Essays on the Economics of Bioenergy and Emissions Trading

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Dedication

This dissertation is dedicated to my family: Jiae, Joonwoo and Sungwoo.

Abstract

The three essays in this dissertation focus on the economics of bioenergy and emissions trading. Chapter Two analyzes the economic impacts of cellulosic feedstock production in a major watershed of south-central Minnesota. A regional economic model of agricultural production in the watershed is constructed. By integrating environmental parameters from a biophysical simulation analysis of the watershed, the model focuses on economic and environmental issues associated with increasing use of two cellulosic feedstocks, corn stover and switchgrass, at the watershed level. Results indicate that corn stover can be produced at a relatively low marginal cost compared to switchgrass. Sediment and nutrient losses from corn stover production make switchgrass more promising on environmental grounds but the high marginal cost of production causes switchgrass to cover only small part of crop land if farmers have unrestricted choice about how to supply cellulosic feedstocks.

Chapter Three extends the model of chapter Two to examine the tradeoffs between cellulosic feedstock production and water quality by analyzing policy options targeted to address those tradeoffs. Policy alternatives considered include restrictions on total nitrate-N load in the watershed and production subsidies for switchgrass – an energy crop with potential environmental benefits. Restricting nitrate-N loads increases the cost of cellulosic feedstock supply and in some circumstances makes switchgrass production an economical alternative. Switchgrass production subsidies, if sufficiently high can increase feedstock supply while reducing or eliminating the negative effects of feedstock production on water quality.

Chapter Four examines how uncertainty in emissions affects firms' decision of permit purchase and abatement. This paper extends previous models of emissions trading by considering uncertainty as well as the order of firms' decisions about abatement and permit trading. When there is uncertainty about emissions, total expected emissions are the same regardless of the order of moves. The results show that whether firms abate more under uncertainty is dependent on the expected penalty cost and marginal abatement cost. If the expected marginal penalty cost is greater than the marginal abatement cost, the firm will choose to reduce emissions and abate more under uncertainty. When expected penalty is greater than marginal cost of abatement, increase in uncertainty makes expected emissions decrease given unit penalty fee.

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Chapter 1. Introduction

My dissertation consists of three essays focusing on the economics of bioenergy and emissions trading. Two essays analyze the economic and environmental impacts of cellulosic feedstock production and examine policy options to mitigate environmental impacts from cellulosic feedstock production. The last essay examines how the order of emissions permit trading and abatement decisions affect equilibrium emissions.

Interest in alternative energy sources has been growing for a variety of reasons including volatile oil prices, recognition of the harmful effects of greenhouse gas (GHG) and national security concerns over oil imports from politically unstable regions (Hill et al., 2009). Recent policy initiatives reflect this concern. For example, the Energy Security and Independence Act of 2007 sets a goal of producing 36 billion gallons of biofuels by 2022. At least 21 billion gallon of biofuel must come from advanced biofuel that, unlike ethanol derived from corn starch, does not have direct competition between fuel and food production. Crop residue and energy crop such as switchgrass are considered promising cellulosic feedstock sources.

Chapter Two analyzes the economic and environmental impacts of cellulosic feedstock production. This study focuses on whether cellulosic feedstocks such as corn stover and switchgrass are attractive considering economic and environmental aspects. A regional economic model of agricultural production is constructed in a major watershed of south-central Minnesota. The economic model is constructed using the Generalized Algebraic Modeling System (GAMS) software. This model, based on mathematical programming, has a multi-region structure of crop production to capture the cost of transporting feedstock produced in various regions to a biofuel processing plant. The model examines how various scenarios of producing cellulosic feedstock impact crop production activities and water quality from sediment and nutrient losses. Technical coefficients for the model use SWAT simulation results of crop yield and water quality such as sediment yield and nutrients losses.

Chapter Three evaluates various policy options to manage effluents from cellulosic feedstock production. This chapter extends the model of Chapter Two to analyze policy alternatives such as total nitrate-nitrogen load restriction and a subsidy for switchgrass production. As is typical of corn-belt agriculture, corn and soybeans are the dominant crops in the Le Sueur Watershed. Significant potential exists for cellulosic feedstock production including corn stover, a co-product of corn grain production, and energy crops such as switchgrass. However, the potential environmental consequences of biofuel production are a particular concern in the Le Sueur.

Findings indicate that restricting nitrate-N loads increases the cost of cellulosic feedstock supply. When switchgrass production is subsidized, the negative impacts of cellulosic feedstock production on water quality are reduced or eliminated. The paper examines the potential tradeoffs between cellulosic feedstock production and water quality and how environmental and energy policies might be targeted toward reducing the cost of water quality improvements when biofuel markets exist.

Chapter Four analyzes emissions trading when there is both uncertainty about emissions and consideration of timing of emissions abatement, permit trading, and realization of actual emissions. Emissions trading has received attention in the past several decades as a cost-effective way to implement environmental regulation to reduce emissions. Emissions trading is a market-based and incentives-based regulation that can achieve an environmental objective at lowest possible cost.

With full information and no market imperfections, emissions trading attain environmental goals at minimum cost. But that result is based on a static model and assumes that there is complete information about abatement costs. In reality there are numerous decision points where firms choose how much to abate and how much to buy and sell permits within a time period in which emissions are capped. There may also be uncertainty about emissions and emission abatement cost. This paper extends previous models of emissions trading by considering uncertainty as well as the order of firms' decisions about abatement and permit trading. The results show that whether firms abate more under uncertainty is dependent on the expected penalty cost and marginal abatement cost. When expected penalty is greater than marginal cost of abatement, increase in uncertainty makes expected emissions decrease given unit penalty fee.

Chapter 2. A Watershed Level Economic Analysis of Cellulosic Biofuel Feedstock Production with Consideration of Water Quality

2.1. Introduction

Interest in alternative energy sources has been growing for a variety of reasons including volatile oil prices, recognition of the harmful effects of greenhouse gas (GHG) and national security concerns over oil imports from politically unstable regions (Hill et al., 2009). Recent policy initiatives reflect this concern. For example, the Energy Security and Independence Act of 2007 sets a goal of producing 36 billion gallons of ethanol and other renewable biofuels by 2022. The Act sets a cap of 15 billion gallons of ethanol produced with corn grain, requiring the remaining production to come from advanced renewable biofuels such as cellulosic ethanol. There is a large potential for the U.S. agricultural sector to provide biomass (Hoekman, 2009). However, trade-offs related to the environment, economic cost, and food security are major concerns (Khanna et al., 2009).

Cellulosic feedstocks are composed of cellulose, hemicellulose and lignin, which comprise a significant proportion of the biomass of plants. The cellulose and hemicellulose can be converted into ethanol by chemical or biochemical reactions and lignin can be used for combustion/gasification in order to produce process steam and electricity (Huang et al., 2009). Various feedstocks are being considered for producing cellulosic ethanol, including corn stover, wheat straw, switchgrass and woodchips.

Though currently most biorefineries use corn grain as a feedstock, cellulosic ethanol has advantages over corn ethanol. Using corn grain for ethanol creates competition between fuel and food production (Runge and Senauer, 2007). Some sources of cellulosic feedstock, such as corn stover, are co-products of food production. Cellulosic ethanol is estimated to reduce greenhouse gases more than corn ethanol. Farrell et al.

(2006) predict that corn ethanol would reduce GHG emissions by about 13% relative to gasoline. Hill et al. (2009) predict that cellulosic ethanol production would lead to lower GHG emissions than corn ethanol or gasoline. Their results indicate that corn ethanol has more life-cycle GHG emissions than gasoline when emissions resulting from land use change are included and corn ethanol process heat is from natural gas or coal. Fargione et al. (2008) find that converting grassland or abandoned crop land in US to corn-ethanol production releases 48 to 93 times more CO_2 than the annual GHG reductions these biofuels provide by displacing fossil fuels. They find that biofuels from perennials grown on marginal or abandoned cropland can offer immediate and sustained GHG advantages. Schmer et al. (2008) estimate that switchgrass ethanol emits 94% less GHG than gasoline.

Using corn stover for cellulosic ethanol production could lead to changes in crop rotations and the composition of production in the region. Intensive corn production requires heavy fertilizer use, which is increased further when stover is removed to compensate for the nutrients lost in the residue. Thus, use of stover as a biofuel feedstock can be expected to have negative impacts on the environment from soil and water degradation.

Energy crops, such as switchgrass can be used as cellulosic feedstocks and have environmental benefits relative to corn production, particularly when the corn stover is harvested (Folle, 2010). Switchgrass is a warm season grass native to North America and grows well under wide range of climate conditions (Vogel, 1996). It is a perennial grass that develops a deep and dense root system, promoting soil stability increasing infiltration and reducing runoff (Redfearn et al., 1997; Woolsey, 1992). Once established, a switchgrass stand can persist for many years under the right conditions, which leads to low maintenance costs relative to conventional row crops (Tiffany et al., 2006). Switchgrass could be planted on degraded and abandoned crop land for biofuel production, reducing ecosystem destruction and greenhouse gas emissions (Fargione et al., 2008).

This paper focuses on economic and watershed level environmental issues associated with the production of two cellulosic feedstocks: corn stover and switchgrass. The following questions are addressed: 1) How will crop production activities change as the demand for cellulosic feedstock increases? 2) How will the supply of cellulosic feedstocks and the composition of those feedstocks change under various market conditions and environmental regulations? And 3) How will cellulosic feedstock production impact water quality as measured by sediment and nutrient load levels in streams?

A regional economic model of agricultural production in the watershed is used to analyze the supply response of cellulosic feedstocks. By integrating environmental parameters from a biophysical simulation analysis of the watershed, the model is able to estimate the impacts on water quality of the adjustments in production that accompany feedstock supply. The general structure of the economic model is similar to that of many endogenous supply, multi-region, agricultural sectors models that use mathematical programming to capture market behavior. With the focus on a specific watershed, it is possible to include a high level of spatial detail in both the production activities and the transportation of feedstocks from farms to a centrally-located bioenergy processing plant. The economic model is constructed using the Generalized

Algebraic Modeling System (GAMS) software. Results from a recent biophysical simulation analysis of the impacts of crop production, including alternative biofuel feedstocks, were used to estimate environmental parameters for the economic model. Folle (2010) used the Soil and Water Assessment Tool (SWAT) model to simulate the effects of a range of crop production practices on soil and water quality in the Le Sueur River Watershed (LRW) in southern Minnesota.

The contribution of this paper is to analyze the impacts of cellulosic feedstock production by modeling producers' decisions about land use and showing trade-offs between water quality and increased feedstock production. Previous studies have estimated potential cellulosic feedstock production at a regional scale or state level (Gallagher et al., 2003; Walsh et al., 2003) and estimated the marginal cost of cellulosic ethanol (Brechbill and Tyner, 2008; Petrolia, 2008). But these papers have not considered how producers might adjust crop production activities to meet the cellulosic feedstock demand and how proximity to the processing plant might influence the response of feedstock producers. This paper provides a more realistic depiction of the impacts of cellulosic feedstock production by including a high degree of spatial detail from biophysical model and modeling predominant and alternative production practices that a producer might choose.

2.2. Literature Review

2.2.1. Research on Lignocellulosic Feedstock Production

Kaylen et al. (2000) assess the economic feasibility of a lignocellulosic feedstock-to-ethanol plant in Missouri. They construct a non-linear optimization model and consider energy crops, crop residues and woody biomass as potential feedstocks. They find that production of ethanol from lignocellulosic feedstock resources is economical if higher valued chemicals like furfural are produced as co-products with the ethanol. The study assumes an exogenous feedstock price and annually available feedstock volume but does not consider how crop activities and land use might change in response to the demand for feedstocks.

Perlack and Turhollow (2003) evaluate the cost of collecting, handling, and hauling corn stover to an ethanol conversion facility. They assume the amount of stover that can be removed is the same as corn grain yield per acre. The study does not consider how the feed stock cost will change under various crop rotations or harvest rates.

Petrolia (2008) compares two collection methods, round bales and square bales, to derive corn stover delivered cost for a proposed biomass-to-ethanol conversion facility located in southern Minnesota. The paper assumes that all baled stover is staged at the field edge then hauled to storage by semi trucks. The study does not consider a alternative stover harvest rates and assumes average corn grain and stover yields for each county within the study region.

Brechbill and Tyner (2008) compute corn stover and switchgrass production costs and estimate biomass supply curves for three Indiana coal-fired electric utilities from county-level production data. They derive biomass production cost by considering whether equipment is owned or custom hired, what baling options are used, the size of the farm, and the transport distance. Payments for extended storage and a profit premium are introduced to compensate producers for providing biomass to plant. Total per ton costs for a 30 mile radius around the plant ranges between $39 and $46 for corn stover and $57 and $63 for switchgrass.

Gallagher et al. (2003) examine biomass supply from crop residues. The estimates span major crops and agricultural regions of the United States. While the paper allows yields and nutrient-replacement costs to vary across counties, it uses the same cost parameters for all counties and crops.

Khanna et al. (2008) develop a dynamic land use allocation model that determines the profit maximizing land use choices to meet a targeted level of corn grain and cellulosic ethanol output in Illinois over the 16-year planning horizon of 2007-2022. The study includes corn stover, miscanthus and switchgrass as alternative cellulosic feedstocks. The model includes historical and hypothetical crop mixes to analyze future increases in crop land for feedstock production. The paper shows total greenhouse gas emissions over the period are reduced by 54% from the replacement of gasoline and total nitrogen use is increased by 25% from intensive corn production to produce stover.

Eidman et al. (2009) estimate the profitability of a hypothetical Minnesota biorefinery plant using stover and hardwood feedstocks. They estimate the cost of harvesting and delivering the feedstock to the plant. The internal rate of return is used to measure the profitability of plants and their results show that larger plants could see economies of size that offset increasing biomass transportation costs.

Using a spatial equilibrium, non-linear programming model, Taylor and Koo (2010) determine the optimal number, locations and sizes of cellulosic ethanol processing plants in North Dakota. They use three feedstocks, wheat straw, corn stover and CRP grasses, and consider 50%, 65% and 80% of available biomass is used for ethanol production. The model minimizes the sum of processing costs of biomass for ethanol, transportation costs of biomass from producing regions to ethanol plants and transportation costs of ethanol from processing plants to blending facilities. Results show that average plant size ranges from 75 to 110 million gallons per year and average of total cost varies from \$1.28 to \$1.95 dollar per gallon of ethanol with three cases of biomass availability.

Chen and Önal (2012) develop a dynamic mathematical programming model and estimate the impact of U.S. biofuels mandates. To consider crop land allocation, they use historical crop mixes augmented by crop mixes estimated using acreage elasticities with respect to crop prices and lagged crop acreage. They find using historical and expanded crop mixes together reduces the inflexibility of supply response from using historical crop mixes alone.

2.2.2. Integrated Economic and Biophysical Model

Several papers use integrated economic and biophysical models to analyze the environmental impacts of crop production. In these studies, biophysical models such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) and the Environmental Policy Integrated Climate (EPIC) model (Williams, 1995) are used to estimate the environmental impacts associated with changes in land use.

Nelson et al. (2006) analyze switchgrass production on land used for grain. Using SWAT model, they evaluate the impact of switchgrass production on water quality indicators, sediment yield, surface runoff and edge-of field erosion in the Delaware Basin in Northeast Kansas. The study finds the break-even prices for switchgrass production replacing four conventional crop rotations. Using switchgrass yields from SWAT, they estimate the replacement of crop land with switchgrass and payments to switchgrass for reducing sediment loads by 10%, 25% and 40%.

Adams et al. (2005) integrate SWAT and a linear programming model of crop production including wheat, sorghum and peanut. Effluent levels estimated with SWAT are used in a mathematical programming model to measure the trade-off between farm income and levels of three pollutants, sediment, phosphorus and nitrogen, in the Ft. Cobb watershed in Southwestern Oklahoma. They estimate the minimum incentive necessary to achieve environmental goals from the difference in farm income between the baseline and reductions of 10% and 20% in sediment and nutrient runoff.

Kurkalova et al. (2010) integrate economic and environmental models to examine how alternative crop and corn stover prices affect the crop mix and stover availability in Iowa. They use the EPIC model to estimate the impact of stover removal on nutrient runoff and soil erosion. They show land use changes and environmental impacts for stover prices ranging from $0 to $100/Mt. Kurkalova et al. (2010) is similar to our study in that the impacts of stover harvest on environmental outcomes and crop mixes are included. They use a single stover removal rate (50%) and do not include other cellulosic feedstocks.

Egbendewe-Mondzozo et al. (2010) examines the land use change and environmental consequences from cellulosic feedstock production. They use EPIC and a regional economic model to study cellulosic biomass production in nine counties in Southern Michigan. EPIC is used to generate crop yields and environmental outcomes of water quality, soil erosion and greenhouse gas emissions. The regional economic model maximizes profit for a representative producer with nine biomass and 74 cropping systems including alternative crop rotations, tillage practices, land fertilities and residue removal rate. The model defines 71 regions by subdividing 37 watersheds into good and poor crop land. They show how cellulosic biomass production and crop land use change by increasing biomass price to $200/Mt. Corn stover production starts at $21/Mt and switchgrass becomes profitable at $46/Mt. Their approach is similar to our analysis in that they consider alternative crop mixes in a regional economic model. The analysis includes a single 50% rate of stover harvest and does not consider crop price changes.

2.3. Regional Economic Model

For this paper, a regional economic model of agricultural production in a northern corn-belt watershed was constructed to analyze the impacts of cellulosic feedstock production cropping practices and water quality. The economic model is a multi-region, linear programming model of the agriculture sector in the watershed. The multi-region framework is critical to account for logistics costs and their impacts in determining a spatial equilibrium for the feedstock market. Exogenously determined market prices are assumed for corn grain and soybeans. Input supplied other than crop land are assumed to be infinitely elastic at current market price. Supplied of crop land a various types is assumed fixed with each region of the watershed. The behavior of producers in the model is captured through the use of aggregate production activities and constraints that characterize production activities. Product supply and derived demand for inputs are endogenous to the model and found by choosing profit-maximizing activities subject to market equilibrium conditions.

The economic model has r regions, each producing n products. Each region chooses s aggregate production activities that need m regional inputs. The demand function for product i is expressed as $P_i = a_i$ and the supply function for input k is $R_k = c_k$ assuming product demand and input supply is infinitely price elastic. The model determines a market equilibrium by maximizing consumer and producer surplus over all regions as described below in equations (1) to (5):

Maximize:
X, Y, Z, T

$$(1)\ \sum_{g=1}^{r}\sum_{i=1}^{n} a_i Y_{gi} - \sum_{g=1}^{r}\sum_{h=1}^{r,h\neq g}\sum_{i=1}^{n} t_{ghi}T_{ghi} - \sum_{g=1}^{r}\sum_{k=1}^{m} c_k Z_{gk}$$

Subject to:

$$(2)\quad \sum_{j=1}^{s}\sum_{u} v_{gjuk}X_{gju} - Z_{gk} \leq 0$$

$$(3)\quad \sum_{j=1}^{s} X_{gju} - Q_{gu} \leq 0$$

$$(4)\quad Y_{gi} - \sum_{j=1}^{s}\sum_{u} e_{gjui}X_{gju} - \sum_{h=1}^{r,h\neq g} T_{hgi} + \sum_{h=1}^{r,h\neq g} T_{ghi} \leq 0$$

$$(5)\quad X_{gju}, Y_{gi}, Z_{gk}, T_{ghi} \geq 0$$

and g=1…r, h=1…r, h≠g, i=1…n, j=1…s, k=1…m, l=1…q

where g represents the region and each region has a different number of land types subscripted by u. Y_{gi} is the i product demand in g region. Z_{gk} is the supply of input k and Q_{gu} is the supply of crop land. X_{gju} is the level of production activity j in the land type u at region g. T_{ghi} is the shipment of product i from region g to region h and t_{ghi} is the unit cost for shipping product i from region g to region h. e_{gjui} is the output of regional product i per unit of production activity j and v_{gjuk} is the requirement of input k per unit of production activity j in the land type u at region g.

Constraints (2) limit input use to no more than the quantities supplied, and constraints (3) limit crop land use. Product demand in any region is no more than the quantities produced in that region plus shipments to the region less shipments from the region (constraints 4). The market equilibrium is characterized by the Kuhn-Tucker-Karush conditions which appear in appendix. The dual variables related with the output constraints for the products are the equilibrium prices of the products in that region. The duals of the input constraints are interpreted as the market prices of those inputs as well.

To analyze the emergence of a cellulosic biofuels market, it was assumed that a processing plant is in a central region of the watershed. The model is then solved with feedstock demand at the plant fixed at levels from zero to the maximum possible output for whole watershed to estimated feedstock supply. Corn stover and switchgrass is transported to the central region where the biorefinery plant is located.

2.4. Data and Assumptions in the Model

The Minnesota River flows for a distance of 332 miles in the state of Minnesota and joins the Mississippi River. The Le Sueur River Watershed (LRW), located in south central Minnesota, is one of the twelve major watersheds in the Minnesota River Basin (Figure 2-1). The LRW covers 2,850 square kilometers with agricultural land use accounting for 87% of the geographic area (Folle, 2010). All or part of 47 townships fall within the LRW, with each township approximately 9.6 kilometers by 9.6 kilometers. The township boundaries form a uniform grid that makes them well-suited for use as regions within the economic model.

2.4.1. SWAT data

The Soil and Water Assessment Tool (SWAT) is a basin-scale bio-physical simulation model developed by the USDA-Agricultural Research Service (Arnold et al., 1998; Arnold and Fohrer 2005). The model is used to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions (Neitsch et al., 2005).

Folle (2010) uses SWAT to simulate the effects of soybean, corn grain, stover and switchgrass production on soil and water quality over the 13 year period of 1994 to 2006 in the LRW. Folle quantifies the spatial and temporal patterns of sediment, nutrient (nitrate-nitrogen and phosphorus) and pesticide (atrazine, acetochlor and metolachlor) losses from the LRW using SWAT. For this analysis, the LRW was divided into 84 sub-watersheds, which are then further subdivided into 4,818 hydrologic response units

(HRUs) that are homogeneous with respect to land use, soil characteristics and management practices.

