ESSAYS ON BIOMASS SUPPLY CHAIN NETWORK DESIGN

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

This dissertation is about the biomass supply chain network design considering the incentives as a financial support for entities in the supply chain such as the growers (farm) and biorefinery (plant) to produce energy (bioethanol) from the corn stover as a renewable energy feedstock. This dissertation consists of two journal papers that I have worked on during the past years of my Ph.D. studies where one of them has been published in *Energy Policy* journal.

In the first paper, we presented a linear program (LP) model for the biomass supply chain network design in bioethanol production using corn stover. The distribution of the corn stover from farm to storage and plant, and the bioethanol from the plant to customer is modeled with the consideration of financial incentives. We explore the dollar value paid to the farmers to encourage them to convert the corn stover into bioethanol rather than burn it in the farm. Results show that only 37% of corn stover can be converted to bioethanol due to plant capacity limitation.

In the second paper found in Chapter 3 in this dissertation, we presented a mixed integer linear program (MILP) model to overcome the plant capacity problem in the previous model. To make sure 100% corn stover converted to bioethanol, the MILP model will decide whether to expand the existing plant or build new plant based on *existing plant configuration (EP*) and combination of *existing and new plant configuration (ENP)*. Results indicated that 100% corn stover converted to bioethanol can be achieved by expanding all existing plant and build a few new plants. It is also indicated that some farms are making losses in the *EP* configuration.

Finally, we analyze the interaction of the farm and plant on the corn stover price and transportation cost to increase the profitability of the affected farms that are not making profit in the *EP* configuration.

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DEDICATION

This work is dedicated to:

My loving wife & sweet daughter

Dr. Monizaihasra binti Mohamed

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Your presence has made me stronger, better, and

both of you have filled my life more than I could have ever thought.

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1. INTRODUCTION

1.1. Chapter overview

This chapter serves to highlight some fundamental ideas and notions, and introduce the structure of the research on biomass supply chain network design. First, we will look at the background of the study by explaining general ideas on biomass, and then follow with the motivation of the study which deals with biomass supply chain issues. Next, we will highlight some research questions and objectives of the study. Finally, we will end this chapter with a summary of the chapter by outlining the structure and organization of the dissertation.

1.2. General introduction

Biomass is a term for organic or biological materials that stems from plants and animals including herbaceous plants and grasses, woody plants, manures, aquatic plants, etc. (Mckendry, 2002). Biomass is used as a feedstock (or raw material) to produce energy such as methane gas or transportation fuel such as ethanol, butanol, biodiesel and other hydrocarbon fuels (U.S. EIA, 2017; DOE, 2017). The conversion of biomass into energy, also known as bioenergy, can be processed using different conversion options and infrastructure requirements (McKendry, 2002). To be converted into energy, the biomass feedstock has to be harvested, collected, transported and probably stored in an intermediate storage before being processed. Examples of biomass feedstock includes crop residues such as corn stover, sugarcane bagasse, switchgrass, wheat straw and etc. (Kenney et al, 2013).

Corn stover consists of stalks, leaves and cobs that remain in fields after the corn harvest (Koundinya, 2009). Corn stover is a beneficial and the most important biomass feedstock in producing biofuels in many countries around the world that led to a numerous research and investigations on biofuel production using corn stover (Liu et al., 2018; Saini et al, 2015; Han et al, 2013; Kauffman et al, 2011; Anex et al, 2010) due to its renewable in characteristics, plentiful availability and low cost properties (Liu et al., 2018). In fact, corn stover is the primary biomass feedstock source for producing cellulosic ethanol in the United States (Wilhelm et al, 2007) and also the largest quantity available in the United States which has the potential of supplying 23 to 53 billion liters of fuel (ethanol) to the U.S. transportation market (Koundinya, 2009). Moreover, corn stover is capable of mitigating the dependence on foreign oil while boosting the economics of rural communities (Tumbalam et al., 2016; Farrell et al., 2006) and promote sustainability through renewable energy sources.

Renewable energy plays a crucial role in creating sustainability in every industrial sector all around the world (FAO, 2000). Natural resources as a source of renewable energy production can help mitigate the environmental problems caused by greenhouse gas (GHG) emissions emitted from fossil fuels, such as coal and petroleum. Production of biofuels and biopower derived from plant residues as a biomass feedstock can be a significant source for energy production in the United States. Concerns about the environmental impact from conventional energy sources has been an ongoing debate for decades. The dependency on these sources creates many issues in the economy, society and environment.

GHG emissions are a major concern related to climate change (Edenhofer et al., 2011). Switching to renewable energy sources would be the best solution in order to sustain the economy, society and environment for future generations (Won et al., 2017; Mahbubur and Dulal, 2017). The concerns about climate change are due to a rapid growth in CO_2 emissions attributed to the increase in energy supply resulting from the global usage of fossil fuels such as coal and petroleum (Edenhofer et al., 2011). Asymmetrically, renewable energy has the transformative potential to reduce GHG emissions and contributes to social and economic development by creating job opportunities. (Edenhofer et al., 2011).

1.3. Research issue

The motivation of this study stems from the environmental impact from growers burning out their corn stover in the fields. This occurs because it is the cheapest way to remove the residues. Since the cost of managing the corn stover for biomass treatment is relatively high, the interest in converting it to biofuel is low. Rather than burn the corn stover in the field, which creates CO_2 emissions, it is better to convert it into biomass because of its advantages and sustainable properties as a renewable energy source (Rahman et al., 2017) and also due to the environmental impact in term of emissions produced by fossil fuels (Apergis & Payne, 2014) that we want to reduce. The other concern with open-field crop burning is that it could decrease the organic matter of soil, which is crucial for soil fertility to be maintained while improving the physical, chemical, and biological properties for the next crops (Stan et al., 2014). The models developed in this study will provide policy makers guidance on how to incentivize the use of renewable energy sources for biofuel production, while increasing the economic and social benefits to growers in North Dakota and improving sustainability through cleaner production.

1.4. Research questions

There is much work already done in the biomass supply chain. However, the work featured in this dissertation has its own novelty in terms of how the biomass supply chain differs from entity to entity. Precisely, the study will analyze the biomass supply chain by considering incentives and emission prices with the implementation of an optimization approach in the forms of linear program (LP) and mixed integer linear program (MILP). To the best of our knowledge, this research has not been done by other researchers. The research questions are:

- What is the effect of incentive and emission prices on sustainable biomass supply chain network design?
- How does biomass supply chain network design differ when reducing total emissions is the goal?
- What is the impact of farms and biorefineries decision making on the biomass supply chain network design?

1.5. Research objectives

In line with the research questions, the objectives of this research are threefold. They are as follows:

- To identify the ideal incentive and emission prices to be set to make sure that all corn stover will be converted into biomass in a sustainable way.
- To determine optimal capacity levels and locations of biorefineries to reduce CO_2 emissions.
- To investigate the behavior of biomass feedstock farms and plants in the biomass supply chain entity.

1.6. Summary

In summary, this chapter provide an overview of biomass supply chain issues and the related objectives of this research. The whole research can be divided into three parts, based on its objectives. Chapter 2 is dedicated to the first manuscript of designing biomass feedstock supply chain with incentive considerations which has been published in *Energy Policy* journal. Chapter 3 is for the second manuscript that discussed about the plant location problem and capacity. In Chapter 4, the behavior of farms and plants is presented to sustain the production of biofuel.

2. BIOMASS FEEDSTOCK SUPPLY CHAIN NETWORK DESIGN WITH BIOMASS CONVERSION INCENTIVES[1]

2.1. Abstract

Biomass has the potential to create sustainable energy systems, which is critical for societal welfare. A major issue regarding biomass resources is crop residues or leftover biomass that is burnt by farmers after harvesting; this happens due to high transportation costs which make burning the cheapest way to remove the residue. We develop a decision support system using a large-scale linear program with the goal of maximizing profit with and without the emission cost. This system helps identify farms that would benefit society were they to be incentivized under a biomass crop assistance program (BCAP). A case study of leftover corn stover in the state of North Dakota is analyzed to validate the model. Our results reveal that an incentive of $7.20 per ton of corn stover converted to ethanol when 20% of rail capacity is allocated is ideal, as it produces the lowest emissions of 16,784,953 metric tons with a $73,462,599 profit. Furthermore, penalizing emissions resulting from the transportation of corn stover also helps reduce emissions; a suitable value for the penalty could be at $71.7 per metric ton of CO_2 emitted. Such a policy would result in reducing dependency on petroleum, thus promoting a sustainable biomass supply chain.

[1] The material in this chapter was co-authored by N. Muhammad Aslaam Mohamed Abdul Ghani, Chrysafis Vogiatzis and Joseph Szmerekovsky. N. Muhammad Aslaam Mohamed Abdul Ghani had primary responsibility for collecting data and analysis of the test system. N. Muhammad Aslaam Mohamed Abdul Ghani was the primary developer of the model that are advanced here. N. Muhammad Aslaam Mohamed Abdul Ghani also drafted and revised all versions of this chapter. This chapter appears in Energy Policy (Mohamed Abdul Ghani et al., 2018).

2.2. Introduction

Biofuels and biopower are forms of renewable energy directly derived from biomass, which is originally harvested from organic materials such as plants. Residues from agriculture are an important biomass source to produce bioenergy for transportation, while at the same time providing us with a better, "green" solution for the economy, society, and the environment. This growing interest in biomass for energy production has consequently led to an increase in research on biomass, especially on optimizing the overall supply chain from the initial stages of crop harvesting all the way to final consumption. In fact, biomass from agricultural residues is one of the largest biomass resources in the United States (Perlack et al., 2005). This is not only occurring in the United States, though; on the contrary, biofuel production and consumption have increased throughout the world as a substitute for fossil fuels, such as petroleum and coal (Heyne and Harvey, 2013). Lastly, biomass can transform and has indeed already had a major impact on many aspects of our everyday life, as it provides us with energy at lower costs (Mckendry, 2002) and while emitting less compared to fossil fuel (WNA, 2011). However, it is also no panacea, with high costs of production and transportation, along with greenhouse gas (GHG) emissions across its supply chain (Labriet, 2013). This raises concerns for producers and policy makers, who need to find strategies that reduce costs and at the same time address CO_2 emissions in response to government objectives. According to the Renewable Fuel Standard (RFS), 138 million metric tons of GHG emissions are expected to be reduced when it is fully implemented in 2022 (Schnepf and Yacobucci, 2013). Our research aims to identify an efficient way to reduce costs and emissions across the biomass supply chain, using data from the state of North Dakota for a case study.

Research on biomass and its impact has been rapidly growing over the last years, mostly due to its ability to become an alternative power source that is both more economical and greener compared to fossil fuels like petroleum. It has also been documented that corn stover converted to bio-ethanol can lead to increases income for farmers; moreover, ethanol can help reduce the pressure of international fuel market fluctuations and help achieve energy independence (Gallagher and Johnson, 1999). It comes as no surprise then that many investigators have been looking into the adoption of operations research techniques for improving the design, viability, and effectiveness of modern biomass supply chains (Ghaderi et al., 2016). For an excellent overview of the existing results in biomass supply chain optimization and modeling, we refer the interested reader to the work by Yue et al. (2014).

The advantages of economies of scale for deciding the size of biorefineries was investigated by Gallagher and Johnson (1999). Their analysis depicted the potential gains from adopting biofuel production from agricultural residues and materials. Their gains were shown to be not only financial, but also societal. Later, Ekşioğlu et al. (2009) analyzed the operations of the supply chain to transport biomass to biorefineries and determined the number, size, and location of the biorefineries needed and the amount of biomass shipped, processed, and stored during a time horizon. In this study, the design of long-term (supply chain) and short-term (logistics) decisions were considered and integrated with the goal of minimizing the total cost of delivery. A main insight of their work was that operators prefer to receive biomass within a 50-mile radius due to high biomass transportation costs. In a subsequent work, Roni et al. (2014) proposed the hub-and-spoke design for a biomass supply chain; therein, two models were integrated for short- and long-distance deliveries to coal plants. Moreover, Park et al. (2017) proposed a multimodal transportation scenario for switchgrass-based bioethanol in North

Dakota. However, these studies do not account for incentives in their modeling frameworks. As we will show later in this manuscript, incorporating the effects of monetary incentives and emissions penalties in the decision-making process, we can help towards better streamlining the biomass supply chain.

Recently, Marufuzzaman et al. (2014) proposed a mixed-integer linear program to optimize both cost and emission components in the supply chain by employing wastewater treatment in the production of biofuel: emission components in this work focused on two modes of transportation, namely truck and pipeline, for biodiesel production using wastewater sludge. Their work also looked into regulatory policies, such as a carbon tax, carbon cap-and-trade, and other carbon offset mechanisms. In our study, we consider truck and rail transportation to move corn stover from farms to biorefinery plants either directly or through storage facilities, as well as to move ethanol from biorefineries to customer markets. We did not study emissions in more granularity by including emissions from the corn stover to ethanol conversion process. To that extent, we refer the interested reader to the work by Canter et al. (2016), in which the GREET (Greenhouse gases, Regulated Emissions and Energy use in Transportation) model (Argonne, 2017) was used to perform a full life cycle analysis study.

In other studies related to biomass supply chain management, Cambero et al. (2015) presented a multi-period mixed integer linear programming model for converting forest residues to bioenergy. Employing mathematical programming models for better designing and planning biomass supply chain networks is also investigated in Ahn et al. (2015); such models can result in significant benefit for the supply chain. Once more, the aforementioned studies do not explore the observed supply chain benefits resulting from properly incentivizing biomass.

Other related works on optimizing modern biomass supply chains utilize simulation-based techniques. Mobini et al. (2013) developed a discrete event simulation system that considers a series of interdependencies and uncertainties across the supply chain, such as variations in moisture contents, effect of machine failure, market specifications, and costs, among others. Their model could then estimate the cost of delivery to a range of customers as well as estimate the energy inputs and CO_2 emissions along the supply chain. Shabani and Sowlati (2013) used a nonlinear mixed integer program for biomass procurement, storage, and energy production and management to estimate the amount of biomass to be purchased from each supplier, and then stored and consumed on a month to month basis. Their results showed that optimal biomass procurement policies resulted in 15% lower costs. Later, the authors also proposed a Monte Carlo simulation framework coupled with their optimization model to assess the impact of uncertainty in parameters of the supply chain, such as biomass quality, availability, and electricity prices (Shabani and Sowlati, 2015). A common missing theme is the absence of monetized emission costs. Incorporating monetary incentives and monetized emissions would make these studies more comprehensive. This is one of the gaps that we aim to fill by also investigating the trade-off between the incentive and emission prices.

A study on storage systems for agricultural biomass for cellulosic ethanol production has further revealed a decline of 8% in CO_2 for the logistics operations for roadside storage (Ebadian et al., 2013). Evaluation of slash recovery systems for utilizing biomass has the potential to mitigate the increases in GHG emissions, as previous studies assumed that only one recovery system would be used, with the choice being between comminution in-field and roadside (Lindroos et al., 2011). The use of renewable energy sources has also seen an increased interest for many stakeholders in district heating systems (Ghafghazi et al., 2010). Criteria considered in their work included GHG emissions, particulate matter emissions, maturity of technology, and traffic load. A fundamental result from their work was that a yearly increase of 3% or more in the prices of fossil fuels would render biomass even more attractive. The authors also employed life cycle assessment for all stages including fuel production, fuel transportation, operation, and finally demolition of the district heating system to perform a full computational study (Ghafghazi et al., 2011). However, there is a need to investigate cases of monetized incentives allocated by the government to assist biomass supply chain; such incentives programs can help towards achieving more sustainable supply chains.

Promoting sustainable energy independence is a global challenge. Renewable energy, including biomass, is one of the fastest growing energy industries which contributes towards this goal. To meet this challenge, government intervention has been crucial for supporting and promoting biomass conversion for both small- and large-scale renewable energy producers. This is usually done through incentive programs such as the Biomass Crop Assistance Program (BCAP), which was introduced by the 2008 Farm Bill as a strategy to develop and improve agricultural products in the United States and reduce reliance on foreign oil, as well as mitigate air pollution (USDA, 2016b). The program provides funds to farmers to manage logistics activity for biomass feedstock, including but not limited to operations related to harvesting and transporting biofuel ingredients. The use and generation of renewable energy has also been incentivized by the government in many countries at the state and national levels (Rosaly and Laurèn, 2013) although, as expected, there are different types of policies for each geographic location. The different responses and adoption rates of policy incentives across countries are posing a challenge for researchers to identify the reason behind them in terms of technology and settings (Bangalore et al., 2016).

More specifically, transportation seems to be the major consideration, seeing as it significantly affects the cost of converting raw material to the, ready for consumption, end product. Investigating biopower co-firing to further understand the relationship of this process with other supply chain related costs, including transportation, has recently been performed by Liu et al. (2016). Their study shows that a reduction in transportation costs indeed leads to increased feasibility of reasonably-priced biomass feedstock. For other renewable energy sources, such as wind energy, financial incentives have been shown to be important at both federal and state levels (Black et al., 2014). There are significant positive impacts on the wind energy growth in the U.S. from the tax incentives: Black et al. (2014) discovered that removing this incentive in the state of Idaho would result in tax revenue reduction as well as a decrease in other significant economic metrics such as total output, employment, and state income.

It is becoming increasingly clear, that government intervention in the form of incentives for renewable energy are potentially beneficial. They can prove transformative in our efforts to foster the development of renewable energy that benefits our societies, economies, and the environment. As mentioned by Simsek and Simsek (2013), renewable energy is crucial in bettering energy security and independence, and its increased consumption throughout the world has led to reduced dependence on fossil fuels, which in turn leads to reduced pollution, and higher quality of life. In the same work, the authors present the incentive mechanisms and other related renewable energy policies that are implemented in Turkey. These policies aim to help achieve the goals of utilizing renewable energy in an effective way, so that costs are reduced, and of complying with carbon emission policies by expediting renewable technologies (Simsek and Simsek, 2013). In Nigeria, a biofuel policy and incentives (Ohimain, 2013a) were established to stimulate the bioenergy sector and a thorough performance review has been done by Ohimain

(2013) to identify the policy gaps and provide recommendations and feedback. In Spain, tax incentives, finances, and non-refundable grants have been designated, but are still not adequate and more policies are needed (Pablo-Romero et al., 2013).

While most researchers study the mechanisms of incentive policies for renewable energy and analyze their impact, there are also rigorous studies on the technical aspects of choosing incentives. The use of optimization techniques to analyze the economic, environmental, and societal aspects with regards to different government incentives develops and promotes a new paradigm for the biomass industry. Cobuloglu and Büyüktahtakın (2014) used mixed-integer optimization to formulate and assess the economic and environmental benefits of switchgrass production at the farm level, as well as incorporating incentives in their model. In their work, they treat the budget provided by the government for biomass production as an incentive on marginal land for switchgrass cultivation. Their results show that under a limited budget and assuming high harvesting costs, biomass production should increase whenever switchgrass yield increases from a low to a moderate level.

Even though government policies for incentivizing biomass production are in place, there still exist gaps that need to be studied and addressed. In our work, we deal with the major challenge faced by many farmers and potentially biomass actors, which is whether leftover crops should be burned upon crop harvesting. Doing so decreases biomass availability and increases GHG emissions, yet it is the cheapest solution for farmers interested in growing other crops, especially for remotely located farms. If the growers, on the other hand, opt to sell the leftover yield, they are also responsible for high transportation costs from their farms to the appropriate conversion facilities and/or biofuel plants. This happens because of the bulky and difficult to transport nature of leftover biomass, which in turn results in a lower ratio of energy produced per unit of mass (Marufuzzaman et al., 2014).

To the best of our knowledge, there is no work on incentivizing biomass feedstock conversion. In this regard, our paper introduces a new study for incentivizing entities along the supply chain using mathematical programming. Our goal is to explore the impact of incentives and emission penalties as a financial lever to provide financial compensation which will prevent farmers from burning their leftover biomass feedstock, while at the same time creating more opportunities to convert feedstock into bioenergy, reducing the total supply chain cost and decreasing emissions.

This chapter is outlined as follows. In Section 2.3, we focus on our model development efforts, the mathematical program devised, and the case study. Then, Section 2.4 analyzes and interprets our findings from a financial, societal, and environmental perspective. Last, Section 2.5 concludes this work and offers insight in future directions.

2.3. Methodology

2.3.1. Model development and assumptions

The biomass feedstock supply chain design in this study is formulated as a linear programming model that minimizes three different objective functions for the main stakeholders (farmers, plants, environment), with the final goal of exploring the impact of introducing financial incentives for biomass conversion along with emissions penalties, in the supply chain. Obtaining and analyzing the results, under varying scenarios, will allows us to compare the changes in profits, costs, and emissions to the total dollar value invested in incentives and the total dollar value paid in emissions penalties. We focus our attention on only one type of feedstock (corn stover) and use it in a case study to validate the proposed model and our results.

As shown in Figure 2.1, corn stover flows from the farms to the end customers via storage facilities and power plants. We proceed now to describe the in-house logistics costs for the farms and the plants, as well as the transportation costs involved.

For every farm, there are costs associated with windrowing, baling, collecting and storing stover, as well as other overhead and fixed costs. For plants, the costs associated with the production of biofuel include buying, processing, and overhead and fixed costs. We assume that corn harvesting has already been performed and what remains on the field is stover. Windrowing is defined as the set of activities that create a row of leftover corn stover using a windrower. A baler is then used in the baling process before stover is collected and finally sent to intermediate storage or directly to a plant for conversion. The above in-field logistics are assumed to exist on every corn farm, regardless of size or location. At the plants, costs incurred in the process includes buying, processing, overhead and fixed costs. Finally, the bioenergy will then be distributed to customers and the transportation cost will be borne by the plant.

For the transportation costs, there should be an agreement between the buyer and the seller, that is the farm and the plant. However, in this aggregate model we assume that farms alone will bear the cost of all transportation starting from a farm and with a destination to either a storage or a plant facility. Farmers are assumed to be the sole deciders as to whether corn stover is sent directly to a plant or to a storage facility.

On the other hand, plants are in turn responsible for the transportation cost from a storage facility to the plant and, of course, for all distribution costs to the customers. At this stage of transportation, two modes of transportation are available, namely truck and rail. Last, an underlying assumption in this study is that no corn stover is lost through transportation. Losses can easily be accommodated by introducing an average loss ratio per transportation means per stage. The big picture of biomass supply chain movement is provided in Figure 2.1.

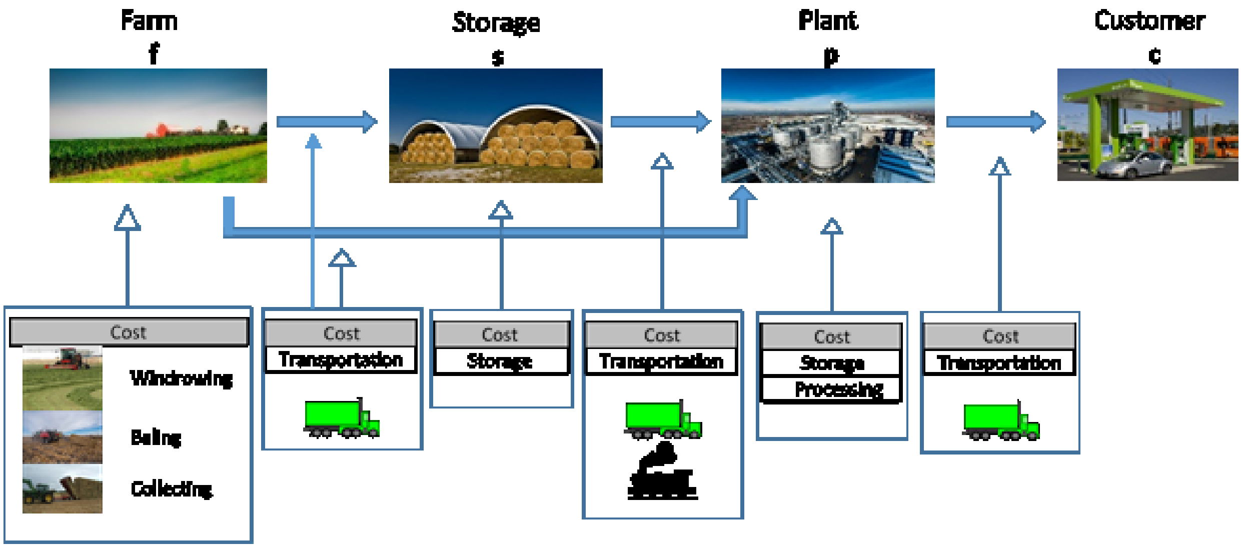


Figure 2.1. Supply chain network for biomass feedstock and the costs associated with each stage.

2.3.2. Objective functions and constraints

The goals of the proposed model are threefold and aim to capture different aspects of the problem for different stakeholders. The first objective function aims to maximize profits disregarding emissions (that is, emissions are not penalized). Then, the objective function in (2.2) considers emissions and penalizes them with a cost of *EP* (see Table 2.1). Last, the objective function in (2.3) solely considers emissions and aims to minimize them. It is important to note here that the model in (2.1) - (2.18) is not a multi-objective model; instead, selecting a different objective and solving leads to different interpretations for biomass conversion rates based on the incentives and emissions costs selected. The decisions being made are:

- the amount of corn stover harvested for conversion and the amount of corn stover to be burned at every farm,
- the amount of corn stover sent from every farm to the storage facilities,

- the amount of corn stover sent directly from every farm to the plants,
- the amount of corn stover sent from storage facilities to plants as well as the means of transportation, and
- the amount of biofuel sent from plant to final demand.

The notation used in the model is presented in Table 2.1. The objective functions and constraints of the model can then be expressed as in equations (2.1) - (2.18) below:

$$\begin{aligned}\underset{(no\ emission\ penalty)}{\text{Max Profit}}: &\sum_{f\in F}(\phi+\iota)\cdot X_f + \sum_{p\in P}\sum_{c\in C}\pi\cdot B_{pc} - \sum_{f\in F}\alpha_f\cdot X_f - \sum_{p\in P}\sum_{c\in C}\rho_p\cdot B_{pc}\\ &-\sum_{f\in F}\sum_{s\in S}\varrho_{fs}\cdot Y_{fs} - \sum_{f\in F}\sum_{p\in P}\varrho_{fp}\cdot Z_{fp} - \sum_{s\in S}\sum_{p\in P}\varrho_{sp}\cdot H_{sp} - \sum_{s\in S}\sum_{p\in P}\gamma_{sp}\cdot M_{sp}\\ &-\sum_{p\in P}\sum_{c\in C}\varrho_{pc}\cdot B_{pc}\end{aligned} \tag{2.1}$$

$$\begin{aligned}\underset{(with\ emission\ penalty)}{\text{Max Profit}}: &\sum_{f\in F}(\phi+\iota)\cdot X_f + \sum_{p\in P}\sum_{c\in C}\pi\cdot B_{pc} - \sum_{f\in F}\alpha_f\cdot X_f - \sum_{p\in P}\sum_{c\in C}\rho_p\cdot B_{pc}\\ &-\sum_{f\in F}\sum_{s\in S}\varrho_{fs}\cdot Y_{fs} - \sum_{f\in F}\sum_{p\in P}\varrho_{fp}\cdot Z_{fp} - \sum_{s\in S}\sum_{p\in P}\varrho_{sp}\cdot H_{sp} - \sum_{s\in S}\sum_{p\in P}\gamma_{sp}\cdot M_{sp}\\ &-\sum_{p\in P}\sum_{c\in C}\varrho_{pc}\cdot B_{pc}\\ &-\Bigg(\sum_{f\in F}\sum_{s\in S}\zeta_{fs}\cdot Y_{fs}\cdot\Gamma + \sum_{f\in F}\sum_{p\in P}\zeta_{fp}\cdot Z_{fp}\cdot\Gamma + \sum_{s\in S}\sum_{p\in P}\zeta_{sp}\cdot H_{sp}\cdot\Gamma\\ &+\sum_{s\in S}\sum_{p\in P}\eta_{sp}\cdot M_{sp}\cdot\delta + \sum_{p\in P}\sum_{c\in C}\zeta_{pc}\cdot B_{pc}\cdot\Gamma + \sum_{f\in F}X_f\cdot\upsilon + \sum_{f\in F}G_f\cdot\omega\\ &+\sum_{f\in F}(\sigma - X_f)\cdot\varphi\Bigg)\cdot\xi\end{aligned} \tag{2.2}$$

Min Emissions

$$: \sum_{f\in F}\left(\sum_{s\in S}\zeta_{fs}\cdot Y_{fs}+\sum_{p\in P}\zeta_{fp}\cdot Z_{fp}+X_f*\upsilon+G_f*\omega+\left(\sigma-X_f\right)*\varphi\right)\cdot\Gamma$$
$$+\sum_{s\in S}\sum_{p\in P}\left(\zeta_{sp}*H_{sp}*\Gamma+\eta_{sp}*M_{sp}*\delta\right)+\sum_{p\in P}\sum_{c\in C}\zeta_{pc}*B_{pc}*\Gamma \quad (2.3)$$

Subject to:

$$X_f+G_f\leq\varsigma_f\cdot\varpi\cdot\tau, \qquad \forall f\in F \quad (2.4)$$

$$\sum_{f\in F}X_f+\sum_{f\in F}G_f=\sum_{f\in F}\beta_f\,, \quad (2.5)$$

$$\left(\sum_{s\in S}Y_{fs}+\sum_{p\in P}Z_{fp}\right)-X_f=0, \qquad \forall f\in F \quad (2.6)$$

$$\sum_{f\in F}Y_{fs}-\sum_{p\in P}(H_{sp}+M_{sp})=0, \qquad \forall\, s\in S \quad (2.7)$$

$$\left(\sum_{f\in F}Z_{fp}+\sum_{s\in S}(H_{sp}+M_{sp})\right)\cdot\mu-\sum_{c\in C}B_{pc}=0, \qquad \forall\, p\in P \quad (2.8)$$

$$\sum_{f\in F}Y_{fs}\leq\vartheta_s, \qquad \forall s\in S \quad (2.9)$$

$$\sum_{f\in F}Z_{fp}+\sum_{s\in S}(H_{sp}+M_{sp})\leq\pi_p, \qquad \forall p\in P \quad (2.10)$$

$$\sum_{s \in S} \sum_{p \in P} M_{sp} \leq \psi \cdot \theta, (11)$$

(2.11)

$X_f \geq 0,$ $\forall f \in F$ (2.12)

$G_f \geq 0,$ $\forall f \in F$ (2.13)

$Y_{fs} \geq 0,$ $\forall f \in F, \forall\, s \in S$ (2.14)

$Z_{fp} \geq 0,$ $\forall f \in F, \forall\, p \in P$ (2.15)

$H_{sp} \geq 0,$ $\forall s \in S, \forall\, p \in P$ (2.16)

$M_{sp} \geq 0,$ $\forall s \in S, \forall\, p \in P$ (2.17)

$B_{pc} \geq 0,$ $\forall p \in P, \forall\, c \in C$ (2.18)

Table 2.1. Sets, parameters, and decision variables for the model in (2.1) – (2.18).

