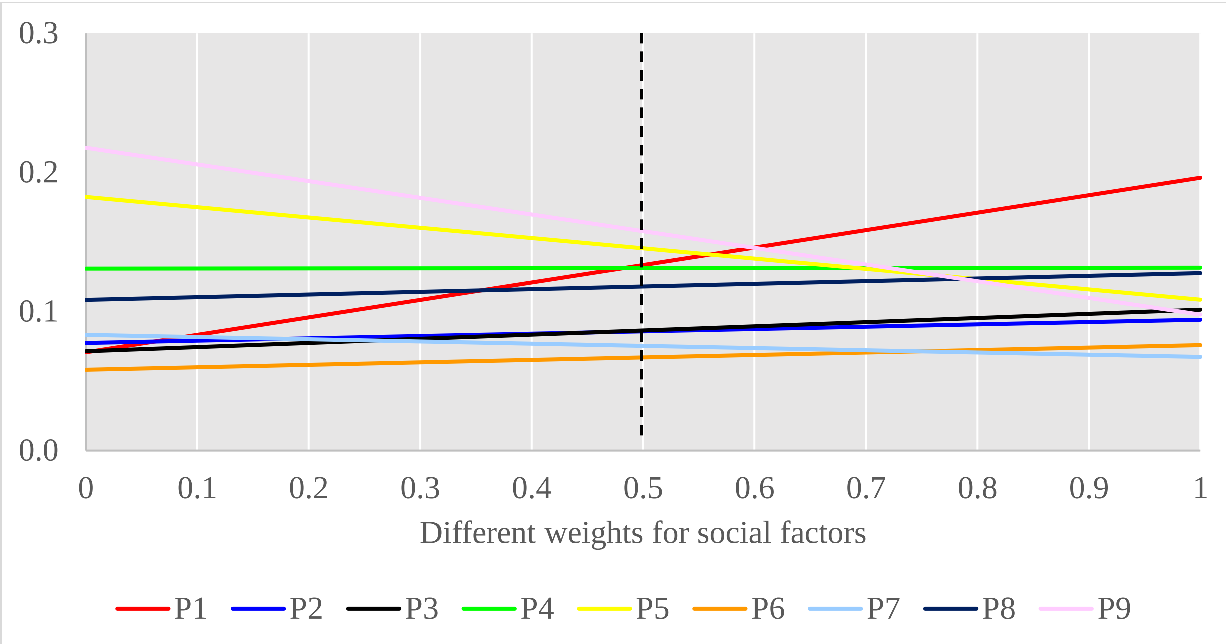

Figure 4.6: Sensitivity analysis at the second level of hierarchy with different weights for social factors