Parameters in the regional economic model are based on average annual estimates from SWAT of crop yield (corn, soybeans, stover, and switchgrass), sediment yield and nutrients (nitrate-nitrogen, phosphorus) losses in 4,178 HRUs that are used for crop land.

2.4.2. Defining of crop production activities

A challenge in modeling the economic behavior of crop producers in the watershed involves including an appropriate range of technical alternatives so the producers' response to changing market conditions and policies is adequately captured. For this study, the focus was on expressing in a realistic way the range of crop product mixes that producers might use with the emergence of a market for cellulosic feedstock. Unique crop production activities are included for each of 4,178 HRUs in the Le Sueur.

Crop products in the economic model include corn grain, corn stover, soybeans and switchgrass. Activities for corn and soybeans include a two-year corn-soybean rotation (currently the predominant cropping system in the area), and a three-year rotation with two years of corn followed by one year of soybeans. The three-year rotation allows for an expansion of corn acreage, and thus corn grain and stover production, in a particular region when market conditions are more favorable to corn.

For each of the corn and soybean rotations, three rates of corn stover removal were included – 0%, 10%, 30% and 60% of the harvestable crop residue. The 60% harvest rate is considered as highest rate for crop residue removal in the region. Lower rates of 10% and 30% are included so the environmental consequences of residue removal may be reduced, while still marketing stover.

A switchgrass production activity is included as a perennial energy crop. This activity represents an option to produce a cellulosic feedstock other than corn stover. The final type of cropping activity is for participation in the Conservation Reserve Program (CRP), which allows land to be idled while reducing environmental impacts of production.

In all, there are up to ten alternative crop production activities in each HRU in each region – two corn-soybean rotations without stover harvest and with three rates of stove removal, plus switch grass and CRP (Table 2-1). Switchgrass production is included in HRUs with the lowest corn yields, with slopes steeper than two percent, and in HRUs that are susceptible runoff. When the 4,178 HRUs defined for the SWAT simulations are mapped to the regions in the watershed, there are a total of 9,251combinations of land types and regions, and a total of 89,400 crop production activities.

2.4.3. Crop Enterprise Budget and Input Data

Empirical data from the Le Sueur Watershed area were used for technical and cost coefficients in the model. Many of the coefficients for the production activities are from enterprises budgets developed for the area by Lazarus (2010). Lazarus developed regional crop budgets for Minnesota using a combination of farm records and USDA-NASS data, augmented with results from experimental trials. Cost parameters in the model use the enterprise budgets developed by Lazarus with the exception of fertilizer costs, which are based instead on the application rate assumed by the SWAT modeling in Folle (2010) (see Table 2-2). Folle (2010) assumes that 134.5 kg/ha N fertilizer of anhydrous ammonia is applied in the two-year corn-soybean rotation. Coefficients for second year of corn in the corn-corn-soybean rotation are derived from those first year corn as follows. The second year yield for corn and stover is assumed to decrease by 8.3% (Duffy, 2010). It is assumed that an additional 43Kg/ha of anhydrous ammonia is applied to second year corn.

Technical coefficients for crop activities with corn stover harvest are derived from the two- and three-year corn-soybean rotation without stover harvest. Assuming 60kg/ha N in corn residue, the removal of 10, 30 and 60% of corn residue, respectively, are accompanied by application of an additional 6, 18 and 36 kg/ha of anhydrous ammonia per year. Because each HRU has a unique corn stover yield, production cost in each HRU under various stover harvest rates is different. Cost differences come from machinery cost, fuel use, and management cost. However, unit cost per feedstock decrease as stover harvest rate increases.

CRP land and switchgrass production activities in the model are assumed to have a 10 year stand life (Lazarus, 2010). Each activity has one year of planting. CRP has nine years of maintenance with no harvest activity. Switchgrass has one year of planting with no harvest and another one year of maintenance. Harvest in the maintenance year is one half of from the yield for year 3 to year 10. Soil Rental Rates (SRR) from the Farm Service Agency of the USDA are used to approximate CRP Payment as in Secchi and Babcock (2007).

2.4.4. Transportation Cost

By including multiple regions, the model determines a spatial market equilibrium with production in surrounding townships transported to the centrally-located processing plant. The feedstock supply response at the plant is estimated by setting a fixed cellulosic feedstock demand in the region where the biofuel plant is located. Demand at the plant is parametrically increased from zero to the maximum possible output for the watershed, with the dual value of the demand constraint revealing the feedstock supply price.

It is assumed that transportation of cellulosic feedstock is by semi-truck. Agricultural Marketing Service, USDA publishes quarterly grain truck transportation cost (USDA, 2009) per distance by truck load. Trucking cost was estimated as the average of rates from the fourth quarter of 2007 to the third quarter of 2010 − $3.00 per kilometer for a truck with a cargo capacity of 23.6 metric tons.

Stover and switchgrass are assumed to be harvested with a round baler. The bales are assumed to be net wrapped and stored temporarily at the field edge. A five percent storage loss is assumed (Morey et al., 2009). The density of round bales is assumed to be 4.1 kg per cubic foot and the round bale load weight implies a load volume of 3,125 cubic feet (Lazarus, 2010). That makes 11.34 Mt per load and unit costs per km in cellulosic feedstock is $0.26/Mt. It is assumed that switchgrass is 92% of a stover equivalent in ethanol yield (Huang et al., 2009) and the biorefinery plant feedstock demand is measured in stover equivalents.

2.4.5. Product Price

USDA-NASS data were used to derive grain price scenarios for the economic analysis. Prices received by Minnesota corn and soybean producers are shown in Figure 2-2. Assuming corn producers respond to prices before planting, an average corn price of $4.62/bushel was calculated from October 2010 to March 2011 and assumed to represent current market conditions.

The relative prices of corn and soybeans are an important determinant of the optimal mix of grain and biofuel feedstock production. The price ratio of corn and soybeans affects whether a producer will choose a two-year or three-year crop rotation. To capture this cross-price effect, average, low and high corn-soybean price ratios were considered. For the period from January 2000 to March 2011, the average price ratio of corn to soybeans was 0.38. A baseline soybean price of $12.22/bushel was derived from an average corn-soybean price ratio of 0.38 and a corn price of $4.62/bushel. The standard deviation of the corn-soybean price ratio, 0.05, is used to estimate high and low soybean price scenarios. Price ratios one standard deviation below and one standard deviation above the mean, 0.33 and 0.43, respectively, imply high and low soybean prices of $14.02 and $10.83, respectively.

2.5. Results

Various scenarios were considered in analyzing the impacts of cellulosic feedstock production. Changes in grain prices are considered with high, average (base) and low soybean price scenarios (High Soy and Low Soy) because the grain price ratio affects the crop rotation decision. In addition, the limits on the rate of stover harvest were analyzed to evaluate the environmental impacts of this production decision. One scenario is to exclude the 60% rate of stover harvest and allow only the 10% and 30% rates. Another scenario of allowing only a 10% rate of stover harvest was also analyzed. For the final scenario, switchgrass is used as the only cellulosic feedstock.

2.5.1. Change in marginal cost of cellulosic feedstock

The cellulosic feedstock demand at centrally-located processing plan is fixed for each model run, and parametrically increased from zero to the maximum possible output to estimate feedstock supply. Feedstock supply in the LRW can reach about 1,700 thousand Mt annually when corn stover and switchgrass are used together. Marginal costs of cellulosic feedstock are estimated for three cases using different feedstock sources: corn stover, switchgrass and both together (Figure 2-3). 800 thousand Mt was used as the highest level of feedstock production because this was the approximate stover production capacity of the watershed given current cropping practices.

Table 2-3 shows how marginal costs change in different scenarios. Marginal costs in baseline range from \$41.0/Mt at a demand of 100 thousand Mt to \$104.4 at 800 thousand Mt. As demand increases, stover must be produced farther from the plan, increasing transportation costs. Also, more crop land is used for what would otherwise be less profitable crop rotations. Marginal costs increase and eventually reach the level where switchgrass production is economical.

With a high soybean to corn price, marginal cost changes from baseline values only after supply exceeds 600 thousand Mt, when corn acreage had expanded in the base case. Marginal cost increases to \$109.0 at 700 thousand Mt to \$123.9 at 800 thousand Mt, with further feedstock demand met by switchgrass production. When the soybean price is relatively low, the marginal cost of feedstock supply is mostly lower than in the baseline case except at the lowest levels of feedstock production. This is because the opportunity cost of expanding corn acreage is lower when the soybean price is relatively low.

Scenarios limiting residue removal rates change the environmental consequences of stover harvest, but also change the marginal cost of feedstock supply. Marginal cost increases sharply when the harvest rate is limited to 10% of the available stover. When the harvest of corn stover is restricted, high levels of feedstock production require production of switchgrass, which causes loss of profit from reduced grain production.

2.5.2. Change in crop mix

Changes in the crop mix within the LSW reveal details about how producers respond to increased feedstock demand. When there is no cellulosic feedstock production in the baseline scenario, the two-year corn-soybean rotation with no stover production (CS-S00) uses most of crop land, with the three-year rotation (corn-corn-soybean, CCS-S00) occupying only 0.6% of crop land (Table 2-4). Land is divided almost equally between corn and soybeans − 46% and 45.8%, respectively, of total crop land (Table 2-6).

With no limits on the harvest rate, the most efficient corn stover production is to harvest at the highest rate – 60% of available stover, because harvest cost per ton increases as the rate of removal is reduced. Initially, as feedstock supply increases in the baseline case, stover is harvested from an increasing proportion of existing corn acreage. However, after 600 thousand Mt production, corn acreage is expanded to meet demand through a shift to the three year rotation. The percentage of crop land in corn increases by 11.9 percent, from 46.x% when no feedstock is producted to 57.9% when 800 thousand Mt is producted. The increased corn area comes primarily from soybean land, which declines by 10.1%.

In the high soybean price scenario, producers shift further toward the two-year crop rotation that already occupied most of the crop land in baseline scenario (Figure 2-4). At demand levels above 600 thousand Mt, expanded feedstock production involves both increased corn acreage and switchgrass production. Switchgrass production expands more than in the baseline case, with acreage in switchgrass reaching 2,879 ha when demand is 800 thousand Mt (Table 2-4).

The low soybean price scenario spurs intensive corn production with increased three-year rotation crop land. Corn land occupies greater than 53% of the total crop land while soybean land stays below 38% (Table 2-6). CCS-S60 and CS-S60 replace existing crop land that has no stover harvest.

With the stover removal restricted to no more than 30%, stover is collected from a larger portion of the corn at the lower levels of feedstock production, and the two-year rotation dominates (Table 2-5, Figure 2-5). However, after 400 thousand Mt of feedstock production, a significant portion of land is used for the three-year rotation with

30% stover harvest to increase feedstock supply. Also, switchgrass is produced, occupying 14.3% of crop land when feedstock demand is 800 thousand Mt.

With the restriction to no more than 10% stover removal, crop land is mostly used for two-year rotation with 10% stover harvest (CS-S10). The percentage of corn and soybean land decreases from 91.8% to 71.3% as feedstock production increases to 800 thousand Mt and switchgrass production replaces crop land. Switchgrass production activity appears early in feedstock supply and land in switchgrass increases to 21.9% at 800 thousand Mt feedstock supply (Table 2-7).

2.5.3. Change in crop production and fertilizer use

The results show that crop production activities change across levels of feedstock demand when grain prices change or stover harvest rate are restricted (Table 2-8). Crop production is similar in baseline and high soybean price scenario as the two-year rotation, the most soybean intensive activity, takes most crop land (Figure 2-6).

Crop production when stover harvest rates are restricted to 30% is similar to baseline results at lower levels of feedstock production, but corn production increases sharply as feedstock production increases. Soybean production declines more than in other scenarios. Both corn and soybean production decline gradually a feedstock production increases when the stover harvest rate is limited to 10%, as switchgrass production replaces the two-year corn-soybean rotation.

Application of fertilizer containing nitrogen (anhydrous ammonia and diammonium phosphate) increases in all grain price scenarios as corn stover production increases (Table 2-9, Figure 2-7). More fertilizer is used when significant area of land is used for the three-year rotation, which occurs in the low soybean price scenario and the 30%R scenario (Table 2-10). Conversion of crop land to switchgrass production reduces fertilizer use. In 30%R, nitrogen fertilizer use decreases after 400 thousand Mt. Impact of fertilizer reduction is larger in the 10%R scenario where switchgrass covers more crop land than in other scenarios.

2.5.4. Transportation of cellulosic feedstock

Figure 2-8 shows the spatial dispersion of corn stover removal by showing the stover harvest per hectare in each HRU and region. For low levels of stover supply, most stover production occurs close to the biorefinery with stover density above 3.0 Mt/ha. However, stover production becomes more dispersed as feedstock demand increases.

Figure 2-9 displays the average transport distance per ton of cellulosic feedstock. As the high stover density area spreads out, kilometers per metric ton of feedstock production increases to 26.6 ton-kilometers in baseline. Limiting the rate of stover harvest increases the distance of feedstock to transport.

2.5.5. Impacts of limiting the source of biomass to Switchgrass

If stover harvest is not allowed and switchgrass is the only source of cellulosic feedstock used in the biorefinery, the marginal cost of stover equivalent feedstock is above $100/Mt (Figure 2-10) and increases gradually with feedstock demand. Marginal cost increases to about $120/Mt at 800 thousand Mt feedstock supply in baseline crop price scenario. The land for switchgrass increases to 24.7% as biomass supply increases to 800 thousand Mt (Table 2-11).

With relatively high soybean prices, for the opportunity cost of producing switchgrass increases, reaching $128/Mt when feedstock production is 800 thousand Mt.

With low soybean prices, the marginal cost declines somewhat relative to the baseline scenario.

Restrictions on the location of switchgrass production shift the supply of feedstock, also. Figure 2-10 shows how marginal cost changes by the type of land on which switchgrass may be produced: Sloped (fields with slopes steeper than 2%, 55,672ha), Critical (critical land which is susceptible runoff, 57,912ha), Low yield (15% low corn yielding land, 23,251ha and All (including all three cases above, 97,712ha). Feedstock production can reach about 1,200 thousand Mt. Restricting the type of land for switchgrass production leads to higher marginal cost and limited supply of biomass. Marginal costs are highest when switchgrass production is restricted to sloped land.

2.5.6. Effluent changes

Sediment and nutrient losses are shown in Table 2-12and Table 2-13. Nitrate-N losses increase in all three scenarios (baseline, high soy, low soy) as cellulosic feedstock production increases (Figure 2-11). Most nitrate-N losses come from the application of anhydrous ammonia which contains 82% nitrogen by weight. The corn-soybean rotation shifts from two-year to three-year rotation, resulting in more anhydrous ammonia use and larger nitrate-N losses as stover removal expands (Figure 2-8). Figure 2-12 shows that changes in nitrate-N losses from zero to various levels of cellulosic feedstock production in the whole watershed.

With low soybean prices, nitrate-N losses increase compared to other scenarios after 400 thousand Mt of feedstock is produced, owing to the expanded use of the three-year rotation with a 60% stover harvest rate. Switchgrass plays an important role in reducing nitrate-N losses in the 30%R and 10%R scenario. Nitrate-N losses decline significantly in 10%R scenario that relies more heavily on switchgrass production. Nitrate-N losses are decreased to 15.84kg/ha at 800 thousand Mt feedstock production compared to 17.10kg/ha at zero feedstock production in baseline.

Figure 2-13 and Figure 2-14 show changes in the spatial dispersion of phosphorus losses and sediment yield as cellulosic feedstock production increases. As land for stover production expands to the whole watershed, the phosphorus and sediment losses spread throughout the whole watershed. Notably, the highest effluent levels occur in HRU's farthest from the plant, and at highest feedstock demand levels, due to the topography of the watershed, which is less sloped close to the plant. As feedstock production increases, phosphorus losses and sediment yield increases owing to larger amount of stover removal. Results show the high soybean price scenario has higher phosphorous losses and sediment yield than other scenario (Table 2-12).

When feedstock production levels are lower, phosphorous and sediment losses in 30%R scenario are higher than in baseline and 10%R scenario. However, due to the increase in switchgrass production, phosphorous and sediment losses decline after 400 thousand Mt in 30%R scenario. As switchgrass production increases in 10%R scenario, phosphorus and sediment losses are lower than in the baseline and 30%R scenario owing to low level of fertilizer use (Table 2-13).

2.6. Conclusion

A regional economic model of agricultural production in the Le Sueur Watershed in South Central Minnesota is constructed to analyze the economic and environmental impacts of cellulosic feedstock production. Production of two cellulosic feedstocks, corn stover and switchgrass, is included in the model. Various market and production scenarios are considered in the analysis to identify the crop mix changes and evaluate the impacts on water quality from sediment and nutrient (phosphorus and nitrogen) losses.

As cellulosic feedstock production increases, producers expand corn production with high stover harvest over the entire watershed even far away from the biorefinery plant. The low soybean price scenario accelerates the expansion of corn land. As intensive corn production expands, there are increased levels of nitrogen losses.

Switchgrass production appears when there are restrictions on the rate of stover harvest. The scenario allowing only 10% stover harvest rate shows a significant decrease in nitrate-N losses owing to switchgrass production. However, if switchgrass is the only biofuel feedstock, marginal cost of stover equivalent feedstock is above $100/Mt.

Results indicate that corn stover can be produced with relatively low marginal cost compared to switchgrass. Sediment and nutrient losses from corn stover production make switchgrass more promising on environmental grounds but the high marginal cost of production causes switchgrass to cover only small part of crop land if farmers have unrestricted choice about how to supply cellulosic feedstocks.

The paper analyzes the impact of cellulosic feedstock production by selecting a typical small watershed in the corn-belt region. The knowledge gained and the methodologies developed in this paper can be applicable to other regions and alternative bio-energy products. Crop land use and environmental impacts of feedstock production would be different if various feedstock and crop production are considered. Imperfect competition might come in with cellulosic feedstocks if the processor is the only buyer. Then the feedstock purchaser may have some pricing power.

Results show that intensive corn production for stover harvest has negative impacts on water quality and that switchgrass can mitigate these negative impacts and produce cellulosic feedstock without environmental degradation. How to manage nutrients losses while producing cellulosic feedstock at a certain level is the subject of next chapter. Evaluating various policy options and production practices to achieve environmental goals will be an important issue for the development of biofuel production. Chapter 3 focuses on the tradeoffs between cellulosic feedstock production and water quality and analyzes policy options to manage water quality from cellulosic feedstock production.

Table 2-1. Crop Production Activities

Activity	Description
CS-S00	Two-Year Rotation, Corn-Soybeans – No Stover
CS-S10	Two-Year Rotation, Corn-Soybeans – 10% Stover Harvest
CS-S30	Two-Year Rotation, Corn-Soybeans – 30% Stover Harvest
CS-S60	Two-Year Rotation, Corn-Soybeans – 60% Stover Harvest
CCS-S00	Three-Year Rotation, Corn-Corn-Soybeans –No Stover
CCS-S10	Three-Year Rotation, Corn-Corn-Soybeans –10% Stover Harvest
CCS-S30	Three-Year Rotation, Corn-Corn-Soybeans –30% Stover Harvest
CCS-S60	Three-Year Rotation, Corn-Corn-Soybeans –60% Stover Harvest
SWCH	Switchgrass Production
CRP	Conservation Reserve Program Land

Table 2-2. Fertilizer and Chemical Use Assumptions (Unit: Kg/Ha)

	Corn in 1st year	Corn in 2nd year	Soybeans	Switchgrass
Anhydrous ammonia*	134.5	177.5		
Diammonium phosphate	182.7	182.7		
Acetochlor	1.8	1.8		
Atrazine	0.7	0.7		
Metolachlor	2.5	2.5	1.0	
UREA				51

*Additional application of 6, 18, 36 kg/ha for 10%, 30%, 60% residue removal

Table 2-3. Marginal cost of feedstock (Unit: $/Mt)

	Cellulosic Feedstock Production (1000 Mt)							
Scenario	100	200	300	400	500	600	700	800
Base	40.95	43.24	45.60	45.94	48.22	50.76	70.02	104.45
High Soy	40.95	43.24	45.60	45.94	48.21	50.76	109.04	123.88
Low Soy	41.05	43.38	43.64	45.93	46.17	48.48	51.03	72.08
30%R	44.16	46.87	51.65	107.17	111.54	114.49	117.88	120.99
10%R	55.28	105.38	108.04	110.46	113.20	115.76	117.98	120.14

Table 2-4. Crop Production Activity Levels by Grain Price Scenario (Unit: Ha)

	Cellulosic Feedstock Production (1000 Mt)								
	0	100	200	300	400	500	600	700	800
	Low Soybean Price (Low Soy)								
CS-S00	125,564	100,486	84,334	70,265	56,990	40,376	27,063	11,663	0
CS-S60	0	23,373	33,972	48,770	54,975	71,524	77,880	88,632	56,002
CCS-S00	119,178	110,287	95,215	76,610	59,440	43,115	25,779	9,278	0
CCS-S30	0	18	0	0	0	0	0	0	0
CCS-S60	0	10,578	31,385	49,277	73,698	90,100	114,587	135,890	191,678
Corn	142,234	142,518	143,552	143,442	144,741	144,760	146,049	146,926	155,786
Soybeans	102,508	102,224	101,353	101,480	100,362	100,355	99,260	98,537	91,894
Switchgrass	0	0	0	0	0	0	0	0	0
CRP	25,015	25,015	24,852	24,835	24,654	24,642	24,448	24,294	22,077
	Base Grain Prices (Base)								
CS-S00	246,178	209,265	172,252	133,999	97,232	59,562	22,376	0	0
CS-S60	0	36,907	73,874	111,976	148,743	186,244	223,240	198,189	73,367
CCS-S00	1,648	1,647	1,593	1,384	1,383	850	304	0	0
CCS-S60	0	7	106	466	467	1,252	2,193	51,778	179,161
Corn	124,187	124,188	124,196	124,221	124,221	124,305	124,473	133,613	156,124
Soybeans	123,638	123,637	123,630	123,604	123,604	123,604	123,640	116,354	96,404
Switchgrass	0	0	0	0	0	0	0	0	61
CRP	21,931	21,931	21,931	21,931	21,931	21,848	21,643	19,790	17,168
	High Soybean Price (High Soy)								
CS-S00	251,251	214,312	177,193	138,577	101,789	63,229	24,815	0	0
CS-S60	0	36,940	74,058	112,657	149,446	187,995	226,419	218,411	117,104
CCS-S00	139	138	136	112	112	102	89	0	0
CCS-S60	0	1	4	47	47	107	120	37,749	138,230
Corn	125,719	125,719	125,719	125,723	125,723	125,751	125,756	134,372	150,706
Soybeans	125,672	125,672	125,672	125,670	125,670	125,682	125,686	121,789	104,629
Switchgrass	0	0	0	0	0	0	0	66	2,879
CRP	18,366	18,366	18,366	18,363	18,363	18,324	18,314	13,530	11,543