Notation

Sets and subscripts

F	Set of farms ($f \in$ F)
S	Set of storage facilities ($s \in$ S)
P	Set of plants ($p \in$ P)
C	Set of all customer ($c \in$ C)

Parameters

α_f	Stover harvesting cost for farm f
ρ_p	Ethanol production cost for plant p
ϱ_{fp}	Transportation cost of stover via truck from farm f to plant p
ϱ_{fs}	Transportation cost of stover via truck from farm f to storage s
ϱ_{sp}	Transportation cost of stover via truck from storage s to plant p
ϱ_{pc}	Transportation cost of ethanol via truck from plant p to customer c
γ_{sp}	Transportation cost of stover via rail from storage s to plant p
ζ_{fs}	Distance from farm to storage (truck)
ζ_{fp}	Distance from farm to plant (truck)
ζ_{sp}	Distance from storage to plant (truck)
η_{sp}	Distance from storage to plant (rail)
ζ_{pc}	Distance from plant to customer (truck)
μ	Biomass to biofuel conversion rate
π	Biofuel selling price
β_f	Amount of corn stover available in farm f
ϖ	Average corn yield per acre of land
τ	Corn yield factor
I	Incentive
ς_f	Land area of farm f (in acres)
ψ	Rail capacity allocation ($\psi \in \{0\%, 10\%, 20\%\}$)
ξ	Emission/Carbon price
σ	Ton of corn stover equivalent to petroleum
φ	Corn stover equivalent petroleum emissions
ϑ_s	Storage capacity for storage facility s
δ	Truck emissions factor
υ	Production emissions factor
ω	Open-field burning emissions factor
Γ	Rail emissions factor
θ	Total rail shipment

Decision variables

X_f	Amount of corn stover harvested for biomass in farm f
G_f	Amount of corn stover burned in farm f
Y_{fs}	Amount of corn stover sent from farm f to storage facility s
Z_{fp}	Amount of corn stover sent from farm f to plant p via truck
H_{sp}	Amount of corn stover sent from storage facility s to plant p via truck
M_{sp}	Amount of corn stover sent from storage facility s to plant p via rail
B_{pc}	Amount of biofuel sent from plant p to customer c

The amount of biomass feedstock available is limited by the land area of each farm and is estimated by corn yields. To estimate corn stover in a field, we multiply the corn yield in bushels by 56 pounds, or 0.028 in tons (Mayer, 2012). The record of U.S. corn yield in 2012 indicated 122 bushels per acre (USDA, 2016a), which makes the amount of corn stover available 3.416 tons per acre (122*0.028). Thus, constraint (2.4) ensures that the amount of corn stover harvested cannot exceed the amount available. Constraint (2.5) guarantees that all corn stover is either sold or burned. Constraints (2.6), (2.7), and (2.8) are typical flow balance constraints at the farm, storage, and plant facilities. The capacity of each storage and plant facility is expressed in constraint families (2.9) and (2.10). Constraints (2.11) indicate the amount of corn stover shipped by rail should be less than or equal to the allocated capacity. Finally, variable restrictions (2.12) - (2.18) ensure the non-negativity of all variables involved.

2.3.3. Case study

To validate and evaluate our linear programming model, we opted to use the North Dakota (ND) corn farms as our case study area. North Dakota produces nearly 450 million gallons of ethanol per year from corn (NDEC, 2009). Hence, even though bio-refineries to convert corn stover to ethanol are not operational in the state, our study shows how important it would be to combine the existing ethanol production infrastructure with biomass feedstock (and especially corn stover). Figure 2.2 presents the locations of 354 corn farms spread out in 45 counties in ND. There are 4 biorefineries in ND, located in Stark, McLean, Cass, and Richland counties. The capacities of each biorefinery are 625,000 tons, 750,000 tons, 1,875,000 tons, and 1,812,500 tons for Stark, Mclean, Cass, and Richland, respectively. Table 2.2 summarizes the information on the number of farms per county in ND for better exposition. Now, to maximize total supply chain profit through this model, income from selling the corn stover and ethanol is considered. We assume a simple network model where the corn stover is transported from farms to plants, either via intermediate storages or directly, for ethanol conversion. Then, ethanol produced in plants is transported to the customers. For each farm, income is calculated based on per unit ton of corn stover using equation $(\phi + I) * X_f$ (2.19); where ϕ is the selling price of corn stover, I is the incentive given, and X_f is the amount of corn stover harvested. The selling price of corn stover in ND is \$45 per ton (Maung and Gustafson, 2011). The farm cost of harvesting corn stover was obtained from Gallagher (2012) at \$32.71 per ton. The corn stover handling activities in North Dakota incur costs which include harvesting, baling, and stacking. These costs are varied between $30 per ton to $55 per ton, depending on factors such as residue removal rate with higher collection costs associated for lower removal rates. Storage cost is estimated at $5 per ton (Gustafson et al., 2011). All distances between farms, storages, plants, and customers are obtained from a geographical information system (GIS) software and are used with a transportation cost of $1.2/mile/truckload for truck, $2.5/mile/railcar for rail, and $1.3/mile/truckload for biofuel transportation which is based on the transportation cost structure by Xie et al. (2014). Any amount of corn stover shipped to a plant (under, of course, the capacity constraints) will be converted to biofuel using a conversion rate of 80.6 gallon/dry ton (Xie et al., 2014). The production cost of biofuel is $1.50/gallon (Mcaloon et al., 2000) which includes all plant processing costs. Finally, the revenue of every plant is calculated by multiplying the ethanol selling price of $2.21/gallon (Tao et al., 2013) by the amount of biofuel produced. The value used is slightly different from the $2.50/gallon mentioned in a more recent work by Gallagher (2014). However, we decided to use a price that is similar to the one identified in states of the Midwest region, such as the neighboring states of Minnesota and South Dakota (at $2.17 and $2.19 per gallon, respectively), and Wisconsin at $2.25/gallon, as provided by Tao et al. (2013). The mean reported for multiple states in the Midwest region of the USA is finally $2.21/gallon which accounts for the distribution of real feedstock compositions in the area. Notice that we also consider the environmental aspects of our supply chain in this study. Parts of a lifecycle analysis that are considered in our work include the equipment used to transport corn stover as input data which is truck and rail transportation. Therefore, we estimate the CO_2 emissions from these two modes of transportation for the corn stover by using truck and rail emission factors obtained from Mathers et al., (2014). The truck and rail emission factor is estimated at 161.8 grams/ton mile and 22.9 grams/ton mile respectively. We then solved our model using Open Solver, an optimizer developed by Andrew Mason (OpenSolver, 2017).

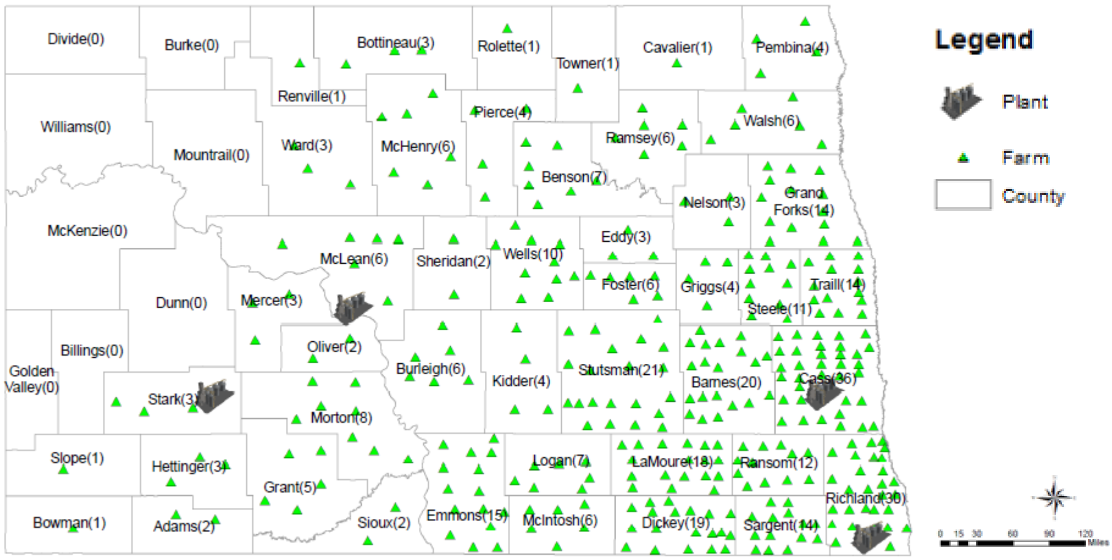


Figure 2.2. Locations of all corn farms and biorefineries in North Dakota. Counties are also shown in this map for convenience.

Table 2.2. List of counties in North Dakota with no. of corn farm size.

County	acre	County	acre	County	acre	County	acre
Divide	-	Emmons	150,000	McLean	60,000	Sargent	140,000
Adams	20,000	Foster	60,000	Mercer	30,000	Sheridan	20,000
Barnes	200,000	Golden Valley	-	Morton	80,000	Sioux	20,000
Benson	70,000	Grand Forks	140,000	Mountrail	-	Slope	10,000
Billings	-	Grant	50,000	Nelson	30,000	Stark	30,000
Bottineau	30,000	Griggs	40,000	Oliver	20,000	Steele	11,000
Bowman	10,000	Hettinger	30,000	Pembina	40,000	Stutsman	210,000
Burke	-	Kidder	40,000	Pierce	40,000	Towner	10,000
Burleigh	60,000	LaMoure	180,000	Ramsey	60,000	Traill	14,000
Cass	360,000	Logan	70,000	Ransom	120,000	Walsh	60,000
Cavalier	10,000	McHenry	60,000	Renville	10,000	Ward	30,000
Dickey	190,000	McIntosh	60,000	Richland	300,000	Wells	100,000
Dunn	-	McKenzie	-	Rolette	10,000	Williams	-
Eddy	30,000						

2.4. Results and discussion

North Dakota corn production is a valuable in the market, and hence growers prefer selling the corn grain rather than providing its stover for biomass production purposes. Furthermore, the lack of volatility in corn prices and production does not allow for anxiety as far as growers and producers are concerned. As shown in Figure 2.3, the fluctuations in the production of corn ranging from 2006 to 2015 follows the same trend as the average corn at the same period. The highest recorded average price for corn was observed in 2012 with $6.46 per bushel, and the total value production of that same year was $2,726,895,000. This serves to show that the corn business is more attractive to farmers than its corn stover counterpart. In fact, though, we show that farmers could stand to generate more income by converting the stover into biofuels. Had they considered corn stover as a side income, a total of $559,540,800 could have been earned in 2012, as shown in Figure 2.4. However, managing the conversion processes is indeed costly seeing as it involves many other logistics activities, as well as technology changes that can affect the supply for raw materials to production (Gallagher and Johnson, 1999).

The benefits from using corn stover are not only reaped in the form of income generation by farmers; the government and society are also able to satisfy part of their energy needs by renewable and sustainable, cleaner production sources, while at the same time, reducing dependency from fossil fuels, such as the commonly used in North Dakota oil and coal. By doing so, we show that this results in not only more sustainable production, but also reduces total production costs, borne by the supply chain. Therefore, government intervention is crucial to the success of corn stover biofuel conversion in the form of providing incentives to growers to make proper use of leftover corn stover.

In our study, incentivizing as an instrument for providing financial assistance or other monetary related packages and process support is crucial for increasing the volume of production and setting it up for success in the future. As a policy consideration, this study offers a range of diverse options by investigating both profit and environmental perspectives of the supply chain, as shown in Tables 2.3 to 2.8. These tables point out the variability of incentive, emission prices, and allocated rail capacity under three different objectives. The objectives are, namely, to maximize profit and ignore any penalty on the total emissions generated, to maximize profit while simultaneously considering a penalty on the generated emissions, and, last, to minimize the overall emissions. The profit maximization objective is then further divided into 3 subcategories, denoted as *low*, *average*, and *high* cases, depending on the incentive selected. The *low* and *high* values of incentives and emission price are determined by the smallest and largest value for which any changes appear in the amount of corn stover converted. To make our identification of the incentive and emission prices clearer, we point the attention of the reader to Tables 2.6, 2.7, and 2.8. When considering only incentives and no emission prices, the corn stover converted to ethanol is 18% without any incentives, and changes to 19% when the incentive is set to $5.7 per ton. Similarly, the highest incentive was selected as the smallest value at which further incentivizing did not lead to any increases ($7.2). The average case was then calculated in between the two extreme cases as $6.45. A similar subdivision was decided for maximizing profit with emission consideration, where *low*, *medium*, and *high* cases were investigated for the value of the emission penalty. The *low* case was set to a penalty of $61.8 per ton of emissions, the minimum cost at which the penalty kicks in and affects the amount of corn stover harvested for biomass purposes. The high case was then set to a penalty of $81.6 per ton of emissions, the minimum value when the penalty stops having an effect. The average case was then simply calculated as the average case of having a penalty between the *low* and *high* cases.

Table 2.3 collects all results with 0% rail capacity (no rail transportation allowed), Table 2.4 does the same with 10% rail capacity, and Table 2.5 shows the results with 20% of rail capacity being used for transporting corn stover from storage to biorefineries.

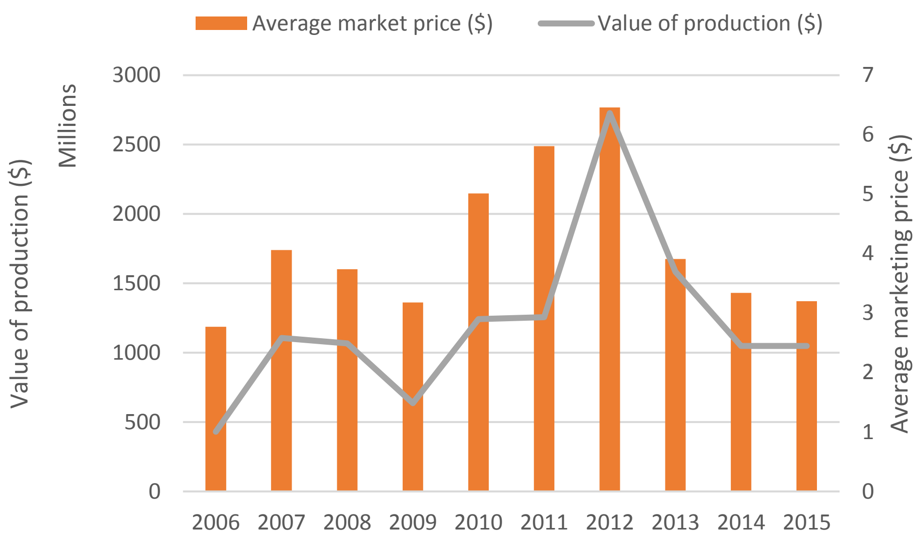


Figure 2.3. Corn production in ND 2006-2015 (USDA, 2016a).

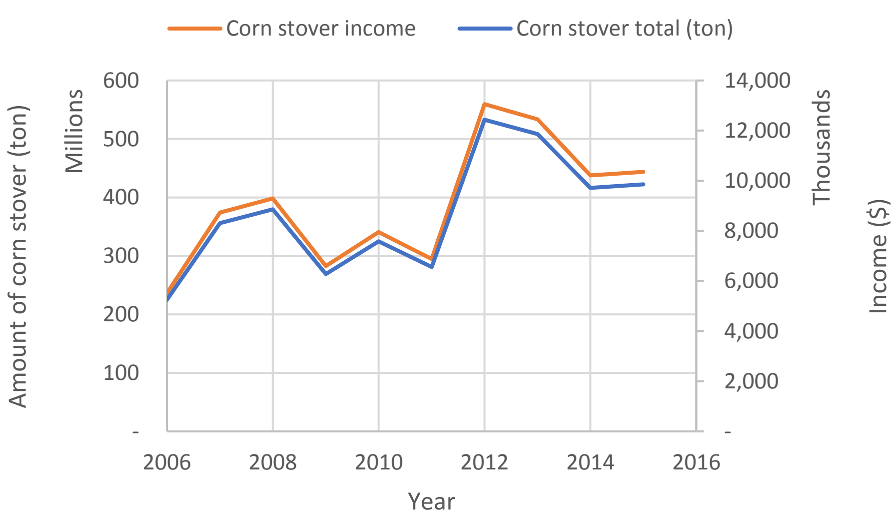


Figure 2.4. Corn stover volume and associated income in ND from 2006-2015 (Source: Estimated from USDA, 2016a).

As shown in Table 2.3, maximizing the profit using a financial incentive of $5.7 under no rail allocation and with an emission cost of $0 will yield a profit of $62,347,604, coupled with 16,941,642 metric tons of emissions. For the same scenario and using the highest incentive value of $7.2 per ton of corn stover, we get that 32% will be converted corresponding to a profit of $66,978,531. The amount of emissions emitted along the supply chain also slightly decreases as the amount of incentive increases from *low* to *high*, and from 16,941,642 to 16,798,117 metric tons.

When the goal is to maximize profit with emission considerations the overall profit is, expectedly, lower in all three cases. With this objective, the incentive and rail capacity is set to zero while varying the cost of emissions. At the *low* case (emission cost set to $61.8), only 19% of corn stover is converted. We also observe here that the emissions are primarily from conventional fossil fuels and the biomass supply chain since we consider energy substitution from petroleum to bioethanol. What is interesting is that more corn stover is converted as emission prices increase: 26% of corn stover is converted at $71.7 for the emission price, and 32% of corn stover is converted when the price is set to $81.6 per ton of emissions. In the *low* case, the amount of emissions is 16,941,642 and keeps decreasing as we move towards the high case. Continuing, when minimizing emissions, the incentive and emission costs are set to zero since there is no effect when varying both elements. However, increasing the rail capacity will indeed reduce the total emissions, as rail is, in general, more environmentally friendly than truck transportation. In fact, minimizing emissions provides us with the lowest emission values compared to the other two objectives. In Table 2.4 with 10% rail capacity, total emissions decreased from 16,745,899 to 16,732,090 metric tons and 37% of corn stover was converted which marks the highest performance that could be reached when minimizing emissions.

Furthermore, both profit maximization objectives show increments in their profits and decreases in the emissions as rail capacity allocation is increased to 10%. The *low* case of maximizing the profit without emissions consideration indicates that a profit of $67,368,476 is gained by incentivizing $5.7 per ton of corn stover to be converted, while the emissions are decreased to 16,931,125 metric tons. As the incentive goes up towards the *high* case, the profit upsurges thus decreasing the amount of emissions. Similarly, penalizing the emissions in the profit maximization objective reduces the amount of emissions as the cost of emissions increases, but it also reduces the profit. In the *low* case, the changing point for the corn stover to be converted is at the $61.8 emissions price with 19% while at the *high* case of $81.6, the maximum amount of corn stover converted is 32% of total corn stover available in the fields. The amount of emissions decreased as the rail capacity increased for the minimization objective as revealed in Table 2.5. About 16,728,106 metric tons of emissions are emitted when 20% of rail capacity is allowed. This shows that transportation of corn stover by rail is preferable when one considers the sustainability of the supply chain network by emitting less emissions, compared to truck transportation. Moreover, increasing the rail capacity also increases the profit in the maximization objective. In the *low* incentive case of $5.7, increasing the rail capacity from 0% to 10% increases the profits borne from $62,347,604 to $67,368,476. The profits increase to $68,266,597 when allowing another 10% of the rail capacity, resulting in a total of 20% of capacity. In the same manner as the emission minimization objective, profit maximization admits a decrease in the amount of emissions as rail capacity is increased. Essentially, if one would like to consider both the emissions and profits as part of their policy making, setting the emission price at $71.7 with 20% rail capacity seems to be the most relevant focal point as it produces the lowest emissions value of 16,794,068 metric tons along with $46,451,219 in profits.

For a comparison of the impact that each dollar value paid in incentives and emissions prices has on supply chain profit and amount of emissions, we also present Tables 2.6, 2.7, and 2.8. These results are based on an experiment where we simultaneously control both the incentive and the emissions prices. We define five subcategories, namely *very low*, *low*, *average*, *high*, and *very high*. At the first case (*very low*), both incentive and emission prices are set to \$0: we treat this as our base case. At 0% rail capacity, \$49,949,555 profit is made with 16,947,942 metric tons of emissions produced. Increasing the rail capacity to 10% and 20% lead to a profit of \$54,970,427 and \$55,870,163 respectively, thus reducing the amount of emissions. For the next case (*low*), a \$5.7 incentive is introduced while penalizing the emissions at \$61.8. These values were obtained from the previous experiment (whose results were presented in Tables 2.3, 2.4 and 2.5). It is indicated that \$61,209,300 in profit is made and 16,798,117 in emissions produced at 0% rail capacity, \$66,206,931 and 16,787,378 at 10% rail capacity, and \$67,681,370 and 16,748,475 at 20% rail capacity.

In the case of *high* incentive and emission price value, \$66,978,531 of profit created with 32% of corn stover converted. Allowing 10% rail capacity increased the profit to 71,969,323 while reducing the supply chain emissions from 16,798,117 to 16,787,273 metric tons. The changing point for the amount of corn stover started at \$7.0 incentive and \$72.4 emissions price when allowing 20% rail capacity. At this stage, the incentive and emission price value should be set at the lower point than before when an upper bound of 20% for rail capacity is used. The *average* case seems to behave similarly to the *high* one, where the incentive and emission price is explored to be \$6.35 and \$67.1, respectively, at 20.

We finally introduce a *very high* case, where the incentive and emission costs are set to the highest point, a clearly unrealistic economically plan, that is though used to achieve the maximum amount of corn stover converted (37%). We also observe that there is a big gap between the incentive and emission values seen in the *high* and the *very high* cases. About $133.7 of incentive and $1,804.3 of emission price are needed to convert 37% of corn stover at 0% rail capacity (from the previously observed 32%). The same applies to the 10% and 20% rail capacity allocations. Overall, in the Tables provided, we explore the impact of incentivizing and penalizing the emission at the same time and we note that both elements are very useful tools to increase profits while reducing total emissions in the supply chain. We observe here that in all three Tables, we provide an area of a total of 9 combinations (depicted in green) where the amount of corn stover converted is unchanged regardless the combination of incentive and emission pricing. We believe this to be the "plateau" of solutions among which an optimal policy can be devised.

The environmental aspect of biomass supply chains is also a very significant point of discussion, seeing as GHG emissions are, and have been for a long time, a crucial topic of debate around the world. Researchers and policy makers alike have made efforts to identify the best approaches and solutions to satisfy energy demand while being environmentally cautious. This study reveals some findings on the amount of CO_2 emissions produced during the process of converting corn stover from farms to the biofuel distributed to the end customers, and compares them with the emissions produced by in-field corn stover open burning. Biofuels, as opposed to the use of conventional fuel, such as petroleum, are advantageous to that extent as they enable shrinking of the amount of GHG emissions, promote sustainability, stabilize agricultural demand and supply, and facilitate the path to regional prosperity (Demirbas, 2009; Demirbas, 2007). Conversely, the use of conventional fuel, and particularly petroleum in ND, is a major contributor of GHG emissions; continuing to choose oil as the main energy source could lead to more severe degradations of our ecosystems (Hossain et al., 2008). Overall, switching our main energy sources to a more renewable, more sustainable, and more environmentally friendly sources is a necessity (Singh and Singh, 2011; He et al., 2010). As far as the ongoing discussion on climate change is concerned, the amount of emissions produced from oil and coal in ND is pessimistic (Bureau of Land Management, 2010). In this regard, higher carbon prices and penalties might be a suitable strategy in order to observe a reduction in the amount of emissions, which is a strategy already planned and applied in many countries worldwide (C2ES, 2013). Based on Environmental and Energy Study Institute (EESI) (2012), the California Bay Area Air Quality Management District has set a \$0.042 per ton of CO_2 emissions tax to any emissions emanating from the industrial sector. On the contrary, within our study, we proposed a decision support system enabling various emissions prices for ND, which can serve as a compass for policy making when also considering maximizing the private sector global supply chain profits.

Table 2.3. Results obtained when allowing for 0% rail capacity (no rail transportation).

Objective	Max Profit			Min Emissions	Max Profit – emission cost		
Case	Low	Medium	High		Low	Medium	High
0% rail capacity	**$5.7 incentive**, 0% rail cap, $0 Emission price	**$6.45 incentive**, 0% rail cap, $0 Emission price	**$7.2 incentive**, 0% rail cap, $0 Emission price	$0 incentive, **0% rail cap**, $0 Emission price	$0 incentive, 0% rail cap, **$61.8 Emission price**	$0 incentive, 0% rail cap, **$71.7 Emission price**	$0 incentive, 0% rail cap, **$81.6 Emission price**
Profit ($)	$62,347,604	$64,372,986.17	$66,978,531	$(49,353,765)	$49,566,875	$44,401,470	$39,518,079
Emissions (metric ton)	16,941,642	16,861,128	16,798,117	16,745,899	16,941,642	16,864,183	16,800,953
Profit-emission cost	$62,347,604	$64,372,986.17	$66,978,531	$(49,353,765)	$(997,426,606)	$(1,164,760,453)	$(1,331,439,658)
% of corn stover converted	19%	26%	32%	37%	19%	26%	32%

Table 2.4. Results obtained when allocating 10% of ND rail capacity for biomass purposes.

Objective	Max Profit			Min Emissions	Max Profit – emission cost		
Case	Low	Medium	High		Low	Medium	High
10% rail capacity	$5.7 incentive, 10% rail cap, $0 Emission price	$6.45 incentive, 10% rail cap, $0 Emission price	$7.2 incentive, 10% rail cap, $0 Emission price	$0 incentive, 10% rail cap, $0 Emission price	$0 incentive, 10% rail cap, $61.8 Emission price	$0 incentive, 10% rail cap, $71.7 Emission price	$0 incentive, 10% rail cap, $81.6 Emission price
Profit ($)	$67,368,476	$69,376,276	$71,981,821	$(44,092,275)	$54,582,650	$49,393,278	$44,508,871
Emissions (metric ton)	16,931,125	16,850,582	16,787,571	16,732,090	16,930,897	16,853,353	16,790,108
Profit-emission cost	$67,368,476	$69,376,276	$71,981,821	$(44,092,275)	$(991,746,811)	$(1,158,992,098)	$(1,325,563,957)
% of corn stover converted	19%	26%	32%	37%	19%	26%	32%

Table 2.5. Results obtained when allocating 20% of ND rail capacity for biomass purposes.

Objective	**Max Profit**			**Min Emissions**	**Max Profit – emission cost**		
Case	Low	Medium	High		Low	Medium	High
20% rail capacity	$5.7 incentive, 20% rail cap, $0 Emission price	$6.45 incentive, 20% rail cap, $0 Emission price	$7.2 incentive, 20% rail cap, $0 Emission price	$0 incentive, 20% rail cap, $0 Emission price	$0 incentive, 20% rail cap, $61.8 Emission price	$0 incentive, 20% rail cap, $71.7 Emission price	$0 incentive, 20% rail cap, $81.6 Emission price
Profit ($)	$68,266,597	$70,578,298	$73,462,599	$(42,393,900)	$55,475,259	$46,451,219	$45,740,767
Emissions (metric ton)	16,930,655	16,787,630	16,784,953	16,728,106	16,930,094	16,794,068	16,784,232
Profit-emission cost	$68,266,597	$70,578,298	$73,462,599	$(42,393,900)	$(990,804,527)	$(1,157,683,431)	$(1,323,852,552)
% of corn stover converted	19%	32%	32%	37%	19%	31%	32%

Table 2.6. Incentives vs. emission costs at 0% rail capacity.