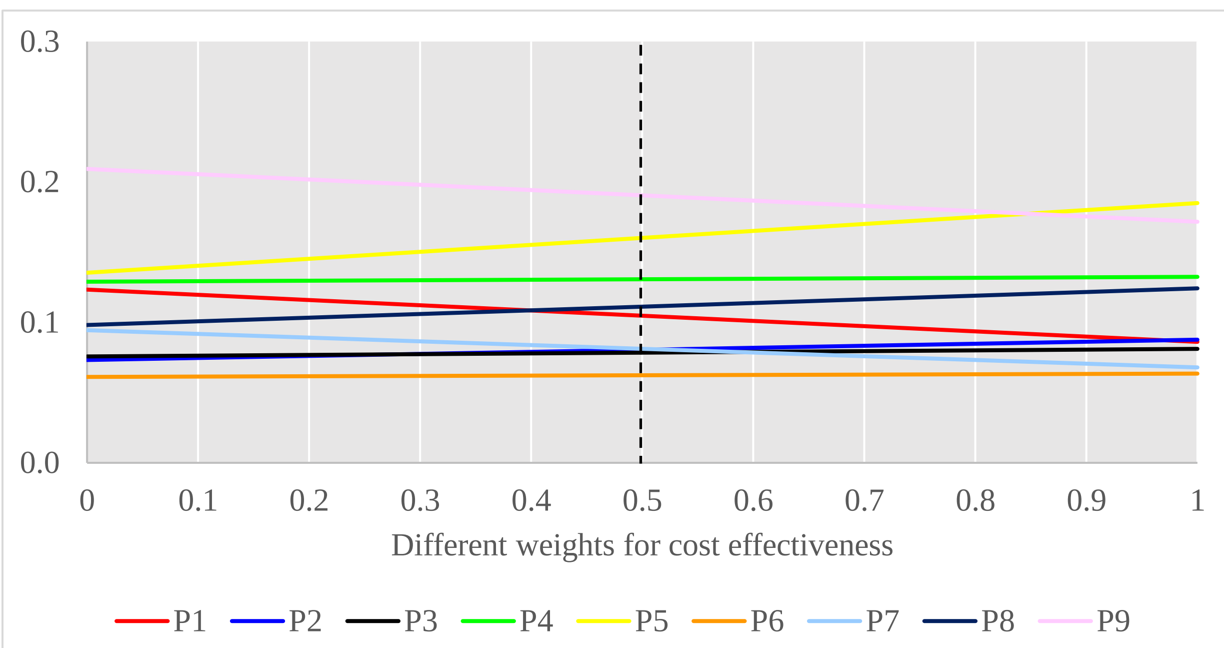

Figure 4.7: Sensitivity analysis at the third level of hierarchy with different weight for cost effectiveness

Throughout the hierarchy, changing the weights of some of the criteria seemed to be critical. However, the overall ranking of the policy options did not change to a great extent. Conservation program and technology support were ranked as the top two policy options during the sensitivity analysis except when the social criterion was given a weight greater than 0.6 making direct payments the top policy option. Thus, the sensitivity analysis validated our results and demonstrated the robustness of our model. Since bioenergy production involves multiple stakeholders with conflicting objectives, our sensitivity analysis performed by varying the weights for the different criteria reflected how preferences of different stakeholders could change the outcome. Since the top two policy options remained mostly the same throughout the sensitivity analysis, our results should be robust with regards to differing views of various stakeholders.

4.4 Discussion

Evaluation of different policy alternatives based on socio-economic, environmental, and governmental criteria revealed that conservations programs could be the most effective option to promote sustainable bioenergy production in Kentucky. Conservation programs such as the Conservation Reserve Program (CRP) was started in the US with a goal to protect environmentally sensitive land by preventing soil erosion, improving water quality, and enhancing biodiversity. Thus, results from this analysis highlight the need to take environmental concerns into consideration while designing policy options for promoting bioenergy crops in the state. Establishing bioenergy crops within conservation programs could result in an increase in biomass price, improve soil and water quality, reduce government spending on other conventional farm programs, and promote rural development (Mapemba et al., 2007). In addition, establishing bioenergy crops on these lands can help reach bioenergy mandates while incentivizing landowners to keep their lands under CRP contracts. However, the government may have to increase rental payments to keep the lands in the program because in some cases the opportunity cost for the lands may outweigh the rental payments.

In addition to conservation programs, technology support was also ranked relatively high in this study. Technology support can help improve biomass productivity (in terms of using improved varieties of crop species, and better planting, maintenance, and harvesting strategies) and provide a long-term supply of feedstocks at lower cost. In addition, technology support can help reduce potential negative environmental impacts, promote efficient transportation and storage of bioenergy feedstocks, and conversion of feedstocks to bioenergy in bioenergy facilities. Although there have been exciting advances in technology, the full extent to which technology can contribute to the future of bioenergy production remains uncertain. Therefore, more support from state and federal governments for R & D could facilitate bioenergy production in the long run.

It must be highlighted that crop insurance was ranked lowest in our analysis. Even though crop insurance can provide a safety net for landowners in case of major disaster, it was the least preferred option considering all the socio-economic, environmental and governmental factors. The cost of implementing crop insurance could be the biggest hurdle. Costs include subsidies of crop insurance premiums, reimbursements to private insurance companies for their administrative costs, and the government's share of participating in underwriting gains/losses (Babcock and Hart, 2006). Zulauf (2016) showed that that the cost to the government for its crop insurance program increased from $3.3 billion in 2000-2004 to $8.6 billion in 2010-2014. In addition to cost, an extensive set of administrative requirements make crop insurance less attractive for promoting bioenergy crop production.

Prioritizing the different policies discussed in this study is arguably important to the state of Kentucky where different initiatives are underway to promote bioenergy from woody biomass. Since policymakers need to consider many factors in making bioenergy production decisions, the results could be used by the state government to help make decisions regarding adopting specific policy approaches to promote bioenergy production in the state. The results showed that policies that incorporate environmental conservation are key to establishing bioenergy crops in Kentucky. However, merely promoting bioenergy crops on conservation lands (such as CRP lands) may not be sufficient in formulating effective policy because these lands are relatively vulnerable and generally less productive than farmland or forestland. Thus, consideration should also be given to efficient technological support to improve productivity on low productive lands at lower cost and to ensure environmental sustainability while growing bioenergy crops. Since our model incorporated landowners' perceptions on different policy alternatives, the state government can take a proactive policy action to ensure public participation for policy making. In addition, as bioenergy production involves multiple stakeholders with diverse interest/objectives (economic, environmental, and social), the state government can use the model developed in this study to communicate better with stakeholders and connect shared information (that highlights preferences and expectations of each stakeholder) to the policy process. Shared knowledge/information among the stakeholders about bioenergy production can be a key to overcome some of the production challenges that may arise due to conflicting interests of the stakeholders.