Table 2-5. Crop Production Activity Levels by Stover Harvest Rate Restriction

	Cellulosic Feedstock Production (1000 Mt)								
	0	100	200	300	400	500	600	700	800
	Allowing up to 60% Stover Removal Rate (Base)								
CS-S00	246,178	209,265	172,252	133,999	97,232	59,562	22,376	0	0
CS-S60	0	36,907	73,874	111,976	148,743	186,244	223,240	198,189	73,367
CCS-S00	1,648	1,647	1,593	1,384	1,383	850	304	0	0
CCS-S60	0	7	106	466	467	1,252	2,193	51,778	179,161
Corn	124,187	124,188	124,196	124,221	124,221	124,305	124,473	133,613	156,124
Soybeans	123,638	123,637	123,630	123,604	123,604	123,604	123,640	116,354	96,404
Switchgrass	0	0	0	0	0	0	0	0	61
CRP	21,931	21,931	21,931	21,931	21,931	21,848	21,643	19,790	17,168
	Allowing up to 30% Stover Removal Rate (30%R)								
CS-S00	246,178	172,289	97,259	22,155	0	0	0	0	0
CS-S30	0	73,845	148,775	223,807	138,533	119,331	113,388	110,324	105,054
CCS-S00	1,648	1,593	1,383	295	0	0	0	0	0
CCS-S30	0	98	409	1,639	108,998	120,028	117,769	112,373	108,985
Corn	124,187	124,195	124,212	124,270	141,931	139,684	135,207	130,077	125,183
Soybeans	123,638	123,631	123,614	123,626	105,599	99,675	95,950	92,620	88,855
Switchgrass	0	0	0	0	3,186	11,697	20,242	29,363	38,673
CRP	21,931	21,931	21,931	21,860	19,040	18,700	18,358	17,697	17,046
	Allowing only 10% Stover Removal Rate (10%R)								
CS-S00	246,178	22,242	0	0	0	0	0	0	0
CS-S10	0	223,887	238,098	230,381	222,683	215,267	207,693	199,612	191,409
CCS-S00	1,648	598	0	0	0	0	0	0	0
CCS-S10	0	1,099	2,739	2,740	2,672	1,993	1,392	1,072	984
Corn	124,187	124,196	120,875	117,017	113,123	108,962	104,775	100,521	96,360
Soybeans	123,638	123,630	119,962	116,104	112,232	108,298	104,311	100,163	96,032
Switchgrass	0	0	8,185	16,194	24,216	32,639	41,263	50,065	58,977
CRP	21,931	21,931	20,735	20,442	20,185	19,857	19,407	19,007	18,387

Table 2-6. Percentage of Land Use by Crop by Grain Price Scenario (Unit: %)

		Cellulosic Feedstock Production (1000 Mt)								
Scenario	Crop	0	100	200	300	400	500	600	700	800
Low Soy	Corn	52.7%	52.8%	53.2%	53.2%	53.7%	53.7%	54.1%	54.5%	57.8%
	Soybeans	38.0%	37.9%	37.6%	37.6%	37.2%	37.2%	36.8%	36.5%	34.1%
	CRP	9.3%	9.3%	9.2%	9.2%	9.1%	9.1%	9.1%	9.0%	8.2%
	Switchgrass	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Base	Corn	46.0%	46.0%	46.0%	46.0%	46.0%	46.1%	46.1%	49.5%	57.9%
	Soybeans	45.8%	45.8%	45.8%	45.8%	45.8%	45.8%	45.8%	43.1%	35.7%
	CRP	8.1%	8.1%	8.1%	8.1%	8.1%	8.1%	8.0%	7.3%	6.4%
	Switchgrass	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
High Soy	Corn	46.6%	46.6%	46.6%	46.6%	46.6%	46.6%	46.6%	49.8%	55.9%
	Soybeans	46.6%	46.6%	46.6%	46.6%	46.6%	46.6%	46.6%	45.1%	38.8%
	CRP	6.8%	6.8%	6.8%	6.8%	6.8%	6.8%	6.8%	5.0%	4.3%
	Switchgrass	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.1%

Table 2-7. Percentage of Land Use by Crop under Stover Harvest Rate Restriction (Unit: %)

		Cellulosic Feedstock Production (1000 Mt)								
Scenario	Crop	0	100	200	300	400	500	600	700	800
Base	Corn	46.0%	46.0%	46.0%	46.0%	46.0%	46.1%	46.1%	49.5%	57.9%
	Soybeans	45.8%	45.8%	45.8%	45.8%	45.8%	45.8%	45.8%	43.1%	35.7%
	CRP	8.1%	8.1%	8.1%	8.1%	8.1%	8.1%	8.0%	7.3%	6.4%
	Switchgrass	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30%R	Corn	46.0%	46.0%	46.0%	46.1%	52.6%	51.8%	50.1%	48.2%	46.4%
	Soybeans	45.8%	45.8%	45.8%	45.8%	39.1%	36.9%	35.6%	34.3%	32.9%
	CRP	8.1%	8.1%	8.1%	8.1%	7.1%	6.9%	6.8%	6.6%	6.3%
	Switchgrass	0.0%	0.0%	0.0%	0.0%	1.2%	4.3%	7.5%	10.9%	14.3%
10%R	Corn	46.0%	46.0%	44.8%	43.4%	41.9%	40.4%	38.8%	37.3%	35.7%
	Soybeans	45.8%	45.8%	44.5%	43.0%	41.6%	40.1%	38.7%	37.1%	35.6%
	CRP	8.1%	8.1%	7.7%	7.6%	7.5%	7.4%	7.2%	7.0%	6.8%
	Switchgrass	0.0%	0.0%	3.0%	6.0%	9.0%	12.1%	15.3%	18.6%	21.9%

Table 2-8. Percentage Change in Crop Production from Zero Feedstock Production (Unit: %)

	Cellulosic Feedstock Production (1000 Mt)								
Scenario	0	100	200	300	400	500	600	700	800
	Change in Corn Production								
Base	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	6.4%	21.5%
High Soy	0.8%	0.8%	0.8%	0.8%	0.8%	0.9%	0.9%	6.3%	17.5%
Low Soy	12.6%	12.8%	13.5%	13.4%	14.3%	14.3%	15.2%	15.8%	21.6%
30%R	0.0%	0.0%	0.0%	0.0%	12.1%	10.2%	6.7%	2.7%	-1.1%
10%R	0.0%	0.0%	-2.5%	-5.6%	-8.7%	-12.0%	-15.3%	-18.6%	-21.9%
	Change in Soybean Production								
Base	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-5.9%	-22.3%
High Soy	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	-2.3%	-16.1%
Low Soy	-16.5%	-16.7%	-17.4%	-17.3%	-18.3%	-18.3%	-19.2%	-19.8%	-25.5%
30%R	0.0%	0.0%	0.0%	0.0%	-14.3%	-18.9%	-21.8%	-24.4%	-27.4%
10%R	0.0%	0.0%	-2.6%	-5.5%	-8.5%	-11.6%	-14.7%	-18.0%	-21.4%

* Corn and soybean production is 1,467 and 335 thousand Mt respectively under zero feedstock production in baseline

Table 2-9. Fertilizer Application in Crop Land by Grain Price Scenario (Unit: Kg/Ha)

	Cellulosic Feedstock Production (1000 Mt)								
Scenario	0	100	200	300	400	500	600	700	800
Anhydrous Ammonia									
Low Soy	77.3	80.0	83.4	85.8	89.5	92.0	95.7	99.0	108.7
Base	62.0	64.5	67.0	69.5	72.0	74.6	77.3	87.2	108.2
High Soy	62.7	65.2	67.6	70.2	72.7	75.3	77.8	86.9	102.6
Diammonium Phosphate (18-46-0)									
Low Soy	96.3	96.5	97.2	97.1	98.0	98.0	98.9	99.5	105.5
Base	84.1	84.1	84.1	84.1	84.1	84.2	84.3	90.5	105.7
High Soy	85.1	85.1	85.1	85.1	85.1	85.2	85.2	91.0	102.1
UREA									
Low Soy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Base	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
High Soy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5

Table 2-10. Fertilizer Application in Crop Land by Stover Harvest Rate Restriction (Unit: Kg/Ha)

	Cellulosic Feedstock Production (1000 Mt)								
Scenario	0	100	200	300	400	500	600	700	800
Anhydrous Ammonia									
Base	62.0	64.5	67.0	69.5	72.0	74.6	77.3	87.2	108.2
30%R	62.0	64.5	67.0	69.6	86.0	85.3	82.7	79.5	76.6
10%R	62.0	64.5	63.1	61.1	59.1	56.9	54.6	52.4	50.2
Diammonium Phosphate (18-46-0)									
Base	84.1	84.1	84.1	84.1	84.1	84.2	84.3	90.5	105.7
30%R	84.1	84.1	84.1	84.2	96.1	94.6	91.6	88.1	84.8
10%R	84.1	84.1	81.9	79.3	76.6	73.8	71.0	68.1	65.3
UREA									
Base	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30%R	0.0	0.0	0.0	0.0	0.6	2.2	3.8	5.6	7.3
10%R	0.0	0.0	1.5	3.1	4.6	6.2	7.8	9.5	11.2

Table 2-11. Percentage of land use by crop (when Switchgrass is used only)

		Cellulosic Feedstock Production (1000 Mt)								
Scenario	Land, %	0	100	200	300	400	500	600	700	800
Low Soy	Corn	52.7%	51.0%	49.3%	47.5%	45.7%	44.0%	42.3%	40.7%	39.0%
	Soybeans	38.0%	36.7%	35.8%	34.8%	33.7%	32.6%	31.4%	30.0%	28.7%
	CRP	9.3%	9.0%	8.8%	8.7%	8.6%	8.5%	8.3%	8.1%	7.8%
	Switchgrass	0.0%	3.3%	6.2%	9.0%	12.0%	14.9%	18.0%	21.2%	24.4%
Base	Corn	46.0%	44.5%	43.1%	41.7%	40.2%	38.7%	37.3%	35.8%	34.2%
	Soybeans	45.8%	44.3%	42.9%	41.5%	40.1%	38.7%	37.2%	35.7%	34.2%
	CRP	8.1%	8.0%	7.9%	7.8%	7.7%	7.6%	7.4%	7.1%	6.9%
	Switchgrass	0.0%	3.2%	6.2%	9.0%	12.0%	15.0%	18.1%	21.4%	24.7%
High Soy	Corn	46.6%	45.0%	43.6%	42.3%	40.8%	39.3%	37.8%	36.2%	34.6%
	Soybeans	46.6%	45.0%	43.6%	42.2%	40.7%	39.3%	37.7%	36.2%	34.6%
	CRP	6.8%	6.7%	6.7%	6.6%	6.5%	6.3%	6.1%	6.1%	5.9%
	Switchgrass	0.0%	3.2%	6.1%	8.9%	12.0%	15.2%	18.4%	21.5%	24.8%

Table 2-12. Effluent in Crop Land under Grain Price Scenario

	Cellulosic Feedstock Production (1000 Mt)								
Scenario	0	100	200	300	400	500	600	700	800
	Nitrate-N (Kg/Ha)								
Low Soy	16.86	17.02	17.31	17.53	18.01	18.24	19.25	19.96	24.64
Base	17.10	17.19	17.29	17.38	17.52	17.64	17.77	18.32	23.59
High Soy	17.37	17.46	17.56	17.65	17.80	17.90	18.02	18.74	20.03
	Phosphorus (Kg/Ha)								
Low Soy	0.48	0.50	0.52	0.54	0.56	0.58	0.62	0.65	0.72
Base	0.51	0.53	0.56	0.59	0.63	0.67	0.71	0.73	0.76
High Soy	0.54	0.56	0.59	0.62	0.66	0.70	0.74	0.81	0.79
	Sediment (Mt/Ha)								
Low Soy	1.20	1.25	1.33	1.40	1.50	1.56	1.69	1.82	2.04
Base	1.21	1.28	1.38	1.48	1.59	1.72	1.86	2.01	2.18
High Soy	1.29	1.36	1.46	1.56	1.67	1.80	1.95	2.26	2.28

Table 2-13. Effluent in Crop Land under Stover Harvest Rate Restriction

	Cellulosic Feedstock Production (1000 Mt)								
Scenario	0	100	200	300	400	500	600	700	800
	Nitrate-N (Kg/Ha)								
Base	17.10	17.19	17.29	17.38	17.52	17.64	17.77	18.32	23.59
30%R	17.10	17.15	17.23	17.32	18.05	17.96	17.79	17.66	17.80
10%R	17.10	16.90	16.80	16.64	16.47	16.30	16.15	15.99	15.84
	Phosphorus (Kg/Ha)								
Base	0.51	0.53	0.56	0.59	0.63	0.67	0.71	0.73	0.76
30%R	0.51	0.54	0.57	0.62	0.63	0.60	0.58	0.56	0.53
10%R	0.51	0.53	0.51	0.49	0.47	0.45	0.42	0.40	0.39
	Sediment (Mt/Ha)								
Base	1.21	1.28	1.38	1.48	1.59	1.72	1.86	2.01	2.18
30%R	1.21	1.30	1.42	1.57	1.72	1.66	1.60	1.55	1.47
10%R	1.21	1.28	1.24	1.20	1.15	1.10	1.04	0.98	0.94

Figure 2-1. Le Sueur River Watershed in Minnesota

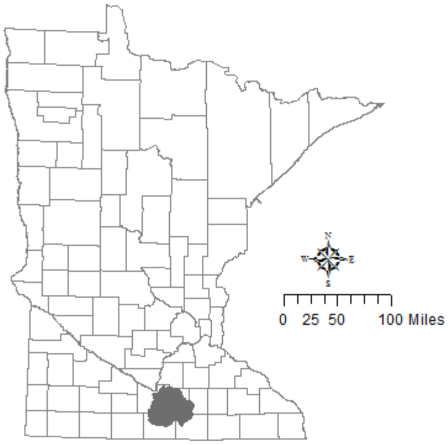


Figure 2-2. Prices Received by Minnesota Producers and the Corn-Soybean Price Ratios

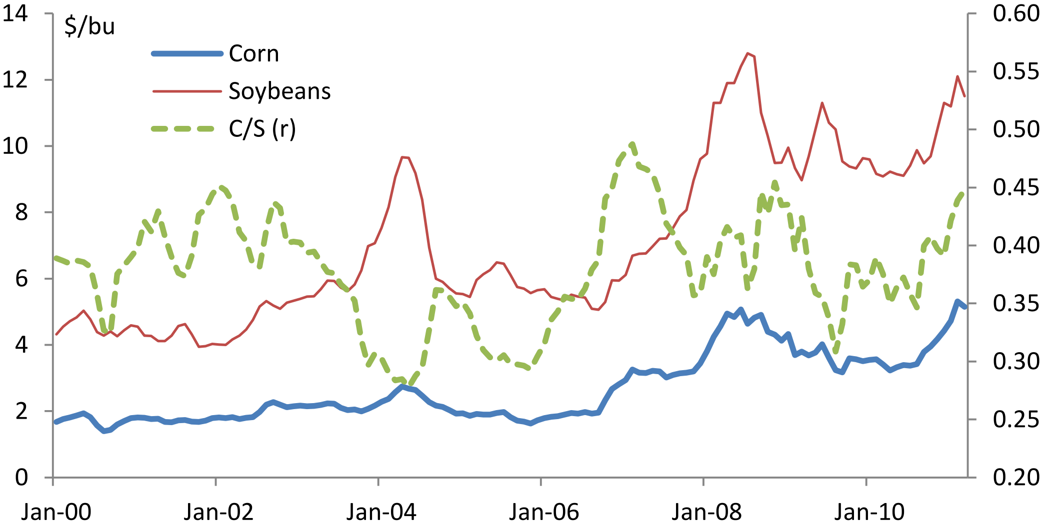


Figure 2-3. Marginal Cost by Cellulosic Feedstock Type

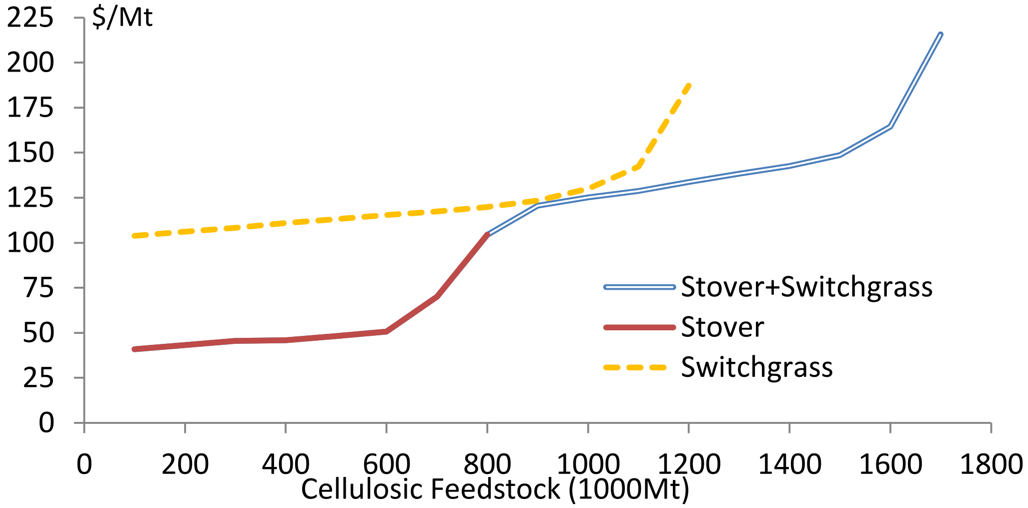
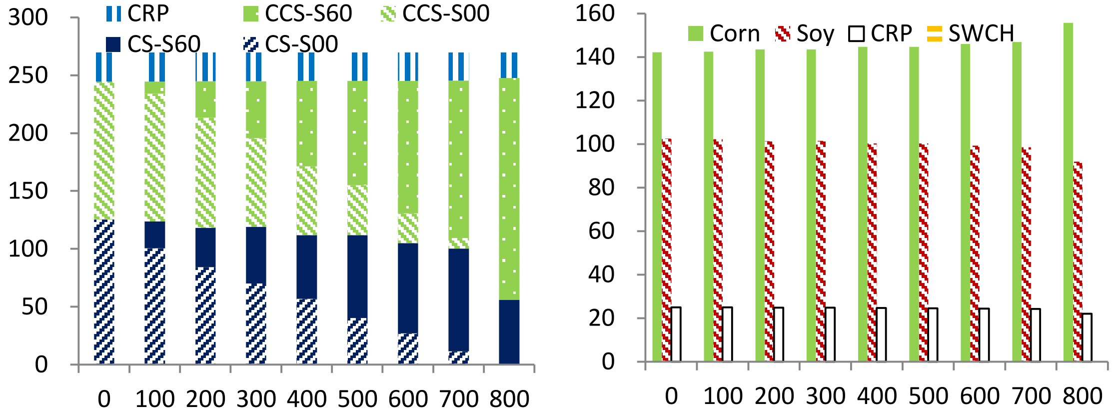
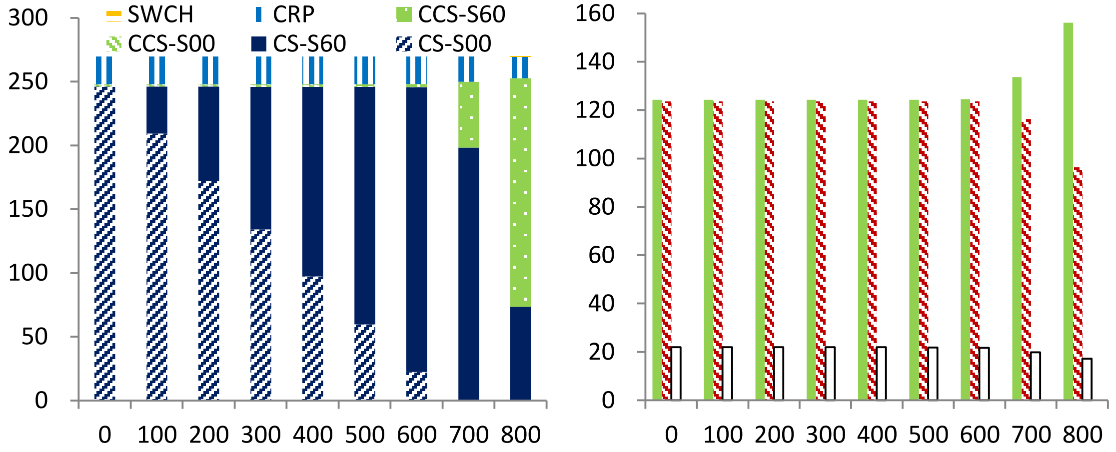