0%				Emission Price				
				Very low $0	Low $61.8	Medium $71.7	High $81.6	Very high $1804.3
Incentive	Very low	$0	Profit ($)	49,949,555	$49,566,875	$44,401,470	$39,518,079	$(49,353,765)
			Emissions (metric ton)	16,947,942	16,941,642	16,864,183	16,800,953	16,745,899
			Profit-emission cost ($)	49,949,555	$(997,426,606)	$(1,164,760,453)	$(1,331,439,658)	$(30,263,980,026)
			% of corn stover converted	18%	19%	26%	32%	37%
	Low	$5.7	Profit ($)	$62,347,604	$61,209,300	$61,209,300	$61,209,300	$(23,617,980)
			Emissions (metric ton)	16,941,642	16,798,117	16,798,117	16,798,117	16,745,899
			Profit-emission cost ($)	$62,347,604	(976,914,332)	$(1,143,215,691)	$(1,309,517,049)	$(30,238,244,241)
			% of corn stover converted	19%	32%	32%	32%	37%
	Medium	$6.45	Profit ($)	$64,372,986	$64,093,915	$64,093,915	$64,093,915	$(20,231,692)
			Emissions (metric ton)	16,861,128	16,798,117	16,798,117	16,798,117	16,745,899
			Profit-emission cost ($)	$64,372,986	$(974,029,717)	(1,140,331,075)	$(1,306,632,434)	$(30,234,857,953)
			% of corn stover converted	26%	32%	32%	32%	37%
	High	$7.20	Profit ($)	$66,978,531	$66,978,531	$66,978,531	$66,978,531	$(16,845,405)
			Emissions (metric ton)	16,798,117	16,798,117	16,798,117	16,798,117	16,745,899
			Profit-emission cost ($)	$66,978,531	$(971,145,101)	$(1,137,446,460)	(1,303,747,818)	$(30,231,471,666)
			% of corn stover converted	32%	32%	32%	32%	37%
	Very high	$133.7	Profit ($)	$554,308,419	$554,308,419	$554,308,419	$554,308,419	$554,308,419
			Emissions (metric ton)	16,745,899	16,745,899	16,745,899	16,745,899	16,745,899
			Profit-emission cost ($)	$554,308,419	$(480,588,162)	$(646,372,566)	$(812,156,970)	(29,660,317,841)
			% of corn stover converted	37%	37%	37%	37%	37%

Table 2.7. Incentives vs. emission costs at 10% rail capacity.

10%				Emission Price				
				Very low $0	Low $61.8	Medium $71.7	High $81.6	Very high $1804.3
Incentive	Very low	$0	Profit ($)	54,970,427	$54,582,650	$49,393,278	$44,508,871	$(43,996,566)
			Emissions (metric ton)	16,937,425	16,930,897	16,853,353	16,790,108	16,732,120
			Profit-emission cost ($)	54,970,427	$(991,746,811)	$(1,158,992,098)	$(1,325,563,957)	$(30,233,761,315)
			% of corn stover converted	18%	19%	26%	32%	37%
	Low	$5.7	Profit ($)	$67,368,476	66,206,931	$66,201,107	$66,200,092	$(18,260,781)
			Emissions (metric ton)	16,931,125	16,787,378	16,787,287	16,787,273	16,732,120
			Profit-emission cost ($)	$67,368,476	(971,253,059)	$(1,137,447,335)	$(1,303,641,348)	$(30,208,025,530)
			% of corn stover converted	19%	32%	32%	32%	37%
	Medium	$6.45	Profit ($)	$69,376,276	$69,091,546	$69,085,723	$69,084,707	$(14,874,494)
			Emissions (metric ton)	16,850,582	16,787,378	16,787,287	16,787,273	16,732,120
			Profit-emission cost ($)	$69,376,276	$(968,368,443)	(1,134,562,720)	$(1,300,756,732)	$(30,204,639,242)
			% of corn stover converted	26%	32%	32%	32%	37%
	High	$7.20	Profit ($)	$71,981,821	$71,976,162	$71,970,338	71,969,323	$(11,488,206)
			Emissions (metric ton)	16,787,571	16,787,378	16,787,287	16,787,273	16,732,120
			Profit-emission cost ($)	$71,981,821	$(965,483,828)	$(1,131,678,104)	(1,297,872,117)	$(30,201,252,955)
			% of corn stover converted	32%	32%	32%	32%	37%
	Very high	$133.7	Profit ($)	$559,949,546	$559,944,326	$559,944,326	$559,944,326	$559,665,618
			Emissions (metric ton)	16,733,134	16,732,985	16,732,985	16,732,985	16,732,120
			Profit-emission cost ($)	$559,949,546	$(474,154,141)	$(639,810,691)	$(805,467,242)	(29,630,099,130)
			% of corn stover converted	37%	37%	37%	37%	37%

Table 2.8. Incentives vs. emission costs at 20% rail capacity.

20%			Emission Price				
Incentive			Very low $0	Low $61.8	Medium $71.7	High $81.6	Very high $1804.3
Very low	$0	Profit ($)	55,870,163	$55,475,259	$46,451,219	$45,740,767	$(42,263,539)
		Emissions (metric ton)	16,936,971	16,930,094	16,794,068	16,784,232	16,728,159
		Profit-emission cost ($)	55,870,163	$(990,804,527)	$(1,157,683,431)	$(1,323,852,552)	$(30,224,880,982)
		% of corn stover converted	18%	19%	31%	32%	37%
Low	$5.7	Profit ($)	$68,266,597	$67,681,370	$67,672,795	$67,663,844	$(16,527,754)
		Emissions (metric ton)	16,930,655	16,784,475	16,784,350	16,784,232	16,728,159
		Profit-emission cost ($)	$68,266,597	(969,599,167)	$(1,135,765,081)	$(1,301,929,474)	$(30,199,145,197)
		% of corn stover converted	19%	32%	32%	32%	37%
Medium	$6.45	Profit ($)	$70,578,298	$70,565,986	$70,557,411	$70,548,460	$(13,141,466)
		Emissions (metric ton)	16,787,630	16,784,475	16,784,350	16,784,232	16,728,159
		Profit-emission cost ($)	$70,578,298	$(966,714,552)	$(1,132,880,465)	$(1,299,044,859)	$(30,195,758,910)
		% of corn stover converted	32%	32%	32%	32%	37%
High	$7.20	Profit ($)	$73,462,599	$73,450,601	$73,442,026	$73,433,075	$(9,755,179)
		Emissions (metric ton)	16,784,953	16,784,475	16,784,350	16,784,232	16,728,159
		Profit-emission cost ($)	$73,462,599	$(963,829,936)	$(1,129,995,850)	$(1,296,160,243)	$(30,192,372,622)
		% of corn stover converted	32%	32%	32%	32%	37%
Very high	$133.7	Profit ($)	$561,814,126	$561,794,162	$561,790,565	$561,785,004	$561,398,645
		Emissions (metric ton)	16,730,175	16,729,463	16,729,408	16,729,337	16,728,159
		Profit-emission cost ($)	$561,814,126	$(472,086,679)	$(637,707,996)	$(803,328,910)	$(29,621,218,797)
		% of corn stover converted	37%	37%	37%	37%	37%

2.5. Conclusions and policy implications

Designing biomass supply chains is not an easy feat; this becomes increasingly hard when considering the variety of different actors (farmers, biorefineries, transportation operators, and government) who need to balance a series of conflicting objectives, such as profit maximization and emissions minimization in our study. The main contribution of this paper is designing a decision support system which helps investigate the impact of incentives vs. emissions prices and their trade-off. In our setup, a series of incentives for farms in ND is used with the goal of preventing open-field burning in favor of converting leftover biomass feedstock. Government intervention on incentivizing biomass production is crucial for sustainability in the U.S. industrial sector. The biomass crop assistance program (BCAP), which was introduced to aid growers to sustain cleaner production, can be a good starting strategy to reduce the total amount of GHG emissions, decrease dependency on fossil fuels, and contribute to more sustainable energy, while assisting farmers to increase their income and reap societal and environmental benefits. Impacts of incentives and emission penalties in the biomass supply chain are explored, contributing to analyzing policy strategies that are incentivizing biomass supplier while achieving sustainability by penalizing the emissions in the supply chain. Thus, incentives and emission price can prove to be useful tools when attempting to increase global supply chain profit while, at the same time, decrease total emissions in the supply chain.

Allowing a monetary incentive of $5.7 per ton of corn stover generates $62,347,604 in profits without allowing for any rail capacity; this total profit increases to $68,266,597 when allowing a maximum of 20% of ND rail capacity. Moreover, increasing the incentive to $7.2 per ton will increase the profits to $66,978,531, while also reducing total emissions. The preferred transportation mode for corn stover from storage to biorefinery is rail, as it is cheaper and produces less emissions. As an extra safety consideration, increasing rail usage also leads to less truck movements on ND roads. Also, increasing the emissions price is another strategy to mitigate the total supply chain emissions. A price of $72.4 per ton of emission is identified as the ideal price to get the lowest emissions while maximizing profits.

The policy implications stem from the incentive and emission prices for emissions regulation. The model proposed, when applied to North Dakota, provides us with a roadmap for how biomass production and consequently open-field burning changes as incentives and objectives change. An important implication is that it is not only the incentive that plays a role in adopting biomass, but also the emission price that should be implemented. The emission price presented in this case study could serve as an indicator of the price that should be set up in North Dakota and similar states as a policy guide to reduce dependency on fossil fuels and hence mitigate GHG emissions.

Finally, as a future direction for research and energy policy, expanding the incentives to include nonmonetary rewards would further broaden the scope of modern biomass supply chains and could provide more insight in renewable energy production under volatility of prices. In this work, it was assumed that the policy-making agency is the sole decider of how farms react to financial incentives; what would be interesting is to formulate the problem in a way where each individual entity (farms, biorefineries) can make its own decisions based on a series of available incentives. Finally, in this case study, the amount of corn stover converted to biomass can never exceed 32% of the available corn stover, due to capacity limitations on the biorefinery side. Investigating how that conversion level can be increased through proper design and location of a new biorefinery would also be beneficial to North Dakota and the region.

3. PLANT CAPACITY LEVEL AND LOCATION AS A MECHANISM FOR SUSTAINABILITY IN BIOMASS SUPPLY CHAIN

3.1. Abstract

Biomass is an important energy source that has the ability to reduce dependencies on fossil fuels, while providing a greener source of energy and helping achieve sustainability. Among the most commonly used biomass feedstock is corn stover, corn residue remaining in the fields after harvesting. One of the biggest challenges of using corn stover as biomass feedstock is that burning it in field is the fastest and cheapest way for many growers so as to remove it and grow new crops. This leftover corn stover could be, instead, converted to bioethanol. In this work, we propose a decision support system for expanding existing biorefineries or building new ones to help stakeholders design a supply chain network model that converts all of the available corn stover to bioethanol. Two configurations presented in this study which is the existing plant expansion (EP) configuration and the combination of existing and new plant configuration (ENP), by exploring the incentive and emission price value for the bioenergy plant to achieve the goal. The aim of converting all corn stover is successfully achieved along with the other goals of achieving sustainability by reducing the amount of emissions in the supply chain. Result shows that the lowest emissions that can be emitted while maximizing the supply chain profit is 16,069,837 metric ton by expanding the existing plants and build new plants.

3.2. Introduction

Biomass is a renewable energy source derived from plants and animals, and it is used to produce different forms of energy such as biofuels and biopower. We have observed an increase in the use of biomass as an alternative energy source around the world, due to its potential to reduce greenhouse gas emissions (GHG) while simultaneously reducing our dependency on fossil fuels. It has been shown that substituting fossil fuel production and consumption with biofuels can mitigate the impact of CO_2 emissions (Ghatak, 2011). The use of biomass energy can also reduce a country's dependence on foreign oil, as well as support its own agricultural and forest product industries. In the United States, biomass consumption for biofuel production in 2016 originated from agricultural residues (48%), wood (41%), and municipal waste (11%) (U.S. Energy Information Administration, 2017b), which shows that biomass from agricultural residues is an important resource (Perlack et al., 2005). In addition, the depletion of fossil fuel reserves and increasing oil prices have led to a renewed interest in biomass sources, on top of its already recognized capacity of providing clean and sustainable energy sources (Sharma et al., 2013). Hence, industrialized countries are actively aligning their objectives and goals towards renewable energy using biomass (Young et al., 2018). Specifically, energy consumption in the United States in the residential, commercial, and industrial building sectors shows a relatively high usage rate (Mohamed et al., 2017). Combined with the depletion of fossil fuel resources (Shafiee and Topal, 2009) that has sparked a worldwide shift to renewable energy, greater emphasis needs to be placed on the technologies used in the process of producing bioenergy (Raftery and Karim, 2017).

Agricultural residues have the potential then to provide a better future from three different viewpoints: societal, environmental, and economical. The first two can be reaped from the decreased emissions from cleaner production and the support of local agricultural economies, as their residues are no longer burned or discarded, but instead sold. The latter though stems from the interdependent nature of the industries associated with bioenergy: for example, industrial sectors that are related to transportation can be enhanced by proper use of biofuels, which in turn can create new industries and employment opportunities, thus contributing to the economy.

In addition to that, biomass supply chain management has created a new paradigm for research on how to select strategies that help adopt energy sources that mitigate GHG emissions. A number of strategies have been suggested towards carbon-free power generation in the energy production sector. For example, power plants can integrate traditional fossil fuels with biomass, aiming to balance biomass source availability with customer electricity demands, and existing power plant configurations. This can be achieved through proper application of operations research and optimization techniques to coordinate the supply chain (Lainez-Aguirre et al., 2017). Technological advancements also play a crucial role in improving the efficiency of biomass resource utilization (Akgul et al., 2012). In this regard, since different sectors (agricultural, transportation, biofuel conversion) are interconnected, cooperation and coordination is crucial for providing smooth supply chain while giving an excess to troubleshoot any disruption in the supply chain. The support also comes from the government and policy makers to address their objectives of reducing emissions while reducing total supply chain cost.

Finally, the size of a biorefinery correlates to the capacity it can handle, and is an important factor affecting the biomass supply chain. Biorefinery capacity is one of the key factors in determining the minimum ethanol selling price (MESP) as well as the environmental impact in bioenergy production (Kim and Dale, 2015). Larger biorefineries will lead to decreased MESP, due to economies of scale. Also, lower environmental impact benefits can be reaped through a centralized system for deciding biorefinery locations (Kim and Dale, 2015). In our work, we propose a centralized decision support system for either expanding existing biorefineries or building new ones to help in the design of a supply chain network model that achieves a 100% conversion of the available corn stover to biofuel.

In our work, the distribution network for corn stover includes farms, storages, biorefineries (plants), and customers. Corn stover is transported from farms to intermediary storage facilities, or directly to nearby plants, using trucks and the road transportation network. In the case of transporting corn stover from storage facilities to plants, railroad can also be used in conjunction to road transportation. Finally, biorefineries are responsible for the distribution of the biofuels produced to the customer markets. Our configuration is also shown in pictorial format in Figure 3.1. Throughout the study, we treat our model as a global supply chain system, implying that there exists full coordination between all entities and the profits and emissions obtained from our model are treated as one global result. The benefit of this approach is that it can serve as a tool the government and the decision-making stakeholders on how to improve the renewable energy production sector.

The remainder of this paper is organized as follows. Section 2 presents a brief literature review on related topics, including biorefinery location optimization, biomass conversion technologies and their effects on the supply chain, and incentive policies, among others. Section 3, then, introduces the materials and methods used in developing our model: more specifically, it presents details on our model development, mathematical formulation, data collection, and the case study for model validation. The results and discussion of the case study in North Dakota is presented in Section 4. Finally, in Section 5 we conclude our paper and offer potential future research directions.

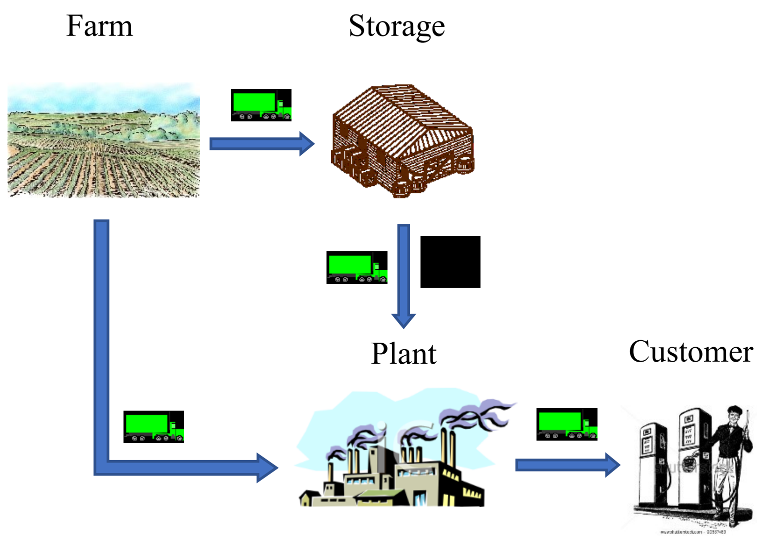


Figure 3.1. Corn stover Supply chain network for bioethanol production.

3.3. Literature review

To better understand the economic viability impact of a biorefinery, Wang et al. (2017) quantify the size of the logistical resources in the biomass supply system with different sizes of biorefinery. Using a simulation approach, three scenarios are considered based on three biorefineries of different sizes, namely small scale, medium scale, and large scale. Their study reveals that as biorefinery size increases, the level of complexity in logistics system rises, too. Moreover, what is very important is that biorefinery size also impacts feedstock movements and, consequently, transportation costs. This can also be observed in a study by Clauser et al. (2016) on small-sized biorefineries.

The facility location problem in biomass supply chain, as presented by Gonzales and Searcy (2017), uses GIS as a tool to determine the location and size of potential biorefineries and depots. County centroids are used in the model, for simplicity, as potential supply points and facilities. A heuristic method is then proposed and developed within the GIS platform to address the facility location problem. As a result of their experiment on six states in the United States, they were able to identify optimal locations for 77 biorefineries and 171 depots. Using GIS tools in facility location problem is common and is also the focus of the study by Sahoo et al. (2016). Therein, the authors identify optimal biorefinery sites for biomass supply chain, which considers the economics of collection and utilization of biomass feedstock. Their proposed model uses multi-criteria geospatial analysis for the biorefinery sites in conjunction with an artificial neural network prediction model to be included within the GIS platform. This integrated model is developed to assess the sustainability of the available crop residues, which are categorized in three different primary sustainability indicators. In another integrated approach, one combining GIS-based analysis with an optimization model, Zhang et al. (2017) locate biorefineries considering the spring breakup period in the biomass supply chain under uncertainty. Two types of costs are calculated and assessed, namely the total system cost and the delivered feedstock cost. Computational results show that there are significant increases in both cost values as the biomass availability decreases or as the annual bioethanol demand increases.

Craige et al. (2016) model a biomass supply chain that selects biorefinery location, transportation, processing, harvest and refining costs, using geospatial programming. The model helps evaluate the economic feasibility of simultaneously producing multiple products from biomass feedstock. Furthermore, in their work, De Meyer et al. (2016) present a multi-period mixed integer linear programming model for biomass supply chain with considerations of the changing biomass characteristics, because of handling operations and biomass growth. Planning for biofuel refinery locations has been studied by Bai et al. (2011) considering the traffic congestion impacts. Their results show that transportation cost of biomass shipments and congestion is reduced upon careful biorefinery location planning.

The biofuel conversion process makes use of a range of types of technologies, including LCE (cellulosic ethanol through hydrolysis and fermentation), LCMD (Fischer Tropsch diesel), LCG (upgrading of pyrolysis oils to gasoline), FAME (fatty acid to methyl esters), and FAHC (hydrotreatment of fatty acids to hydrocarbons) based on research done by Parker et al. (2010). In their study, an optimization model is developed by considering potential biofuel supply points to determine optimal biorefinery locations, technology types, and their sizes. Li et al. (2015) develop an optimization model for biomass supply chain design with facility expansion of cellulosic fuels production and profit maximization for a given time horizon. Their work emphasizes on the importance of locating biorefineries in centralized areas within a region, as well as higher capacity biorefineries to take advantage of economies of scale.

The implications of strategic behavior in biomass supply chain design are examined by Huang and Chen (2014). In their work, they incorporate policy designs to evaluate supply chain operations and the observed market outcomes. Economic performance and energy efficiency of biofuel supply chains is studied by Ng and Maravelias (2017) who consider the impact of biorefinery sizes, the distance between harvesting sites and depots (for pre-treatment), and biomass productivity. Their results show that a supply chain network design without depots gives a better economic outlook and higher energy efficiency for small-scale biorefineries. In another study related to facilities location planning, Hu et al. (2017) propose a bi-objective two-stage robust model for designing an energy conversion facility to assist governments and stakeholders in making informed decisions based on both economic and environmental aspects.

The inherent complexity in biofuel production and the expensive plant technology and transportation costs are among the main barriers that hinder the establishment of economic competitiveness (Lauven, 2014). To mitigate them, a non-linear optimization model is proposed to identify optimal plant capacities and setups, as a strategy to analyze the economic competitiveness of biofuel production. Their work shows that plant capacities at levels of 1 to

1.5 million tons per year result in an optimal trade-off between product sales, economies of scale, and biomass transportation. Therein, the authors conclude that biomass procurement is highly complex due to uncertainties related to sudden biomass price rises, changes in available residual biomass, and the resulting competition. A series of other, logistical challenges is identified by Ekşioğlu et al. (2009), who use a mixed integer programming model to analyze the supply chain from biomass as a feedstock to bioenergy production. Their model helps identify candidate locations for biorefineries and blending facilities, with their analysis showing that biorefinery location decisions are affected by transportation costs and that biomass availability drives biorefineries to be close to harvesting sites.

Another crucial issue is that as technologies advance, biorefinery locations and operations also change. Parker et al. (2010) perform a comparative analysis of a series of conversion technologies (some of them were mentioned in an earlier part of our literature review) for different biomass feedstock. In their work, they identify the optimal biorefinery locations and sizes with the aim of maximizing industry profits. They do so integrating two models: a geographically-explicity biomass resource assessment model, and an infrastructure network model. The authors employ those and the conversion technology technoeconomic models available in the literature to find an optimal biofuel supply chain configuration. The proposed model is also capable of performing a sensitivity analysis to changes in resource types, production yields, changing biorefinery capacity, and the overall efficiency of the supply chain. To establish a facility for bioenergy production, Rentizelas and Tatsiopoulos (2010) consider a wide geographical region around the energy consumer as potential candidate locations. Their model aims to maximize the net present value of the total system by deciding biorefinery locations. They consider a hybrid optimization model to tackle the problem and contrast it with a stochastic genetic algorithm framework and an exact optimization method (namely, sequential quadratic programming). Their results show the success of their hybrid method, which is shown to address the complexity of this facility problem with increased reliability, as opposed to the genetic algorithm and the sequential quadratic programming frameworks used.

On a different perspective in the biomass supply chain and the renewable energy section, there is an increased interest in mitigating GHG emissions, both among academicians and practitioners. This is done by utilizing available environmental analysis tools, such as life cycle assessment on fuel production, transportation, and biorefinery operations, for example (Ghafghazi et al., 2011). In another research product on emissions reported by Ebadian et al. (2013), the authors show an 8% decrease in the amount of CO_2 emissions when using a roadside storage systems, as opposed to satellite in a biomass supply chain for cellulosic ethanol production. Concerned with climate change and environmental sustainability, Chang (2014) develop a heuristic for coordinating hybrid renewable energy system and planning as a decision support system tool. Still concerned with emissions and their impacts, Mattiussi et al. (2014) design a sustainable plant for energy supply that considers emissions. Complex decision making in the energy (Hunt et al., 2013; Kurkalova and Carter, 2017; Hakanen et al., 2011), and transportation sectors (Macharis et al., 2012) are also some other examples of how sustainability can be achieved with the assistance of decision support systems.

Government intervention can help promote sustainability in the energy industry by providing financial incentives to energy producers who adopt or use biomass. The importance of incentives from government can be seen as the necessary booster for the development of the renewable energy industry for the benefit of society, economy, and the environment. In fact, many countries have been advocating for the adoption of incentive programs at the state and national levels to promote the use of renewable energy (Rosaly and Laurèn, 2013), although the differences between adoption rates of incentives policy across countries pose some challenges (Bangalore et al., 2016). Since incentivizing is one of the important elements we are considering in this study, we proceed to highlight some research products by other researchers that showcase how carefully planned incentives can provide support for the well-being and success of a biomass supply chain.

Fully utilizing the potential of renewable energy via technological advancement can be effective when considering incentives mechanism for the aim of reducing cost while complying with emission policies (Simsek and Simsek, 2013). Reducing the dependence on fossil fuel by switching to biofuel leads to a reduction in pollution levels, which in turn raise quality of life levels. In Thailand, an incentive program called premium-price Feed-in Tariff (FIT), or 'Adder' program was introduced and implemented to support the production of renewable energy (Tongsopit and Greacen, 2013). However, this program was said to have some weaknesses and later a more suitable rate for the FIT incentive for hydropower was proposed (Supriyasilp et al., 2017). Furthermore, Ozcan (2014) performed expert elicitation from the perspective of investors for incentive systems for renewable energy sources. This information can lead to a better understanding of how government and state stakeholders play a significant role in improving renewable energy sector by carefully incentivizing. In other studies on biomass incentives, Cobuloglu and Büyüktahtakın (2014) assess the economic and environmental impacts at the farm level.

In our work, we are focusing on a problem specific to corn stover, or corn crop residue, which remains in the farm after harvesting (corn for grain) and will be burned (open-field burning) by the growers to grow new crops. The act of open-field burning is the fastest and cheapest way to get rid of corn stover after harvesting, however it adds to harmful to the environment emissions. Corn stover could be used as biomass feedstock, but high logistics costs for its handling and transportation render this less appealing to farm owners and growers. The influence of transportation in biomass supply chain costs is quite clear and has a significant part in total bioenergy process costs. This is also seen by the fact that reducing transportation costs leads to increasing biomass feedstock prices (Liu et al., 2016). A previous study by Mohamed et al. (2018) in the state of North Dakota showed that only 37% of corn stover can be converted to biofuel, with the rest burned in the field. This occurred due to limited biorefinery processing capacities. This study attempts to increase the percentage of corn stover converted by strategically increasing plant capacities under two scenarios: (i) expanding existing plants to accommodate higher volume, or (ii) building new plants. In addition to this, we also want to explore the amount of additional capacity capabilities that are needed for the existing plants. Last, we also use our models to identify the farms that do not profit from this supply chain model and study the impact that different corn stover prices and transportation costs (at different breakeven points) will have on the obtained plant profits.

3.4. Materials and methods

This section presents our model development, the mathematical formulation of our problem under two different configurations, and the data for our case study for the state of North Dakota in the United States.

3.4.1. Model development

We present a supply chain model for biomass feedstock, formulated as a mixed integer linear program (MILP). The supply chain entities in our model consist of farms, storage facilities, biorefinery (plants), and customers. The biomass feedstock considered in our model is corn stover (i.e., leftover corn crop). The reader is also pointed to Figure 1 for a depiction of the supply chain. Finally, an assumption made here is that corn harvesting has already taken place, and hence only corn stover remains on the fields.

We formulate and solve our optimization models using two objective functions: (i) maximizing total supply chain profits without considerations for emissions penalties, and (ii) maximizing total supply chain profits with an emissions penalty. In a previous study by Mohamed et al. (2018), it was shown that the existing plant configuration and their capacities limit total corn stover converted and prevent mass biopower adoption. Thus, our proposed model attempts to increase the ratio of corn stover converted (and consequently decrease the amount of corn stover burned in field) by increasing plant capacities using two major levers. The first lever is to expand the existing plants by increasing their capacity levels, while the second is to build new plants. At the same time, we want to explore the impact of introducing financial incentives in order to achieve 100% corn stover converted to biofuels. The financial aspects of the biomass supply chain in the proposed model can be seen from the two profit maximization objectives. Varying the incentives dollar value under multiple scenarios grants us an opportunity to analyze the differences and changes in the total profits, as well as the changes in the dollar value paid in the emissions penalties, when expanding existing plants or building new ones.

3.4.2. Formulation

The present two similar, but distinct models, each of which has two objective functions. The two objective functions are selected so as to match the goals of our study. Note that none of the two mathematical programs is formulated as a multi-objective optimization model: instead, we use both objectives to solve two distinct optimization problems. The first model only allows for the expansion of existing facilities, while the second considers also the possibility of creating new plants (from a set of candidate locations). The two models are denoted as *Existing Plant configuration* (EP) and *Existing and New Plant configuration* (ENP) and are presented in subsections 3.4.3 and 3.4.4, respectively.

As for the objective functions selected, the first one is presented in equations (3.1) and (3.19) and aims to maximize the total supply chain profits. The second objective functions, presented in equations (3.2) and (3.20), consider emissions costs on top of the profit maximization. With these objective functions, we can observe both economic and environmental impacts in the biomass supply chain, globally. The decisions made by our models are as follows:

- whether to expand an existing plant, or open a new plant;
- the capacity levels needed for the existing plant expansions;
- the capacity levels needed for newly opened plants;
- the amount of corn stover to be harvested for conversion to biofuel and the amount of corn stover to be burned at every farm;
- the amount of corn stover transported from every farm to the storage facilities, from every farm to the plants, and from every storage facility to the plants, as well as the means of transportation; and
- the biofuel amounts sent from each plant to meet customer demands.

The notation used to represent sets, parameters, and decision variables in the models are provided in Table 3.1. We are now ready to present the two configurations in equations (3.1)—(3.18) and (3.19)—(3.31).