We used AHP as a tool to prioritize policies to promote bioenergy crop production. An advantage of AHP is that it is simple and straightforward to understand. It has the ability to convert a complex problem into a simple hierarchy of a goal, criteria/sub-criteria, and alternatives to facilitate communication of problems and identify solutions. The pair-wise comparison is relatively easy, and the use of verbal comparisons is appealing and user-friendly. The verification of consistency is another major asset of the AHP (Alessio and Ashraf, 2009). In addition, it is possible to combine multiple inputs into one consolidated outcome. For example, people's preferences for different bioenergy policies obtained from a survey was consolidated using geometric means and entered directly in the AHP model. Further, AHP is a flexible tool, it can incorporate multiple and conflicting objectives/criteria and qualitative and quantitative aspects in the decision-making framework. However, building the hierarchy and selecting criteria and sub-criteria may involve a certain level of subjective evaluation by decision makers (Bernasconi et al., 2010). Possibly, if more people work on similar decision problems, different opinions can result in different hierarchies and different weights on criteria/sub-criteria consequently, arriving at different solutions for a particular decision problem (Banuelas and Antony, 2004). Further, there might be inconsistencies with the 1 to 9 scale for decision makers with different capabilities to effectively evaluate the decision problems (Pauer et al., 2016). In this study, we performed all the pair-wise comparisons with state government as the primary stakeholder as analysts and we were able to check the consistency for all the comparisons. Another limitation of AHP is that it requires a large number of paired comparisons by the decision maker, especially for a complex decision problem sometimes making it difficult to maintain consistency among the responses (Islam and Abdullah, 2005). In this study, we focused on only the relatively more important criteria for sustainable bioenergy production to reduce the number of paired comparisons.

4.5 Conclusions

In this study, we applied a systematic multi-criteria decision analysis tool, AHP, to a case study on bioenergy production in Kentucky. The goal of this study was to evaluate different bioenergy policies and prioritize them based on their effectiveness to promote regional bioenergy production. The effectiveness was compared based on the different dimension of sustainability. This approach is of great relevance since various state and federal initiatives are underway to establish and promote bioenergy to improve energy security, generate employment, promote local economic development, and address environmental issues such as climate change. Results from this study showed that conservation programs are relatively better policy options, highlighting the need to take environmental aspects into consideration while designing policies for promoting bioenergy crops. In addition, results show that technology support can also be effective for promoting bioenergy production. Technology support can play a vital role to increase biomass productivity, reduce production cost, and benefit the environment. These results imply that state governments should formulate policies that not only focus on generative revenues but also provide better environmental incentives and promote research and development to support technological advancement to promote sustainable bioenergy production.

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CHAPTER 5

CONCLUSION

This chapter provides an overall summary of the research with key findings for each of the research questions addressed in the dissertation and shows how they fit in the context of broader bioenergy research. In addition, it discusses future research directions to address some of the limitations observed in the study.

5.1 Summary of research

The impetus for this research was the concern for huge dependence on fossil fuels for energy generation. Fossil fuels such as coal are non-renewable energy sources that deplete over time. Further, they have negative impacts on the environment as they emit greenhouse gases that contribute to global climate change. Thus, there is a need to diversify the current energy supply with alternative renewable energy sources. Bioenergy is a renewable energy source that has the potential to partially replace fossil fuels and address concerns about greenhouse gas emissions However, commercial scale production of bioenergy has not yet been established to meet the huge energy demand. Thus, there is a need to explore the full potential of bioenergy production to support energy generation. The main purpose of this dissertation was to assess the feasibility of growing bioenergy crops for energy. This study used multiple approaches including multi-objective optimization, quantitative survey, and multi-criteria decision analysis to explore the potential of bioenergy crop production for a case study in Kentucky. Results from the study can be helpful for regional planning of bioenergy crop production, developing outreach activities and assisting state agencies in selecting and implementing policies that support bioenergy industry. Key findings for the three major objectives for the research are presented below:

5.1.1 Objective 1: To identify trade-offs between socio-economic and environmental factors for bioenergy production

Promoting bioenergy production may incorporate various objectives such as improving biomass yield, protecting the environment, and providing opportunity for rural development in terms of better economic growth and job/employment opportunities. However, obtaining a certain level of outcome for a particular objective would require a sacrifice in the outcome of the other objectives. Therefore, planning for a sustainable bioenergy production requires an understanding of potential trade-offs or interconnectedness between various socio-economic and environmental factors. We developed a multi-objective optimization model that had the ability to incorporate major components of biomass supply chain. The model depicted trade-offs among several factors in the production decision for bioenergy crops for a case study in northern Kentucky. In addition, changing the preferences for those factors also shifted the trade-offs accordingly which implies that the magnitude and the extent of the trade-offs in bioenergy crop production strongly depends on the development of future bioenergy demand which is subject to biomass market as well as land use change. Results from the trade-off analysis showed a need to find the best balance among the trade-offs for better production decisions. Large scale bioenergy crop production planning that neglects trade-offs and does not account for complementary measures could result negative effects on various sustainability indicators such as economic returns, water and soil quality. Policies that aim at maximizing bioenergy production are useful to promote bioenergy but neglecting the trade-off with economic or land resources may not sustain in the long run and may come at the cost of greater environmental degradation. Rather than focusing on maximum yield from bioenergy crops, production should therefore be restricted on certain high-quality lands that have the potential to generate economic growth and focus on efficient use of land and water resources. By considering trade-offs among the various factors in bioenergy crop production, results highlighted the opportunity to design integrated policies for bioenergy, land use, soil and water management as the key to a sustainable bioenergy crop production. Thus, trade-off analysis can be a very useful tool for systematic planning to promote bioenergy crop production that can assist in gaining sustainability goals in bioenergy production.

5.1.2 Objective 2: To understand landowners' perception about bioenergy and their willingness to promote bioenergy crop production

Expansion of bioenergy crops would require participation from private landowners as they own majority of lands. Thus, one of the major focusses of this dissertation was to understand landowners' intent to convert their existing land use to bioenergy crop production. We administered a questionnaire survey for a four-county study area in northern Kentucky to collect information on landowners' current land management practices, their knowledge and understanding of bioenergy crops, their perceptions of bioenergy and various socio-demographic information to examine whether and under what conditions landowners would make their land available for bioenergy crops. Results from the study showed that landowners were relatively more willing to grow bioenergy crops themselves than rent to others however, a relatively higher biomass price was required to engage them in bioenergy crop production. Uncertainty about biomass market and biomass productivity in addition to a huge investment cost incurred during the production process promoted a higher biomass price for landowners' intent to promote bioenergy crops. This information would be helpful in designing better market protocols and incentive mechanisms that ascertains a reliable source of economic returns for landowners who are willing to grow bioenergy crops. Results also showed that many landowners were not interested in renting their land regardless of price offered. Loss of privacy, old age, loss of self-control and potential disturbance from producing and harvesting energy crops were major factors for their low willingness to rent their land. In addition, younger landowners with a positive attitude towards bioenergy crops and those with large acres of land were more willing to promote bioenergy crop production. With this information, outreach activities that focus on enhancing landowners' awareness about beneficial economic and environmental impacts could help promote their participation in bioenergy production in the long run.

5.1.3 Objective 3: To evaluate potential bioenergy policies for promoting sustainable bioenergy crop production

Policy support in terms of bioenergy policies that are well defined, effective, logical and oriented towards providing socio-economic and environmental gains is required to promote bioenergy crop production. To address this, another major focus of this dissertation was to evaluate potential bioenergy policies and prioritize them based on their effectiveness to promote regional bioenergy production. We used a multi-criteria decision analysis tool, AHP to a case study on potential policies for bioenergy production for Kentucky. The AHP incorporated all dimensions of sustainable bioenergy crop production including socio-economic, environmental and policy factors. Results showed that conservation programs are relatively better policy options highlighting the need to take environmental considerations while designing polices to promote bioenergy production. In addition, results revealed that improved technology can also play a vital role to expand bioenergy production. Since various state and federal initiatives are underway to establish the bioenergy industry, this information can help state government formulate policies that not only generate revenues but also provide incentives to promote environmental conservation and promote research and development to support technological advancement to promote a sustainable bioenergy production. The analysis performed in this study was based on objective data/information relative to sustainable bioenergy production. As bioenergy production involves stakeholders with different interests and objectives, state agencies can use the model developed in this study as a tool to communicate knowledge and information with the stakeholders in the policy making process. Effective communication among different stakeholders can be a key to address some of the challenges and reach a policy that is acceptable to all.