Figure 2-4. Crop Production and Crop Mix Results by Grain Price Scenario

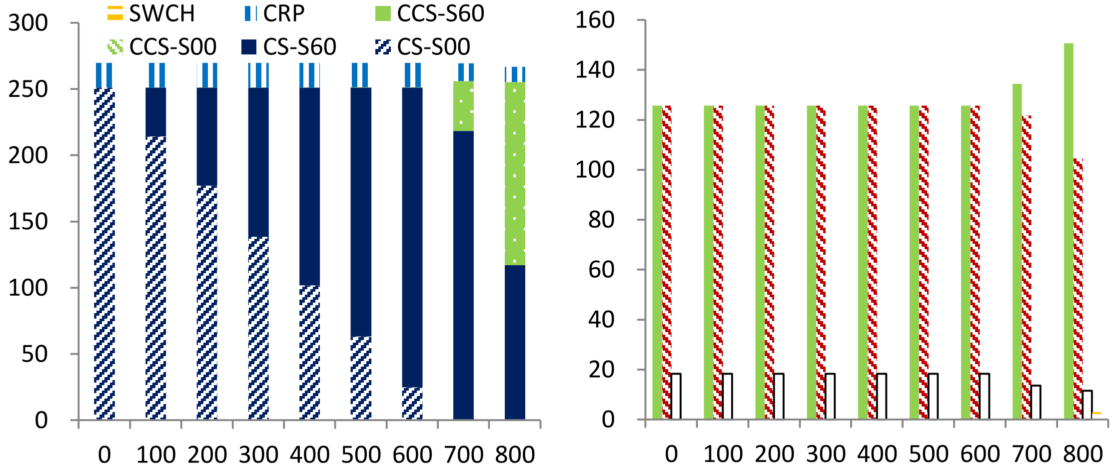
Low Soybean Price Scenario



Baseline



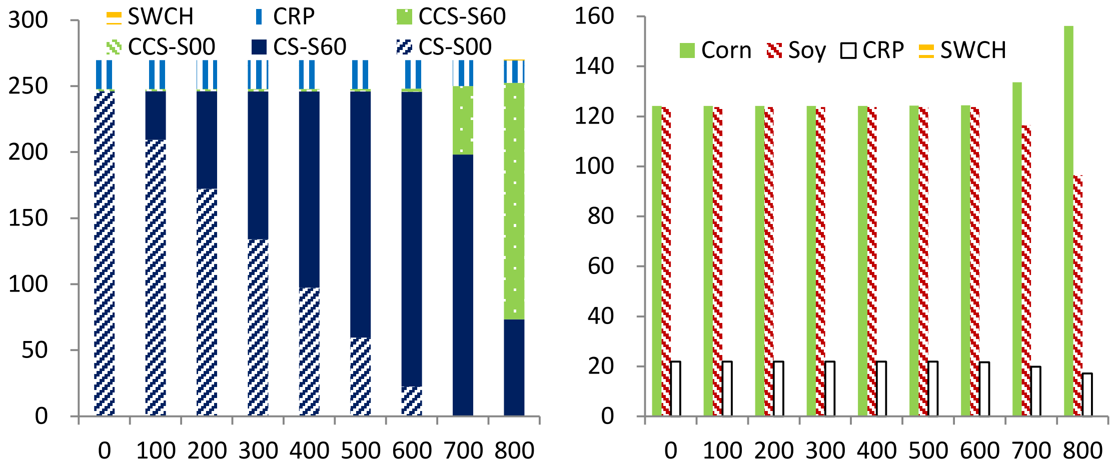
High Soybean Price Scenario



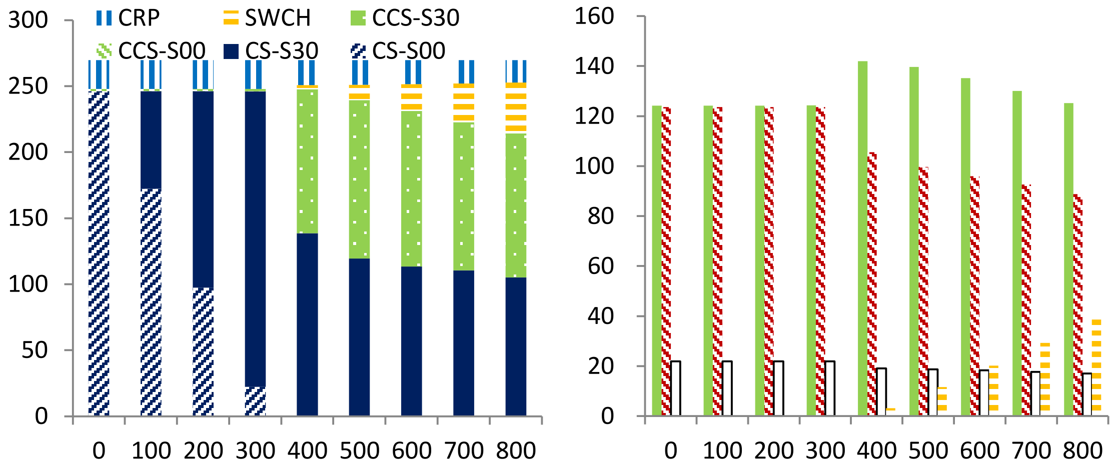
*Unit: Thousand Ha (Y axis) & Thousand Mt (X axis)

Figure 2-5. Crop Production and Crop Mix Results by Stover Harvest Rate Restriction

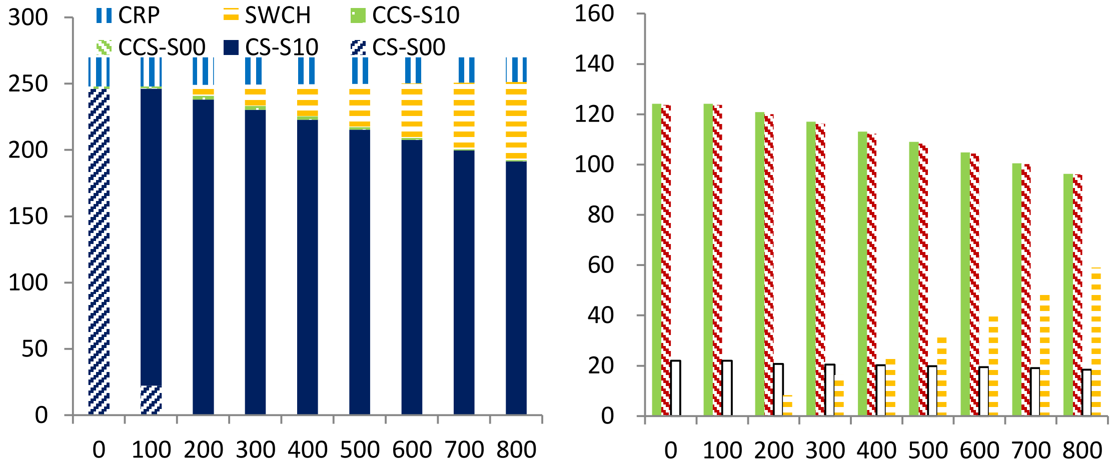
Allowing up to 60% (Baseline)



Allowing up to 30% (30%R)

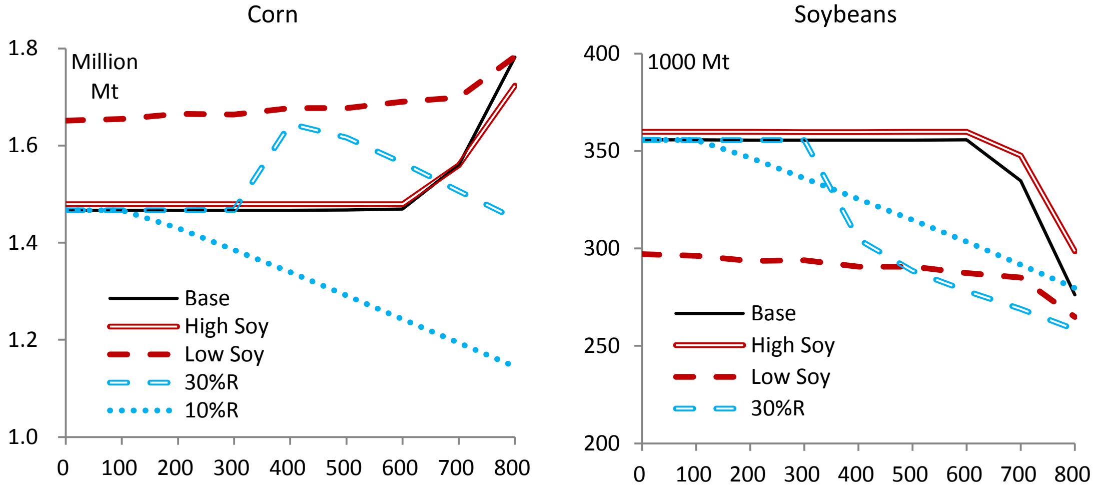


Allowing only 10% (10%R)



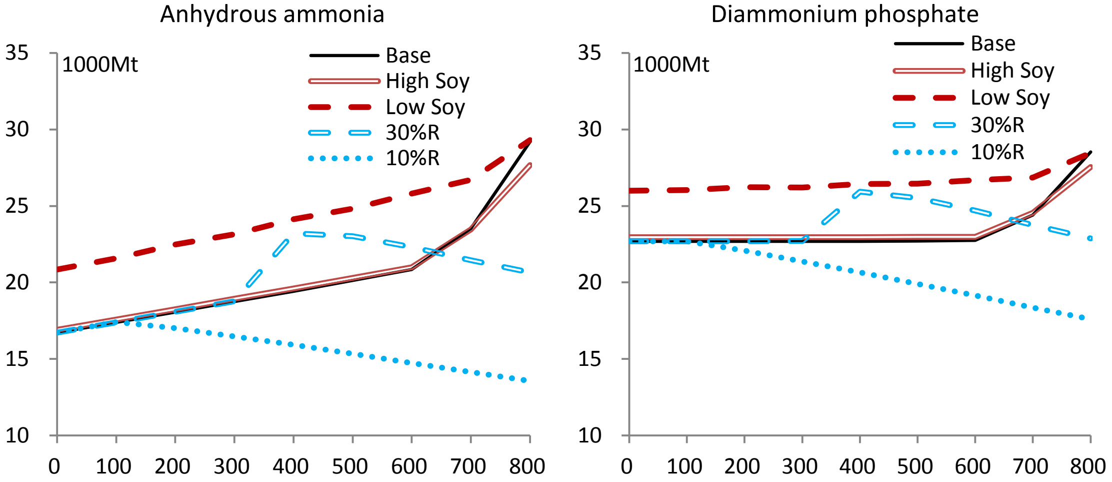
*Unit: Thousand Ha (Y axis) & Thousand Mt (X axis)

Figure 2-6. Crop Production



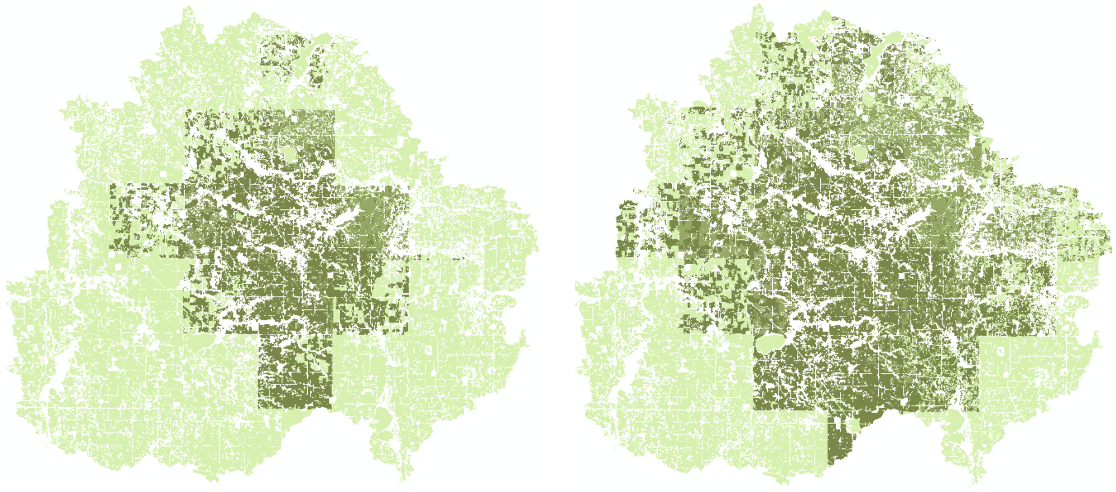
* Thousand Mt of stover equivalent cellulosic feedstock (X axis)

Figure 2-7. Total Fertilizer Use



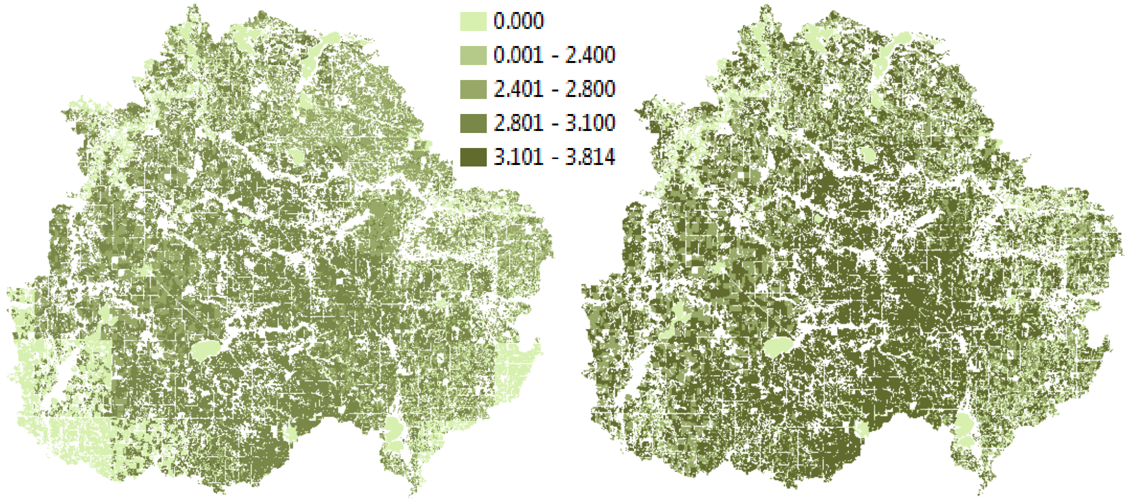
* Thousand Mt of stover equivalent cellulosic feedstock (X axis)

Figure 2-8. Stover Density (Mt/ha) for Various Levels of Cellulosic Feedstock Production



200 Thousand Mt Feedstock

400 Thousand Mt Feedstock



600 Thousand Mt Feedstock

800 Thousand Mt Feedstock

Figure 2-9. Distance Shipped in Kilometers per Mt of Feedstock

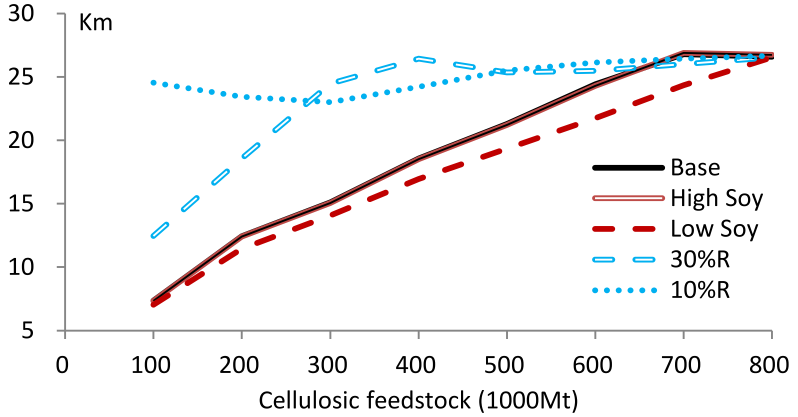
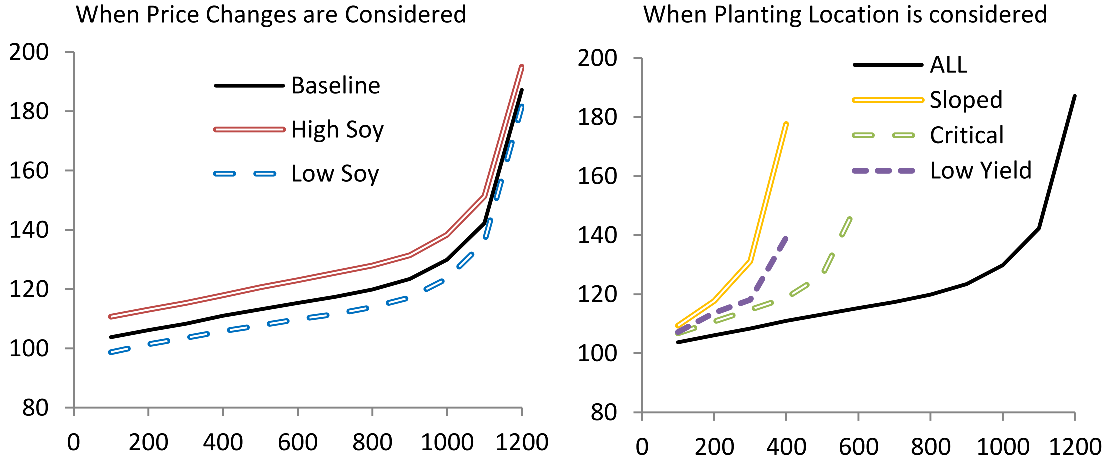


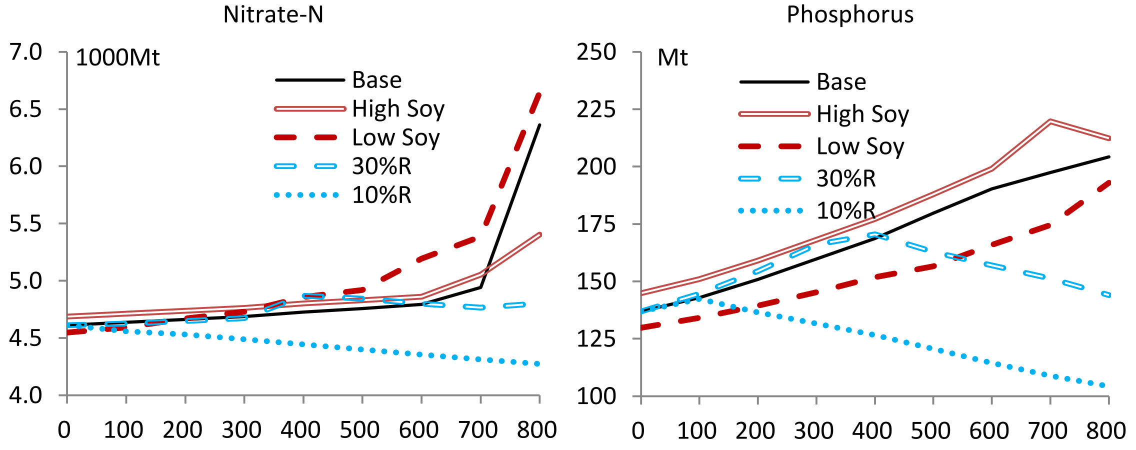
Figure 2-10. Marginal Cost of Feedstock from Switchgrass Only


When Price Changes are Considered

When Planting Location is considered

*Unit: $/Mt(Y axis) & Thousand Mt of stover equivalent cellulosic feedstock (X axis)

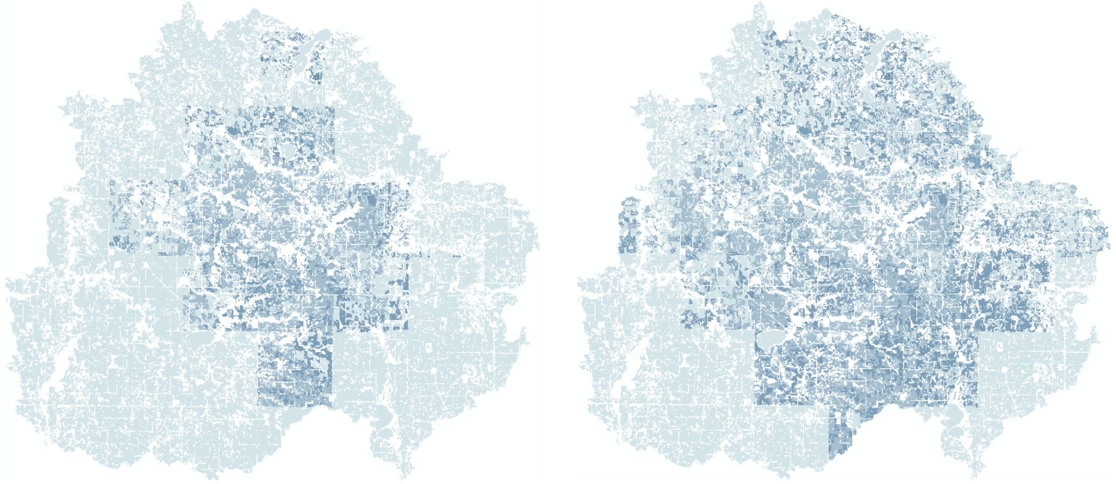
Figure 2-11. Nutrient Losses


Nitrate-N

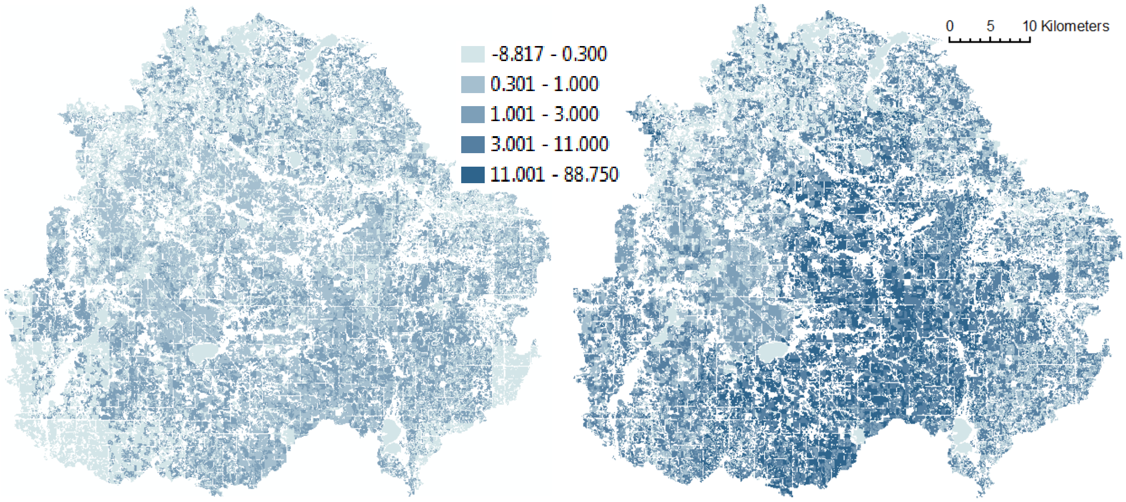
Phosphorus

* Thousand Mt of stover equivalent cellulosic feedstock (X axis)