3.4.3. Existing plant configuration (EP) formulation

$$\begin{aligned}
&\begin{matrix} EP \\ \text{Max Profit} \\ (no\ emission\ penalty) \end{matrix} : \left(\phi \cdot \sum_{f \in F} X_f\right) + \left((\Sigma + \Omega) \cdot \mu \cdot \sum_{p \in P} \sum_{c \in C} B_{pc}\right) \\
&- \left[\left(\sum_{f \in F} \alpha_f \cdot X_f\right) + \left(\sum_{p \in P} \sum_{c \in C} \rho_p \cdot B_{pc}\right) + \varrho \right. \\
&\left. \cdot \left(\sum_{f \in F} \sum_{s \in S} Y_{fs} + \sum_{f \in F} \sum_{p \in P} Z_{fp} + \sum_{s \in S} \sum_{p \in P} H_{sp} + \sum_{p \in P} \sum_{c \in C} B_{pc}\right) + \left(\gamma \cdot \sum_{s \in S} \sum_{p \in P} M_{sp}\right)\right] \\
&- \left[(k \cdot \Lambda) + \mu \cdot \sum_{p \in P} \rho_p \cdot \hat{\pi}_p\right]
\end{aligned} \tag{3.1}$$

$$\begin{array}{c} EP \\ \text{Max Profit} \\ (with\ emission\ penalty) \end{array}: \left(\phi \cdot \sum_{f\in F} X_f\right) + \left((\Sigma + \Omega) \cdot \mu \cdot \sum_{p\in P}\sum_{c\in C} B_{pc}\right)$$

$$- \left[\left(\sum_{f\in F} \alpha_f \cdot X_f\right) + \left(\sum_{p\in P}\sum_{c\in C} \rho_p \cdot B_{pc}\right) + \varrho\right.$$

$$\left. \cdot \left(\sum_{f\in F}\sum_{s\in S} Y_{fs} + \sum_{f\in F}\sum_{p\in P} Z_{fp} + \sum_{s\in S}\sum_{p\in P} H_{sp} + \sum_{p\in P}\sum_{c\in C} B_{pc}\right) + \left(\gamma \cdot \sum_{s\in S}\sum_{p\in P} M_{sp}\right)\right]$$

$$- \left[\left(\Gamma\right.\right.$$

$$\cdot \left(\sum_{f\in F}\sum_{s\in S} \zeta_{fs} \cdot Y_{fs} + \sum_{f\in F}\sum_{p\in P} \zeta_{fp} \cdot Z_{fp} + \sum_{s\in S}\sum_{p\in P} \zeta_{sp} \cdot H_{sp} + \sum_{p\in P}\sum_{c\in C} \zeta_{pc} \cdot B_{pc}\right)$$

$$+ \delta \cdot \left(\sum_{s\in S}\sum_{p\in P} \eta_{sp} \cdot M_{sp}\right) + \left(\upsilon \cdot \sum_{f\in F} X_f\right) + \left(\omega \cdot \sum_{f\in F} G_f\right) + \left.\left(\varphi \cdot \sum_{f\in F} (\sigma - X_f)\right)\right)$$

$$\left. \cdot \xi \right] - \left[(k \cdot \Lambda) + \mu \cdot \sum_{p\in P} \rho_p \cdot \hat{\pi}_p\right]$$

(3.2)

Subject to:

$X_f + G_f \leq \varsigma_f \cdot \varpi \cdot \tau,$ $\quad \forall f \in F$ (3.3)

$\left(\sum_{s\in S} Y_{fs} + \sum_{p\in P} Z_{fp}\right) - X_f = 0,$ $\quad \forall f \in F$

(3.4)

$\sum_{f\in F} Y_{fs} - \sum_{p\in P} (H_{sp} + M_{sp}) = 0,$ $\quad \forall\, s \in S$

(3.5)

$$\left(\sum_{f\in F} Z_{fp} + \sum_{s\in S}(H_{sp} + M_{sp})\right)\cdot \mu - \sum_{c\in C} B_{pc} = 0, \qquad \forall\, p \in P \tag{3.6}$$

$$\sum_{f\in F} Y_{fs} \leq \vartheta_s, \qquad \forall s \in S \tag{3.7}$$

$$\sum_{f\in F} Z_{fp} + \sum_{s\in S}(H_{sp} + M_{sp}) \leq \pi_p + \hat{\pi}, \qquad \forall p \in P, \forall k \in K \tag{3.8}$$

$$\textstyle\sum_{p\in P} \hat{\pi}_p \leq \hat{p}, \tag{3.9}$$

$$\hat{\pi}_p \leq \bar{p}\cdot \hat{r}_p, \qquad \forall p \in P \tag{3.10}$$

$$\sum_{s\in S}\sum_{p\in P} M_{sp} \leq \psi \cdot \theta, \qquad \forall s \in S, \forall\, p \in P \tag{3.11}$$

$$X_f \geq 0, \qquad \forall f \in F \tag{3.12}$$

$$G_f \geq 0, \qquad \forall f \in F \tag{3.13}$$

$$Y_{fs} \geq 0, \qquad \forall f \in F, \forall\, s \in S \tag{3.14}$$

$$Z_{fp} \geq 0, \qquad \forall f \in F, \forall\, p \in P \tag{3.15}$$

$$H_{sp} \geq 0, \qquad \forall s \in S, \forall\, p \in P \tag{3.16}$$

$$M_{sp} \geq 0, \qquad \forall s \in S, \forall\, p \in P \tag{3.17}$$

$$B_{pc} \geq 0, \qquad \forall p \in P, \forall\, c \in C \tag{3.18}$$

3.4.4. Existing plant and new plant configuration (*ENP*) formulation

$$
\begin{aligned}
&\underset{(no\ emission\ penalty)}{\overset{ENP}{\text{Max Profit}}}: \left(\phi \cdot \sum_{f\in F} X_f\right) + \left((\Sigma + \Omega)\cdot \mu \cdot \sum_{p\in P}\sum_{c\in C} B_{pc}\right) \\
&- \Bigg[\left(\sum_{f\in F} \alpha_f \cdot X_f\right) + \left(\sum_{p\in P}\sum_{c\in C} \rho_p \cdot B_{pc}\right) + \varrho \\
&\cdot \left(\sum_{f\in F}\sum_{s\in S} Y_{fs} + \sum_{f\in F}\sum_{p\in P} Z_{fp} + \sum_{s\in S}\sum_{p\in P} H_{sp} + \sum_{p\in P}\sum_{c\in C} B_{pc}\right) + \left(\gamma \cdot \sum_{s\in S}\sum_{p\in P} M_{sp}\right)\Bigg] \\
&+ \left[(\Sigma + \Omega)\cdot \mu \cdot \sum_{w\in W}\sum_{c\in C} \widehat{B}_{wc}\right] \\
&- \Bigg[\left(\sum_{w\in W}\sum_{c\in C} \rho_p \cdot \widehat{B}_{wc}\right) + \varrho \\
&\cdot \left(\sum_{f\in F}\sum_{w\in W} \hat{Z}_{fw} + \sum_{s\in S}\sum_{w\in W} \widehat{H}_{sw} + \sum_{s\in S}\sum_{w\in W} \widehat{M}_{sw} + \sum_{w\in W}\sum_{c\in C} \widehat{B}_{wc}\right) \\
&+ \left(\gamma \cdot \sum_{s\in S}\sum_{w\in W} \widehat{M}_{sw}\right)\Bigg] - \left[(k\cdot \Lambda) + \mu \cdot \sum_{p\in P} \rho_p \cdot \hat{\pi}_p\right] - \left[Q \cdot \sum_{p\in P} \hat{r}_p\right] \\
&- \left[\hat{T} \cdot \sum_{w\in W} \widehat{w}_w\right]
\end{aligned}
\tag{3.19}
$$

$$
\begin{aligned}
&\underset{(with\ emission\ penalty)}{\overset{ENP}{\text{Max Profit}}}:\ \left(\phi\cdot\sum_{f\in F}X_f\right)+\left((\Sigma+\Omega)\cdot\mu\cdot\sum_{p\in P}\sum_{c\in C}B_{pc}\right)\\
&-\left[\left(\sum_{f\in F}\alpha_f\cdot X_f\right)+\left(\sum_{p\in P}\sum_{c\in C}\rho_p\cdot B_{pc}\right)+\varrho\right.\\
&\left.\cdot\left(\sum_{f\in F}\sum_{s\in S}Y_{fs}+\sum_{f\in F}\sum_{p\in P}Z_{fp}+\sum_{s\in S}\sum_{p\in P}H_{sp}+\sum_{p\in P}\sum_{c\in C}B_{pc}\right)+\left(\gamma\cdot\sum_{s\in S}\sum_{p\in P}M_{sp}\right)\right]\\
&-\left[\left(\Gamma\right.\right.\\
&\cdot\left(\sum_{f\in F}\sum_{s\in S}\zeta_{fs}\cdot Y_{fs}+\sum_{f\in F}\sum_{p\in P}\zeta_{fp}\cdot Z_{fp}+\sum_{s\in S}\sum_{p\in P}\zeta_{sp}\cdot H_{sp}+\sum_{p\in P}\sum_{c\in C}\zeta_{pc}\cdot B_{pc}\right)+\delta\\
&\left.\left.\cdot\left(\sum_{s\in S}\sum_{p\in P}\eta_{sp}\cdot M_{sp}\right)+\left(\upsilon\cdot\sum_{f\in F}X_f\right)+\left(\omega\cdot\sum_{f\in F}G_f\right)+\left(\varphi\cdot\sum_{f\in F}(\sigma-X_f)\right)\right)\cdot\xi\right]\\
&+\left[(\Sigma+\Omega)\cdot\mu\cdot\sum_{w\in W}\sum_{c\in C}\hat{B}_{wc}\right]\\
&-\left[\left(\sum_{w\in W}\sum_{c\in C}\rho_p\cdot\hat{B}_{wc}\right)+\varrho\cdot\left(\sum_{f\in F}\sum_{w\in W}\hat{Z}_{fw}+\sum_{s\in S}\sum_{w\in W}\hat{H}_{sw}+\sum_{w\in W}\sum_{c\in C}\hat{B}_{wc}\right)\right.\\
&\left.+\left(\gamma\cdot\sum_{s\in S}\sum_{w\in W}\hat{M}_{sw}\right)\right]\\
&-\left[\left(\Gamma\cdot\left(\sum_{f\in F}\sum_{w\in W}\zeta_{fw}\cdot\hat{Z}_{fw}+\sum_{s\in S}\sum_{w\in W}\zeta_{sw}\cdot\hat{H}_{sw}+\sum_{w\in W}\sum_{c\in C}\zeta_{wc}\cdot\hat{B}_{wc}\right)\right.\right.\\
&\left.\left.+\left(\delta\cdot\sum_{s\in S}\sum_{w\in W}\eta_{sw}\cdot\hat{M}_{sw}\right)\right)\cdot\xi\right]-\left[(k\cdot\Lambda)+\mu\cdot\sum_{p\in P}\rho_p\cdot\hat{\pi}_p\right]-\left[Q\cdot\sum_{p\in P}\hat{r}_p\right]\\
&-\left[\hat{T}\cdot\sum_{w\in W}\hat{w}_w\right]
\end{aligned}
\tag{3.20}
$$

Subject to:

$(3.3), (3.7) - (3.18)$

$$\left(\sum_{s\in S} Y_{fs} + \sum_{p\in P} Z_{fp} + \sum_{w\in W} \hat{Z}_{fw}\right) - X_f = 0, \qquad \forall f \in F \tag{3.21}$$

$$\sum_{f\in F} Y_{fs} - \sum_{p\in P}\sum_{w\in W} (H_{sp} + M_{sp} + \widehat{H}_{sw} + \widehat{M}_{sw}) = 0, \qquad \forall\, s \in S \tag{3.22}$$

$$\left(\sum_{f\in F} \hat{Z}_{fw} + \sum_{s\in S} (\widehat{H}_{sw} + \widehat{M}_{sw})\right) \cdot \mu - \sum_{c\in C} \widehat{B}_{wc} = 0, \qquad \forall\, w \in W \tag{3.23}$$

$$\sum_{f\in F} \hat{Z}_{fw} + \sum_{s\in S} (\widehat{H}_{sw} + \widehat{M}_{sw}) \le \hat{n} \cdot \widehat{w}_w, \qquad \forall\, w \in W, \forall f \in F, \forall\, s \in S \tag{3.24}$$

$$\sum_{s\in S}\sum_{w\in W} \widehat{M}_{sw} \le \psi \cdot \theta, \qquad \forall s \in S, \forall\, w \in W \tag{3.25}$$

$$\hat{r}_p, \widehat{w}_w \in \{0,1\} \qquad \forall p \in P, \forall\, w \in W \tag{3.26}$$

$$\hat{Z}_{fw} \ge 0, \qquad \forall f \in F, \forall\, w \in W \tag{3.27}$$

$$\widehat{H}_{sw} \ge 0, \qquad \forall s \in S, \forall\, w \in W \tag{3.28}$$

$$\widehat{M}_{sw} \ge 0, \qquad \forall s \in S, \forall\, w \in W \tag{3.29}$$

$$\widehat{B}_{wc} \ge 0, \qquad \forall w \in W, \forall\, c \in C \tag{3.30}$$

(3.31)

Table 3.1. List Parameters and decision variables for the biomass supply chain model as a decision support system.

Notation

Sets and subscripts

F	Set of farms ($f \in$ F)
S	Set of storage facilities ($s \in$ S)
P	Set of plants ($p \in$ P)
C	Set of all customer ($c \in$ C)
W	Set of candidate plants ($w \in$ W)

Parameters

α_f	Stover harvesting cost for farm f
ρ_p	Ethanol processing cost for plant p
ρ_w	Ethanol processing cost for new plant w
ϕ	Corn stover selling price
Σ	Biofuel selling price
μ	Biomass to biofuel conversion rate
ϖ	Average corn yield per acre of land
τ	Corn yield factor
k	Plant expansion fixed production cost
ξ	Emission/Carbon price
φ	Corn stover equivalent petroleum emissions
Λ	Amortization rate
ς_f	Land area of farm f (in acres)
ψ	Rail capacity allocation
$\hat{T}$	New plant fixed investment cost
Ω	Incentives for plant
ϑ_s	Storage capacity for storage facility s
π_p	Plant capacity
Q	Plant expansion fixed investment cost
Γ	Truck emissions factor
δ	Rail emissions factor
υ	Production emissions factor
ω	Open-field burning emissions factor
σ	Ton of corn stover equivalent to petroleum
$\hat{p}$	Upper limit for overall expansion plant capacity
$\bar{p}$	Upper limit for individual expansion plant capacity
$\hat{n}$	Level of new plant capacity restriction
ζ_{fs}	Distance from farm f to storage s (via truck)
ζ_{fp}	Distance from farm f to existing plant p (truck)
ζ_{sp}	Distance from storage s to existing plant p (via truck)
η_{sp}	Distance from storage s to existing plant p (via rail)
ζ_{pc}	Distance from existing plant p to customer c (via truck)
ζ_{fw}	Distance from farm f to candidate plant w (via truck)
ζ_{sw}	Distance from storage s to candidate plant w (via truck)
η_{sw}	Distance from storage s to candidate plant w (via rail)
ζ_{wc}	Distance from candidate plant w to customer c (via truck)
ϱ	Transportation cost of corn stover via truck
γ	Transportation cost of stover via rail

Decision variables

X_f	Amount of corn stover harvested for biomass in farm f
G_f	Amount of corn stover burned in farm f
Y_{fs}	Amount of corn stover sent from farm f to storage facility s
Z_{fp}	Amount of corn stover sent from farm f to plant p via truck
H_{sp}	Amount of corn stover sent from storage facility s to plant p via truck
M_{sp}	Amount of corn stover sent from storage facility s to plant p via rail
B_{pc}	Amount of biofuel sent from plant p to customer c
$\hat{B}_{wc}$	Amount of biofuel sent from new plant w to customer c
$\hat{Z}_{fw}$	Amount of corn stover sent from farm f to new plant w via truck
$\hat{H}_{sw}$	Amount of corn stover sent from storage facility s to new plant w via truck
$\hat{M}_{sw}$	Amount of corn stover sent from storage facility s to new plant w via rail
$\hat{\pi}$	Plant expansion capacity needed
$\hat{r}_p$	Binary of 1 if expand existing plant, otherwise 0
$\hat{w}_w$	Binary of 1 if open new plant, otherwise 0

Equation (3.1) and (3.2) (resp., Equations (3.19) and (3.20)) represent the objective function for the *EP* (resp., *ENP*) configuration version of the problem: with two objective functions namely maximize profit without emission cost and maximize profit with emission cost.

Objective functions (3.1) and (3.19) contain components that involve profits gained from selling corn stover (from farms to plants), and from selling biofuel (from plants to customers). Their costs include harvesting, processing (with plant expansion costs), and transportation costs, with (3.19) also having costs specific to the development of new plants. Transportation costs consist of corn stover transportation through truck from farms to plants and storages, and transportation through truck and rail from storages to plants, as well as biofuel transportation from plants to customers. Finally, objective functions (3.2) and (3.20) include an extra penalty term to account for an emissions cost.

Constraint family (3.3) ensures that the amount of corn stover cannot exceed the amount available in that farm, an amount that depends on the land area of the farm and historical corn yield data. Constraints (3.4)—(3.6) represent the flow balance at the farm, storage and existing plants; their ENP counterparts are presented in constraints (3.22)—(3.24). Storage capacities are enforced through constraints (3.7); similarly, constraints (3.8) restrict plant capacities, including their expansions—a similar constraint for the ENP configuration concerning new plants is given in (3.25). An upper bound on all expansions available is provided in equations (3.9). An upper bound for each facility available increase is given in (3.10). Constraints (3.11) ensure we respect rail capacities for all amounts transported using the railroad. The same purpose is served, but for new plants, by constraints (3.26). Finally, constraints (3.12)—(3.18), and (3.29)—(3.31) in the ENP configuration, restrict all variables to be nonnegative, and enforce the binary nature of the expansion selection and new plant selection variables. We can now proceed to the next section, which will discuss the implementation details of our model to our case study and the process of data collection.

3.4.5. Data and case study

As a case study to validate the practicality of our decision support system, we use our mathematical models to analyze North Dakota (ND) corn farms. There exists a total of 354 corn farms across 45 counties in ND. The corn stover estimation is based on the corn yield for each farm, using 122 bushels per acre (USDA, 2016a) multiplied by 56 pounds, or 0.028 in tons (Mayer, 2012) which finally gives 3.416 tons of corn stover per acre (which is the value we use). At the moment, ND has *four* active ethanol plants with different capacities. A previous study shows a limitation on the plant capacity to convert all corn stover from all farms in ND. In this regard, this study will look at the possibility to increase the capacity level of an existing plant or determine a need to build a new plant so as to convert 100% of the available corn stover, without leaving any leftovers at the farm level. The main concern here is to prevent open-field burning of the corn stover that has environmental impacts, as well as to utilize a renewable energy source (corn stover) to produce bioenergy to achieve higher environmental sustainability.

Maung and Gustafson (2011) set the selling price of corn stover in ND at about $45 per ton, while the selling price for ethanol is $2.21 per gallon (Tao et al., 2013). Harvesting costs of corn stover are valued at $32.71 per ton (Gallagher, 2012) with a storage cost of $5 per ton (Gustafson et al., 2011). We also use $1.2/mile/truckload for the truck to transport the corn stover and $1.3/mile/truckload for biofuel from plant to customer. For the rail transportation (used to transport corn stover from suitable storage locations to plants) we use $2.5/mile/railcar. Both transportation cost figures are obtained from Xie et al. (2014). For corn stover converted to bioethanol we use a conversion rate of 80.6 gallon/dry ton (Xie et al., 2014). Finally, the total cost of ethanol processing is estimated at $1.50/gallon (Mcaloon et al., 2000).

The customers (markets) considered in our model are the 12 largest cities in ND in terms of population. The final product (bioethanol) is shipped to customers. Distances for the corn stover and biofuel network was obtained through ArcGIS 10.3, developed by Environmental Systems Research Institute (ESRI, 2016). Potential new plant locations are selected to be in the center of each county seat (Osmani and Zhang, 2017; Gonzales and Searcy, 2017). Finally, the model is solved using an optimizer called Open Solver which is developed by Andrew Mason (OpenSolver, 2017).

3.5. Results and discussion

In this section, we discuss the financial and environmental outcomes of our supply chain models (presented in the previous section) when solved to optimality. In the following subsections, we explore the variability of the dollar value paid to energy plants as an incentive to increase the amount of corn stover converted to bioethanol. Our study also focuses on finding the optimal plant capacity level increments needed for existing plants, as well as optimal locations and capacities for new ones. To explore the effect monetary incentives and emission price values have, we use four different scenarios (cases) which are denoted by *Low, Middle Low, Middle High* and *High*.

The scenarios are created as follows. In the *Low* case, we varied the incentive and emission prices to get the smallest value for which changes start to occur for the corn stover converted, while in the *High* case, we found a value for which the corn stover converted reaches the goal of 100%. We amortize the cost of corn stover conversion at an amortization rate of 8% (Brechbill and Tyner, 2008; James, 2013) with three different period: the amortization periods are selected depending on the period where the goal of 100% corn stover conversion is reached. We now proceed to discuss all of our findings in the next sections.

3.5.1. EP configuration results

We start by noting that in the *Low* case here, with only a one-year amortization period, only 37% of available corn stover is converted. This maximum is limited by the available plant capacity in the area. Table 3.2 (where only profit maximization is considered) shows an increment in the amount of corn stover converted to 49%, as the incentive value increases from \$1.18 per gallon to \$1.23 per gallon. This transition of the incentive from *Low* to *Middle Low* results in a reduction of 58,087 metric tons of emissions. To reach a 100% conversion rate, an incentive of \$1.38 per ton is needed, and the profit that can be gained is estimated at \$862.81 million. Increasing the incentive value at \$1.28 (Middle High) and \$1.38 (High) also decreases the amount of emissions to 16,405,076 and 16,132,282, respectively. Clearly, the higher the monetary incentive values injected to the plants, the higher the corn stover conversion rate and the lower the amount of emissions. Considering all cases, amortization plays a significant role in changing the volume of corn stover converted. Amortizing the cost over a period of two years leads to a 100% conversion rate for the *Low* and *Middle Low* cases. A year and a half of amortization period is needed to a 100% conversion when an incentive of \$1.28 is given. However, total conversion can be made with incentives worth \$1.38 (*High*) in just a one-year amortization period.

On the other hand, when considering the emission costs (Table 3.3) we note the changes in the amount of corn stover converted to bioethanol by varying the emission prices. The value of this emissions penalty starts at \$1,090 per metric ton of emissions, which this is the highest value at which corn stover conversion stops increasing (at 37%). When emissions are penalized, there is a loss of \$17,941.20 million with a total 16,732,258 emissions emitted in the supply chain. Increasing the emission price to \$1,245 expectedly lowers the amount of emissions to

16,536,870 metric tons, thus decreasing the profit to $65.67 million. In order to reach a conversion rate of 100%, an emissions penalty of $1,710 needs to be introduced. The amount of emissions emitted at this point is 16,128,339 metric tons. Notice that as emission prices increase, corn stover conversions rates are also increased while simultaneously reducing the amount of emissions in the supply chain.

Since the *EP* configuration, by definitions, does not consider new plant decisions, the capacity level decisions are much more emphasized. In the first incentive level, no expansion is needed while the existing capacity is fully utilized. However, increasing the incentive value to the *Middle Low* level leads to an expansion of the two plants located in Richland and Cass counties with the required capacity of 774,826 and 582,319 tons respectively. To that extent, in the *Middle High* and *High* cases we observe a capacity expansion to all plants.

Penalizing the emissions in the profit maximization objective shows no expansion for the existing plants; that said, the plants in Cass and Richland counties are seen to increase their capacity levels as the emissions cost is set at $1,245 in the *Middle Low* case. We also see that as corn stover conversion rates increase to 79% with the emissions cost at the *Middle High* case, there are three plants expanding their facilities (the ones in Cass, Richland, and McLean counties). In the highest emission price point of the *EP* configuration, we see that all four plants are expanding their facilities. The amortization period is another significant element in achieving a 100% corn stover conversion, profit maximization, and emissions reduction. As the incentives increase, the amortization period during which a 100% conversion is achieved is reduced. The same pattern, but with bigger amortization periods is observed when we also consider emissions.

Table 3.2. Maximizing Profit for the existing plant configuration (EP).

Objective	**Max Profit**									
Case	Low			Middle Low			Middle High			High
	$1.18 incentive, $0 Emission price			**$1.23 incentive**, $0 Emission price			**$1.28 incentive**, $0 Emission price			**$1.38 incentive**, $0 Emission price
	Amortization (Year)			**Amortization (Year)**			**Amortization (Year)**			**Amortization (Year)**
	1	1.5	2	1	1.5	2	1	1.25	1.5	1
% of corn stover converted	37%	86%	100%	49%	86%	100%	70%	95%	100%	100%
Emissions (metric ton)	16,733,153	16,254,811	16,132,282	16,615,066	16,254,811	16,132,282	16,405,076	16,172,538	16,132,282	16,132,282
Profit (million dollars)	726.82	752.33	802.01	747.14	752.33	850.74	775.71	805.06	846.65	862.81
Profit-emission cost (million dollars)	726.82	752.33	802.01	747.14	752.33	850.74	775.71	805.06	846.65	862.81

Table 3.3. Maximizing profit with penalties on the emissions for the existing plant configuration (EP).

Objective	**Max Profit – emission cost**									
Case	Low			Middle Low			Middle High			High
	$0 incentive, **$1,090 Emission price**			$0 incentive, **$1,245 Emission price**			$0 incentive, **$1,400 Emission price**			$0 incentive, **$1,710 Emission price**
	Amortization (Year)			**Amortization (Year)**			**Amortization (Year)**			**Amortization (Year)**
	1	4.5	8	1	2.4	3.8	1	1.5	2	1
% of corn stover converted	37%	93%	100%	56%	96%	100%	79%	97%	100%	100%
Emissions (metric ton)	16,732,258	16,186,736	16,148,078	16,536,870	16,160,016	16,128,400	16,314,634	16,157,585	16,128,339	16,128,339
Profit (million dollars)	296.96	(195.13)	(209.18)	65.67	(282.47)	(274.38)	(227.73)	(360.34)	(349.37)	(507.93)
Profit-emission cost (million dollars)	(17,941.20)	(17,838.68)	(17,810.59)	(20,522.74)	(20,401.69)	(20,354.24)	(23,068.22)	(22,980.96)	(22,929.04)	(28,087.39)

In addition to the previous experiment, we also check to see which plants are more prone to be expanded (due to their location amidst many farms) under capacity expansion constraints. In Tables 3.4—3.13 and Figures 3.2—3.11, we present our findings for varying individual capacity expansion restrictions as well as overall (total) capacity expansion restrictions. In the Figures, a darker shade implies a bigger investment.

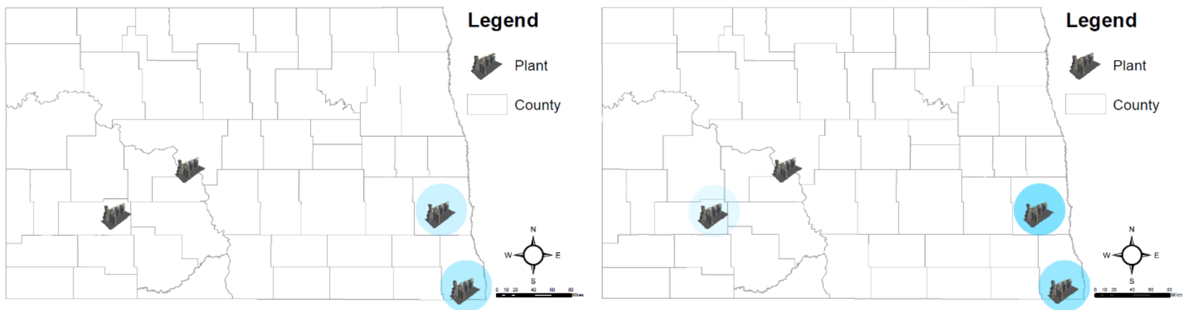
Initially (Table 3.4 and Figure 3.2), all plants are restricted to share a 1 million units (tons) expansion increase, with the expansion going to the Richland county plant (getting a ratio of 70.65% of the expansion) and the Cass county plant (receiving the remaining 29.35%). As capacity expansion budgets increase, we also see an increase in the number of plants who can benefit. As an example, in Table 3.5 (and Figure 3.2), with a total and individual capacity expansion budget of 2 million units, the Stark county plant is entered in the mix. More interestingly, though, we note that Cass county is now receiving most of the expansion, contrary to the initial, more restricted case. Similar interesting patterns are observed in Tables 3.6—3.9 and corresponding Figures 3.3—3.4.

Table 3.4. One-million-ton all capacity scenario.

No. of plant expand	Scenario		Plant location	Capacity increased (ton)
	Total capacity limit			
	1 million (ton)			
2	Individual capacity limit (ton)	1 million	Richland	706,506
		1 million	Cass	293,494

Table 3.5. Two-million-ton all capacity scenario.