5.2 Contribution to geography and bioenergy production planning

Bioenergy crops can provide a reliable source of feedstock to support the bioenergy industry, reduce our dependence on fossil fuels and address concerns related to energy security, economic development and environmental issues such as climate change and global warming. However, promoting bioenergy crops would require major changes in land use and management practices that can have long term impacts on socio-economic and environmental conditions. In addition, the impacts from bioenergy crop production can be different based on where and how the bioenergy crops are grown. In this research, I mainly focused on the feasibility of bioenergy crop production at a regional level. The location of the study area including the physical (site and soil conditions) and social (landowners' land use behavior and their opinion and attitude towards bioenergy) environment influenced how systematic planning should be carried out, what landowners' intent was and what incentives they seek for converting their existing land use, and what policies would be effective for promoting bioenergy crop production. Thus, this research focused on place-based bioenergy crop production planning that was subjected to the context of a particular location and feedstock types. This research adds to the human-environmental interaction literature by investigating socio-economic and environmental indicators to provide an understanding of a bioenergy production system's sustainability. Most geography research has focused on environmental aspects of bioenergy production and highlighted the potential of bioenergy crops to reduce GHG. This research investigated all aspects of sustainability, examined the relationship among them and considered the preferences of different stakeholders in the planning for regional bioenergy crop production. Additionally, this is the first study in northern Kentucky that proposed marginal land (low productive lands) as potential sites for growing bioenergy crops. Results could provide insights for regional bioenergy planning in similar geographic regions where bioenergy crop production has been recommended.

5.3 Future work

Results from the three studies demonstrated the importance of considering all the sustainability dimensions and their interconnections to promote sustainable bioenergy production. While this is important, I have few recommendations for future research.

5.3.1 Study area expansion

Although the extent of the study area was appropriate and unique based on its geographic location for analyzing the potential of bioenergy production, a broader spatial extent would be better. A major limitation specifically, for understanding landowners' intent, was low response rate. Extending the study area to include adjacent counties may improve survey responses however, those counties would still have similar socio-economic and environmental conditions which could lead to similar response rates obtained in this study. A better approach would be to include another case study from a different geographic region (such as western Tennessee) and perform a comparative study to show how the results would be different.

5.3.2 Land use types

We focused on marginal lands as potential sites for growing bioenergy crops mainly because they do not compete with food production or promote forest conversion or intervene with any existing management practices. However, it must be noted that marginal lands are lands with lower productivity and less favorable site conditions. As a result, areas feasible for promoting bioenergy crops on such lands could have been lesser than on existing cropland or forestland. Therefore, future research should include other land use types such as existing croplands and forests. In addition, people's intent for growing bioenergy crops could have been different if they were asked their preferences for growing bioenergy crops in different land use types. Further, we focused on short rotation woody crops as potential crops in the study area. However, perennial grasses such as switchgrass could also be included as potential bioenergy crops. In future research, diverse land use types with different species including perennial grasses should be used.

5.3.3 Qualitative data

Questionnaire surveys used to understand landowners' willingness mainly focused on gathering quantitative information. A major recommendation for future research would be to conduct focus group discussions with landowners to acquire qualitative information to supplement information gathered from the questionnaire survey. Focus group discussions allow interaction between landowners and provide a platform to bring different viewpoints or concerns landowners may have about bioenergy production. Further, focus group discussions can help landowners formulate or reconsider their insights on bioenergy production (Cameron, 2010). In addition, focal group discussions done prior to sending questionnaire survey may help improve the response rate.

5.3.4 Inclusion of stakeholders for AHP

We performed the AHP as an analyst and ensured that objective evaluations were made considering all aspects of potential policy options to visualize best policy to promote bioenergy crop production. However, bioenergy production incorporates different stakeholders with different, and often conflicting objectives. Getting inputs from real stakeholders relevant to all aspects of bioenergy production not only provide different but also more affirmative decisions for promoting bioenergy crop production. Therefore, future studies should incorporate evaluation from different stakeholders (policy makers at the state level and stakeholders engaged in bioenergy production). Interviews with the stakeholders; policy makers, environmental organizations, and the coal industry could be a great way to bring together different views for bioenergy planning. Stakeholders' differences in decision criteria to evaluate policies also provide insight into possible gaps and help design better policies that address all stakeholders for promoting bioenergy production.

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VITA

Sandhya Nepal was born and raised in Nepal, a small country in the foothills of the Himalayas. Sandhya received her B.S and M.S degrees in Forestry from Tribhuvan University, Nepal (2005) and University of Kentucky (2014). She also holds M.S degree in Environmental Management from the University of North Dakota (2009). Sandhya completed her PhD in Geography from the University of Tennessee in December 2018. During her time as a PhD student, she worked as a graduate teaching assistant. She was awarded with McCroskey Memorial grant and Chancellor Top off Fellowship to support her research. She has also received several travel grants to attend regional and national conferences and disseminate her research works.