Figure 2-12. Changes in Nitrate-N losses at Various Levels of Cellulosic Feedstock Production (Kg/Ha), Relative to Zero Feedstock Production

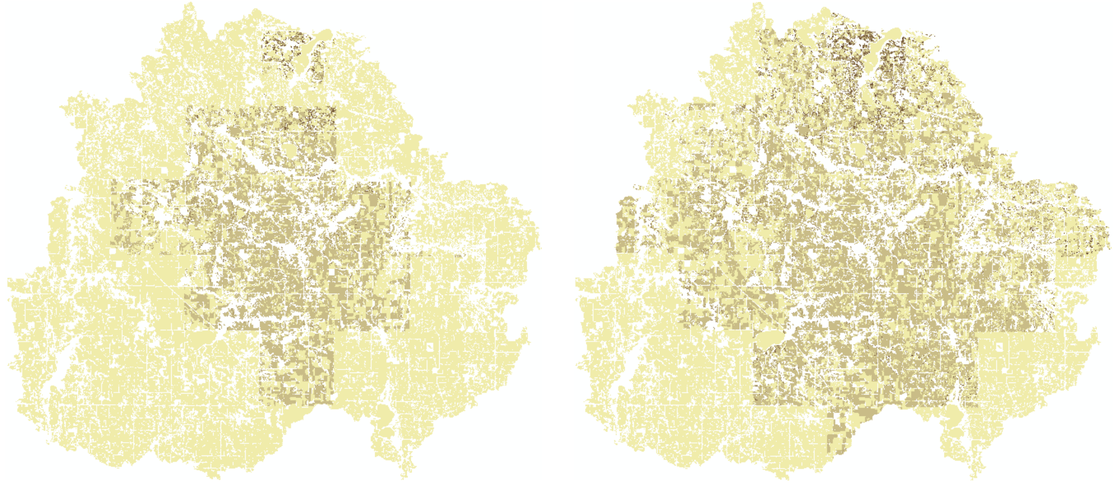


200 Thousand Mt Feedstock 400 Thousand Mt Feedstock



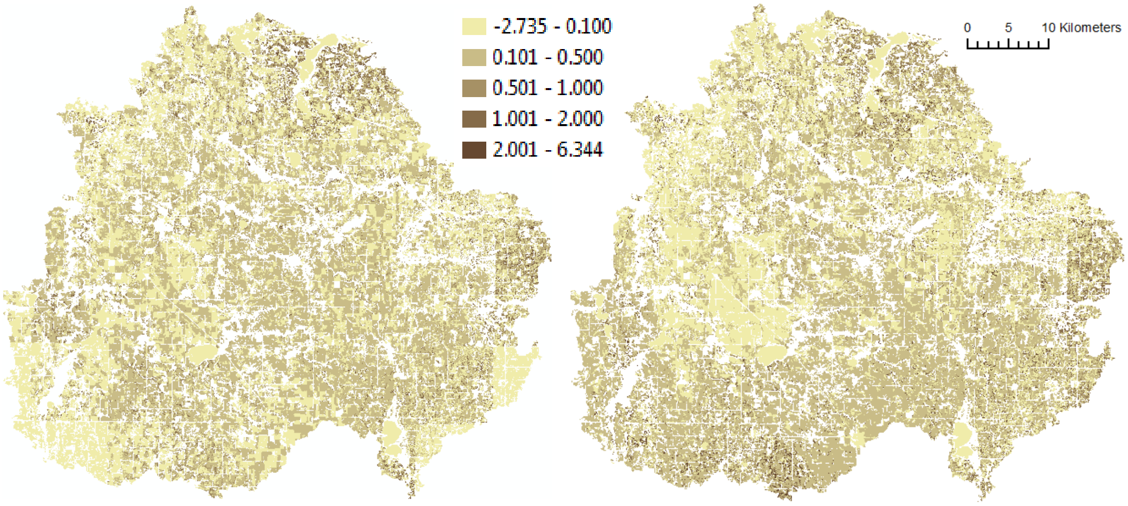
600 Thousand Mt Feedstock 800 Thousand Mt Feedstock

Figure 2-13. Changes in Phosphorus losses at Various Levels of Cellulosic Feedstock Production (Kg/Ha), Relative to Zero Feedstock Production



200 Thousand Mt Feedstock

400 Thousand Mt Feedstock



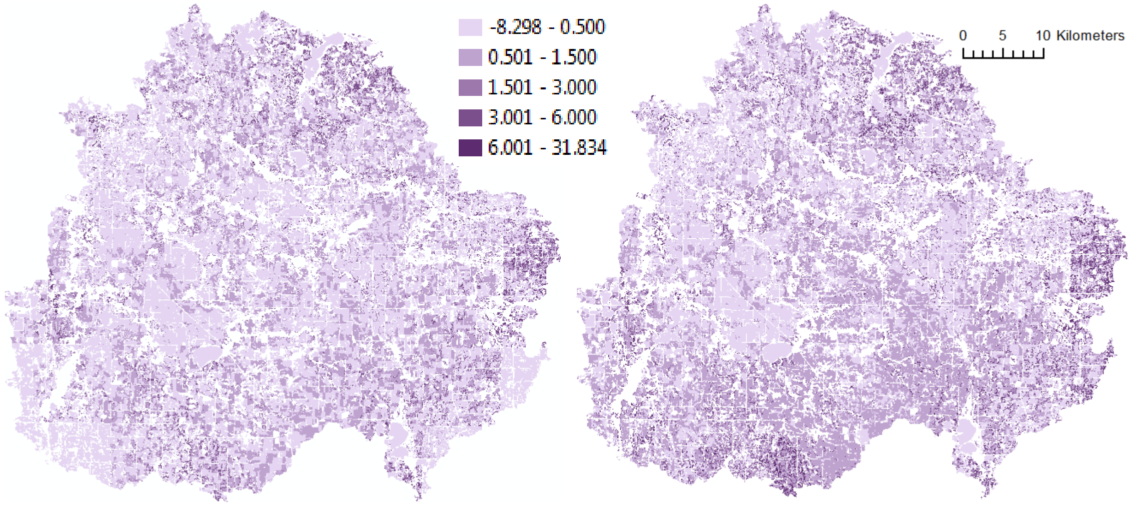
600 Thousand Mt Feedstock

800 Thousand Mt Feedstock

Figure 2-14. Changes in Sediment Yield at Various Levels of Cellulosic Feedstock Production (Mt/Ha), Relative to Zero Feedstock Production

200 Thousand Mt Feedstock

400 Thousand Mt Feedstock



600 Thousand Mt Feedstock

800 Thousand Mt Feedstock

Chapter 3. Evaluating Policy Options for Mitigating Environmental Impacts from Cellulosic Feedstock Production

3.1 Introduction

Crop residue on fields provides valuable environmental benefits including control of nutrient runoff and water contamination (Mann et al., 2002) and soil protection from wind and water erosion (Smil 1999; Johnson et al., 2006). When corn-stover is harvested for use as a biofuel feedstock, plants nutrients contained in the stover are also removed. Additional fertilizer must be applied to compensate for the nutrient losses. Removal of stover may also lead to significant increases in ground and surface water contamination. When sediment is transported through runoff and soil erosion, discharges of nitrogen and phosphorus are the leading contributors to reduced water quality (Kurkalova et al., 2010).

Expansion of advanced biofuel markets, especially from cellulosic ethanol, could spur more intensive corn grain and stover production in the Midwest, requiring higher rates of fertilizer and pesticide use as land is shifted from soybean production. Other energy crops, such as grassland perennials, use chemicals less intensively (Tilman et al., 2006). Even in the absence of cellulosic feedstock markets, crop nutrient management is an environmental challenge. Ribaudo et al. (2011) show that two-thirds of U.S. cropland is not meeting three criteria for good nitrogen management related to the rate, timing and method of application. The highest stream concentrations of nitrate occur in the corn-belt where nitrogen inputs such as fertilizer and manure application are highest (National Research Council, 2008). Intensified corn production, spurred by the emergence of markets for stover, could lead to even more soil erosion and more pressure on water quality.

Switchgrass has been identified as promising cellulosic feedstock (Graham et al., 2007; McLaughlin et al.,1999). Switchgrass provides year-round soil cover that reduces soil erosion and potential water contamination from sediment and nutrients (Folle, 2010). A recent survey of Minnesota farmers has indicated growing interest in switchgrass production (Smith et al., 2011). Issues of producer adoption, transportation and the development of market institutions and infrastructures need to be resolved for large-scale production to occur (Malcolm, 2008).

Chapter Two shows that corn stover can be produced at a marginal cost that is low compared to switchgrass. While per acre costs of production are relatively high, revenue from both corn grain and the stover co-product make corn-based cropping systems highly profitable relative to energy crops when a stover market is present. However, sediment yield and nutrient losses, already relatively high from corn grain production, increase when corn stover is harvested. Thus, switchgrass becomes a more promising option when environmental benefits are considered. However, if there are no substantial policy interventions under current commercial technology, none of the potential feedstocks except corn starch are economical for biofuels production (Schnepf, 2010).

Considering the economic and environmental impacts from cellulosic feedstock production, this chapter focuses on evaluating various policy options to manage effluents from cellulosic feedstock production. Research questions related to the environmental impacts of cellulosic feedstock production include: 1) How would environmental and energy policies targeted to water quality and cellulosic feedstock production influence economic and environmental outcomes in a watershed? 2) How will the mix of feedstocks and crop production practices change under policies to limit effluent levels, including nutrient and sediment losses, in the presence of a biofuels market? And 3) How will alternative environmental and energy policies influence the tradeoffs between cellulosic feedstock production and water quality?

This chapter extends the model presented in Chapter Two by including an analysis of policy alternatives by incorporating restrictions on nutrient loads and subsidies of switchgrass production. As is typical of corn-belt agriculture, corn and soybeans are the dominant crops in the Le Sueur River Watershed (LRW). Significant potential exists for cellulosic feedstock production including corn stover, a co-product of corn grain production, and energy crops such as switchgrass. However, the potential environmental consequences of biofuel production are a particular concern in the Le Sueur. The Minnesota Pollution Control Agency assesses the LRW as having impaired water quality due to sediment pollution.

This study evaluates various policy options to manage effluents associated with grain and cellulosic feedstock production. Policy options to reduce nutrient losses related to crop production have been widely studied (Doering et al., 1999; Ribaudo et al., 2001; Wu and Tanaka, 2005; Rabotyagov et al., 2010). Studies that include the impacts of biofuel feedstock market, however, are fewer in number and mainly focus on the greenhouse gas emissions (Khanna et al., 2009; Egbendewe-Mondzozo et al., 2010). This study analyzes how cellulosic feedstock production will affect water quality and the impacts of policy instruments on those impacts in a northern corn-belt watershed. The analyses provide both a realistic depiction of water quality impacts as well as ways those impacts may be efficiently mitigated. Knowledge of these outcomes will be important for the development of appropriate environmental and energy policies in management recommendations for feedstock production. The results provide insights into the potential tradeoffs between cellulosic feedstock production and water quality and how environmental and energy policies might be targeted toward reducing the cost of water quality improvements when biofuel markets exist.

3.2 Literature Review

Previous studies have integrated economic and biophysical models to evaluate the impacts on agricultural production of restrictions on effluent loads. A range of different policy alternatives to manage environmental impacts have been considered (Table 3-1) involving different crops and geographic locations. Several studies examine nutrient reduction in the Mississippi river basin to mitigate hypoxia in the Gulf of Mexico.

Doering et al. (1999) analyzes the cost effectiveness of alternative policies to reduce nitrogen level in the Gulf of Mexico. They use the U.S. Mathematical Programing (USMP) model with 45 agricultural production regions throughout the United States and ten crops. EPIC (the Environment Productivity Impact Calculator) is used to simulate the environmental effects of various management practices (crop rotations, tillage practices, and rates of fertilizer application) in the economic model. They evaluate how social welfare changes from various alternatives including reduction of nitrogen loads, fertilizer reduction, fertilizer tax, wet land restoration and riparian buffers. They assess a 20% reduction of nitrogen as “the best combination of sizable nitrogen-loss reductions and acceptable economic costs”. Cellulosic feedstock production was not included in the study.

Ribaudo et al. (2001) extend the model used by Doering et al. (1999) to compare reductions in nitrogen fertilizer use with wetland restoration in the Mississippi River Basin. They impose constraints on total nitrogen fertilizer use in the basin. Wetland restoration cost is measured by summing the cost of converting crop land to wetlands and the opportunity cost of removing crop land from production. There results show that fertilizer restriction is more cost effective than wetland restoration up to 26% of nitrogen-loss reduction.

Whittaker (2005) evaluates alternative polices to reduce non-point source water pollutants from agriculture on the Columbia Plateau of Washington, Oregon and Idaho. The study compares a command and control policy to an incentive policy by analyzing a mandated 25% reduction in nitrogen fertilizer and a 300% tax on nitrogen fertilizer that is equivalent to the tax. The economic model maximizing producer profit chooses optimal input use in the two alternatives. These input levels are used in the SWAT (Soil and Water Assessment Tool) model to estimate the level of nitrogen loss. The model shows that a tax policy is more efficient in achieving nitrogen reduction by comparing profit loss.

Wu and Tanaka (2005) estimate the social cost of reducing nitrogen loads from the Upper Mississippi River Basin to the Gulf of Mexico. They integrate an econometric model with the Soil and Water Assessment Tool (SWAT) model to study four alternative policies: a fertilizer use tax and incentive payments for conservation tillage, corn-soybean rotation and CRP participation. A logit model is used to predict farmers' choice of crop, tillage practice and participation in the Conservation Reserve Program (CRP) based on the estimated probability of choosing crop and tillage practice in 44,221 National Resource Inventory (NRI) sites. They use SWAT to simulate nitrate-N concentrations based on the estimated land use and farming practices in each subbasin. They find that a fertilizer-use tax is more cost effective than the other three incentive alternatives.

Babcock (2007) estimates switchgrass subsidies for converting crop land to switchgrass production in a watershed in eastern Iowa. Considering switchgrass yield and the price of ethanol, significant conversion subsidies are required (from \$44.33 per ton to \$106.75 per ton). Using SWAT, they evaluate the effect on the sediment and nutrient losses from production of switchgrass and corn. Results show conversion of all cropland to switchgrass in a watershed would result in an 84% and 53% reduction in sediment and nitrogen, respectively. Continuous corn with 50% of the stover harvested increases sediment yield and nitrogen by 23% and 150%, respectively. This study only focuses on continuous corn or switchgrass production and does not include how producer can change crop rotation from cellulosic feedstock demand.

Secchi et al. (2008) investigate water quality impacts from crop and switchgrass production in the Upper Mississippi River Basin (UMRB). Integrating SWAT and economic model of maxmization profits from farming, they show how switchgrass production impacts on water qualtiy compared to row crop only scenarios. They consider scenario of replacing 10% of crop land with switchgrass and also consider restricting switchgrass cultivation to erodible land. Their results show switchgrass production reduces sediment loss. Their results show switchgrass production cause the reduction of sediment loss. They consider specfic land type for switchgrass production and two sets of corn and soybean price to compare corn favarable market condition. However the study only includes swtichgrass for biomass and does not provide the amount of subsidy to induce switchgrass production.

Rabotyagov et al. (2010) examine the least cost of combinations of conservation practices in the Upper Mississippi River Basin (UMRB) to achieve 30% nutrient reduction of nitrate-nitrogen and phosphorous. They combine a simulation optimization framework with the SWAT model to show the trade-off between cost and nutrient reductions. They make 32 conservation practices by combining four tillage practices with contour farming, grassed waterways, terraces and 20% fertilizer reduction in each HRU of the 131 sub-watershed in UMRB. They find 30% reduction of phosphorus load at the outlet of UMRB reduces nitrate loadings by 9% with estimated cost of $370 million per year. Same rate of nitrate restriction automatically reduces phosphorus loading by 36% with $1.4 billion cost per year. Estimating cost to attain nutrient loss reduction is similar to our paper. Though they include various combination of conservation practices to manage water quality, they do not consider the impacts of cellulosic feedstock production.

Some previous studies have integrated economic and biophysical models to capture tradeoffs between economic and environmental outcomes. But most studies have focused on nutrient losses related to grain production. Some of the studies analyze water quality impacts from cellulosic feedstock production by changing the biomass price as explained in chapter Two (Egbendewe-Mondzozo et al., 2010; Kurkalova et al., 2010). Considering biofuel markets and cellulosic feedstock production, our paper addresses how producers might adjust land use to meet the cellulosic feedstock demand while responding to environmental and energy policies. This paper examines the cost of water quality improvements and land use changes resulting from policy options considered in the previous works: restricting total nutrient loss and switchgrass production subsidies.

3.3 Modeling & Data

To analyze environmental policy alternatives under cellulosic feedstock production in the Le Sueur watershed, the regional model of agricultural production in the watershed developed in Chapter Two is extended to include restrictions on effluent levels and subsidies for switchgrass production.

Folle (2010) uses SWAT to simulate the effects of corn stover and switchgrass production on soil and water quality over the 13 year period of 1994 to 2006 in the LRW. Folle (2010) divided the LRW into 84 sub-watersheds, which are then further subdivided into 4,818 hydrologic response units (HRUs) that are homogeneous with respect to land use, soil characteristics and management practices.

SWAT simulation results (Table 3-2) show that a three-year rotation of corn-corn-soybean production has significantly higher average levels of nutrient loss and sediment yield than the two-year corn-soybean rotation (Folle, 2010). SWAT results are shown also for switchgrass production on HRU's of particular interest. Switchgrass production was simulated on three types of crop land: 1) HRU's with slopes steeper than two percent (Sloped), 2) critical land with relatively high effluent levels (Critical), and 3) the fifteen percent of crop land with the lowest corn yields (Low Yield).

Compared to the corn and soybean rotations, switchgrass has lower effluent levels (Table 3-2). Of the 269,757 hectares of crop land in the Le Sueur Watershed, Table 3-3 shows the quantity of sloped, critical and low yield land. Some HRU's are comprised of crop land in two or all three of the categories – these areas are shown in Table 3-3 also.

Chapter Two shows corn stover is the only feedstock produced for demand levels up to 800 thousand Metric tons (Mt) in the LRW. Above 800 thousand Mt, stover and switchgrass are harvested together. The supply of feedstock would include corn stover produced outside the watershed and transported farther if feedstock production is not limited to the LRW. This model focuses on the production levels up to 800 thousand Mt of feedstock production.

The analysis in this chapter includes baseline results and results under three policy scenarios. In the first scenario, nitrate-N losses in the watershed are limited to 10% and 30% of the baseline level without feedstock production. The second scenario is to promote switchgrass production by providing subsidies from $20 to $80 per metric ton of switchgrass produced on sloped, critical or low yield land. The third policy scenario is to provide the switchgrass subsidy to production on sloped land only.

Regulating nutrient losses is focused on nitrate-N losses in this study. The most profitable corn yield is achieved by nitrogen (N) fertilizers (Rehm et al., 2006) and N fertilization is a major cost of production (Duffy 2011). In addition, crop residue removal needs additional nitrogen fertilizer to compensate for plant nutrient loss[1]. The first policy scenario is modeled by adding upper limits on total nutrient load. The second and last scenario is constructed by adding revenue from a switchgrass production subsidy to the objective function in the model.

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[1] Analysis for limiting phosphorus losses is in appendix.

3.4 Results

3.4.1. Change in Crop Mix and Feedstock Composition

When total nitrate-N losses are restricted, crop production activities with the lowest opportunity costs for reducing nutrient loss enter the equilibrium solution. Table 3-4 and Figure 3-1 show the crop production activity and crop mix results for feedstock supply levels from 0 to 800 thousand metric tons (Mt) without restrictions on nitrate-N loss and with 10%, 20% and 30% reductions in total nitrate-N load. The reduced effluent levels are relative to the estimated loss without feedstock production, which can be viewed as the current, baseline average total nitrate-N load.

When nitrate-N losses are reduced by 10% from the base level, rates of stover removal decrease from 60% to a combination of 30% and 10% in a small number of HRU's. Across all levels of feedstock production, CRP area increases and corn area declines relative to the base scenario. Switchgrass is not produced until the total feedstock supply reaches 700 thousand Mt. Up to that point, the expansion of stover production must occur by harvesting stover from more land and hauling the feedstock over greater distances. The proportion of land in the two-year rotation that is harvested for stover increases – all corn in the two-year rotation is used for stover harvest after feedstock production reaches 600 thousand MT. Table 3-7 shows the average transport distance per ton of feedstock. As feedstock production increases to 600 thousand Mt, kilometers per metric ton of feedstock supply increases from 9.8 to 26.5 ton-kilometers.

Increasing the restriction on nitrate-N losses to 20% leads to further reductions in grain production, lower stover harvest rates and increased CRP area at each level of feedstock supply. The average stover removal rate decreases from 60% to 51% at 400

Mt of feedstock production as the stover removal rate decreases to 30% and 10% in some HRU's. Switchgrass production appears a bit sooner, at a supply of 600 thousand Mt.

Eventually, at supply levels of 700 and 800 thousand Mt, switchgrass displaces corn, soybean and CRP land and increases to 20% and 32%, respectively, of total feedstock supply. Notably, as switchgrass enters the crop mix, all stover harvest is at the highest rate of 60%, implying that the higher value of the feedstock makes the opportunity cost of reducing effluent levels by lowering the stover harvest rates too costly on the land types where stove is harvested. Similar adjustment patterns occur when nitrate-N losses are reduced by 30%. At lower levels of feedstock supply, stover harvest rates decrease to 50%. However, at higher supply levels, when switchgrass production occurs, only the highest rate of corn stover removal is economical.

As the limits on nitrate-N loss are increased, expanded stover production relies less on expanding the area of the three-year corn-soybean rotation because the three-year rotation has higher nitrate-N losses. At the highest levels of cellulosic feedstock production, switchgrass production increases. CRP land expands mainly by displacing land in the two-year corn-soybean rotation. CRP area increases three fold as N loss decreases by 30% from base levels. Most CRP land in baseline is adopted in sloped land as shown in Table 3-14. Sloped land type also mostly occupies the most CRP land in the nitrate-N restriction scenario but the proportion of sloped land decreases as nitrate-N restriction increases. The distance for transporting feedstock increases slightly relative to baseline before switchgrass makes up all of feedstock supplied.