No. of plant expand	Scenario		Plant location	Capacity increased (ton)
	Total capacity limit			
	2 million (ton)			
3	Individual capacity limit (ton)	2 million	Richland	877,306
		2 million	Stark	27,190
		2 million	Cass	1 million



One-million-ton all capacity scenario

Two-million-ton all capacity scenario

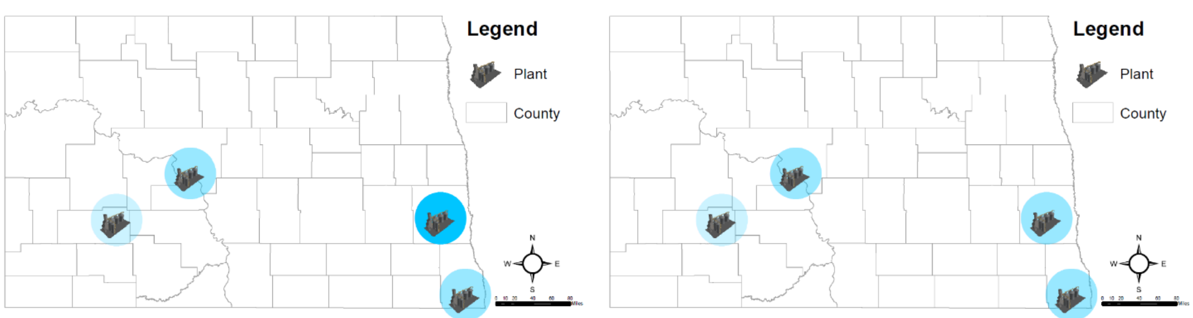
Figure 3.2. One-million and two-million ton all capacity scenario.

Table 3.6. Eight-million-ton all capacity scenario.

No. of plant expand	Scenario		Plant location	Capacity increased (ton)
	Total capacity limit			
	8 million (ton)			
4	Individual capacity limit (ton)	8 million	McLean	1.48 million
		8 million	Richland	1.66 million
		8 million	Stark	422,806
		8 million	Cass	4 million

Table 3.7. Eight and two-million-ton all capacity scenario.

No. of plant expand	Scenario		Plant location	Capacity increased (ton)
	Total capacity limit			
	8 million (ton)			
4	Individual capacity limit (ton)	2 million	McLean	2 million
		2 million	Richland	2 million
		2 million	Stark	456,966
		2 million	Cass	2 million



Eight-million-ton all capacity scenario

Eight and two-million-ton all capacity scenario

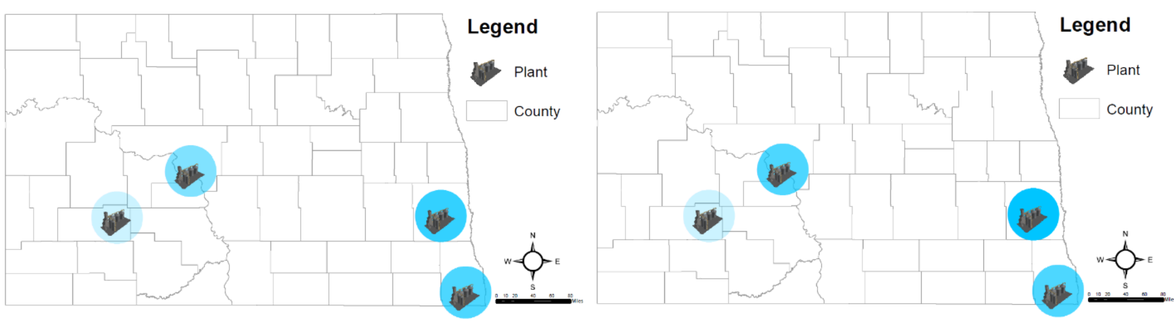
Figure 3.3. Eight-million all capacity and eight and two-million ton all capacity scenario.

Table 3.8. Eight and three-million-ton capacity scenario.

No. of plant expand	Scenario Total capacity limit 8 million (ton)		Plant location	Capacity increased (ton)
4	Individual capacity limit (ton)	3 million	McLean	1.74 million
		3 million	Richland	2.38 million
		3 million	Stark	422,806
		3 million	Cass	3 million

Table 3.9. Eight and four-million-ton capacity scenario.

No. of plant expand	Scenario Total capacity limit 8 million (ton)		Plant location	Capacity increased (ton)
4	Individual capacity limit (ton)	4 million	McLean	1.48 million
		4 million	Richland	1.67 million
		4 million	Stark	422,806
		4 million	Cass	4 million



Eight and three-million-ton capacity scenario

Eight and four-million-ton capacity scenario

Figure 3.4. Eight and three-million-ton and eight and four-million ton all capacity scenario.

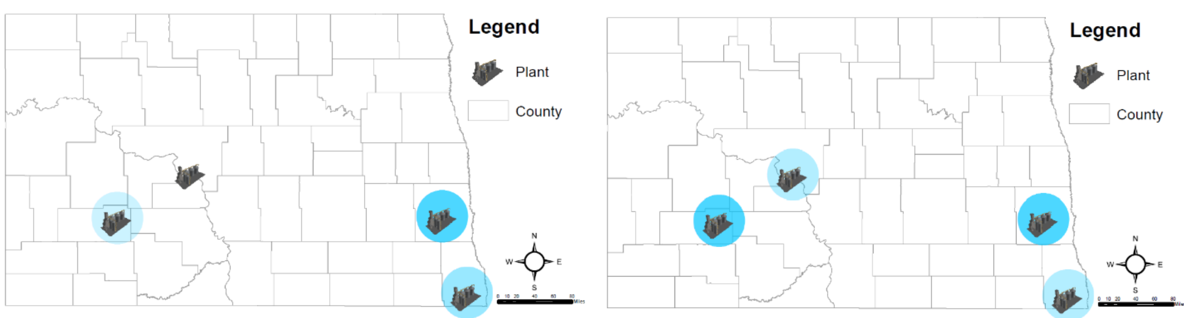
Another interesting experiment has to do with allowing capacity increases at each capacity at most equal to a multiple of their existing capacity. At the same time, we keep the total capacity budget equal to 2 million and 4 million tons. We note that existing plant capacities are known and equal to 66,896 ton (McLean), 557,414 ton (Richland), 1.61 million ton (Stark) and 1.67 million ton (Cass). Table 3.10 (and Figure 3.5) presents a similar picture to the one we discussed in Table 3.5, with Cass and Richland getting almost all of the increase. More specifically, Richland county receives the upper bound of its expansion and hence doubles the capacity of its plant. Table 3.11 and Figure 3.5 show the results when the total capacity expansion budget is increased. Finally, we allow for plants to have a capacity expansion equal to twice their original capacities (shown in Tables 3.12 and 3.13, and corresponding Figures 3.6.

Table 3.10. Two-million-ton and existing plant capacity value scenario.

No. of plant expand	Scenario		Plant location	Capacity increased (ton)
	Total capacity limit			
	2 million (ton)			
3	Individual capacity limit (ton)	557,414	Richland	557,414
		1.61 million	Stark	27,190
		1.67 million	Cass	1.41 million

Table 3.11. Four-million-ton and existing plant capacity value scenario.

No. of plant expand	Scenario		Plant location	Capacity increased (ton)
	Total capacity limit			
	4 million (ton)			
4	Individual capacity limit (ton)	668,896	McLean	668,896
		557,414	Richland	557,414
		1.61 million	Stark	1.1 million
		1.67 million	Cass	1.67 million



Two-million-ton and existing plant capacity value scenario

Four-million-ton and existing plant capacity value scenario

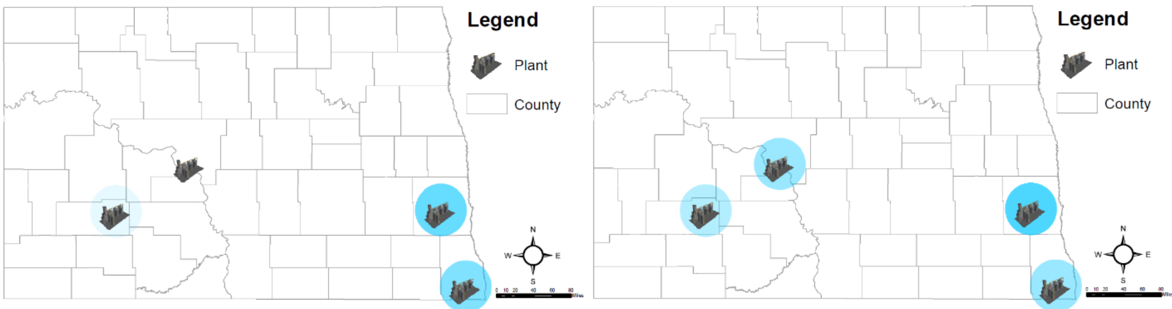
Figure 3.5. Two-million-ton and eight and four-million with existing capacity scenario.

Table 3.12. Three-million-ton and twice of the existing plant capacity value scenario.

No. of plant expand	Scenario		Plant location	Capacity increased (ton)
	Total capacity limit			
	3 million (ton)			
3	Individual capacity limit (ton)	1.11 million	Richland	1.08 million
		3.23 million	Stark	183,686
		3.34 million	Cass	1.73 million

Table 3.13. Six-million-ton and twice of the existing plant capacity value scenario.

No. of plant expand	Scenario		Plant location	Capacity increased (ton)
	Total capacity limit			
	6 million (ton)			
4	Individual capacity limit (ton)	1.33 million	McLean	1.11 million
		1.11 million	Richland	1.11 million
		3.23 million	Stark	422,806
		3.34 million	Cass	3.34 million



Three-million-ton and twice of the existing plant capacity value scenario

Six-million-ton and twice of the existing plant capacity value scenario

Figure 3.6. Three-million and six-million-ton with twice of the existing capacity scenario.

3.5.2. ENP configuration results

The aim of converting all of the corn stover available in our biomass supply chain model of the *ENP* configuration requires us to make a decision of whether to expand the existing plant or build new plant with optimal plant capacity (based on its location). Results for the *ENP* configuration in Table 3.14 indicate that the lowest incentive value before the amount of corn stover begins to change is at $2.20 per gallon (with conversion rate equal to 37%) with a profit of $1,104.45 million, for a one-year amortization period. In the *Middle Low* case, 59% of corn stover is converted and leads to an increase in the profit value to $1,158.25 million. The amount of emissions also decreases from 16,733,347 to 16,501,990 metric tons. As expected, the amount of emissions keeps decreasing as the amount of corn stover converted increases, as the value of incentive goes from $2.40 to $2.60. The lowest amount of emissions generated is equal to 16,069,837, and it is achieved when converting 100% of the corn stover.

The *ENP* configuration shows that when the incentive value is at $2.30, the best decision would be to expand all four plants instead of building new plants as depicted in Figure 3.7. However, in the *Middle High* case ($2.40 incentives), the decision made is to expand all existing plants along with building four new plants (Figure 3.7). The optimal locations of the new plants are identified to be in LaMoure, Morton, Renville, and Stutsman counties. To achieve a conversion rate of 100% (*High* case with incentive of $2.60) shows that 13 new plants need to be built while expanding the existing plants (Figure 3.8).

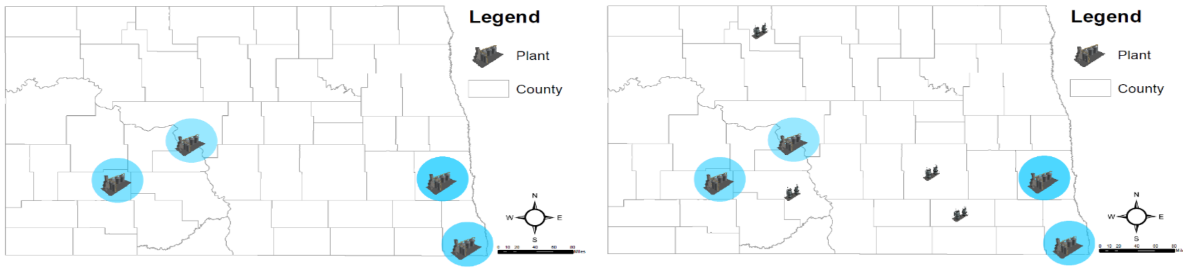
When moving to the profit maximization considering emissions penalties objective function (whose results are presented in Table 3.15), the amount of emissions is lower than the profit-only maximization objective in the *Low* case, and when converting 100% of the available corn stover in the *High* case. Starting in the *Low* case of a $1,960 emissions cost, there is no plant expansion or new plant needed. In the *Middle Low* case, 51% corn stover is converted with a profit value of $16.85 million and a total of 16,588,892 metric tons of emissions. At this stage, only one new plant is planned in Morton county, while three existing plants in Cass, Richland, and Stark counties are expanding their facilities (Figure 3.8). The optimal locations of new plants change in the *Middle High* case with Barnes, Grand Forks, Ramsey, and Stutsman counties identified, while the expansion decisions for existing plants remain the same (Figure 3.9). The emissions recorded in this case are 16,244,254 metric tons, and result in a ratio of 83% of corn stover converted in a one-year amortization period. The highest emissions price that leads to a 100% corn stover conversion rate is $2,490 and results in the smallest amount of emissions of 16,065,477 metric tons. In this case, eight new plants are needed, located in Barnes, Grand Forks, LaMoure, McHenry, Morton, Ramsey, Stutsman, and Trail counties, as shown in Figure 3.9. All four existing plants are also selected for expansion.

Table 3.14. Maximizing Profit for the existing plant and new plant configuration *(ENP)*.

Objective	**Max Profit**									
Case	Low			Middle Low			Middle High			High
	$2.20 incentive, $0 Emission price			**$2.30 incentive**, $0 Emission price			**$2.40 incentive**, $0 Emission price			**$2.60 incentive**, $0 Emission price
	Amortization (Year)			**Amortization (Year)**			**Amortization (Year)**			**Amortization (Year)**
	1	1.06	1.1	1	1.05	1.1	1	1.02	1.1	1
% of corn stover converted	37%	54%	100%	59%	99%	100%	61%	99%	100%	100%
Emissions (metric ton)	16,733,347	16,556,958	16,069,240	16,501,990	16,081,535	16,069,240	16,489,542	16,075,597	16,069,837	16,069,837
Profit (million dollars)	1,104.45	1,106.70	1,172.66	1,158.25	1,173.52	1,239.23	1,216.28	1,233.25	1,258.46	1,401.72
Profit-emission cost (million dollars)	1,104.45	1,106.70	1,172.66	1,158.25	1,173.52	1,239.23	1,216.28	1,233.25	1,258.46	1,401.72

Table 3.15. Maximizing Profit with penalties on the emissions for the existing plant and new plant configuration *(ENP)*.

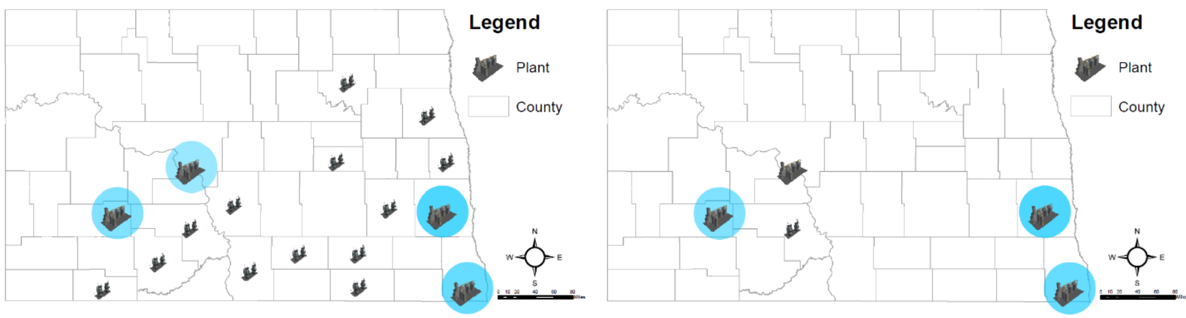
Objective	**Max Profit – emission cost**									
Case	Low			Middle Low			Middle High			High
	$0 incentive, **$1,960 Emission price**			$0 incentive, **$2,092.5 Emission price**			$0 incentive, **$2,225 Emission price**			$0 incentive, **$2,490 Emission price**
	Amortization (Year)			**Amortization (Year)**			**Amortization (Year)**			**Amortization (Year)**
	1	1.1	1.3	1	1.08	1.2	1	1.03	1.1	1
% of corn stover converted	37%	87%	100%	51%	98%	100%	83%	97%	100%	100%
Emissions (metric ton)	16,731,204	16,193,719	16,065,133	16,588,892	16,086,163	16,065,115	16,244,254	16,092,260	16,060,986	16,065,477
Profit (million dollars)	303.01	(708.98)	(796.08)	16.85	(974.14)	(900.23)	(728.53)	(1,032.10)	(1,011.17)	(1,133.53)
Profit-emission cost (million dollars)	(32,490.15)	(32,448.67)	(32,283.74)	(34,695.41)	(34,634.43)	(34,516.48)	(36,872.00)	(36,837.38)	(36,746.86)	(41,136.57)



ENP configuration for maximizing profit objective at $2.30 incentives

ENP configuration for maximizing profit objective at $2.40 incentives

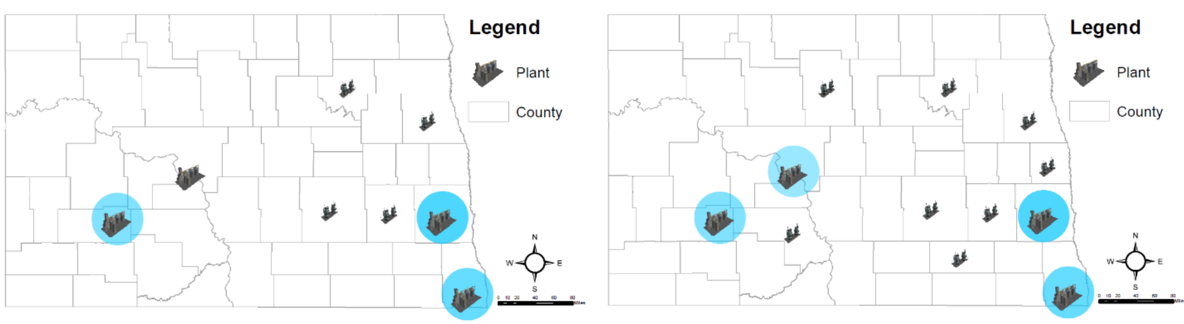
Figure 3.7. *ENP* configuration for maximization profit objective at $2.30 and $2.40 incentives.



ENP configuration for maximizing profit objective at $2.60 incentives

ENP configuration for maximizing profit (with emission penalties) objective at $2,092.5 emission price

Figure 3.8. *ENP* configuration for maximization profit at $2.60 incentives and maximization profit with emission penalties at $2,092.5 emission price.



ENP configuration for maximizing profit (with emission penalties) objective at $2,225 emission price

ENP configuration for maximizing profit (with emission penalties) objective at $2,490 emission price

Figure 3.9. *ENP* configuration for maximization profit with emission penalties at $2,225 and $2,490 emission price.

3.6. Conclusions

The importance of renewable energy in providing sustainability to the economy, social and environment has change the way of energy consumption which lead to a greener production in every sector around the world. Government's structure of spending money to promote sustainability also have changed and give a huge impact to producers especially in energy sector. Treating corn stover as a sustainable feedstock in energy production gives a lot of benefits to all stakeholders and societies for a better living. The sustainable way of production can lead to a cleaner and greener industrial activities while creating healthy lifestyle for communities. Government intervention plays significant role in making this real by providing incentives and supports in any medium that can contribute huge impact to the country. Generally, energy producers need supports from the government in developing sustainable and cleaner production. The practice of incentivizing has a long track record of boosting the economy of private sector which in turn will benefits the government to improve the society's welfare. Incentivizing the energy production to increase the capacity level can help the government to achieve sustainability.

Our study proposed a biomass supply chain network design model as a decision support system for corn stover with the goal of achieving 100% corn stover converted to bioethanol either by expanding the existing plant to increase the capacity level or build new plant, with the assistance of financial incentives. We explore the dollar value paid to the plant as an incentive in two configurations which is the existing plant configuration (*EP*) and Combination of the existing plant and new plant configuration (*ENP*). Results indicated that all existing plants need expansion to increase their capacity when $1.38 of incentive is set in the *EP* configuration to gain 100% corn stover converted to bioethanol. On the other hand, the *ENP* configuration shows the decision of opening 13 new plants and expanding all four existing plants at $2.60 incentive value. An interesting point to highlight from the result is that the *ENP* configuration gives a lower emissions value than the *EP* configuration which is 16,069,837 and 16,132,282 metric ton respectively. In terms of environmental aspect, the *ENP* configuration is more advisable for decision and policy makers to choose when concerning about greening energy production that can sustained for future generation.

As a decision support system in the biomass supply chain, the model in this study provide variations in decision making in terms of locating new bioenergy plants and capacity level with varied incentives and emission penalties to achieve sustainability. The importance of government's incentive program for energy producers to promote sustainability is highlighted in our study. Clearly, injecting the incentive to agricultural sector can reduce the environmental impact while at the same time provide alternative to convert agricultural residues into energy. While increasing the global supply chain profit, the role of incentive can be seen as the booster to the economy, social and environment in achieving sustainability.

As a future research, an extension model can be developed due to farm losses identified in the proposed model when converting 100% of corn stover. As the future model attempt to increase the global supply chain profit, it is imperative to look at each farm so that all entities in the biomass supply chain can share the profits while mitigating environmental burden impact.

4. THE INTERACTION OF FARM AND PLANT ON THE CORN STOVER PRICE AND TRANSPORTATION COST

4.1. Introduction

The biomass supply chain model in Chapter 2 reveals the important side of optimization as an alternative approach to sustain the production of bioenergy using renewable energy sources feedstock. The plant capacity and location also plays a significant role in providing sustainability in the biomass supply chain. We discovered the decision of expanding existing plant to convert 100% of the corn stover to bioethanol for the *Existing Plant Configuration (EP*) in the maximizing profit objective in Chapter 3. Results indicated that 53 farms were affected in making losses.

In this chapter, we observe the interaction between farms and plants in the biomass supply chain by looking at the corn stover price and transportation cost as a component to improve the profitability of the farm and discover the changes in the plant's profit. Farms that are making losses in the EP configuration were identified and grouped for further analysis and is shown in Figure 4.1.

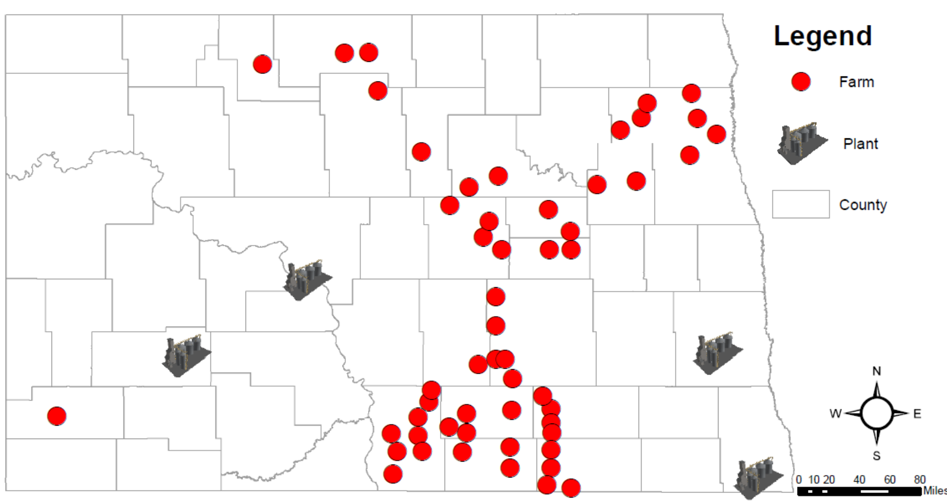


Figure 4.1. Location of farms with no profit.

4.2. Volatility in corn stover selling price for profit increment

The distribution of corn stover from each farm to assigned plant is determined and classified. There are 24 farms sent their corn stover to the plant in McLean county, eight farms sent to Richland, one farm directly to Stark and 21 farms sent to the plant located in Cass county. The breakeven price is determined for the analysis and once it is identified, the highest breakeven price in each plant is collected and used as a scenario analysis.

The selling price of the corn stover in North Dakota is documented as $45 per ton (Maung and Gustafson, 2011) and were used as a base price for the analysis. Results indicated that the highest price that can be set for farm Benson4 to McLean plant is $49.69 per ton, a 9% increase from the original selling price of $45 to get the breakeven, with the lowest price that can be offered to McLean plant is at $45.33 per ton by farm Emmon6. Thus, farms that are willing to sell corn stover to McLean should be at least $49.69 per ton. For the corn stover that sent to plant in Richland with the highest price is from farm Mcintosh5 which is at $48.40 with an increment of 7% from the base selling price for breakeven. Farm Slope shows a positive value of $59,502.34 in profit. Although the analysis is about the loss made by farm, we opt to include farm Slope in the analysis for completeness purposes of the number of plants that considered in the mixed integer linear program (MILP) model in the previous chapter. Hence, to be fair in finding the breakeven corn stover price, farm Slope has to reduce the price to $43.26 per ton, which is sent to plant in Stark. For the plant in Cass county, the highest price that can be obtained is at $50.29 per ton which is from farm Walsh2, an increase of 11% from the original selling price. This indicates that $50.29 is the highest corn stover selling price that can be offered among all plants to achieve breakeven point. Appendix A shows the variability of corn stover price value that can be set to achieve breakeven and also the possibility scenarios of using highest corn stover price in each plant. The percentage of increase and decrease of the selling price is presented in Appendix B.

Applying the highest breakeven price in McLean ($49.69) as a new selling price for each affected farm, it shows that four farms increase their profits of about 10% which is Emmons6, Stutsman2, Dickey11 and Nelson2. However, Logan1 and Walsh2 are still not making profits and a 1% from the base selling price is needed to get at least in a breakeven position.

About nine farms is still in loses when the highest selling price in Richland ($48.40) is used to improve the profitability of the affected farms. The highest profit increments recorded in this scenario is at 7% for about four farms (Emmons6, Stutsman1, Dickey11 and Nelson2).

Notice that farm Slope (that shipped the corn stover to Stark county) is the highest profitable farm in all scenarios (McLean, Richland and Cass). Due to completeness purposes of the analysis, we pick the lowest selling price that can be offered of the profitable farms in the MILP model in the previous chapter. Since farm Slope is making a profit by default, we found the breakeven selling price that shows a reduction of 4% with $43.26 per ton. By using the value as a selling price, it definitely gives more increases in loses of those 53 affected farms with the highest reduction of 14% in Logan1 (-$238,024.73).

Using the highest breakeven selling price in plant in Cass county ($50.29) shows the highest profit value in farm Nelson2 of $176,023.29 profit value with an 11% increment. It is also indicated that all farms are getting profits. As previously highlighted, this is the highest breakeven selling price among all scenarios which could be a standard price or basis in imposing the corn stover selling price for the affected farms to gain profits.

4.3. Improving profit values via transportation cost

The cost of transportation plays a significant role in determining the fluctuations in profitability of farm and plant. Appendix C shows the profits of the affected farms after varying the transportation cost with the initial transportation cost at $0.096 per ton mile. Reducing the transportation cost in the supply chain can improve the profit of the farms. The breakeven transportation cost is determined to improve the profit by looking at the lowest transportation cost possible that could be applied to all affected farms while converting 100% corn stover to bioethanol. Using the same approach of the previously discussed corn stover selling price, we identified the flow of the distributing corn stover to the four plants and pinpoint the lowest transportation that can be introduced to achieve more profit or at least break even. The lowest transportation cost identified in McLean channel is $0.0615 per ton mile, a reduction of 36% from the initial cost of $0.096. The lowest value in McLean gives an advantage to farm Nelson2 to gain high profit value of $112,570.56 that make it the highest profit among all affected farms. The transportation cost for transporting the corn stover from farm LaMoure2 to plant Richland cannot exceed $0.0823 as this value is the lowest in Richland category. Using $0.0823 per ton mile to transport the corn stover from farm Walsh2 make it more losses with the increased percentage of 29% from its breakeven cost at $0.0584 (Appendix D). However, the $0.0584 appeared to be the lowest cost to transport the corn stover to the plant that located in Cass category, in addition it is the lowest transportation among all plant categories.

4.4. The diversification of plant's values pertaining to corn stover price and transportation cost

The changes in corn stover price could be the one of the major affecting factor in bioethanol production in terms of economy and operations of an individual farm and plant, even more to the whole supply chain. The fluctuations in plant's profit can be seen when the corn stover price is changed depending on the farm's variability in profit and loss values. Table 4.1 shows the impact on the plant's profit on the occasion that the price of the corn stover is varied based on the price offered by the farm. We observe the changes made on the plant's profit when the plant buys the corn stover with the highest price of each distribution route (farm to plant). Plant's buying cost using the breakeven price (in the farm's adjustment) shows a reduction in plant's profit especially plant located in Stark county with 1.12% reduction. The highest initial profit among all plants are the one in Cass county with $ 858,744,094.44 profit value, however it shows the lowest reduction of only 0.40%. The highest buying cost of $50.29 (in Cass county) shows a reduction of 1.95% which is the highest reduction compared to other buying cost values.

Table 4.1. Percentage of profit changes for plant pertaining to corn stover price.

	At normal Purchasing Price	Profit changes in plant				Breakeven Price
		MCLEAN	RICHLAND	STARK	CASS	
Purchasing price	**$ 45.00**	**$ 49.69**	**$ 48.40**	**$ 43.26**	**$ 50.29**	
MCLEAN	$ 323,044,242.26	-1.61%	-0.87%	2.07%	-1.95%	-1.07%
RICHLAND	$ 336,789,364.45	-1.54%	-0.83%	1.98%	-1.87%	-1.03%
STARK	$ 309,070,055.40	-1.68%	-0.91%	2.16%	-2.04%	-1.12%
CASS	$ 858,744,094.44	-0.60%	-0.33%	0.78%	-0.73%	-0.40%

Another approach to improve the profitability of the affected farms, plant can play a role in supporting the farms by paying the transportation cost where it is initially paid by the farm. Table 4.2 shows the profit that can be achieved by the plant in the case that the plant pays the transportation cost based on different cost values. As obtained in the previous analysis of the affected farms, all plants are experiencing losses when imposing the breakeven cost values. The same values are used in the Richland scenario ($0.0823 per ton mile) where the reductions are between 0.07% to 0.18% in profits. The lowest transportation cost in Cass shows a reduction in plant's profit of between 0.51% to 1.36%.