Since switchgrass production results in lower effluent levels than current used cropping systems, subsidizing switchgrass production might improve water quality while encouraging biofuel production. The subsidy here is credited directly to the switchgrass producer, not at the processing plant. Table 3-5 and Figure 3-2 show the results across feedstock supply levels with switchgrass subsidies of $20, $40, $50, $60 and $80 per metric ton. All corn stover is harvested at the highest rate, 60%, since the harvest cost per ton decreases as the removal rate increases.

A subsidy below $40/Mt changes the composition of feedstock production only at the highest level of feedstock supply – 800 thousand Mt (Table 3-8). At lower levels of feedstock production, all feedstock is corn stover with most of the stover from the two-year rotation as in the baseline scenario. When feedstock supply reaches 800 thousand Mt, switchgrass and stover from the two-year rotation displace part of the stover from the three-year rotation.

As the subsidy is increased to $40/Mt, significant switchgrass production occurs only above 600 thousand Mt of feedstock supply, although small amounts of switchgrass appear beginning at 200 thousand Mt. As before, at the higher levels of supply, stover from the three-year rotation is displaced by stover from the two-year rotation and switchgrass.

Significant quantities of switchgrass are produced at every level of feedstock supply when the subsidy reaches $50. Switchgrass becomes the main source of feedstock as the subsidy reaches $60. As the subsidy increases, stover harvest area decreases and the two-year rotation without stover harvest (CS-S00) increases at each level of feedstock production because the increase in switchgrass production reduces the dependence on stover (Table 3-5, Figure 3-2). Using switchgrass as the feedstock also changes the transportation of corn stover. Compared to the baseline, as the switchgrass subsidy increases, average ton-kilometers increases generally for all feedstocks and for switchgrass, but declines for stover (Table 3-7). This is due to geographic location of HRU's on which switchgrass production is possible, which tend to be farther from the biofuel plant.

Increasing the subsidy to $80 shifts all feedstock production to switchgrass for supply levels up to 700 thousand Mt. Stover is harvested only when supply reaches 800, which is beyond the capacity of the watershed to produce switchgrass on the designated HRU's. Land for corn and soybean production is at its lowest level. The CRP area is not significantly affected by the increase in the switchgrass subsidy (Figure 3-2). Most CRP land appears in sloped and low yield area (Table 3-15). As the subsidy is increased, switchgrass production expands primarily on critical land, with more than half of the switchgrass produced on this land type.

In the final policy scenario, the switchgrass production subsidy is targeted to sloped land only (Table 3-6, Figure 3-3). Crop land use for subsidies under $40 is similar to the previous results because switchgrass production is low (Table 3-8). Predictably, more stover and less switchgrass is produced with the targeted subsidy. Switchgrass becomes the main feedstock when the subsidy increases to $80. The CRP land appears in sloped land and some of sloped land in switchgrass production are critical and low yield land (Table 3-16).

3.4.2. Impacts on Crop Production and Feedstock Supply

The three sets of policy scenarios have different impacts on crop production, land use and efficient combination of feedstocks. Limiting nitrate-N loss increases CRP land. Expansion of CRP land comes from decreases in corn and soybean area (Table 3-4, Figure 3-1) and total grain production declines (Table 3-9). Even when no cellulosic feedstock is produced, corn production (1,467 thousand Mt under baseline) decreases from 6.0% to 19.1% as the limits on nitrate-N loss are increased from 10% to 30%, respectively. Corn and soybean production decrease by 25.8% and 30.0%, respectively, when 800 thousand Mt of feedstock is produced and nitrate-N is reduced by 30%. As the subsidy begins to have a substantial effect of switchgrass production (generally over \$60/Mt), a substantial decline in grain production occurs, as land is diverted from corn and soybeans to switchgrass. When applied only to sloped land, the impacts of the switchgrass subsidy on grain production are reduced somewhat.

Table 3-10 and Figure 3-4 show the marginal cost of feedstock at the plant – the feedstock supply function. Increasing restrictions on nitrate-N loss increase marginal cost as production must shift to more distant and higher cost HRU’s. Switchgrass subsidies, on the other hand, increase feedstock supply. At the highest the subsidy level considered, \$80/Mt, most feedstock comes from switchgrass production and the marginal cost of feedstock is lowest. As expected, when the switchgrass subsidy is restricted to sloped land, decreases in marginal cost are reduced.

3.4.3. Impacts of Policies on Effluent Levels

Nutrient losses and sediment yield increase in baseline case as feedstock production increases due to the more intensive production of corn and the impacts of stover harvest.

The impacts of an environmental policy restricting total nitrate-N loads in the watershed involved adding a constraint on the effluent level to the model. For each equilibrium solution, the dual value of that constraint, represents the marginal cost of limiting the nitrate-N load. These marginal costs are shown in Table 3-11 for each level of nitrate-N reduction and each level of feedstock production. When no feedstock is produced and the nitrate-N load is reduced by 10%, the marginal cost of reducing the load is $14,536 per Mt. The value increases to $19,851 when the load is reduced by 30%. Expansion of feedstock production also increases the marginal cost of nitrate-N load reduction. When regional feedstock supply is 800 thousand Mt, the marginal cost of reducing the effluent is $19,975 and $26,488 with load reductions of 10% and 30%, respectively.

Table 3-12 shows the percentage change in nutrient losses and sediment yields at various level of feedstock production, relative to the levels when no feedstock is produced. When nitrate-N loads are constrained, reduction of 10%, 20% and 30% are achieved by definition. Changes in regional production resulting from the switchgrass subsidy also effect nitrate-N loads. Nitrate-N losses remain steady or decline as the switchgrass subsidy increases, with the sharpest declines occurring at the highest levels of feedstock production and subsidy levels above $50 per Mt. When the subsidy is $50, nitrate-N load still increases as feedstock production expands, with the maximum percentage change of 2.6% occurring at 600 thousand Mt, then declining slightly.

When the subsidy increases above $60, switchgrass production makes up a more significant part of feedstock demand and expands to the whole watershed (Figure 3-5). As switchgrass production increases, nitrate-N losses decline, as shown in Table 3-12, by 0.9% to 6.1%. Figure 3-6 shows decrease of nitrate-N load expands to whole watershed.

The changes in production practices resulting from limits on nitrate-N loss lead also to reductions in phosphorus and sediment yields at lower levels of feedstock production. At higher levels of feedstock supply, phosphorus and sediment loads actually increase when nitrate-N loads are reduced by 10% and 20%. When nitrate-N is reduced by 30%, phosphorus levels decline at all levels of feedstock production, while sediment yields decrease initially, increase, and then decline slightly. With a $60 subsidy, phosphorus and sediment loads stay below the base levels except at the highest levels of feedstock production, and at $80, phosphorus and sediment levels decline from base levels as feedstock supply increases.

If switchgrass subsidy is limited to sloped land, the impacts on effluent levels are reduced in most cases. However, at lower levels of feedstock production, phosphorus and sediment loads actually decline when the subsidy is $80 and limited to switchgrass production on sloped land (see Figure 3-7).

3.4.4. Changes in Cost of Implementing Policies

The baseline and three policy scenarios generate costs to produce cellulosic feedstock and implement policies. Policy makers need to consider public as well as the private costs and benefits to the policies. CRP payments and switchgrass subsidies are public costs for associated with inducing producers to adopt conservation practices and to supply feedstock. CRP payments in the baseline case decrease slightly as feedstock production increases (Table 3-13). Because increasing the limits on nitrate-N loss expands CRP land, CRP payments increase more than three times compared to baseline when the nitrate-N load is reduced by 30%.

CRP payments in the scenario of switchgrass subsidies do not change significantly as the switchgrass subsidy increases. However, the total cost of CRP payments and switchgrass subsidies increases sharply when switchgrass becomes the main source of cellulosic feedstocks – at a subsidy level of $80. Because switchgrass production is lower when the subsidy applies only to production on sloped land, the total cost of CRP payment and production subsidy is less than when the subsidy is applied more broadly. This makes it possible to increase subsidy rate somewhat while maintaining a constant total public expenditure. For example, total CRP payment and subsidy cost at $50 subsidy level is $20.1 million when 800 thousand Mt of feedstock is supplied (Table 3-13). By focusing on specific land types and providing the subsidy only to production on sloped land, subsidy can be increased from $50 to $60 without sharp increases in policy budget, while leading to larger reductions in nutrient loss and sediment yield (Table 3-12, Figure 3-7).

The private cost of implementing each policy is reflected in the change in objective function. Because producer surplus is objective function in the model, changes in producer surplus represent the implicit cost to producers of implementing each policy and increasing feedstock production. These changes are shown in Table 3-17. Though the model provides an estimate of the marginal cost or the implicit supply price of corn stover, revenue from stover production is not included in the objective function. As the reduction in nitrate-N loss is increased to 30%, producer surplus declines by $76.9 million when feedstock supply is 800 thousand Mt. Switchgrass subsidy payments are subtracted from the objective function values to compare the implicit costs between the baseline and policy scenarios. When a switchgrass subsidy of $80/Mt is provided to production on all three types of land on which switchgrass may be produced, producer surplus declines by $83.9 million when feedstock supply is 800 thousand Mt. Decrease in producer surplus in the scenario of providing subsidy to sloped land is less than in second scenario. While the targeted switchgrass production subsidy has more modest public and private costs, the social benefit of the policies must compare these costs to the benefits of improved water quality, which vary across policies and are not addressed in this paper.

3.5 Conclusion

This chapter examines the potential tradeoffs between cellulosic feedstock production and water quality and potential polices to influence those tradeoffs. Because corn stover removal increases nutrient loads and requires increased fertilizer use, policies to limit nitrate-N losses are considered. And because production of switchgrass as an energy crop can lower nutrient loads relative to conventional crops and stover, production subsidies for switchgrass are analyzed.

Policies promoting cellulosic feedstock production need to consider the potential impacts on crop production, policy implementation costs, feedstock composition and environmental outcomes. Regulation of nitrate-N losses might attain environmental goals but have significant impacts on crop production and may be difficult to administer. Switchgrass production subsidies can be an option to consider. Results here provide estimates of how producers will respond to various switchgrass subsidy levels and the extent to which dependence on corn stover production can be reduced. When switchgrass production is subsidized, the negative impacts of cellulosic feedstock production on water quality are reduced or eliminated. With a subsidy above $60/Mt, switchgrass becomes the main source of feedstock and nutrient losses and sediment yields are reduced compared to the no-subsidy case, when corn stover is the primary feedstock. However, such a high subsidy leads to a substantial decline in grain production and a sharp increase in subsidy payments. If a switchgrass subsidy is targeted to specific types of land, the impacts of the subsidy on grain production are reduced because more stover is produced. While the water quality benefits of the targeted subsidy are generally somewhat less, they must be weighed against a substantially lower public and private cost.

A switchgrass subsidy would be an alternative policy to manage water quality and supply cellulosic feedstock. With the subsidy, nutrient and sediment losses increase slightly or decrease, while increasing significantly without the subsidy as feedstock production increases. Targeting the subsidy to specific types of land would be an effective policy that could address the adverse impacts of cellulosic feedstock production and reduce implementation costs. The analysis examined the private costs of implementing a production subsidy but the actual cost would be less if the social benefits from reducing effluents are considered. Results show as subsidy increases to 80$/Mt and feedstock supply reaches 800 thousand Mt, nitrate-N losses decrease by 6.1% and phosphorus and sediment loads decrease by 34.5% and 36.9% respectively compared to no feedstock production. The decrease in nitrate-N, phosphorus and sediment loads expands to 32.0%, 56.1% and 64.9% respectively, compared to the same level of feedstock production without subsidy policy. Social welfare from subsidy policy could be measured by valuing reductions in nutrient and sediment loads. Incorporating the social benefits could highlight the importance of policy considering both of environmental and energy perspectives.

This study examines policy alternatives to produce cellulosic feedstock and mitigate nutrient losses and sediment yield in a relatively small watershed. This study can be extended by considering other advanced cellulosic feedstock production and environmental impacts. Extending to other regions and including feasible biorefinery plants would be helpful to evaluate various policy options.

Table 3-1. Summary of Previous Studies integrating Economic and Biophysical Models

Study	Model Type	Policy Alternatives in the Model
Doering et al. (1999)	Mathematical Programming & EPIC	Nitrogen & fertilizer reduction, fertilizer tax Wet land restoration, riparian buffers
Ribaudo et al. (2001)	Mathematical Programming & EPIC	Fertilizer reduction, wet land restoration
Whittaker (2005)	Mathematical Programming & SWAT	Fertilizer reduction, tax on fertilizer
Wu & Tanaka (2005)	Econometric Logit Model & SWAT	Fertilizer tax, Incentive payment
Babcock (2007)	Calculation of Subsidy & SWAT	Switchgrass subsidy
Secchi et al. (2008)	Profit maximization & SWAT	10% Crop land replacement for switchgrass Switchgrass production to erodible land
Rabotyagov et al. (2010)	Simulation Optimization & SWAT	Reduction of nitrogen and phosphorus

Table 3-2. Summary of SWAT Estimates of Nutrient Losses and Sediment Yields by Crop Rotation and Switchgrass*

	Nitrate-N, Kg/Ha				Phosphorus, Kg/Ha				Sediment, Mt/Ha			
	0%	10%	30%	60%	0%	10%	30%	60%	0%	10%	30%	60%
Two-Year	18.97	18.98	19.25	19.74	0.76	0.78	0.87	1.04	1.93	2.00	2.43	2.88
Three-Year	29.02	29.26	31.52	33.51	0.86	0.95	1.09	1.15	2.20	2.48	3.01	3.32
	Nitrate-N, Kg/Ha				Phosphorus, Kg/Ha				Sediment, Mt/Ha			
Land Type**	Slope	CCA	LY	All	Slope	CCA	LY	All	Slope	CCA	LY	All
Switchgrass	11.06	10.60	14.39	11.14	0.05	0.01	0.10	0.02	0.18	0.02	0.38	0.09

* Average over all types of crop land.

** Slope, CCA, LY, All: Slope, Critical, Low crop yield, and all of them respectively. Switchgrass yield in each type of land is estimated as 10.26, 14.66, 5.86 and 13.55 Mt/Ha, respectively.

Table 3-3. Area in Hectares by Crop Land Type and Percentage of Total Crop Land

Type	Sloped	CCA	LY	Sloped & CCA	Sloped & LY	CCA & LY	Sloped & CCA & LY
Area	55,672	57,912	23,251	15,920	23,204	5,130	5,130
%	20.6%	21.5%	8.6%	5.9%	8.6%	1.9%	1.9%
Type	Sloped only	CCA only	LY only	Sloped or CCA	Sloped or LY	CCA or LY	Sloped or CCA or LY
Area	21,679	41,992	48	97,664	55,720	76,033	97,712
%	8.0%	15.6%	0.0%	36.2%	20.7%	28.2%	36.2%

* CCA and LY are critical and low yield land types, respectively.

Table 3-4. Crop Land Area by Corn-Soybean Rotation under Total Nitrate-N Load Restrictions

		Cellulosic Feedstock Production (1000 Mt)								
Rotation	(Unit: 1000 Ha, %)	0	100	200	300	400	500	600	700	800
		--Baseline----------------------------------								
Two-Year	Total Area	246.2	246.2	246.1	246.0	246.0	245.8	245.6	198.2	73.4
	Stover Harvest Area	0.0	36.9	73.9	112.0	148.7	186.2	223.2	198.2	73.4
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%
Three-Year	Total Area	1.6	1.7	1.7	1.9	1.9	2.1	2.5	51.8	179.2
	Stover Harvest Area	0.0	0.0	0.1	0.5	0.5	1.3	2.2	51.8	179.2
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%
		-----------------------10% Reduction in Nitrate-N Losses--------------------								
Two-Year	Total Area	229.1	228.8	228.2	227.8	227.2	226.3	223.5	192.0	176.6
	Stover Harvest Area	0.0	38.7	79.1	122.6	166.9	204.0	223.5	192.0	176.6
	Ave. Removal Rate	0%	58%	57%	55%	54%	55%	59%	60%	60%
Three-Year	Total Area	1.5	1.5	1.6	1.3	1.2	1.1	2.2	28.9	37.8
	Stover Harvest Area	0.0	0.0	0.0	0.0	0.2	0.5	2.2	28.9	37.8
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%
		-----------------------20% Reduction in Nitrate-N Losses--------------------								
Two-Year	Total Area	214.1	213.8	213.3	212.8	211.8	211.0	189.4	180.3	172.5
	Stover Harvest Area	0.0	39.6	81.1	124.5	176.3	205.0	189.4	180.3	172.5
	Ave. Removal Rate	0%	57%	55%	54%	51%	55%	60%	60%	60%
Three-Year	Total Area	1.6	1.5	1.5	1.2	1.4	0.6	19.4	23.1	24.4
	Stover Harvest Area	0.0	0.0	0.0	0.0	0.1	0.5	19.4	23.1	24.4
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%
		-----------------------30% Reduction in Nitrate-N Losses--------------------								
Two-Year	Total Area	196.5	196.3	195.7	195.0	194.1	191.8	171.3	162.1	156.8
	Stover Harvest Area	0.0	45.0	87.4	133.4	173.7	191.5	171.3	162.1	156.8
	Ave. Removal Rate	0%	50%	51%	51%	52%	58%	60%	60%	60%
Three-Year	Total Area	1.5	1.4	1.3	1.2	0.9	1.2	17.7	21.3	19.8
	Stover Harvest Area	0.0	0.0	0.0	0.0	0.4	1.2	17.7	21.3	19.8
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%

Table 3-5. Crop Land Area by Corn-Soybean Rotation under Switchgrass Subsidies*

		Cellulosic Feedstock Production (1000 Mt)								
Rotation	(Unit: 1000 Ha, %)	0	100	200	300	400	500	600	700	800
		Baseline								
Two-Year	Total Area	246.2	246.2	246.1	246.0	246.0	245.8	245.6	198.2	73.4
	Stover Harvest Area	0.0	36.9	73.9	112.0	148.7	186.2	223.2	198.2	73.4
Three-Year	Total Area	1.6	1.7	1.7	1.9	1.9	2.1	2.5	51.8	179.2
	Stover Harvest Area	0.0	0.0	0.1	0.5	0.5	1.3	2.2	51.8	179.2
		$20/Mt of subsidy								
Two-Year	Total Area	246.2	246.2	246.1	246.0	246.0	245.8	245.6	198.2	99.6
	Stover Harvest Area	0.0	36.9	73.9	112.0	148.7	186.2	223.2	198.2	99.6
Three-Year	Total Area	1.6	1.7	1.7	1.9	1.9	2.1	2.5	51.8	148.8
	Stover Harvest Area	0.0	0.0	0.1	0.5	0.5	1.3	2.2	51.8	148.8
		$40/Mt of subsidy								
Two-Year	Total Area	246.2	246.2	246.1	245.9	245.9	245.5	245.1	238.2	215.0
	Stover Harvest Area	0.0	36.9	73.8	111.8	148.5	185.4	221.4	238.2	215.0
Three-Year	Total Area	1.6	1.7	1.7	1.9	1.9	2.1	2.5	6.4	21.1
	Stover Harvest Area	0.0	0.0	0.1	0.5	0.5	1.3	2.2	6.4	21.1
		$50/Mt of subsidy								
Two-Year	Total Area	246.2	245.0	243.9	243.6	241.4	241.1	238.2	233.7	228.9
	Stover Harvest Area	0.0	32.6	65.5	102.1	129.9	166.7	190.2	206.5	221.5
Three-Year	Total Area	1.6	1.7	1.7	1.7	1.8	1.8	2.0	2.3	2.6
	Stover Harvest Area	0.0	0.0	0.1	0.2	0.4	0.5	1.1	2.0	2.6
		$60/Mt of subsidy								
Two-Year	Total Area	246.2	237.6	231.6	227.7	223.0	221.5	218.8	216.6	215.1
	Stover Harvest Area	0.0	0.0	8.2	25.2	39.7	69.1	93.5	119.0	150.2
Three-Year	Total Area	1.6	1.6	1.5	1.1	1.0	1.0	0.8	0.7	0.7
	Stover Harvest Area	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3	0.3
		$80/Mt of subsidy								
Two-Year	Total Area	246.2	237.5	229.8	222.5	215.0	207.1	198.9	190.4	186.3
	Stover Harvest Area	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.4
Three-Year	Total Area	1.6	1.6	1.5	1.0	0.6	0.5	0.3	0.3	0.2
	Stover Harvest Area	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Average Removal Rate is 60% in all cases.

Table 3-6. Crop Land Area by Corn-Soybean Rotation under Switchgrass Subsidies on Sloped Land*

		Cellulosic Feedstock Production (1000 Mt)								
Rotation	(Unit: 1000 Ha, %)	0	100	200	300	400	500	600	700	800
		Baseline								
Two-Year	Total Area	246.2	246.2	246.1	246.0	246.0	245.8	245.6	198.2	73.4
	Stover Harvest Area	0.0	36.9	73.9	112.0	148.7	186.2	223.2	198.2	73.4
Three-Year	Total Area	1.6	1.7	1.7	1.9	1.9	2.1	2.5	51.8	179.2
	Stover Harvest Area	0.0	0.0	0.1	0.5	0.5	1.3	2.2	51.8	179.2
		$20/Mt of subsidy								
Two-Year	Total Area	246.2	246.2	246.1	246.0	246.0	245.8	245.6	198.2	98.9
	Stover Harvest Area	0.0	36.9	73.9	112.0	148.7	186.2	223.2	198.2	98.9
Three-Year	Total Area	1.6	1.7	1.7	1.9	1.9	2.1	2.5	51.8	149.4
	Stover Harvest Area	0.0	0.0	0.1	0.5	0.5	1.3	2.2	51.8	149.4
		$40/Mt of subsidy								
Two-Year	Total Area	246.2	246.2	246.1	245.9	245.9	245.5	245.1	235.1	182.3
	Stover Harvest Area	0.0	36.9	73.8	111.8	148.5	185.4	221.4	235.1	182.3
Three-Year	Total Area	1.6	1.7	1.7	1.9	1.9	2.1	2.5	9.5	56.6
	Stover Harvest Area	0.0	0.0	0.1	0.5	0.5	1.3	2.2	9.5	56.6
		$50/Mt of subsidy								
Two-Year	Total Area	246.2	245.1	244.2	244.0	242.4	241.7	239.9	238.1	226.6
	Stover Harvest Area	0.0	33.2	66.9	103.9	135.1	170.2	200.5	229.2	226.6
Three-Year	Total Area	1.6	1.7	1.7	1.7	1.8	1.9	2.0	2.3	7.0
	Stover Harvest Area	0.0	0.0	0.1	0.2	0.4	0.6	1.2	2.1	7.0
		$60/Mt of subsidy								
Two-Year	Total Area	246.2	239.0	237.1	235.6	235.0	233.4	233.0	231.5	229.0
	Stover Harvest Area	0.0	8.3	35.1	65.1	99.0	128.1	164.0	192.3	218.2
Three-Year	Total Area	1.6	1.5	1.1	1.0	0.8	0.7	0.7	0.7	0.6
	Stover Harvest Area	0.0	0.0	0.0	0.1	0.1	0.3	0.3	0.4	0.5
		$80/Mt of subsidy								
Two-Year	Total Area	246.2	237.1	230.1	222.8	221.6	221.0	220.8	220.8	220.4
	Stover Harvest Area	0.0	0.0	0.0	3.0	34.4	68.9	104.7	141.0	175.6
Three-Year	Total Area	1.6	1.5	0.5	0.2	0.2	0.2	0.1	0.1	0.1
	Stover Harvest Area	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1

*Average Removal Rate is 60% in all cases.

Table 3-7. Distance Shipped in Kilometers per Mt of Feedstock

		Cellulosic Feedstock Production (1000 Mt)							
Scenario		100	200	300	400	500	600	700	800
		Corn Stover and Switchgrass Feedstock							
Baseline		7.4	12.4	15.1	18.6	21.3	24.4	26.8	26.6
Nitrate-N Load Restriction	10%	9.8	14.1	17.4	20.4	23.3	26.5	26.5	26.4
	20%	10.3	14.7	18.1	21.4	24.4	26.4	26.2	26.4
	30%	10.7	15.5	19.1	22.5	25.8	26.2	26.2	26.7
Switchgrass Production Subsidy	$20	7.4	12.4	15.1	18.6	21.3	24.4	26.8	26.5
	$40	7.4	12.4	15.1	18.6	21.2	24.3	26.7	26.4
	$50	8.2	12.7	14.9	18.0	20.1	22.4	23.9	25.7
	$60	21.4	20.8	20.1	20.7	21.0	21.4	22.7	23.6
	$80	21.1	23.4	25.4	26.6	27.3	28.1	29.1	27.7
Switchgrass Production Subsidy on Sloped Land only	$20	7.4	12.4	15.1	18.6	21.3	24.4	26.8	26.6
	$40	7.4	12.4	15.1	18.6	21.2	24.3	26.8	27.2
	$50	8.2	12.7	15.0	18.4	20.5	23.2	25.9	27.5
	$60	20.0	17.8	18.4	19.2	21.1	22.5	24.7	26.8
	$80	26.8	30.4	31.2	26.5	24.9	24.3	25.0	26.1
		Corn Stover							
Baseline		7.4	12.4	15.1	18.6	21.3	24.4	26.8	26.6
Nitrate-N Reduction	10%	9.8	14.1	17.4	20.4	23.3	26.5	27.0	27.2
	20%	10.3	14.7	18.1	21.4	24.4	26.8	27.1	27.2
	30%	10.7	15.5	19.1	22.5	25.8	26.9	27.1	27.1
Switchgrass Production Subsidy	$20	7.4	12.4	15.1	18.6	21.3	24.4	26.8	26.7
	$40	7.4	12.4	15.1	18.6	21.2	24.3	26.9	27.0
	$50	7.1	11.7	14.4	17.4	19.9	22.3	24.0	26.1
	$60	0.0	0.0	6.5	7.6	12.7	14.4	17.7	20.0
	$80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.1
Switchgrass Production Subsidy on Sloped Land only	$20	7.4	12.4	15.1	18.6	21.3	24.4	26.8	26.7
	$40	7.4	12.4	15.1	18.6	21.2	24.3	26.8	26.8
	$50	7.2	11.8	14.4	17.7	20.0	22.9	25.8	26.7
	$60	0.0	7.3	11.8	14.3	17.4	19.9	22.7	25.3
	$80	0.0	0.0	0.0	7.3	12.4	15.2	18.8	21.7
		Switchgrass							
Baseline		0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.7
Nitrate-N Load Restriction	10%	0.0	0.0	0.0	0.0	0.0	0.0	21.0	22.1
	20%	0.0	0.0	0.0	0.0	0.0	15.4	21.0	22.7
	30%	0.0	0.0	0.0	0.0	0.0	20.1	21.8	23.9
Switchgrass Production Subsidy	$20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.8
	$40	0.0	19.3	13.3	13.3	17.8	20.6	21.4	22.1
	$50	15.6	18.8	18.7	20.6	20.6	20.8	21.8	22.5
	$60	19.7	21.6	22.2	23.5	23.9	24.3	24.9	25.1
	$80	19.4	21.5	23.4	24.5	25.1	25.8	26.8	26.9
Switchgrass Production Subsidy on Sloped Land only	$20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23.2
	$40	0.0	19.3	13.3	13.3	17.8	20.6	23.8	26.7
	$50	16.6	19.7	20.3	23.0	23.6	24.1	24.6	27.9
	$60	23.9	25.2	25.7	26.5	27.0	27.3	27.8	28.4
	$80	24.7	27.9	29.5	29.7	29.8	29.8	29.8	29.8

Table 3-8. Cellulosic Feedstock Composition (Unit: 1000 Mt)

		Cellulosic Feedstock Production (1000 Mt)*							
Scenario		100	200	300	400	500	600	700	800
		Corn Stover Production							
Baseline		100.0	200.0	300.0	400.0	500.0	600.0	700.0	799.6
Nitrate-N Load Restriction	10%	100.0	200.0	300.0	400.0	500.0	600.0	612.7	602.0
	20%	100.0	200.0	300.0	400.0	500.0	573.5	561.7	545.4
	30%	100.0	200.0	300.0	400.0	500.0	519.5	507.1	488.0
Switchgrass Production Subsidy	$20	100.0	200.0	300.0	400.0	500.0	600.0	700.0	769.3
	$40	100.0	199.9	299.5	399.5	497.7	595.3	653.8	643.8
	$50	88.7	177.5	274.0	350.0	447.0	512.5	557.3	598.9
	$60	0.0	22.3	68.9	106.7	187.1	250.9	321.0	402.3
	$80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	53.4
Switchgrass Production Subsidy on Sloped Land only	$20	100.0	200.0	300.0	400.0	500.0	600.0	700.0	769.7
	$40	100.0	199.9	299.5	399.5	497.7	595.3	656.8	678.7
	$50	90.3	181.4	278.6	364.4	455.9	540.2	618.4	628.7
	$60	22.8	95.3	176.4	266.0	345.3	439.3	516.5	585.5
	$80	0.0	0.0	8.2	93.6	187.2	281.4	379.9	472.2
		Switchgrass Production**							
Baseline		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
Nitrate-N Load Restriction	10%	0.0	0.0	0.0	0.0	0.0	0.0	94.9	215.3
	20%	0.0	0.0	0.0	0.0	0.0	28.8	150.3	276.7
	30%	0.0	0.0	0.0	0.0	0.0	87.4	209.7	339.1
Switchgrass Production Subsidy	$20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.4
	$40	0.0	0.1	0.5	0.6	2.5	5.1	50.3	169.8
	$50	12.3	24.5	28.3	54.3	57.6	95.1	155.1	218.6
	$60	108.7	193.2	251.2	318.8	340.1	379.5	411.9	432.3
	$80	108.7	217.4	326.1	434.8	543.5	652.2	760.9	811.5
Switchgrass Production Subsidy on Sloped Land only	$20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.9
	$40	0.0	0.1	0.5	0.6	2.5	5.1	47.0	131.9
	$50	10.5	20.3	23.3	38.7	47.9	65.0	88.7	186.2
	$60	84.0	113.8	134.3	145.7	168.2	174.7	199.4	233.2
	$80	108.7	217.4	317.1	333.0	340.0	346.3	347.9	356.3

* Total feedstock supply is in corn-stover equivalent. It is assumed that switchgrass is 92% of stover equivalent in ethanol yield (Huang et al. 2009).

Table 3-9. Percentage Change in Crop Production from Zero Feedstock Production in Baseline*

		Cellulosic Feedstock Production (1000 Mt)								
Scenario		0	100	200	300	400	500	600	700	800
		Corn Production								
Baseline		0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	6.4%	21.5%
Nitrate-N Load Restriction	10%	-6.0%	-6.1%	-6.3%	-6.6%	-6.9%	-7.4%	-7.9%	-6.9%	-8.5%
	20%	-12.0%	-12.1%	-12.4%	-12.7%	-13.0%	-13.7%	-12.8%	-14.6%	-17.1%
	30%	-19.1%	-19.3%	-19.5%	-19.9%	-20.4%	-21.2%	-21.0%	-22.9%	-25.8%
Switchgrass Production Subsidy	$20	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	6.4%	16.9%
	$40	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.6%	-2.2%
	$50	0.0%	-0.4%	-0.7%	-0.8%	-1.6%	-1.6%	-2.7%	-4.3%	-6.0%
	$60	0.0%	-3.1%	-5.5%	-7.2%	-9.1%	-9.7%	-10.9%	-11.8%	-12.4%
	$80	0.0%	-3.1%	-6.2%	-9.3%	-12.5%	-15.6%	-18.9%	-22.3%	-23.9%
Switchgrass Production Subsidy on Sloped Land only	$20	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	6.4%	17.0%
	$40	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-0.2%	3.1%
	$50	0.0%	-0.3%	-0.6%	-0.7%	-1.1%	-1.4%	-1.9%	-2.5%	-4.4%
	$60	0.0%	-2.5%	-3.4%	-4.0%	-4.3%	-4.9%	-5.1%	-5.7%	-6.7%
	$80	0.0%	-3.2%	-6.3%	-9.2%	-9.7%	-9.9%	-10.0%	-10.0%	-10.1%
		Soybean Production								
Baseline		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-5.9%	-22.3%
Nitrate-N Load Restriction	10%	-5.8%	-6.0%	-6.2%	-6.4%	-6.7%	-7.1%	-8.0%	-13.4%	-17.1%
	20%	-11.9%	-12.0%	-12.2%	-12.5%	-12.9%	-13.4%	-17.0%	-19.7%	-22.4%
	30%	-19.0%	-19.1%	-19.4%	-19.7%	-20.2%	-21.1%	-24.8%	-27.5%	-30.0%
Switchgrass Production Subsidy	$20	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-5.9%	-19.4%
	$40	0.0%	0.0%	0.0%	0.0%	0.0%	-0.1%	-0.1%	-1.6%	-6.6%
	$50	0.0%	-0.3%	-0.7%	-0.8%	-1.5%	-1.6%	-2.6%	-4.2%	-5.9%
	$60	0.0%	-2.9%	-5.2%	-6.8%	-8.6%	-9.2%	-10.3%	-11.1%	-11.7%
	$80	0.0%	-3.0%	-5.9%	-8.8%	-11.9%	-15.0%	-18.3%	-21.7%	-23.4%
Switchgrass Production Subsidy on Sloped Land only	$20	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	-5.9%	-19.5%
	$40	0.0%	0.0%	0.0%	0.0%	0.0%	-0.1%	-0.1%	-1.9%	-10.2%
	$50	0.0%	-0.3%	-0.5%	-0.6%	-1.1%	-1.3%	-1.8%	-2.4%	-5.4%
	$60	0.0%	-2.3%	-3.1%	-3.6%	-3.8%	-4.4%	-4.6%	-5.2%	-6.1%
	$80	0.0%	-3.0%	-5.8%	-8.6%	-9.1%	-9.3%	-9.4%	-9.4%	-9.5%

* Corn and soybean production is 1,467 and 335 thousand Mt respectively under zero feedstock production in baseline scenario.

Table 3-10. Marginal Cost of Feedstock (Unit: $/Mt)

		Cellulosic Feedstock Production (1000 Mt)							
Scenario		100	200	300	400	500	600	700	800
Baseline	0%	41.0	43.2	45.6	45.9	48.2	50.8	70.0	104.4
Nitrate-N Load Restriction	10%	44.4	46.6	49.0	51.4	55.0	67.4	106.6	112.9
	20%	44.9	47.3	50.0	53.1	58.3	100.4	106.7	113.9
	30%	45.4	48.2	51.1	55.4	66.1	101.8	109.2	115.1
Switchgrass Production Subsidy	$20	41.0	43.2	45.6	45.9	48.2	50.8	70.0	87.7
	$40	41.0	43.2	45.6	45.9	48.2	50.8	59.5	65.5
	$50	40.8	43.2	43.7	45.7	46.3	48.3	50.6	53.1
	$60	36.5	39.3	40.7	42.9	43.3	44.5	45.8	46.4
	$80	13.7	16.9	20.0	23.2	26.0	29.8	36.2	40.6
Switchgrass Production Subsidy on Sloped Land only	$20	41.0	43.2	45.6	45.9	48.2	50.8	70.0	89.1
	$40	41.0	43.2	45.6	45.9	48.2	50.8	61.0	71.0
	$50	40.8	43.2	43.8	45.8	47.1	48.5	51.4	61.2
	$60	38.5	40.9	43.2	43.7	45.7	46.4	48.5	51.1
	$80	17.8	26.2	38.0	40.9	43.2	45.6	46.0	48.3

Table 3-11. Marginal Cost of Nitrate-N Load Constraint (Unit: $/Mt of Nitrate-N Loss)

	Cellulosic Feedstock Production (1000 Mt)								
Nitrate-N Loss	0	100	200	300	400	500	600	700	800
10% Reduction	14,536	14,640	14,825	14,973	15,080	15,377	16,801	19,772	19,975
20% Reduction	17,496	17,554	17,725	17,979	18,364	18,973	23,296	23,488	23,863
30% Reduction	19,851	19,979	20,185	20,334	20,809	21,996	25,595	26,149	26,488

* Value in the table represents the marginal cost in dollars of meeting the constraint on total nitrate-N loss.

Table 3-12. Percentage Change in Effluent Relative to Levels When Feedstock is Not Produced*

		Cellulosic Feedstock Production (1000 Mt)								
Scenario		0	100	200	300	400	500	600	700	800
						Nitrate-N				
Baseline		0.0%	0.5%	1.1%	1.7%	2.5%	3.2%	4.0%	7.2%	38.0%
Nitrate-N Load Restriction	10%	-10.0%	-10.0%	-10.0%	-10.0%	-10.0%	-10.0%	-10.0%	-10.0%	-10.0%
	20%	-20.0%	-20.0%	-20.0%	-20.0%	-20.0%	-20.0%	-20.0%	-20.0%	-20.0%
	30%	-30.0%	-30.0%	-30.0%	-30.0%	-30.0%	-30.0%	-30.0%	-30.0%	-30.0%
Switchgrass Production Subsidy	$20	0.0%	0.5%	1.1%	1.7%	2.5%	3.2%	4.0%	7.2%	20.9%
	$40	0.0%	0.5%	1.1%	1.6%	2.5%	3.1%	3.8%	4.4%	4.1%
	$50	0.0%	0.3%	0.8%	1.2%	1.7%	2.2%	2.6%	2.4%	2.3%
	$60	0.0%	-0.9%	-1.5%	-1.8%	-2.2%	-1.7%	-1.8%	-1.4%	-1.1%
	$80	0.0%	-0.9%	-1.9%	-2.7%	-3.6%	-4.3%	-5.2%	-6.1%	-6.1%
Subsidy (Sloped land only)	$20	0.0%	0.5%	1.1%	1.7%	2.5%	3.2%	4.0%	7.2%	20.9%
	$40	0.0%	0.5%	1.1%	1.6%	2.5%	3.1%	3.8%	4.5%	6.3%
	$50	0.0%	0.3%	0.8%	1.3%	1.9%	2.3%	2.8%	3.4%	3.4%
	$60	0.0%	-0.6%	-0.4%	0.0%	0.4%	0.9%	1.3%	2.0%	2.4%
	$80	0.0%	-0.9%	-1.5%	-1.8%	-1.2%	-0.7%	0.1%	0.9%	1.8%
						Phosphorus				
Baseline		0.0%	4.5%	10.3%	16.7%	23.3%	31.3%	39.0%	44.3%	49.2%
Nitrate-N Load Restriction	10%	-15.9%	-11.8%	-7.3%	-2.1%	3.5%	9.8%	17.2%	13.5%	9.2%
	20%	-21.6%	-17.6%	-13.1%	-7.9%	-2.2%	3.8%	7.7%	4.8%	-0.7%
	30%	-28.0%	-23.9%	-19.4%	-14.1%	-8.1%	-1.2%	-1.6%	-5.7%	-12.1%
Switchgrass Production Subsidy	$20	0.0%	4.5%	10.3%	16.7%	23.3%	31.3%	39.0%	44.3%	39.0%
	$40	0.0%	4.5%	10.2%	16.6%	23.2%	30.3%	37.8%	38.7%	30.8%
	$50	0.0%	2.8%	7.0%	11.3%	15.6%	20.0%	24.3%	24.8%	26.0%
	$60	0.0%	-6.8%	-9.4%	-9.7%	-10.1%	-6.5%	-5.0%	-1.9%	1.0%
	$80	0.0%	-6.8%	-11.0%	-14.8%	-19.5%	-23.1%	-28.3%	-33.5%	-34.5%
Subsidy (Sloped land only)	$20	0.0%	4.5%	10.3%	16.7%	23.3%	31.3%	39.0%	44.3%	38.1%
	$40	0.0%	4.5%	10.2%	16.6%	23.2%	30.3%	37.8%	37.8%	25.6%
	$50	0.0%	2.9%	7.2%	11.6%	16.5%	20.7%	25.4%	29.3%	19.0%
	$60	0.0%	-7.3%	-6.7%	-3.9%	-0.8%	2.4%	5.9%	9.6%	10.6%
	$80	0.0%	-10.2%	-18.9%	-27.7%	-25.9%	-22.0%	-18.2%	-13.2%	-9.4%
						Sediment				
Baseline		0.0%	5.9%	13.4%	21.9%	30.9%	42.0%	53.8%	66.1%	79.5%
Nitrate-N Reduction	10%	-18.1%	-12.6%	-6.5%	0.6%	8.6%	17.7%	28.7%	27.5%	23.6%
	20%	-23.2%	-17.8%	-11.7%	-4.3%	3.7%	12.7%	20.8%	17.8%	11.6%
	30%	-29.1%	-23.6%	-17.4%	-9.9%	-1.2%	8.9%	11.1%	6.6%	-1.2%
Switchgrass Production Subsidy	$20	0.0%	5.9%	13.4%	21.9%	30.9%	42.0%	53.8%	66.1%	66.6%
	$40	0.0%	5.9%	13.4%	21.8%	30.8%	40.7%	52.1%	55.5%	47.9%
	$50	0.0%	3.9%	9.5%	15.2%	21.4%	27.7%	34.6%	37.0%	40.3%
	$60	0.0%	-7.2%	-9.6%	-9.5%	-9.0%	-4.3%	-1.8%	3.0%	7.5%
	$80	0.0%	-7.3%	-11.4%	-15.3%	-20.2%	-24.0%	-29.8%	-36.0%	-36.9%
Switchgrass Production Subsidy on Sloped Land only	$20	0.0%	5.9%	13.4%	21.9%	30.9%	42.0%	53.8%	66.1%	65.5%
	$40	0.0%	5.9%	13.4%	21.8%	30.8%	40.7%	52.1%	54.6%	43.6%
	$50	0.0%	4.1%	9.7%	15.4%	22.2%	28.5%	35.7%	42.4%	31.3%
	$60	0.0%	-8.3%	-6.8%	-2.9%	1.3%	6.1%	11.2%	16.8%	19.3%
	$80	0.0%	-11.4%	-21.5%	-32.5%	-29.9%	-25.0%	-20.0%	-13.2%	-7.9%

*Effluent losses in nitrate-N, phosphorus and sediment are 4,612Mt, 137Mt, 327 thousand Mt respectively under zero feedstock production in baseline scenario.