Table 4.2. Percentage of profit changes for plant pertaining to transportation cost financially supported by plant.

	At normal Transportation cost	Profit changes in plant				
		MCLEAN	RICHLAND	STARK	CASS	Breakeven Cost
Transportation cost	$ 0.096	$ 0.0615	$ 0.0823	$ 0.1166	$ 0.0584	
MCLEAN	$ 323,044,242.26	-1.16%	-0.18%	-2.41%	-1.36%	-1.07%
RICHLAND	$ 336,789,364.45	-1.12%	-0.18%	-2.31%	-1.31%	-1.03%
STARK	$ 309,070,055.40	-1.22%	-0.19%	-2.52%	-1.42%	-1.12%
CASS	$ 858,744,094.44	-0.44%	-0.07%	-0.91%	-0.51%	-0.40%

4.5. Conclusions

Sustaining bioenergy sector by strengthening its supply chain is a challenge and cumbersome. The importance of renewable energy in providing sustainability to the economy, social and environment has change the way of energy consumption which lead to a greener production in every sector around the world. The analysis of the corn stover price and transportation cost in this chapter reveals the interaction of farms and plants in the supply chain to increase the profitability of the affected farms and observe the profit value gained by plant. It is indicated that the finest corn stover price that can be offered is $50.29 per ton while the transportation cost that can be paid by plant is at $0.0584 per ton mile in order to enhance the profitability of the affected farms.

5. FURTHER DISCUSSIONS AND FUTURE RESEARCH DIRECTION

5.1. Profit/loss of farms and building new plant scenarios

Note that some farms in our study are not making profit due to our assumption that all decisions are made centrally. In Figure 5.1, we can see the location of all farms that are making profits or are observing losses (in green and red, respectively). It shows that most of the farms that are not making any profits are concentrated in an area in the state between all existing plant locations. It can be said, those that are far from the plants are losing money. The farm located in Slope county is not making a profit despite its proximity to the plant due to lack of access to rail transportation towards the plant. We also note that a number of the affected farms are located in the south of the state. This is revealing of the fact that these farms might go across state lines (and to the plants in the north part of South Dakota, the neighboring state) to sell their corn stover. Access to rail transportation also could be a reason why the farms cannot gain profits. For farms that are located far away from the plants, e.g., in Roulette, Towner, Cavalier and Pembina counties, they have access to the railroad that makes it easy for them to send their corn stover to the plant. Average profits and losses for each county in the state are presented in Table 5.1 with a pictorial GIS representation shown in Figure 5.2.

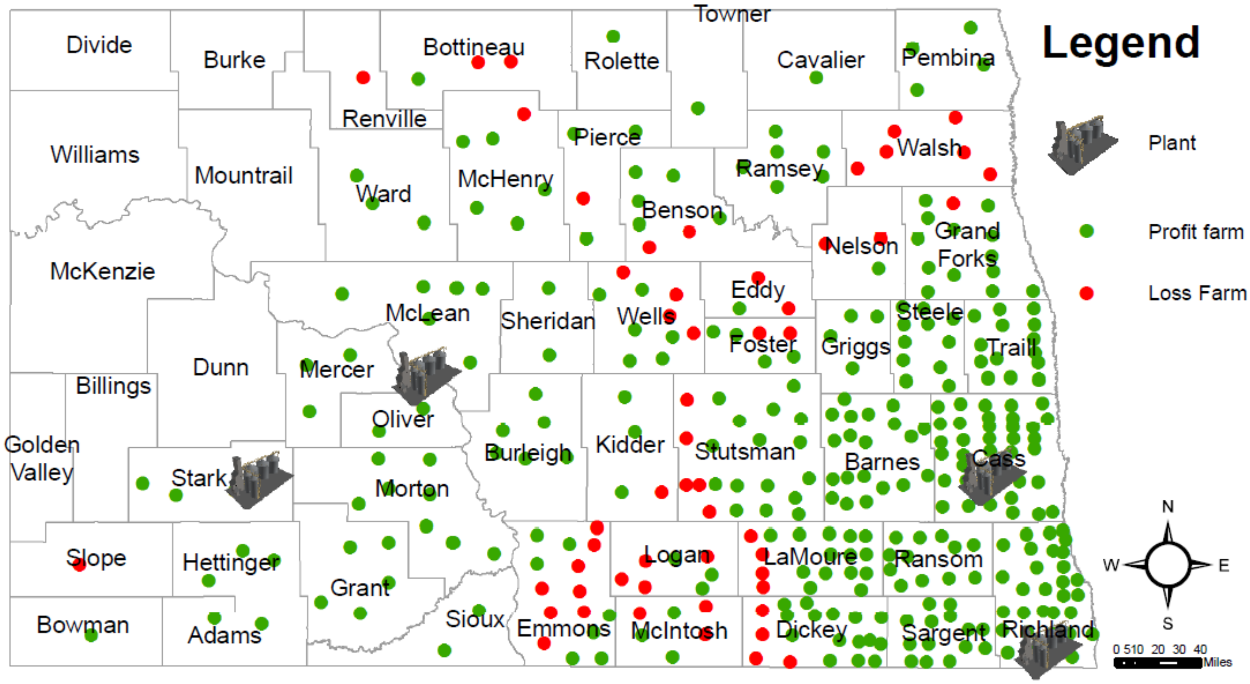


Figure 5.1. Farms that are making profit and loss

Table 5.1. Average profit and loss of farms for each county in North Dakota.

No.	County	Average Profit/Loss
1.	Adams	$127,552.33
2.	Barnes	$227,445.83
3.	Benson	$221,730.55
4.	Bottineau	$(68,124.88)
5.	Bowman	$260,206.40
6.	Burleigh	$219,823.66
7.	Cass	$330,447.18
8.	Cavalier	$278,804.75
9.	Dickey	$76,916.44
10.	Eddy	$68,567.25
11.	Emmons	$76,841.00
12.	Foster	$156,636.84
13.	Grand Forks	$134,350.81
14.	Grant	$201,945.15
15.	Griggs	$64,715.72
16.	Hettinger	$252,347.47
17.	Kidder	$128,386.27
18.	LaMoure	$110,307.09
19.	Logan	$58,647.59
20.	McHenry	$58,184.22
21.	Mcintosh	$111,056.15
22.	McLean	$275,049.50
23.	Mercer	$228,828.92
24.	Morton	$170,703.86
25.	Nelson	$(9,113.40)
26.	Oliver	$252,101.45
27.	Pembina	$345,902.67
28.	Pierce	$154,839.15
29.	Ramsey	$336,772.07
30.	Ransom	$189,799.86
31.	Renville	$(44,269.30)
32.	Richland	$322,815.00
33.	Rolette	$344,452.31
34.	Sargent	$250,349.98
35.	Sheridan	$190,646.57
36.	Sioux	$(15,840.05)
37.	Slope	$59,502.34
38.	Stark	$286,892.26
39.	Steele	$163,533.53
40.	Stutsman	$63,477.77
41.	Towner	$400,070.72
42.	Trail	$238,418.60
43.	Walsh	$(121,604.19)
44.	Ward	$74,065.10
45.	Wells	$52,887.86

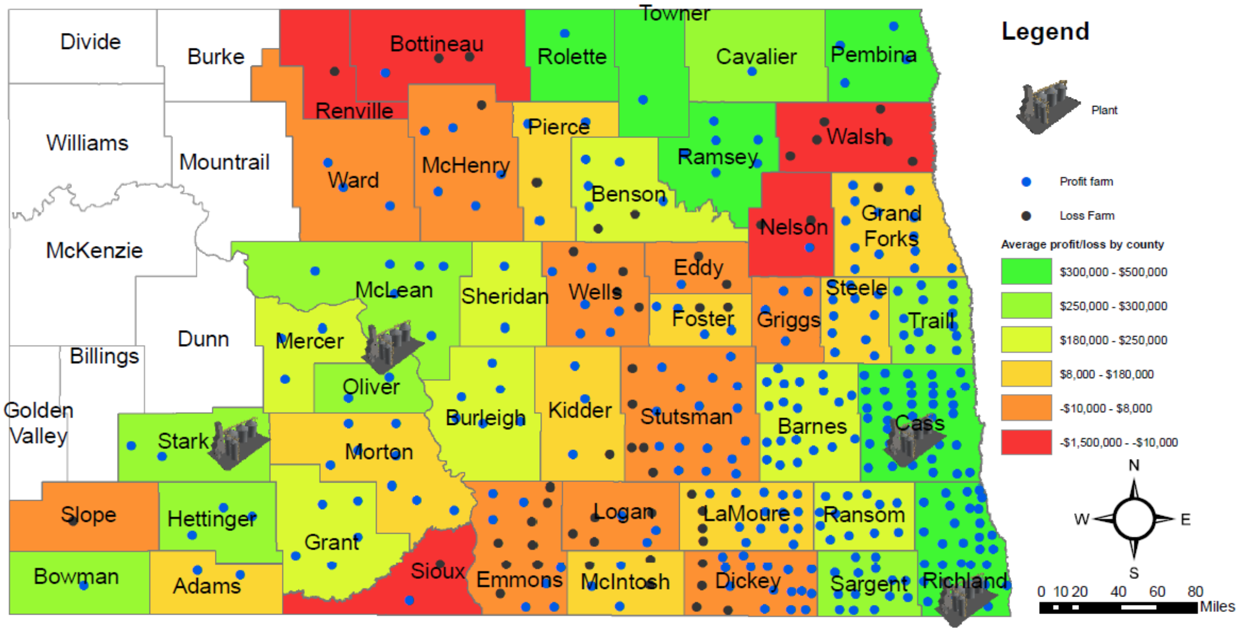


Figure 5.2. Average profits and losses observed by county.

The concentration of farms in Cass and Richland county in Figure 5.2 shows that the existing plant can sustain their energy production operation as the feedstock can be reached in a short distance thus reducing the transportation cost. By aggregating farms in each county, we can find the average profit gained and identify the most profitable (as well as the least profitable) farms at the county level. The most profitable counties are found to see profits between $300,000 to $500,000 on average. Cass, Richland, Mclean, Stark, Hettinger and Oliver are among the counties that see the largest profits: they reap the benefits of being located at a short distance to the existing plants. However, some counties, such as Sioux, Renville, Bottineau, Nelson and Walsh, are seeing big losses when selling their corn stover. These farms are identified to be far in distance from the existing plants in ND. As mentioned earlier, there is a high probability that these farms can opt to send their corn stover to plants located out of state. In addition, the low price of corn stover can also lead to farms not making profits. Last, some farms have no access to rail transportation, forcing them to use truck to send the corn stover to the plant as an alternative.

In this section, we further analyzed the location of new plants and their capacity with a restriction on the number of plants that can be opened. In the following model, we use the same parameters used in the model in Chapter 3 and introduce two new parameters. The first new parameter is the number of allowed new plants, which is denoted by $\bar{\bar{w}}$. The second parameter is $\bar{a}$, which is the financial budget allocation for building new plants. Following are the complete formulations of the models:

$$
\begin{aligned}
\underset{(no\ emission\ penalty)}{\text{Max Profit}}: &\left(\phi \cdot \sum_{f\in F} X_f\right) + \left((\Sigma + \Omega)\cdot \mu \cdot \sum_{p\in P}\sum_{c\in C} B_{pc}\right) \\
&- \left[\left(\sum_{f\in F} \alpha_f \cdot X_f\right) + \left(\sum_{p\in P}\sum_{c\in C} \rho_p \cdot B_{pc}\right) + \varrho \right. \\
&\left. \cdot \left(\sum_{f\in F}\sum_{s\in S} Y_{fs} + \sum_{f\in F}\sum_{p\in P} Z_{fp} + \sum_{s\in S}\sum_{p\in P} H_{sp} + \sum_{p\in P}\sum_{c\in C} B_{pc}\right) + \left(\gamma \cdot \sum_{s\in S}\sum_{p\in P} M_{sp}\right)\right] \\
&+ \left[(\Sigma + \Omega)\cdot \mu \cdot \sum_{w\in W}\sum_{c\in C} \hat{B}_{wc}\right] \\
&- \left[\left(\sum_{w\in W}\sum_{c\in C} \rho_p \cdot \hat{B}_{wc}\right) + \varrho \right. \\
&\cdot \left(\sum_{f\in F}\sum_{w\in W} \hat{Z}_{fw} + \sum_{s\in S}\sum_{w\in W} \hat{H}_{sw} + \sum_{s\in S}\sum_{w\in W} \hat{M}_{sw} + \sum_{w\in W}\sum_{c\in C} \hat{B}_{wc}\right) \\
&\left. + \left(\gamma \cdot \sum_{s\in S}\sum_{w\in W} \hat{M}_{sw}\right)\right] - \left[(k\cdot \Lambda) + \mu \cdot \sum_{p\in P} \rho_p \cdot \hat{\pi}_p\right] - \left[Q \cdot \sum_{p\in P} \hat{r}_p\right] \\
&- \left[\hat{T} \cdot \sum_{w\in W} \hat{w}_w\right]
\end{aligned}
\tag{5.1}
$$

$$
\begin{aligned}
&\underset{(\textit{with emission penalty})}{\text{Max Profit}}: \left(\phi \cdot \sum_{f\in F} X_f\right) + \left((\Sigma + \Omega) \cdot \mu \cdot \sum_{p\in P}\sum_{c\in C} B_{pc}\right) \\
&- \left[\left(\sum_{f\in F} \alpha_f \cdot X_f\right) + \left(\sum_{p\in P}\sum_{c\in C} \rho_p \cdot B_{pc}\right) + \varrho \right. \\
&\left. \cdot \left(\sum_{f\in F}\sum_{s\in S} Y_{fs} + \sum_{f\in F}\sum_{p\in P} Z_{fp} + \sum_{s\in S}\sum_{p\in P} H_{sp} + \sum_{p\in P}\sum_{c\in C} B_{pc}\right) + \left(\gamma \cdot \sum_{s\in S}\sum_{p\in P} M_{sp}\right)\right] \\
&- \left[\left(\Gamma \right.\right. \\
&\cdot \left(\sum_{f\in F}\sum_{s\in S} \zeta_{fs} \cdot Y_{fs} + \sum_{f\in F}\sum_{p\in P} \zeta_{fp} \cdot Z_{fp} + \sum_{s\in S}\sum_{p\in P} \zeta_{sp} \cdot H_{sp} + \sum_{p\in P}\sum_{c\in C} \zeta_{pc} \cdot B_{pc}\right) + \delta \\
&\left.\left. \cdot \left(\sum_{s\in S}\sum_{p\in P} \eta_{sp} \cdot M_{sp}\right) + \left(\upsilon \cdot \sum_{f\in F} X_f\right) + \left(\omega \cdot \sum_{f\in F} G_f\right) + \left(\varphi \cdot \sum_{f\in F} (\sigma - X_f)\right)\right) \cdot \xi \right] \\
&+ \left[(\Sigma + \Omega) \cdot \mu \cdot \sum_{w\in W}\sum_{c\in C} \hat{B}_{wc}\right] \\
&- \left[\left(\sum_{w\in W}\sum_{c\in C} \rho_p \cdot \hat{B}_{wc}\right) + \varrho \cdot \left(\sum_{f\in F}\sum_{w\in W} \hat{Z}_{fw} + \sum_{s\in S}\sum_{w\in W} \hat{H}_{sw} + \sum_{w\in W}\sum_{c\in C} \hat{B}_{wc}\right)\right. \\
&\left. + \left(\gamma \cdot \sum_{s\in S}\sum_{w\in W} \hat{M}_{sw}\right)\right] \\
&- \left[\left(\Gamma \cdot \left(\sum_{f\in F}\sum_{w\in W} \zeta_{fw} \cdot \hat{Z}_{fw} + \sum_{s\in S}\sum_{w\in W} \zeta_{sw} \cdot \hat{H}_{sw} + \sum_{w\in W}\sum_{c\in C} \zeta_{wc} \cdot \hat{B}_{wc}\right)\right.\right. \\
&\left.\left. + \left(\delta \cdot \sum_{s\in S}\sum_{w\in W} \eta_{sw} \cdot \hat{M}_{sw}\right)\right) \cdot \xi \right] - \left[(k \cdot \Lambda) + \mu \cdot \sum_{p\in P} \rho_p \cdot \hat{\pi}_p\right] - \left[Q \cdot \sum_{p\in P} \hat{r}_p\right]
\end{aligned}
$$

$$-\left[\hat{T}\cdot\sum_{w\in W}\widehat{w}_w\right] \tag{5.2}$$

Subject to:

$$X_f + G_f \leq \varsigma_f \cdot \varpi \cdot \tau, \qquad \forall f \in F \tag{5.3}$$

$$\left(\sum_{s\in S} Y_{fs} + \sum_{p\in P} Z_{fp} + \sum_{w\in W} \hat{Z}_{fw}\right) - X_f = 0, \qquad \forall f \in F \tag{5.4}$$

$$\sum_{f\in F} Y_{fs} - \sum_{p\in P}\sum_{w\in W}(H_{sp} + M_{sp} + \widehat{H}_{sw} + \widehat{M}_{sw}) = 0, \qquad \forall\, s \in S \tag{5.5}$$

$$\left(\sum_{f\in F} \hat{Z}_{fw} + \sum_{s\in S}(\widehat{H}_{sw} + \widehat{M}_{sw})\right)\cdot \mu - \sum_{c\in C}\widehat{B}_{wc} = 0, \qquad \forall\, w \in W \tag{5.6}$$

$$\sum_{f\in F} Y_{fs} \leq \vartheta_s, \qquad \forall s \in S \tag{5.7}$$

$$\sum_{f\in F} Z_{fp} + \sum_{s\in S}(H_{sp} + M_{sp}) \leq \pi_p + \hat{\pi}, \qquad \forall p \in P, \forall k \in K \tag{5.8}$$

$$\sum_{f\in F} \hat{Z}_{fw} + \sum_{s\in S}(\widehat{H}_{sw} + \widehat{M}_{sw}) \leq \hat{n}\cdot\widehat{w}_w, \qquad \forall\, w \in W, \forall f \in F, \forall\, s \in S \tag{5.9}$$

$$\textstyle\sum_{p\in P}\hat{\pi}_p \leq \hat{p}, \tag{5.10}$$

$$\hat{\pi}_p \leq \bar{p}\cdot\hat{r}_p, \qquad \forall p \in P \tag{5.11}$$

$$\sum_{s\in S}\sum_{p\in P} M_{sp} \leq \psi\cdot\theta, \qquad \forall s \in S, \forall\, p \in P \tag{5.12}$$

$$\sum_{s\in S}\sum_{w\in W}\widehat{M}_{sw} \leq \psi \cdot \theta, \qquad \forall s \in S, \forall\, w \in W \tag{5.13}$$

$$\sum_{w\in W}\widehat{w}_w \leq \overline{\overline{w}} \qquad \forall\, w \in W \tag{5.14}$$

$$\hat{r}_p, \widehat{w}_w \in \{0,1\} \qquad \forall p \in P, \forall\, w \in W \tag{5.16}$$

$$X_f \geq 0, \qquad \forall f \in F \tag{5.17}$$

$$G_f \geq 0, \qquad \forall f \in F \tag{5.18}$$

$$Y_{fs} \geq 0, \qquad \forall f \in F, \forall\, s \in S \tag{5.19}$$

$$Z_{fp} \geq 0, \qquad \forall f \in F, \forall\, p \in P \tag{5.20}$$

$$H_{sp} \geq 0, \qquad \forall s \in S, \forall\, p \in P \tag{5.21}$$

$$M_{sp} \geq 0, \qquad \forall s \in S, \forall\, p \in P \tag{5.22}$$

$$B_{pc} \geq 0, \qquad \forall p \in P, \forall\, c \in C \tag{5.23}$$

$$\hat{Z}_{fw} \geq 0, \qquad \forall f \in F, \forall\, w \in W \tag{5.24}$$

$$\widehat{H}_{sw} \geq 0, \qquad \forall s \in S, \forall\, w \in W \tag{5.25}$$

$$\widehat{M}_{sw} \geq 0, \qquad \forall s \in S, \forall\, w \in W \tag{5.26}$$

$$\widehat{B}_{wc} \geq 0, \qquad \forall w \in W, \forall\, c \in C \tag{5.27}$$

Both equation (5.1) and (5.2) represent the objective function of maximizing profit and maximize profit with emission cost, respectively. Constraint family (5.3) ensures that the amount of corn stover cannot exceed the amount available in that farm. Constraints (5.4)—(5.6) represent the flow balance at the farm, storage and existing plants. Storage capacities are enforced through constraints (5.7); similarly, constraints (5.8) restrict plant capacities, including their expansions, a similar constraint for the new plants is given in (5.9). An upper bound on all expansions available is provided in equations (5.10). An upper bound for each facility's available increase is given in (5.11). Constraints (5.12) ensure we respect rail capacities for all amounts transported using the railroad. The same purpose is served, but for new plants, by constraints (5.13). The number of plants that should be built in ND are restricted in constraint (5.14). In the case where the number of new plants to be opened is left unrestricted, but instead we are provided with a budget for opening new plants, we can replace (5.14) with the following equation:

$$\sum_{w \in W} \hat{r}_w \cdot \hat{w}_w \leq \bar{a}.$$

Finally, constraints (5.16)—(5.27) restrict all variables to be nonnegative, and enforce the binary nature of the expansion selection and new plant selection variables

5.2. Results and discussion

As shown in Table 5.2, we provide results of opening one, two, three, four and five potential new plants and identify the locations and capacity levels. Starting at the \$2.20 incentive value, we observe the possibility of building one new plant. It shows that Ramsey county is chosen to be the potential location. However, when the model was set to open two plants, Bowman and Morton were selected. Increasing the incentive value to \$2.30 per gallon indicates that Ramsey dominates the decision on opening a new plant as it appears in every scenario (open one plant to five plants scenarios). The $2.40 incentive shows the same pattern with the $2.30 value in opening two plants where Ramsey and Morton were selected with the capacities of 7,440,950 and 136,640 respectively. The four plants decision shows the same county for both incentive values ($2.30 and $2.40) where Ramsey, Stutsman, Morton and Trail were selected as potential locations to build new plants. The highest incentive value ($2.60) indicates that Morton is the most suitable location to build one new plant. Ramsey and Stutsman counties are identified to be the best locations to build new plants when the decision is to open three, four and five plants. The graphical solutions (GIS maps) of opening one to five plants with different incentive values can be seen in figures 5.3 to 5.6.

Table 5.2. Opening 1 – 5 new plants in potential location with capacity level (Maximize Profit Objective)

	Open 1 Plant		Open 2 Plant		Open 3 Plant		Open 4 Plant		Open 5 Plant	
Incentive value	Plant	Capacity (ton)	Plant	Capacity (ton)	Plant	Capacity (ton)	Plant	Capacity (ton)	Plant	Capacity (ton)
$2.2	Ramsey	7,577,590	Bowman	34,160	Ramsey	7,031,030	Morton	136,640	Morton	136,640
			Morton	7,543,430	Stutsman	307,440	Ramsey	7,099,350	Ramsey	6,860,230
					Trail	239,120	Stutsman	307,440	Stutsman	307,440
							Ward	34,160	Trail	239,120
									Ward	34,160
$2.3	Ramsey	7,577,590	Ramsey	7,440,950	Ramsey	7,133,510	Ramsey	6,894,390	Ramsey	6,723,590
			Morton	136,640	Stutsman	307,440	Stutsman	307,440	Stutsman	307,440
					Morton	136,640	Morton	136,640	Burleigh	102,480
							Trail	239,120	Trail	239,120
									LaMoure	204,960
$2.4	Grand Forks	7,577,590	Ramsey	7,440,950	Ramsey	7,031,030	Ramsey	6,894,390	Ramsey	6,689,430
			Morton	136,640	Stutsman	307,440	Stutsman	307,440	Stutsman	307,440
					Trail	239,120	Trail	239,120	Trail	239,120
							Morton	136,640	Morton	136,640
									LaMoure	204,960
$2.6	Morton	7,577,590	Ramsey	7,475,110	Ramsey	7,031,030	Ramsey	6,894,390	Ramsey	6,860,230
			Burleigh	102,480	Stutsman	307,440	Stutsman	307,440	Stutsman	307,440
					Trail	239,120	Trail	239,120	Trail	239,120
							Morton	136,640	Morton	136,640
									Ward	34,160

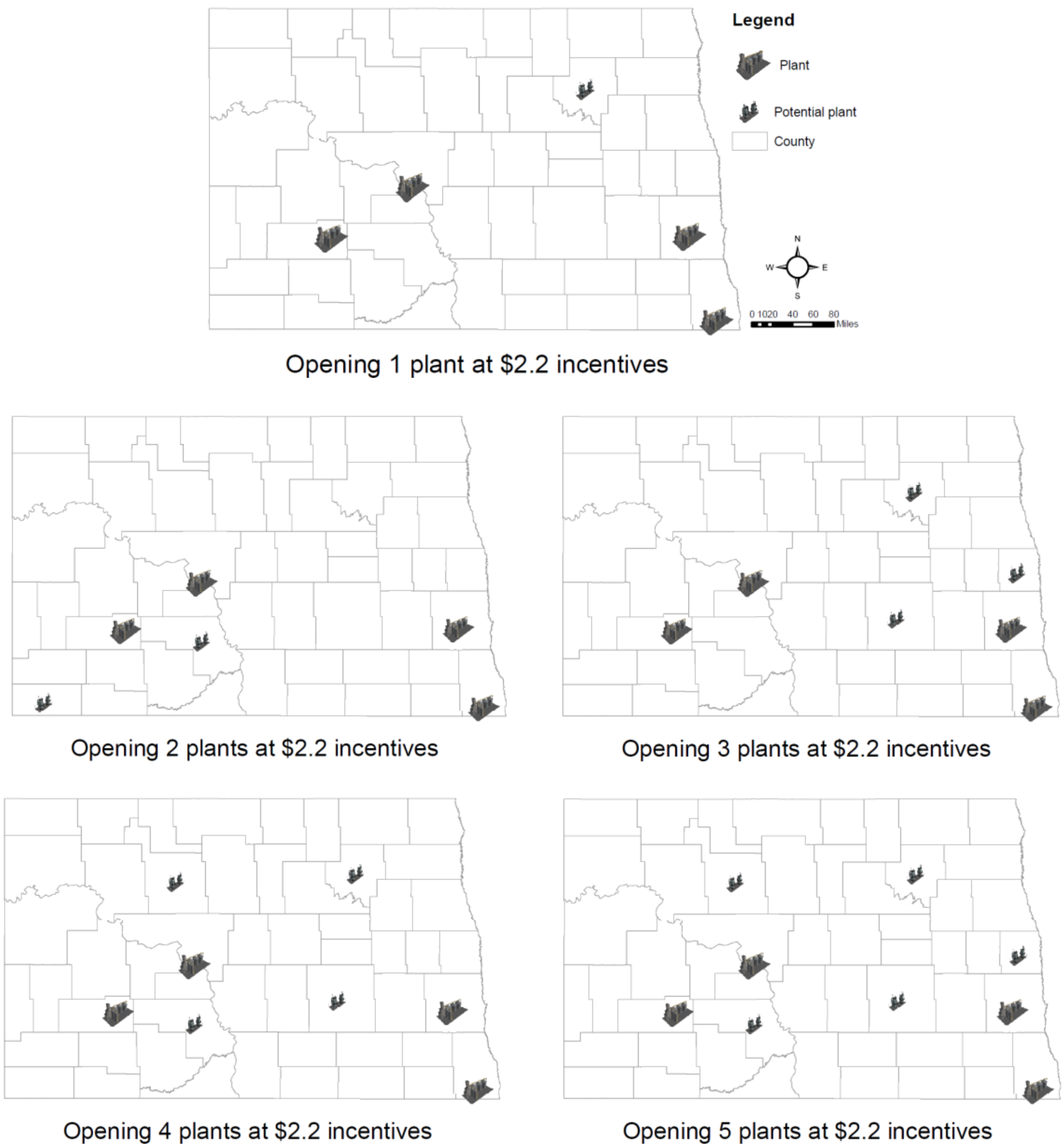


Figure 5.3. Opening one to five new plants scenarios at $2.2 incentive value.

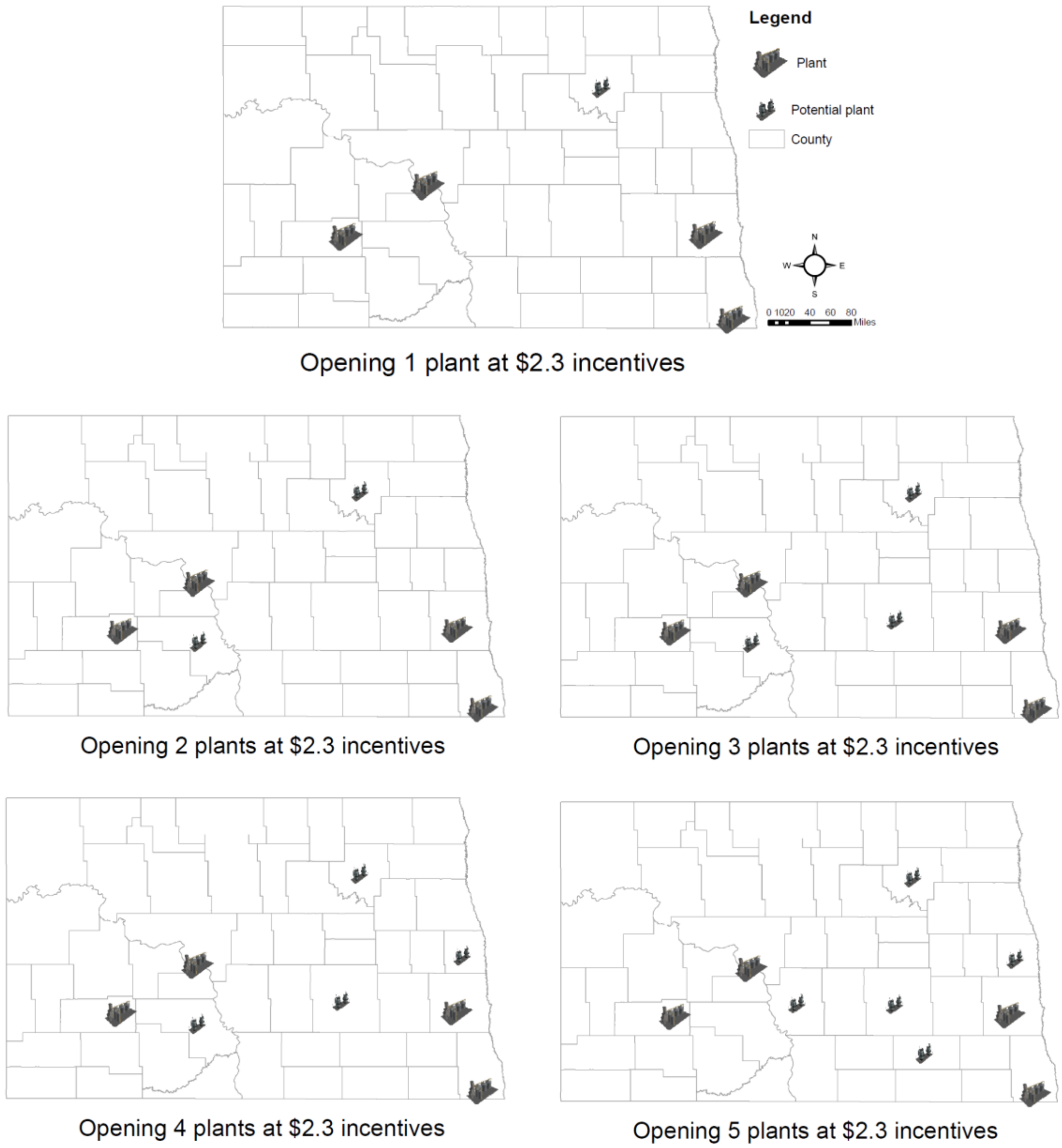


Figure 5.4. Opening one to five new plants scenarios at $2.3 incentive value.

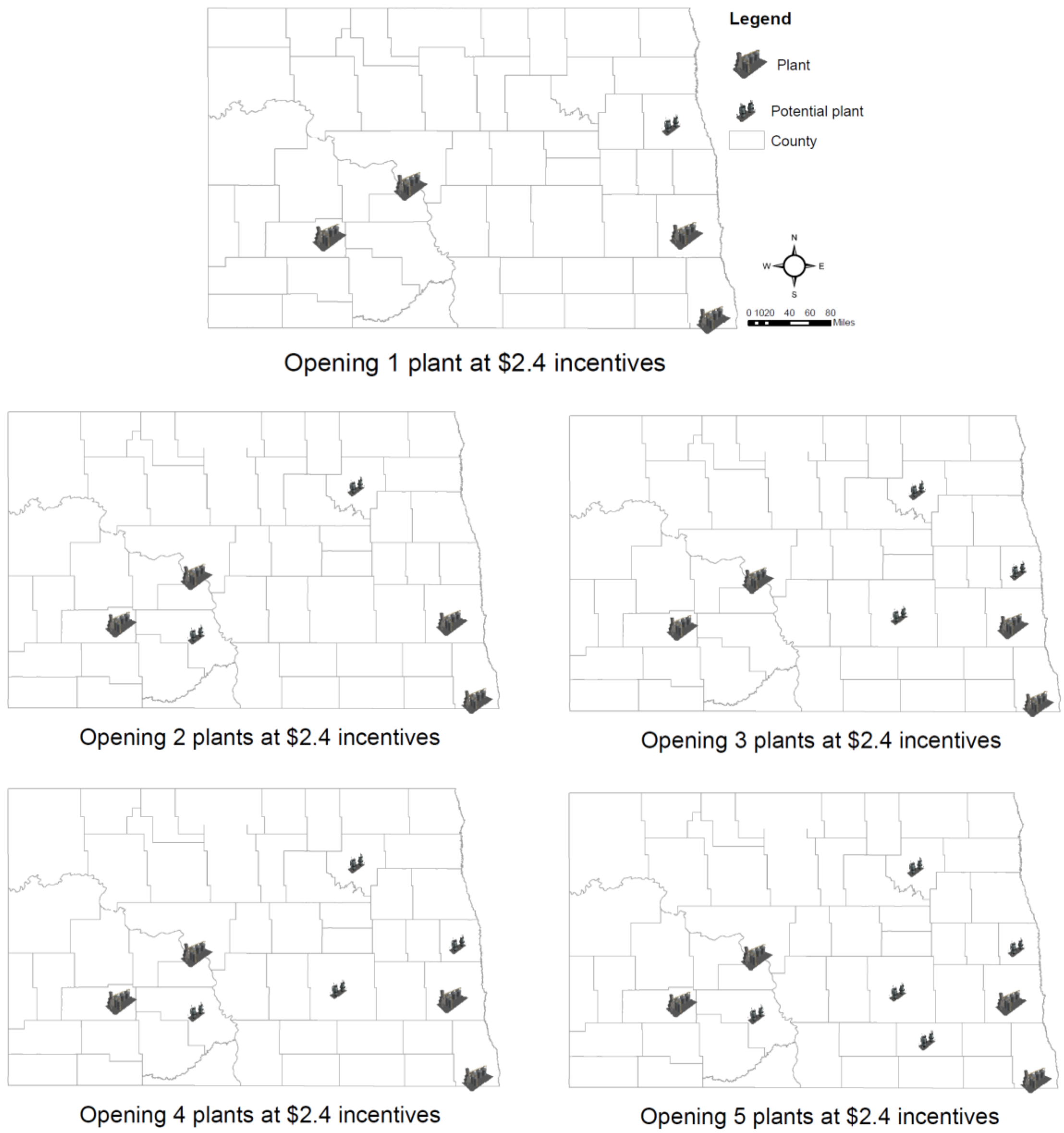


Figure 5.5. Opening one to five new plants scenarios at $2.4 incentive value.

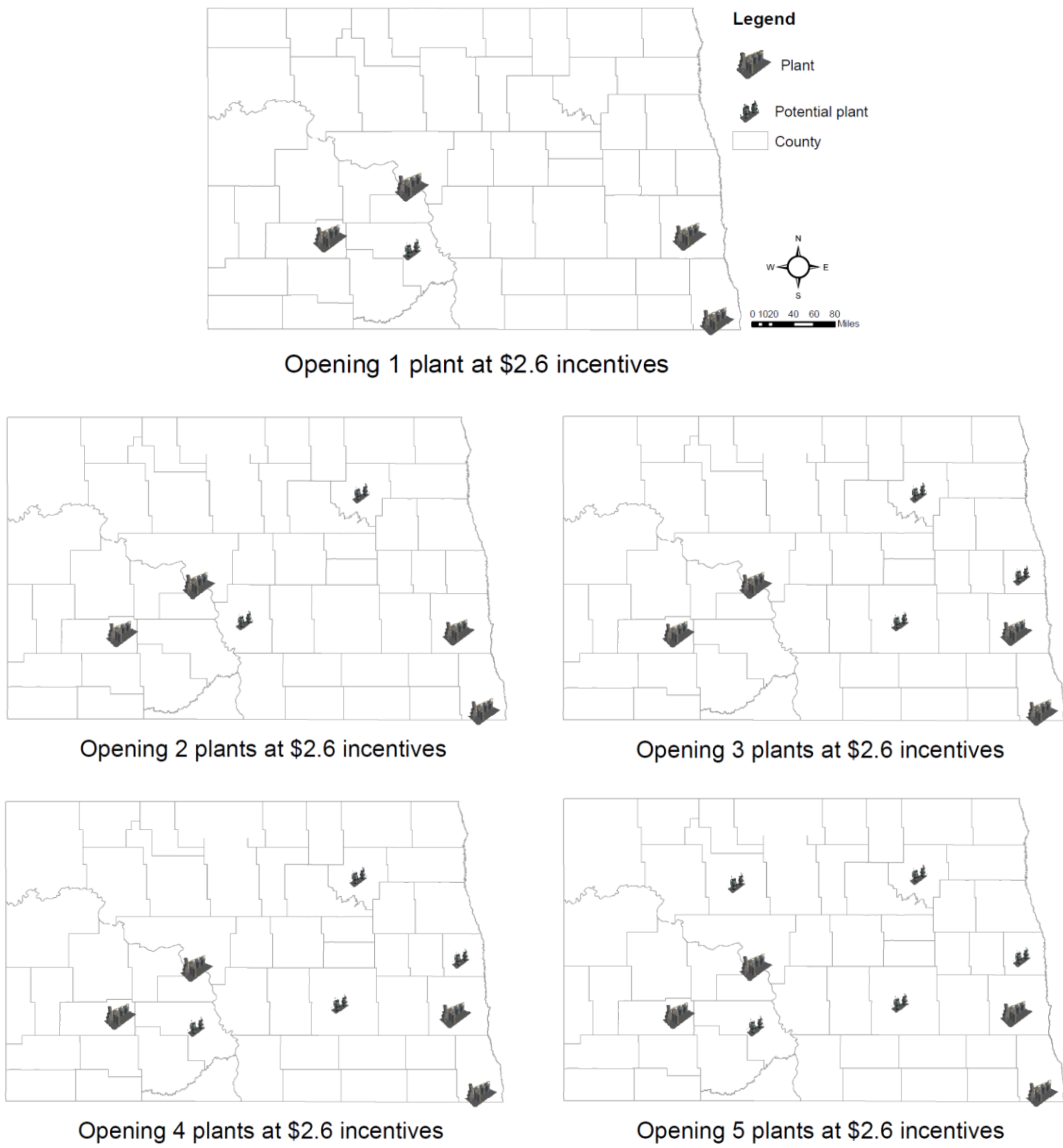


Figure 5.6. Opening one to five new plants scenarios at $2.6 incentive value.

In Table 5.3, we present results of building one to five new plants around ND (based on each county) with the capacity needed to get 100% corn stover converted to biofuel by setting the objective function of maximizing profit with penalties on the emissions. Results show that Ramsey county is the most preferred location to build a new plant since it appears in all scenarios of opening a new plant and for all incentive value cases. When the decision is to build two new plants, Barnes and Ramsey counties are chosen. Building three new plants around ND shows the two counties are selected plus the additional one in Stutsman. Building additional plants to four and five plants indicated that Grand Forks and Morton are selected (including Barnes, Ramsey and Stutsman). Notice that, when we include the emissions penalties in the objective function, the locations for new plants are the same for all scenarios. The graphical solution of the results can be found in the GIS maps of Figures 5.7 to 5.10.

Table 5.3. Opening 1 – 5 new plants in potential location with capacity level (Maximize Profit – emission price Objective)

	Open 1 Plant		Open 2 Plant		Open 3 Plant		Open 4 Plant		Open 5 Plant	
Incentive value	Plant	Capacity (ton)	Plant	Capacity (ton)	Plant	Capacity (ton)	Plant	Capacity (ton)	Plant	Capacity (ton)
$1,960	Ramsey	7,577,590	Barnes	1,639,680	Barnes	1,332,240	Barnes	1,298,080	Barnes	1,298,080
			Ramsey	5,937,910	Ramsey	3,894,240	Grand Forks	1,937,865	Grand Forks	1,937,865
					Stutsman	2,351,110	Ramsey	2,152,080	Morton	959,805
							Stutsman	2,189,565	Ramsey	1,742,160
									Stutsman	1,639,680
$2,092.5	Ramsey	7,577,590	Barnes	1,639,680	Barnes	1,332,240	Barnes	1,298,080	Barnes	1,298,080
			Ramsey	5,937,910	Ramsey	3,894,240	Grand Forks	1,937,865	Grand Forks	1,937,865
					Stutsman	2,351,110	Ramsey	2,152,080	Morton	959,805
							Stutsman	2,189,565	Ramsey	1,742,160
									Stutsman	1,639,680
$2,225	Ramsey	7,577,590	Barnes	1,708,000	Barnes	1,434,720	Barnes	1,298,080	Barnes	1,298,080
			Ramsey	5,869,590	Ramsey	3,860,080	Grand Forks	1,937,865	Grand Forks	1,937,865
					Stutsman	2,282,790	Ramsey	2,117,920	Morton	754,845
							Stutsman	2,223,725	Ramsey	1,742,160
									Stutsman	1,844,640
$2,490	Ramsey	7,577,590	Barnes	1,742,160	Barnes	1,434,720	Barnes	1,332,240	Barnes	1,332,240
			Ramsey	5,835,430	Ramsey	3,829,245	Grand Forks	1,903,705	Grand Forks	1,903,705
					Stutsman	2,313,625	Ramsey	2,087,085	Morton	754,845
							Stutsman	2,254,560	Ramsey	1,742,160
									Stutsman	1,844,640

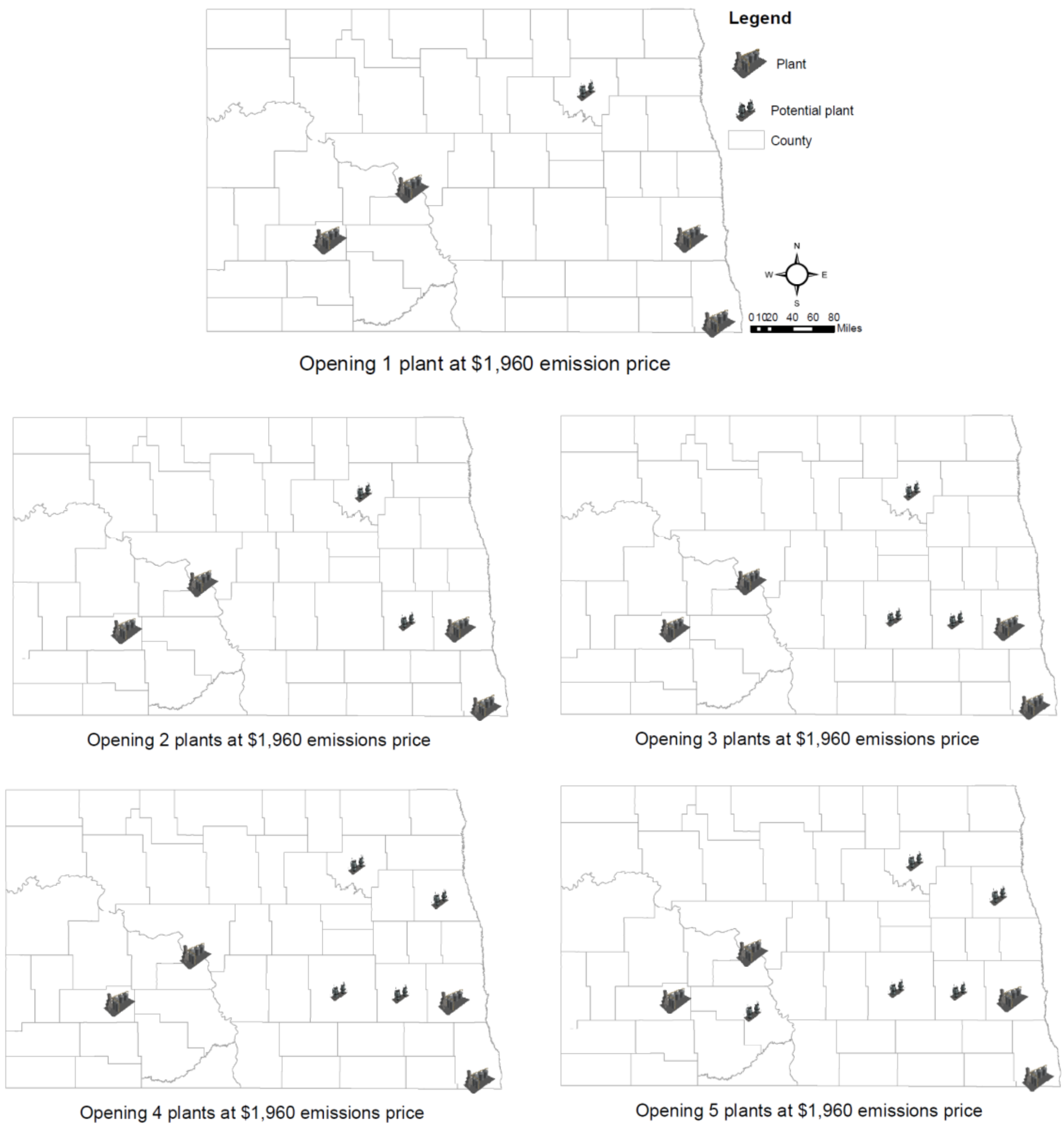


Figure 5.7. Opening one to five new plants scenarios at $1,960 emissions price.

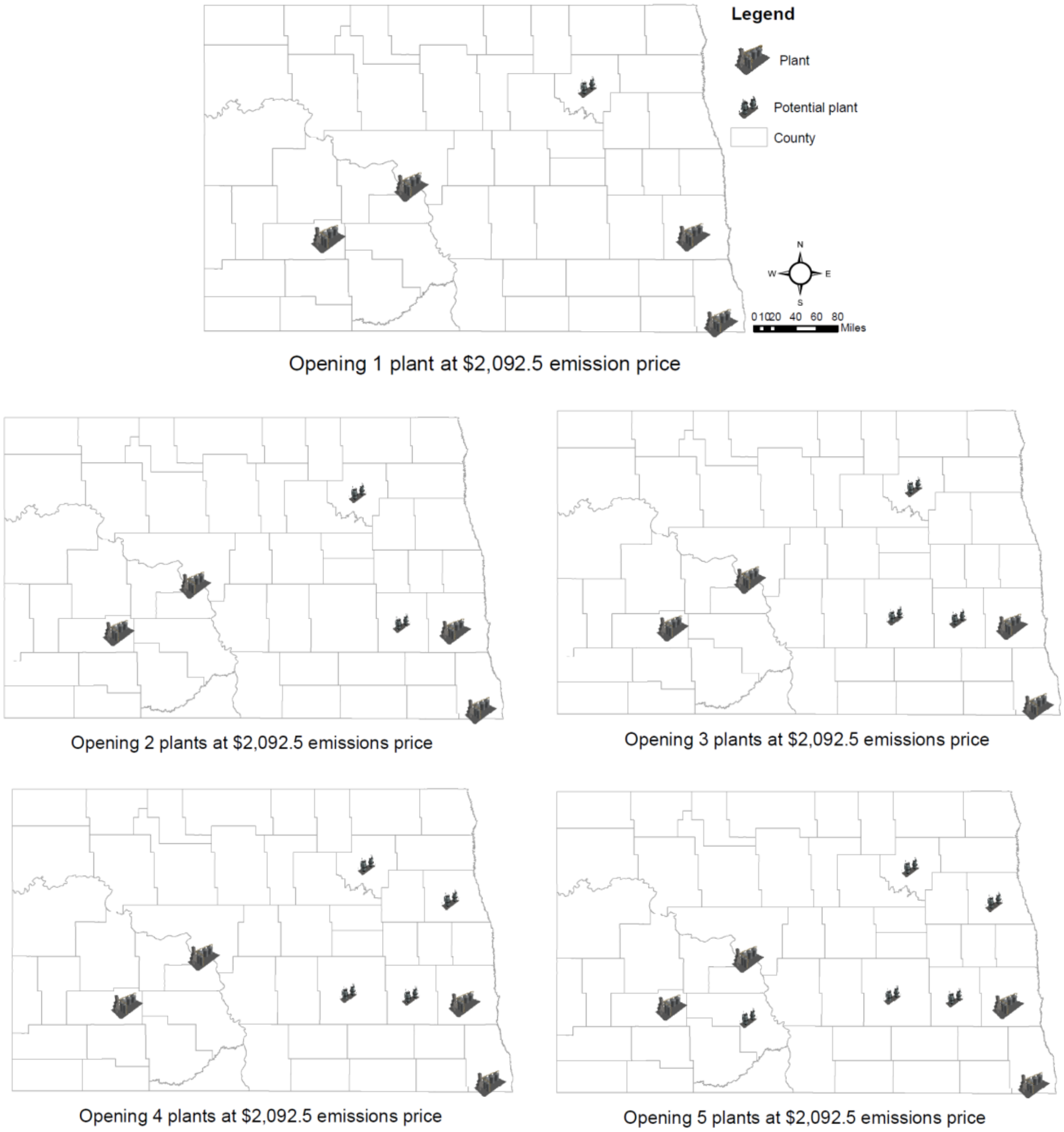


Figure 5.8. Opening one to five new plants scenarios at $2,092.5 emissions price.

Figure 5.9. Opening one to five new plants scenarios at $2,225 emissions price.

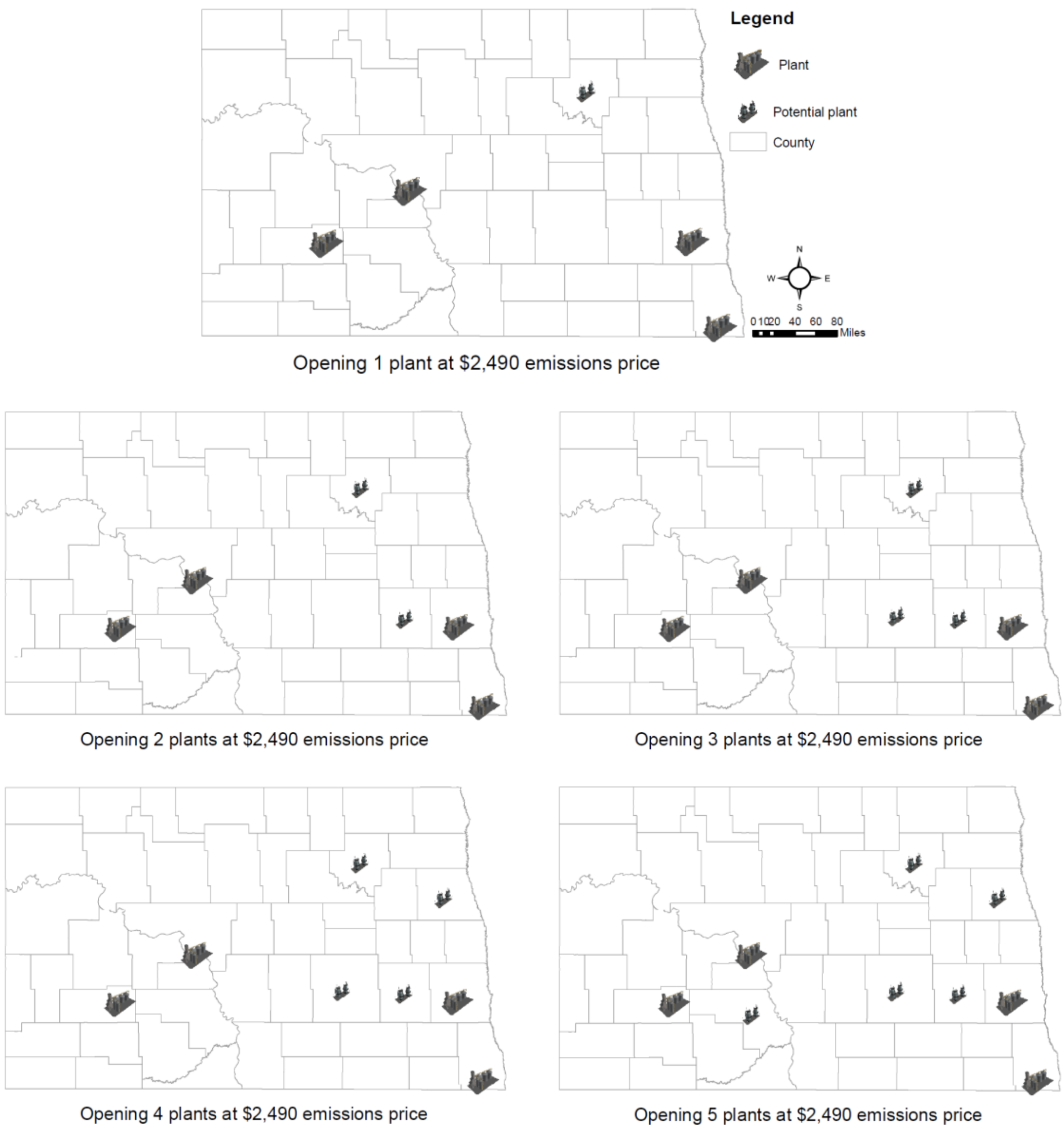


Figure 5.10. Opening one to five new plants scenarios at $2,490 emissions price.

In the plant location analysis, we also provide results of identifying suitable locations for building new plants under a financial budget allocation limitation. We introduce two budget allocations in our model which are $30 million and $60 million. Table 5.4 indicates the results of the experiments, showing that only one plant which is in Stutsman county can be built with a $30 million budget with the expansion of the existing plant located in Cass county. The total cost of opening a new plant and expanding the existing plant is $43,621,899. An additional budget allocation up to $60 million shows that new plants in Stutsman and Morton should be built, with the expansion of the existing plant in Cass county. The cost associated with building new plants and expanding the existing plant is $65,436,283 in total. The graphical solutions (GIS maps) of opening new plant with financial budget allocation can be seen in figure 5.11.

Table 5.4. Potential plant location with budget allocation.

Budget allocation for opening new plant					
$30 million			**$60 million**		
Build new plant	**Expand**	**New plant + expand cost**	**Build new plant**	**Expand**	**New plant + expand cost**
Stutsman	Cass	$43,621,899	Morton Stutsman	Cass	$65,436,283

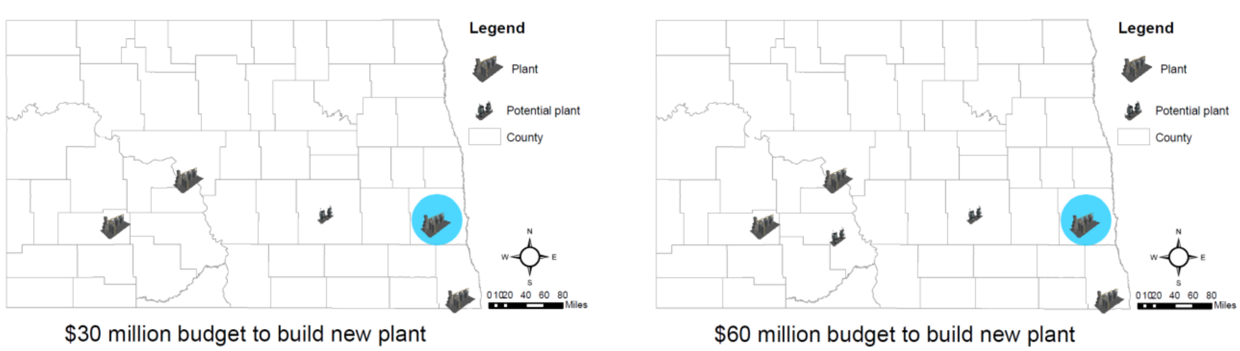


Figure 5.11. Opening new plant with budget allocation restriction

5.3. Future research

In this study, we have full control of the incentive and emission price to get 100% corn stover converted to biofuel. Linear and mixed integer linear programs are utilized to analyze the incentive and emission price values given decisions on amount of corn stover sent from origins to final destinations, locations of potential new plants, and capacity levels. By varying the two parameters (incentive and emission price) we can see the changes on those decisions as well as the profit of both farms and plants. However, treating the incentive and/or emission price as a variable can be a challenge as it will result in a non-linear program which can be hard to be solve since it takes longer time to find optimal solutions. The non-linearity in the model could be an interesting topic for future research.

Furthermore, looking into individual farms and plants can also be a new research direction where one can see how the decisions of the plants can be affected by the decisions of the farms by treating this as a bi-level optimization problem.

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APPENDIX A. FARM'S PROFIT WITH DIFFERENT SELLING PRICE

		FARM'S PROFIT (SELLING PRICE)						
From farm:	**To plant:**	**At normal Selling Price**	**Breakeven Price**		**MCLEAN**	**RICHLAND**	**STARK**	**CASS**
		$ 45.00			**$49.69**	**$48.40**	**$43.26**	**$50.29**
Benson4	MCLEAN	(73,936.63)	$ 47.16	0.0	86,420.27	42,253.20	(133,438.97)	106,875.55
Benson5	MCLEAN	(160,356.91)	$ 49.69	0.0	0.0	(44,167.07)	(219,859.25)	20,455.28
Bottineau2	MCLEAN	(91,020.61)	$ 47.66	0.0	69,336.30	25,169.22	(150,522.95)	89,791.57
Bottineau3	MCLEAN	(117,891.22)	$ 48.45	0.0	42,465.69	(1,701.38)	(177,393.56)	62,920.97
Emmons1	MCLEAN	(86,589.71)	$ 47.53	0.0	73,767.20	29,600.12	(146,092.05)	94,222.47
Emmons10	MCLEAN	(33,043.87)	$ 45.97	0.0	127,313.03	83,145.96	(92,546.21)	147,768.31
Emmons12	MCLEAN	(29,653.72)	$ 45.87	0.0	130,703.18	86,536.11	(89,156.06)	151,158.46
Emmons13	MCLEAN	(16,069.50)	$ 45.47	0.0	144,287.40	100,120.33	(75,571.84)	164,742.68
Emmons14	MCLEAN	(79,861.21)	$ 47.34	0.0	80,495.70	36,328.62	(139,363.55)	100,950.98
Emmons4	MCLEAN	(59,272.93)	$ 46.74	0.0	101,083.98	56,916.90	(118,775.27)	121,539.26
Emmons5	MCLEAN	(44,886.90)	$ 46.31	0.0	115,470.01	71,302.93	(104,389.24)	135,925.29
Emmons6	MCLEAN	(11,150.14)	$ 45.33	0.0	149,206.76	105,039.69	(70,652.48)	169,662.04
Kidder3	MCLEAN	(32,945.11)	$ 45.96	0.0	127,411.79	83,244.72	(92,447.45)	147,867.07
Logan2	MCLEAN	(129,463.50)	$ 48.79	0.0	30,893.41	(13,273.67)	(188,965.84)	51,348.69
Logan3	MCLEAN	(143,046.33)	$ 49.19	0.0	17,310.58	(26,856.50)	(202,548.67)	37,765.85
McHenry2	MCLEAN	(32,321.65)	$ 45.95	0.0	128,035.26	83,868.18	(91,823.99)	148,490.54
Mcintosh2	MCLEAN	(153,835.05)	$ 49.50	0.0	6,521.85	(37,645.22)	(213,337.39)	26,977.13
Pierce1	MCLEAN	(68,892.38)	$ 47.02	0.0	91,464.53	47,297.46	(128,394.72)	111,919.81
Renville	MCLEAN	(44,269.30)	$ 46.30	0.0	116,087.60	71,920.53	(103,771.64)	136,542.88
Stutsman1	MCLEAN	(13,021.92)	$ 45.38	0.0	147,334.99	103,167.92	(72,524.26)	167,790.27
Wells4	MCLEAN	(15,358.50)	$ 45.45	0.0	144,998.41	100,831.34	(74,860.84)	165,453.69
Wells5	MCLEAN	(23,385.26)	$ 45.68	0.0	136,971.65	92,804.58	(82,887.60)	157,426.93
Wells6	MCLEAN	(22,311.28)	$ 45.65	0.0	138,045.63	93,878.55	(81,813.62)	158,500.91
Wells8	MCLEAN	(37,292.07)	$ 46.09	0.0	123,064.84	78,897.76	(96,794.41)	143,520.12
Dickey10	RICHLAND	(40,837.08)	$ 46.20	0.0	119,519.82	75,352.75	(100,339.42)	139,975.10

		FARM'S PROFIT (SELLING PRICE)						
From farm:	**To plant:**	**At normal Selling Price**	**Breakeven Price**		**MCLEAN**	**RICHLAND**	**STARK**	**CASS**
		$ 45.00			**$49.69**	**$48.40**	**$43.26**	**$50.29**
Dickey11	RICHLAND	(5,310.89)	$ 45.16	0.0	155,046.02	110,878.94	(64,813.23)	175,501.30
Dickey8	RICHLAND	(31,674.51)	$ 45.93	0.0	128,682.40	84,515.33	(91,176.85)	149,137.68
Dickey9	RICHLAND	(23,649.36)	$ 45.69	0.0	136,707.55	92,540.47	(83,151.70)	157,162.83
LaMoure17	RICHLAND	(50,569.22)	$ 46.48	0.0	109,787.68	65,620.61	(110,071.56)	130,242.96
LaMoure2	RICHLAND	(51,803.76)	$ 46.52	0.0	108,553.15	64,386.08	(111,306.09)	129,008.43
Mcintosh4	RICHLAND	(114,687.93)	$ 48.36	0.0	45,668.97	1,501.90	(174,190.27)	66,124.25
Mcintosh5	RICHLAND	(116,189.83)	$ 48.40	0.0	44,167.07	0.0	(175,692.17)	64,622.35
Slope	STARK	59,502.34	$ 43.26	0.0	219,859.25	175,692.17	0.0	240,314.53
Eddy1	CASS	(138,164.80)	$ 49.04	0.0	22,192.10	(21,974.97)	(197,667.14)	42,647.38
Eddy3	CASS	(55,605.80)	$ 46.63	0.0	104,751.11	60,584.04	(115,108.14)	125,206.39
Foster2	CASS	(39,880.07)	$ 46.17	0.0	120,476.84	76,309.76	(99,382.41)	140,932.12
Foster3	CASS	(22,334.75)	$ 45.65	0.0	138,022.15	93,855.08	(81,837.09)	158,477.43
GrandForks7	CASS	(18,890.16)	$ 45.55	0.0	141,466.75	97,299.68	(78,392.50)	161,922.03
LaMoure1	CASS	(39,920.23)	$ 46.17	0.0	120,436.68	76,269.61	(99,422.57)	140,891.96
LaMoure18	CASS	(29,330.11)	$ 45.86	0.0	131,026.80	86,859.73	(88,832.44)	151,482.08
Logan1	CASS	(178,522.39)	$ 50.23	0.0	(18,165.49)	(62,332.56)	(238,024.73)	2,289.79
Logan5	CASS	(91,702.92)	$ 47.68	0.0	68,653.98	24,486.91	(151,205.26)	89,109.26
Nelson2	CASS	(4,788.90)	$ 45.14	0.0	155,568.01	111,400.94	(64,291.24)	176,023.29
Nelson3	CASS	(58,441.68)	$ 46.71	0.0	101,915.22	57,748.15	(117,944.02)	122,370.50
Stutsman10	CASS	(45,418.70)	$ 46.33	0.0	114,938.20	70,771.13	(104,921.04)	135,393.48
Stutsman11	CASS	(29,810.69)	$ 45.87	0.0	130,546.22	86,379.14	(89,313.03)	151,001.50
Stutsman12	CASS	(30,028.28)	$ 45.88	0.0	130,328.63	86,161.56	(89,530.61)	150,783.91
Stutsman19	CASS	(59,642.78)	$ 46.75	0.0	100,714.12	56,547.05	(119,145.12)	121,169.40
Walsh1	CASS	(162,102.72)	$ 49.75	0.0	(1,745.81)	(45,912.88)	(221,605.06)	18,709.47
Walsh2	CASS	(180,812.19)	$ 50.29	0.0	(20,455.28)	(64,622.35)	(240,314.53)	0.0
Walsh3	CASS	(118,236.14)	$ 48.46	0.0	42,120.77	(2,046.31)	(177,738.48)	62,576.05

From farm:	To plant:	FARM'S PROFIT (SELLING PRICE)						
		At normal Selling Price	Breakeven Price		MCLEAN	RICHLAND	STARK	CASS
		$ 45.00			$49.69	$48.40	$43.26	$50.29
Walsh4	CASS	(77,533.30)	$ 47.27	0.0	82,823.61	38,656.54	(137,035.64)	103,278.89
Walsh5	CASS	(39,783.29)	$ 46.16	0.0	120,573.62	76,406.54	(99,285.63)	141,028.89
Walsh6	CASS	(151,157.48)	$ 49.42	0.0	9,199.43	(34,967.65)	(210,659.82)	29,654.71

APPENDIX B. CORN STOVER SELLING PRICE PERCENTAGE

From farm:	To plant:	SELLING PRICE PERCENTAGE						
		At normal Selling Price	Breakeven Price		MCLEAN	RICHLAND	STARK	CASS
		$ 45.00			$ 49.69	$ 48.40	$ 43.26	$ 50.29
Benson4	MCLEAN	(73,936.63)	$ 47.16	5%	5%	3%	-8%	7%
Benson5	MCLEAN	(160,356.91)	$ 49.69	9%	**0%**	-3%	-13%	1%
Bottineau2	MCLEAN	(91,020.61)	$ 47.66	6%	4%	2%	-9%	6%
Bottineau3	MCLEAN	(117,891.22)	$ 48.45	7%	3%	0%	-11%	4%
Emmons1	MCLEAN	(86,589.71)	$ 47.53	5%	5%	2%	-9%	6%
Emmons10	MCLEAN	(33,043.87)	$ 45.97	2%	8%	5%	-6%	9%
Emmons12	MCLEAN	(29,653.72)	$ 45.87	2%	8%	6%	-6%	10%
Emmons13	MCLEAN	(16,069.50)	$ 45.47	1%	9%	6%	-5%	11%
Emmons14	MCLEAN	(79,861.21)	$ 47.34	5%	5%	2%	-9%	6%
Emmons4	MCLEAN	(59,272.93)	$ 46.74	4%	6%	4%	-7%	8%
Emmons5	MCLEAN	(44,886.90)	$ 46.31	3%	7%	5%	-7%	9%
Emmons6	MCLEAN	(11,150.14)	$ 45.33	1%	10%	7%	-5%	11%
Kidder3	MCLEAN	(32,945.11)	$ 45.96	2%	8%	5%	-6%	9%
Logan2	MCLEAN	(129,463.50)	$ 48.79	8%	2%	-1%	-11%	3%
Logan3	MCLEAN	(143,046.33)	$ 49.19	9%	1%	-2%	-12%	2%
McHenry2	MCLEAN	(32,321.65)	$ 45.95	2%	8%	5%	-6%	9%
Mcintosh2	MCLEAN	(153,835.05)	$ 49.50	9%	0%	-2%	-13%	2%
Pierce1	MCLEAN	(68,892.38)	$ 47.02	4%	6%	3%	-8%	7%
Renville	MCLEAN	(44,269.30)	$ 46.30	3%	7%	5%	-7%	9%
Stutsman1	MCLEAN	(13,021.92)	$ 45.38	1%	10%	7%	-5%	11%
Wells4	MCLEAN	(15,358.50)	$ 45.45	1%	9%	6%	-5%	11%
Wells5	MCLEAN	(23,385.26)	$ 45.68	1%	9%	6%	-5%	10%
Wells6	MCLEAN	(22,311.28)	$ 45.65	1%	9%	6%	-5%	10%
Wells8	MCLEAN	(37,292.07)	$ 46.09	2%	8%	5%	-6%	9%
Dickey10	RICHLAND	(40,837.08)	$ 46.20	3%	8%	5%	-6%	9%

From farm:	To plant:	SELLING PRICE PERCENTAGE						
		At normal Selling Price	Breakeven Price		MCLEAN	RICHLAND	STARK	CASS
		$ 45.00			**$ 49.69**	**$ 48.40**	**$ 43.26**	**$ 50.29**
Dickey11	RICHLAND	(5,310.89)	$ 45.16	0%	10%	7%	-4%	11%
Dickey8	RICHLAND	(31,674.51)	$ 45.93	2%	8%	5%	-6%	10%
Dickey9	RICHLAND	(23,649.36)	$ 45.69	2%	9%	6%	-5%	10%
LaMoure17	RICHLAND	(50,569.22)	$ 46.48	3%	7%	4%	-7%	8%
LaMoure2	RICHLAND	(51,803.76)	$ 46.52	3%	7%	4%	-7%	8%
Mcintosh4	RICHLAND	(114,687.93)	$ 48.36	7%	3%	0%	-11%	4%
Mcintosh5	RICHLAND	(116,189.83)	$ 48.40	7%	3%	**0%**	-11%	4%
Slope	STARK	59,502.34	$ 43.26	-4%	15%	12%	**0%**	16%
Eddy1	CASS	(138,164.80)	$ 49.04	8%	1%	-1%	-12%	3%
Eddy3	CASS	(55,605.80)	$ 46.63	3%	7%	4%	-7%	8%
Foster2	CASS	(39,880.07)	$ 46.17	3%	8%	5%	-6%	9%
Foster3	CASS	(22,334.75)	$ 45.65	1%	9%	6%	-5%	10%
GrandForks7	CASS	(18,890.16)	$ 45.55	1%	9%	6%	-5%	10%
LaMoure1	CASS	(39,920.23)	$ 46.17	3%	8%	5%	-6%	9%
LaMoure18	CASS	(29,330.11)	$ 45.86	2%	8%	6%	-6%	10%
Logan1	CASS	(178,522.39)	$ 50.23	10%	-1%	-4%	-14%	0%
Logan5	CASS	(91,702.92)	$ 47.68	6%	4%	2%	-9%	5%
Nelson2	CASS	(4,788.90)	$ 45.14	0%	10%	7%	-4%	11%
Nelson3	CASS	(58,441.68)	$ 46.71	4%	6%	4%	-7%	8%
Stutsman10	CASS	(45,418.70)	$ 46.33	3%	7%	4%	-7%	9%
Stutsman11	CASS	(29,810.69)	$ 45.87	2%	8%	6%	-6%	10%
Stutsman12	CASS	(30,028.28)	$ 45.88	2%	8%	5%	-6%	10%
Stutsman19	CASS	(59,642.78)	$ 46.75	4%	6%	4%	-7%	8%
Walsh1	CASS	(162,102.72)	$ 49.75	10%	0%	-3%	-13%	1%
Walsh2	CASS	(180,812.19)	$ 50.29	11%	-1%	-4%	-14%	**0%**
Walsh3	CASS	(118,236.14)	$ 48.46	7%	3%	0%	-11%	4%

From farm:	To plant:	SELLING PRICE PERCENTAGE						
		At normal Selling Price	Breakeven Price		MCLEAN	RICHLAND	STARK	CASS
		$ 45.00			$ 49.69	$ 48.40	$ 43.26	$ 50.29
Walsh4	CASS	(77,533.30)	$ 47.27	5%	5%	2%	-8%	6%
Walsh5	CASS	(39,783.29)	$ 46.16	3%	8%	5%	-6%	9%
Walsh6	CASS	(151,157.48)	$ 49.42	9%	1%	-2%	-12%	2%

APPENDIX C. FARM'S PROFIT WITH DIFFERENT TRANSPORTATION COST

From farm:	To plant:	FARM'S PROFIT (TRANSPORTATION COST) At normal Transportation cost	Breakeven cost		MCLEAN	RICHLAND	STARK	CASS
		$ 0.096			$ 0.0615	$ 0.0823	$ 0.1166	$ 0.0584
Benson4	MCLEAN	(73,936.63)	$ 0.0773	0.0	62,534.57	(19,701.81)	(155,474.50)	74,702.46
Benson5	MCLEAN	(160,356.91)	$ 0.0615	0.0	0.0	(96,629.70)	(256,165.84)	14,297.56
Bottineau2	MCLEAN	(91,020.61)	$ 0.0737	0.0	50,172.43	(34,909.29)	(175,379.65)	62,761.33
Bottineau3	MCLEAN	(117,891.22)	$ 0.0686	0.0	30,728.59	(58,828.43)	(206,687.55)	43,979.67
Emmons1	MCLEAN	(86,589.71)	$ 0.0746	0.0	53,378.67	(30,965.07)	(170,217.05)	65,858.38
Emmons10	MCLEAN	(33,043.87)	$ 0.0869	0.0	92,124.97	16,699.30	(107,828.89)	103,285.14
Emmons12	MCLEAN	(29,653.72)	$ 0.0878	0.0	94,578.12	19,717.08	(103,878.90)	105,654.74
Emmons13	MCLEAN	(16,069.50)	$ 0.0914	0.0	104,407.80	31,809.21	(88,051.45)	115,149.66
Emmons14	MCLEAN	(79,861.21)	$ 0.0760	0.0	58,247.48	(24,975.63)	(162,377.44)	70,561.37
Emmons4	MCLEAN	(59,272.93)	$ 0.0805	0.0	73,145.37	(6,648.76)	(138,389.30)	84,951.90
Emmons5	MCLEAN	(44,886.90)	$ 0.0839	0.0	83,555.24	6,157.11	(121,627.62)	95,007.26
Emmons6	MCLEAN	(11,150.14)	$ 0.0928	0.0	107,967.50	36,188.23	(82,319.72)	118,588.13
Kidder3	MCLEAN	(32,945.11)	$ 0.0869	0.0	92,196.44	16,787.21	(107,713.82)	103,354.17
Logan2	MCLEAN	(129,463.50)	$ 0.0665	0.0	22,354.77	(69,129.62)	(220,170.83)	35,891.02
Logan3	MCLEAN	(143,046.33)	$ 0.0642	0.0	12,526.10	(81,220.51)	(235,996.67)	26,397.08
McHenry2	MCLEAN	(32,321.65)	$ 0.0871	0.0	92,647.58	17,342.19	(106,987.40)	103,789.95
Mcintosh2	MCLEAN	(153,835.05)	$ 0.0625	0.0	4,719.28	(90,824.20)	(248,567.00)	18,856.12
Pierce1	MCLEAN	(68,892.38)	$ 0.0784	0.0	66,184.64	(15,211.61)	(149,597.26)	78,228.22
Renville	MCLEAN	(44,269.30)	$ 0.0841	0.0	84,002.14	6,706.87	(120,908.04)	95,438.94
Stutsman1	MCLEAN	(13,021.92)	$ 0.0922	0.0	106,613.06	34,522.05	(84,500.59)	117,279.82
Wells4	MCLEAN	(15,358.50)	$ 0.0916	0.0	104,922.29	32,442.12	(87,223.03)	115,646.63
Wells5	MCLEAN	(23,385.26)	$ 0.0894	0.0	99,114.05	25,297.02	(96,575.29)	110,036.19
Wells6	MCLEAN	(22,311.28)	$ 0.0897	0.0	99,891.19	26,253.03	(95,323.96)	110,786.86
Wells8	MCLEAN	(37,292.07)	$ 0.0858	0.0	89,050.94	12,917.73	(112,778.61)	100,315.79

From farm:	To plant:	FARM'S PROFIT (TRANSPORTATION COST) At normal Transportation cost	Breakeven cost		MCLEAN	RICHLAND	STARK	CASS
		$ 0.096			$ 0.0615	$ 0.0823	$ 0.1166	$ 0.0584
Dickey10	RICHLAND	(40,837.08)	$ 0.0849	0.0	86,485.73	9,762.09	(116,909.04)	97,837.94
Dickey11	RICHLAND	(5,310.89)	$ 0.0944	0.0	112,192.84	41,386.10	(75,516.20)	122,669.57
Dickey8	RICHLAND	(31,674.51)	$ 0.0872	0.0	93,115.86	17,918.26	(106,233.39)	104,242.28
Dickey9	RICHLAND	(23,649.36)	$ 0.0893	0.0	98,922.94	25,061.92	(96,883.00)	109,851.59
LaMoure17	RICHLAND	(50,569.22)	$ 0.0826	0.0	79,443.46	1,098.93	(128,248.30)	91,035.50
LaMoure2	RICHLAND	(51,803.76)	$ 0.0823	0.0	78,550.14	0.0	(129,686.70)	90,172.60
Mcintosh4	RICHLAND	(114,687.93)	$ 0.0692	0.0	33,046.52	(55,976.99)	(202,955.29)	46,218.65
Mcintosh5	RICHLAND	(116,189.83)	$ 0.0689	0.0	31,959.73	(57,313.92)	(204,705.21)	45,168.88
Slope	STARK	59,502.34	$ 0.1166	0.0	159,092.33	99,080.26	0.0	167,971.86
Eddy1	CASS	(138,164.80)	$ 0.0650	0.0	16,058.43	(76,875.17)	(230,309.03)	29,809.10
Eddy3	CASS	(55,605.80)	$ 0.0814	0.0	75,798.94	(3,384.43)	(134,116.59)	87,515.10
Foster2	CASS	(39,880.07)	$ 0.0852	0.0	87,178.24	10,613.99	(115,793.98)	98,506.86
Foster3	CASS	(22,334.75)	$ 0.0897	0.0	99,874.20	26,232.13	(95,351.31)	110,770.46
GrandForks7	CASS	(18,890.16)	$ 0.0906	0.0	102,366.74	29,298.37	(91,337.89)	113,178.11
LaMoure1	CASS	(39,920.23)	$ 0.0851	0.0	87,149.18	10,578.24	(115,840.77)	98,478.79
LaMoure18	CASS	(29,330.11)	$ 0.0878	0.0	94,812.29	20,005.15	(103,501.85)	105,880.94
Logan1	CASS	(178,522.39)	$ 0.0587	0.0	(13,144.73)	(112,799.89)	(277,331.10)	1,600.49
Logan5	CASS	(91,702.92)	$ 0.0736	0.0	49,678.70	(35,516.65)	(176,174.64)	62,284.41
Nelson2	CASS	(4,788.90)	$ 0.0946	0.0	112,570.56	41,850.76	(74,908.01)	123,034.43
Nelson3	CASS	(58,441.68)	$ 0.0807	0.0	73,746.87	(5,908.82)	(137,420.78)	85,532.91
Stutsman10	CASS	(45,418.70)	$ 0.0838	0.0	83,170.43	5,683.72	(122,247.24)	94,635.54
Stutsman11	CASS	(29,810.69)	$ 0.0877	0.0	94,464.54	19,577.35	(104,061.79)	105,545.03
Stutsman12	CASS	(30,028.28)	$ 0.0877	0.0	94,307.09	19,383.67	(104,315.31)	105,392.94
Stutsman19	CASS	(59,642.78)	$ 0.0805	0.0	72,877.74	(6,977.99)	(138,820.23)	84,693.38
Walsh1	CASS	(162,102.72)	$ 0.0612	0.0	(1,263.29)	(98,183.75)	(258,199.95)	13,077.30
Walsh2	CASS	(180,812.19)	$ 0.0584	0.0	(14,801.64)	(114,838.1)	(279,999.01)	0.0

From farm:	To plant:	FARM'S PROFIT (TRANSPORTATION COST)						
		At normal Transportation cost	Breakeven cost		MCLEAN	RICHLAND	STARK	CASS
		$ 0.096			$ 0.0615	$ 0.0823	$ 0.1166	$ 0.0584
Walsh3	CASS	(118,236.14)	$ 0.0685	0.0	30,479.00	(59,135.47)	(207,089.43)	43,738.57
Walsh4	CASS	(77,533.30)	$ 0.0765	0.0	59,931.99	(22,903.41)	(159,665.10)	72,188.51
Walsh5	CASS	(39,783.29)	$ 0.0852	0.0	87,248.26	10,700.14	(115,681.23)	98,574.51
Walsh6	CASS	(151,157.48)	$ 0.0629	0.0	6,656.80	(88,440.73)	(245,447.26)	20,727.65

APPENDIX D. TRANSPORTATION COST PERCENTAGE

From farm:	To plant:	TRANSPORTATION COST PERCENTAGE						
		At normal Transportation cost	Breakeven cost		MCLEAN	RICHLAND	STARK	CASS
		$ 0.096			**$ 0.0615**	**$ 0.0823**	**$ 0.1166**	**$ 0.0584**
Benson4	MCLEAN	(73,936.63)	$ 0.0773	-19%	-26%	6%	34%	-32%
Benson5	MCLEAN	(160,356.91)	$ 0.0615	-36%	**0%**	25%	47%	-5%
Bottineau2	MCLEAN	(91,020.61)	$ 0.0737	-23%	-20%	10%	37%	-26%
Bottineau3	MCLEAN	(117,891.22)	$ 0.0686	-29%	-12%	17%	41%	-17%
Emmons1	MCLEAN	(86,589.71)	$ 0.0746	-22%	-21%	9%	36%	-28%
Emmons10	MCLEAN	(33,043.87)	$ 0.0869	-10%	-41%	-6%	25%	-49%
Emmons12	MCLEAN	(29,653.72)	$ 0.0878	-9%	-43%	-7%	25%	-50%
Emmons13	MCLEAN	(16,069.50)	$ 0.0914	-5%	-49%	-11%	22%	-56%
Emmons14	MCLEAN	(79,861.21)	$ 0.0760	-21%	-24%	8%	35%	-30%
Emmons4	MCLEAN	(59,272.93)	$ 0.0805	-16%	-31%	2%	31%	-38%
Emmons5	MCLEAN	(44,886.90)	$ 0.0839	-13%	-36%	-2%	28%	-44%
Emmons6	MCLEAN	(11,150.14)	$ 0.0928	-3%	-51%	-13%	20%	-59%
Kidder3	MCLEAN	(32,945.11)	$ 0.0869	-9%	-41%	-6%	25%	-49%
Logan2	MCLEAN	(129,463.50)	$ 0.0665	-31%	-8%	19%	43%	-14%
Logan3	MCLEAN	(143,046.33)	$ 0.0642	-33%	-4%	22%	45%	-10%
McHenry2	MCLEAN	(32,321.65)	$ 0.0871	-9%	-42%	-6%	25%	-49%
Mcintosh2	MCLEAN	(153,835.05)	$ 0.0625	-35%	-2%	24%	46%	-7%
Pierce1	MCLEAN	(68,892.38)	$ 0.0784	-18%	-27%	5%	33%	-34%
Renville	MCLEAN	(44,269.30)	$ 0.0841	-12%	-37%	-2%	28%	-44%
Stutsman1	MCLEAN	(13,021.92)	$ 0.0922	-4%	-50%	-12%	21%	-58%
Wells4	MCLEAN	(15,358.50)	$ 0.0916	-5%	-49%	-11%	21%	-57%
Wells5	MCLEAN	(23,385.26)	$ 0.0894	-7%	-45%	-9%	23%	-53%
Wells6	MCLEAN	(22,311.28)	$ 0.0897	-7%	-46%	-9%	23%	-54%
Wells8	MCLEAN	(37,292.07)	$ 0.0858	-11%	-40%	-4%	26%	-47%

		TRANSPORTATION COST PERCENTAGE						
From farm:	**To plant:**	**At normal Transportation cost**	**Breakeven cost**		**MCLEAN**	**RICHLAND**	**STARK**	**CASS**
		$ 0.096			**$ 0.0615**	**$ 0.0823**	**$ 0.1166**	**$ 0.0584**
Dickey10	RICHLAND	(40,837.08)	$ 0.0849	-12%	-38%	-3%	27%	-45%
Dickey11	RICHLAND	(5,310.89)	$ 0.0944	-2%	-54%	-15%	19%	-62%
Dickey8	RICHLAND	(31,674.51)	$ 0.0872	-9%	-42%	-6%	25%	-49%
Dickey9	RICHLAND	(23,649.36)	$ 0.0893	-7%	-45%	-9%	23%	-53%
LaMoure17	RICHLAND	(50,569.22)	$ 0.0826	-14%	-34%	0%	29%	-41%
LaMoure2	RICHLAND	(51,803.76)	$ 0.0823	-14%	-34%	**0%**	29%	-41%
Mcintosh4	RICHLAND	(114,687.93)	$ 0.0692	-28%	-12%	16%	41%	-18%
Mcintosh5	RICHLAND	(116,189.83)	$ 0.0689	-28%	-12%	16%	41%	-18%
Slope	STARK	59,502.34	$ 0.1166	-22%	-90%	-42%	**0%**	-100%
Eddy1	CASS	(138,164.80)	$ 0.0650	-32%	-6%	21%	44%	-11%
Eddy3	CASS	(55,605.80)	$ 0.0814	-15%	-32%	1%	30%	-39%
Foster2	CASS	(39,880.07)	$ 0.0852	-11%	-38%	-3%	27%	-46%
Foster3	CASS	(22,334.75)	$ 0.0897	-7%	-46%	-9%	23%	-54%
GrandForks7	CASS	(18,890.16)	$ 0.0906	-6%	-47%	-10%	22%	-55%
LaMoure1	CASS	(39,920.23)	$ 0.0851	-11%	-38%	-3%	27%	-46%
LaMoure18	CASS	(29,330.11)	$ 0.0878	-9%	-43%	-7%	25%	-50%
Logan1	CASS	(178,522.39)	$ 0.0587	-39%	5%	29%	50%	-1%
Logan5	CASS	(91,702.92)	$ 0.0736	-23%	-20%	11%	37%	-26%
Nelson2	CASS	(4,788.90)	$ 0.0946	-1%	-54%	-15%	19%	-62%
Nelson3	CASS	(58,441.68)	$ 0.0807	-16%	-31%	2%	31%	-38%
Stutsman10	CASS	(45,418.70)	$ 0.0838	-13%	-36%	-2%	28%	-43%
Stutsman11	CASS	(29,810.69)	$ 0.0877	-9%	-43%	-7%	25%	-50%
Stutsman12	CASS	(30,028.28)	$ 0.0877	-9%	-43%	-7%	25%	-50%
Stutsman19	CASS	(59,642.78)	$ 0.0805	-16%	-31%	2%	31%	-38%
Walsh1	CASS	(162,102.72)	$ 0.0612	-36%	1%	26%	48%	-5%
Walsh2	CASS	(180,812.19)	$ 0.0584	-39%	5%	29%	50%	**0%**

From farm:	To plant:	TRANSPORTATION COST PERCENTAGE						
		At normal Transportation cost	Breakeven cost		MCLEAN	RICHLAND	STARK	CASS
		$ 0.096			**$ 0.0615**	**$ 0.0823**	**$ 0.1166**	**$ 0.0584**
Walsh3	CASS	(118,236.14)	$ 0.0685	-29%	-11%	17%	41%	-17%
Walsh4	CASS	(77,533.30)	$ 0.0765	-20%	-24%	7%	34%	-31%
Walsh5	CASS	(39,783.29)	$ 0.0852	-11%	-39%	-3%	27%	-46%
Walsh6	CASS	(151,157.48)	$ 0.0629	-34%	-2%	24%	46%	-8%