Table 3-13. Cost of CRP Payment and Switchgrass Subsidy (Unit: 1000 Dollar)

Scenario		0	100	200	300	400	500	600	700	800
Baseline		CRP Payment								
		9,696	9,696	9,696	9,696	9,696	9,664	9,577	8,724	7,560
Nitrate-N Load Restriction		CRP Payment								
	10%	16,879	17,042	17,269	17,556	17,859	18,331	19,032	18,131	17,223
	20%	23,351	23,512	23,770	24,080	24,425	25,118	25,444	24,039	22,770
	30%	31,090	31,233	31,542	31,900	32,463	33,308	32,300	30,881	29,627
Switchgrass Production Subsidy		CRP Payment (A)								
	$20	9,696	9,696	9,696	9,696	9,696	9,664	9,577	8,724	7,971
	$40	9,696	9,696	9,696	9,696	9,696	9,658	9,554	9,061	8,697
	$50	9,696	9,654	9,589	9,566	9,529	9,519	9,449	9,277	9,198
	$60	9,696	9,471	9,343	9,301	9,154	9,147	9,065	8,938	8,916
	$80	9,696	9,471	9,338	9,154	8,938	8,534	8,123	7,512	7,192
		Switchgrass Subsidy (B)								
	$20	0	0	0	0	0	0	0	0	668
	$40	0	0	3	20	23	100	205	2,010	6,791
	$50	0	615	1,225	1,413	2,717	2,879	4,754	7,757	10,929
	$60	0	6,522	11,592	15,070	19,128	20,407	22,767	24,714	25,935
	$80	0	8,696	17,391	26,087	34,783	43,478	52,174	60,870	64,922
		Total Cost (A+B)								
	$20	9,696	9,696	9,696	9,696	9,696	9,664	9,577	8,724	8,639
	$40	9,696	9,696	9,699	9,716	9,719	9,758	9,759	11,071	15,488
	$50	9,696	10,269	10,814	10,979	12,246	12,398	14,202	17,034	20,127
	$60	9,696	15,993	20,935	24,371	28,283	29,554	31,832	33,652	34,852
	$80	9,696	18,167	26,729	35,241	43,721	52,013	60,297	68,382	72,113
Switchgrass Production Subsidy on Sloped Land only		CRP Payment (C)								
	$20	9,696	9,696	9,696	9,696	9,696	9,664	9,577	8,724	7,916
	$40	9,696	9,696	9,696	9,696	9,696	9,658	9,554	8,997	8,192
	$50	9,696	9,654	9,589	9,566	9,529	9,470	9,449	9,267	8,302
	$60	9,696	9,374	9,301	9,149	9,091	8,938	8,916	8,529	8,263
	$80	9,696	9,303	8,532	7,422	7,185	7,057	6,753	6,642	6,216
		Switchgrass Subsidy (D)								
	$20	0	0	0	0	0	0	0	0	659
	$40	0	0	3	20	23	100	205	1,879	5,276
	$50	0	527	1,013	1,165	1,937	2,395	3,252	4,437	9,309
	$60	0	5,037	6,825	8,060	8,740	10,092	10,483	11,966	13,992
	$80	0	8,696	17,391	25,372	26,643	27,200	27,702	27,831	28,506
		Total Cost(C+D)								
	$20	9,696	9,696	9,696	9,696	9,696	9,664	9,577	8,724	8,574
	$40	9,696	9,696	9,699	9,716	9,719	9,758	9,759	10,875	13,468
	$50	9,696	10,181	10,602	10,731	11,466	11,865	12,701	13,704	17,611
	$60	9,696	14,412	16,126	17,209	17,831	19,030	19,400	20,495	22,255
	$80	9,696	17,998	25,924	32,794	33,828	34,258	34,455	34,473	34,723

Table 3-14. Hectares of CRP and Switchgrass by Land Type under Nitrate-N Load Constraints

	Cellulosic Feedstock Production (1000 Mt)								
	0	100	200	300	400	500	600	700	800
	No Reduction(Baseline)								
CRP	21,931	21,931	21,931	21,931	21,931	21,848	21,643	19,790	17,168
Sloped	21,883	21,883	21,883	21,883	21,883	21,800	21,596	19,742	17,120
Critical	4,286	4,286	4,286	4,286	4,286	4,284	4,276	3,734	2,346
Low Yield	20,558	20,558	20,558	20,558	20,558	20,545	20,506	19,409	17,069
Switchgrass	0	0	0	0	0	0	0	0	61
Sloped									61
Critical									34
Low Yield									61
	10% Reduction in Nitrate-N Losses								
CRP	39,125	39,479	39,979	40,624	41,317	42,351	44,046	41,827	39,643
Sloped	31,976	32,020	32,041	32,177	32,102	31,982	31,922	29,921	28,951
Critical	8,598	8,645	8,702	8,795	8,716	8,636	8,608	7,997	7,507
Low Yield	23,204	23,204	23,204	23,204	23,204	23,204	23,204	23,186	23,078
Switchgrass	0	0	0	0	0	0	0	7,054	15,707
Sloped								2,745	5,326
Critical								5,519	12,773
Low Yield								17	123
	20% Reduction in Nitrate-N Losses								
CRP	54,074	54,424	54,968	55,690	56,514	58,108	58,899	55,680	52,709
Sloped	33,244	33,244	33,220	33,382	33,403	33,637	32,506	31,645	30,336
Critical	10,300	10,276	10,445	10,711	10,786	11,064	10,784	10,028	8,947
Low Yield	23,204	23,204	23,204	23,204	23,204	23,204	23,204	23,196	23,186
Switchgrass	0	0	0	0	0	0	2,134	10,687	20,127
Sloped							795	2,807	6,935
Critical							1,816	9,379	15,975
Low Yield								7	17
	30% Reduction in Nitrate-N Losses								
CRP	71,755	72,096	72,747	73,509	74,738	76,692	74,572	71,327	68,427
Sloped	34,892	34,886	34,887	34,703	34,809	34,577	33,304	32,187	31,338
Critical	12,379	12,520	12,565	12,529	12,599	12,843	12,150	10,863	10,119
Low Yield	23,204	23,204	23,204	23,204	23,204	23,204	23,204	23,196	23,186
Switchgrass	0	0	0	0	0	0	6,176	15,010	24,774
Sloped							1,323	4,161	8,839
Critical							5,643	12,734	19,215
Low Yield								7	17

Table 3-15. Hectares of CRP and Switchgrass by Land Type under Switchgrass Subsidies

	Cellulosic Feedstock Production (1000 Mt)								
	0	100	200	300	400	500	600	700	800
				No Subsidy (Baseline)					
CRP	21,931	21,931	21,931	21,931	21,931	21,848	21,643	19,790	17,168
Sloped	21,883	21,883	21,883	21,883	21,883	21,800	21,596	19,742	17,120
Critical	4,286	4,286	4,286	4,286	4,286	4,284	4,276	3,734	2,346
Low Yield	20,558	20,558	20,558	20,558	20,558	20,545	20,506	19,409	17,069
Switchgrass	0	0	0	0	0	0	0	0	61
Sloped									61
Critical									34
Low Yield									61
				$20/Mt of Switchgrass Production Subsidy					
CRP	21,931	21,931	21,931	21,931	21,931	21,848	21,643	19,790	18,040
Sloped	21,883	21,883	21,883	21,883	21,883	21,800	21,596	19,742	17,992
Critical	4,286	4,286	4,286	4,286	4,286	4,284	4,276	3,734	2,656
Low Yield	20,558	20,558	20,558	20,558	20,558	20,545	20,506	19,409	17,887
Switchgrass	0	0	0	0	0	0	0	0	3,260
Sloped									2,678
Critical									1,972
Low Yield									804
				$40/Mt of Switchgrass Production Subsidy					
CRP	21,931	21,931	21,931	21,931	21,931	21,831	21,581	20,492	19,668
Sloped	21,883	21,883	21,883	21,883	21,883	21,783	21,534	20,444	19,620
Critical	4,286	4,286	4,286	4,286	4,286	4,284	4,252	3,924	3,520
Low Yield	20,558	20,558	20,558	20,558	20,558	20,529	20,468	19,712	19,223
Switchgrass	0	0	10	56	64	281	595	4,725	13,930
Sloped			10	56	64	281	595	3,815	8,384
Critical				46	50	235	369	2,667	9,241
Low Yield			10	24	29	129	293	745	1,829
				$50/Mt of Switchgrass Production Subsidy					
CRP	21,931	21,828	21,672	21,625	21,531	21,501	21,336	20,941	20,749
Sloped	21,883	21,780	21,624	21,577	21,484	21,453	21,288	20,893	20,701
Critical	4,286	4,259	4,188	4,182	4,115	4,112	4,023	3,840	3,706
Low Yield	20,558	20,517	20,446	20,440	20,368	20,338	20,239	20,034	19,901
Switchgrass	0	1,265	2,464	2,802	5,040	5,282	8,234	12,839	17,433
Sloped		1,144	2,175	2,445	3,991	4,135	5,931	7,874	9,490
Critical		849	1,405	1,552	3,003	3,158	5,063	8,399	12,014
Low Yield		399	484	489	738	768	1,002	1,676	1,914
				$60/Mt of Switchgrass Production Subsidy					
CRP	21,931	21,393	21,093	20,983	20,645	20,621	20,428	20,144	20,090
Sloped	21,883	21,345	21,045	20,936	20,597	20,573	20,380	20,096	20,042
Critical	4,286	4,025	3,834	3,773	3,650	3,627	3,534	3,403	3,386
Low Yield	20,558	20,252	20,043	19,983	19,859	19,836	19,667	19,560	19,506
Switchgrass	0	9,151	15,565	19,951	25,081	26,643	29,738	32,292	33,850
Sloped		6,180	8,899	10,543	12,196	12,854	14,234	15,456	16,011
Critical		5,791	10,446	13,563	17,651	18,736	20,790	22,438	23,638
Low Yield		965	1,691	1,868	2,199	2,222	2,424	2,582	2,669
				$80/Mt of Switchgrass Production Subsidy					
CRP	21,931	21,393	21,080	20,645	20,143	19,255	18,322	16,989	16,236
Sloped	21,883	21,345	21,032	20,597	20,096	19,207	18,275	16,941	16,188
Critical	4,286	4,025	3,821	3,650	3,402	3,203	2,877	2,253	2,036
Low Yield	20,558	20,252	20,030	19,859	19,559	18,759	17,857	16,590	15,916
Switchgrass	0	9,236	17,319	25,605	34,025	42,863	52,226	62,080	67,087
Sloped		6,232	9,352	12,244	16,034	19,511	24,035	28,904	31,727
Critical		5,831	11,893	18,168	23,805	30,102	36,339	42,882	45,920
Low Yield		996	1,766	2,199	2,598	3,578	4,702	6,102	6,935

Table 3-16. Hectares of CRP and Switchgrass by Land Type under Switchgrass Subsidies on Sloped Land

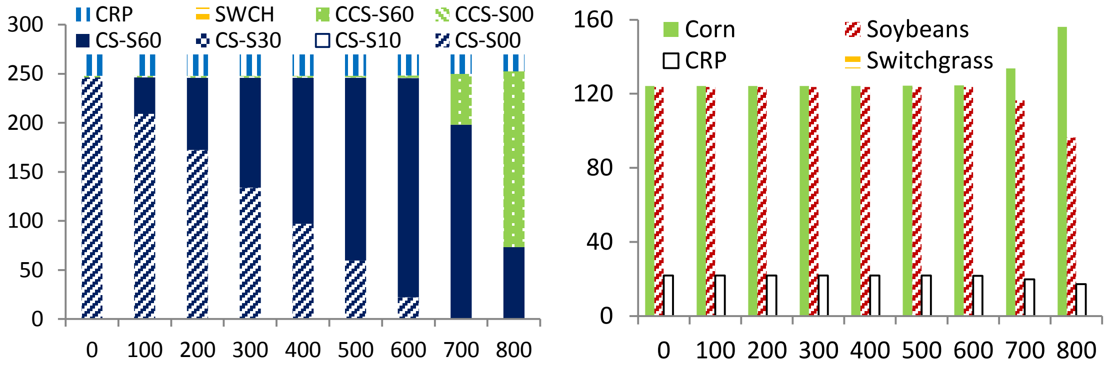
	Cellulosic Feedstock Production (1000 Mt)								
	0	100	200	300	400	500	600	700	800
No Subsidy (Baseline)									
CRP	21,931	21,931	21,931	21,931	21,931	21,848	21,643	19,790	17,168
Sloped	21,883	21,883	21,883	21,883	21,883	21,800	21,596	19,742	17,120
Critical	4,286	4,286	4,286	4,286	4,286	4,284	4,276	3,734	2,346
Low Yield	20,558	20,558	20,558	20,558	20,558	20,545	20,506	19,409	17,069
Switchgrass	0	0	0	0	0	0	0	0	61
Sloped									61
Critical									34
Low Yield									61
$20/Mt of Switchgrass Production Subsidy									
CRP	21,931	21,931	21,931	21,931	21,931	21,848	21,643	19,790	17,899
Sloped	21,883	21,883	21,883	21,883	21,883	21,800	21,596	19,742	17,851
Critical	4,286	4,286	4,286	4,286	4,286	4,284	4,276	3,734	2,547
Low Yield	20,558	20,558	20,558	20,558	20,558	20,545	20,506	19,409	17,774
Switchgrass	0	0	0	0	0	0	0	0	3,501
Sloped									3,501
Critical									1,742
Low Yield									912
$40/Mt of Switchgrass Production Subsidy									
CRP	21,931	21,931	21,931	21,931	21,931	21,831	21,581	20,348	18,541
Sloped	21,883	21,883	21,883	21,883	21,883	21,783	21,534	20,300	18,494
Critical	4,286	4,286	4,286	4,286	4,286	4,284	4,252	3,865	3,025
Low Yield	20,558	20,558	20,558	20,558	20,558	20,529	20,468	19,634	18,404
Switchgrass	0	0	10	56	64	281	595	4,723	12,348
Sloped			10	56	64	281	595	4,723	12,348
Critical				46	50	235	369	2,374	4,989
Low Yield			10	24	29	129	293	877	2,618
$50/Mt of Switchgrass Production Subsidy									
CRP	21,931	21,828	21,672	21,625	21,531	21,387	21,336	20,917	18,745
Sloped	21,883	21,780	21,624	21,577	21,484	21,339	21,288	20,869	18,697
Critical	4,286	4,259	4,188	4,182	4,115	4,064	4,023	3,818	3,074
Low Yield	20,558	20,517	20,446	20,440	20,368	20,278	20,239	20,010	18,364
Switchgrass	0	1,144	2,175	2,475	3,991	4,800	6,511	8,490	17,351
Sloped		1,144	2,175	2,475	3,991	4,800	6,511	8,490	17,351
Critical		727	1,116	1,212	1,953	2,392	2,867	3,723	6,155
Low Yield		399	484	489	738	856	1,431	1,800	3,797
$60/Mt of Switchgrass Production Subsidy									
CRP	21,931	21,165	20,983	20,624	20,496	20,144	20,090	19,241	18,648
Sloped	21,883	21,118	20,936	20,577	20,448	20,096	20,042	19,193	18,600
Critical	4,286	3,842	3,773	3,631	3,552	3,403	3,386	3,201	2,953
Low Yield	20,558	20,052	19,983	19,840	19,724	19,560	19,506	18,746	18,198
Switchgrass	0	8,071	10,638	12,489	13,420	15,450	15,984	18,372	21,528
Sloped		8,071	10,638	12,489	13,420	15,450	15,984	18,372	21,528
Critical		3,494	4,180	4,878	5,160	5,601	5,774	6,371	7,353
Low Yield		1,682	1,888	2,219	2,334	2,582	2,669	3,578	4,287
$80/Mt of Switchgrass Production Subsidy									
CRP	21,931	20,988	19,250	16,754	16,219	15,930	15,268	15,033	14,104
Sloped	21,883	20,940	19,202	16,707	16,172	15,882	15,220	14,985	14,056
Critical	4,286	3,778	3,198	2,193	2,020	1,908	1,768	1,768	1,661
Low Yield	20,558	19,987	18,754	16,370	15,900	15,643	15,101	14,867	13,937
Switchgrass	0	10,181	19,899	30,025	31,781	32,622	33,554	33,815	35,108
Sloped		10,181	19,899	30,025	31,781	32,622	33,554	33,815	35,108
Critical		4,091	6,833	9,964	10,585	10,940	11,242	11,250	11,561
Low Yield		1,864	3,721	6,357	6,951	7,275	7,826	8,061	9,061

Table 3-17. Change in Producer Surplus (Unit: Million $)

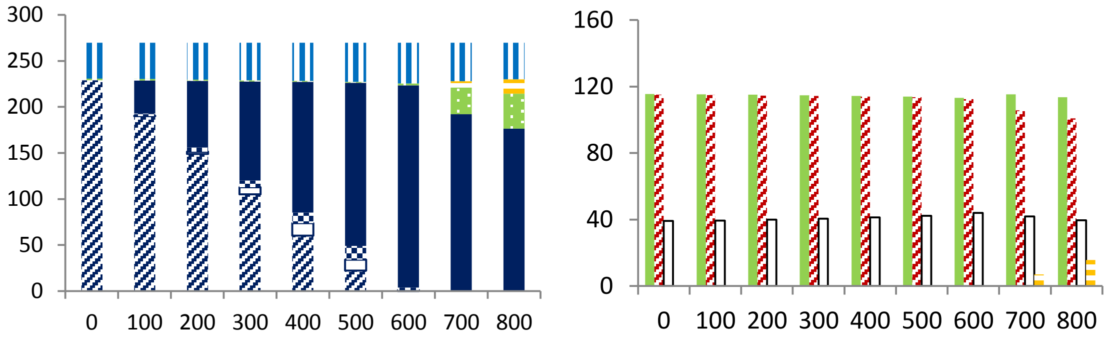
		Cellulosic Feedstock Production (1000 Mt)								
Scenario		0	100	200	300	400	500	600	700	800
Baseline		0.0	-4.0	-8.3	-12.7	-17.2	-21.9	-26.8	-32.6	-40.7
Nitrate-N Load Restriction	10%	-4.6	-8.8	-13.4	-18.1	-23.2	-28.5	-34.3	-44.2	-55.2
	20%	-11.9	-16.2	-20.8	-25.7	-30.8	-36.4	-43.8	-54.2	-65.2
	30%	-20.6	-24.9	-29.6	-34.6	-39.9	-45.8	-55.1	-65.7	-76.9
Switchgrass Production Subsidy	$20	0.0	-4.0	-8.3	-12.7	-17.2	-21.9	-26.8	-32.6	-41.0
	$40	0.0	-4.0	-8.3	-12.7	-17.3	-22.0	-27.0	-34.2	-45.3
	$50	0.0	-4.6	-9.4	-14.0	-19.8	-24.6	-31.2	-39.1	-47.5
	$60	0.0	-9.8	-18.7	-26.2	-34.4	-40.0	-46.7	-53.2	-59.1
	$80	0.0	-9.7	-20.0	-30.5	-41.4	-52.5	-64.0	-76.0	-83.9
Switchgrass Production Subsidy on Sloped Land only	$20	0.0	-4.0	-8.3	-12.7	-17.2	-21.9	-26.8	-32.6	-41.0
	$40	0.0	-4.0	-8.3	-12.7	-17.3	-22.0	-27.0	-34.1	-44.2
	$50	0.0	-4.5	-9.2	-13.7	-19.1	-24.1	-29.8	-36.0	-46.5
	$60	0.0	-8.5	-14.3	-19.8	-24.8	-30.7	-35.7	-42.0	-49.0
	$80	0.0	-9.9	-20.8	-32.0	-37.3	-42.1	-47.0	-51.7	-57.1

Figure 3-1. Crop Production Activities and Crop Mixes by Feedstock Production Level with Restrictions on Nitrate-N Loads*

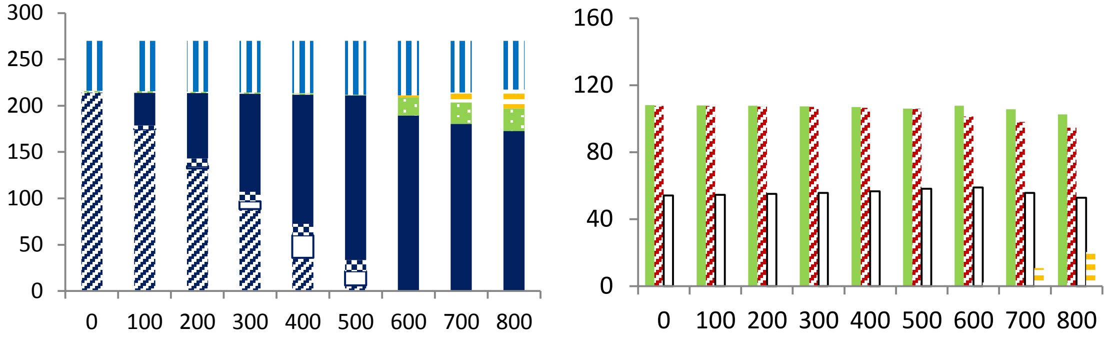
Baseline



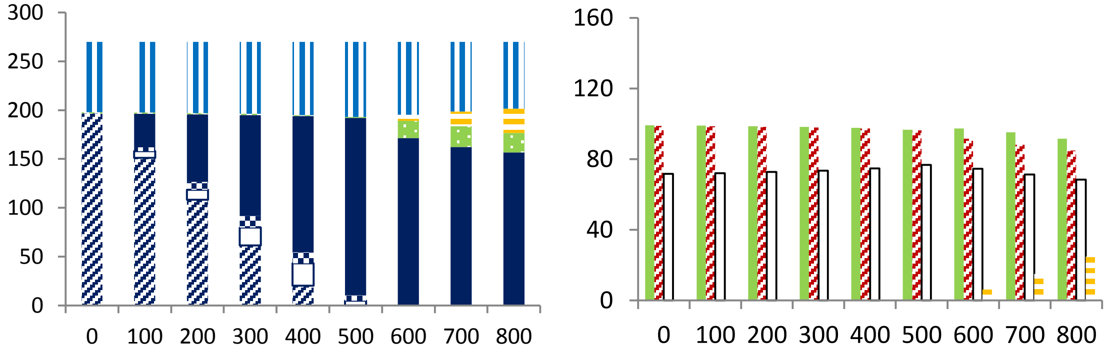
10% Reduction in Total Nitrate-N



20% Reduction in Total Nitrate-N



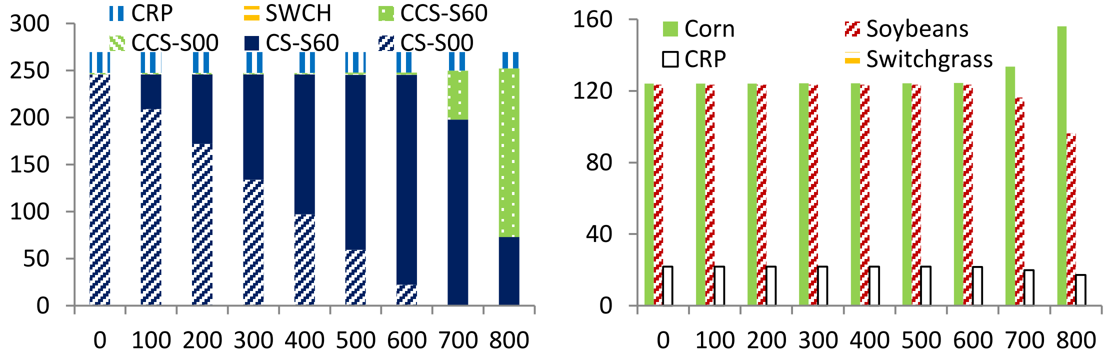
30% Reduction in Total Nitrate-N



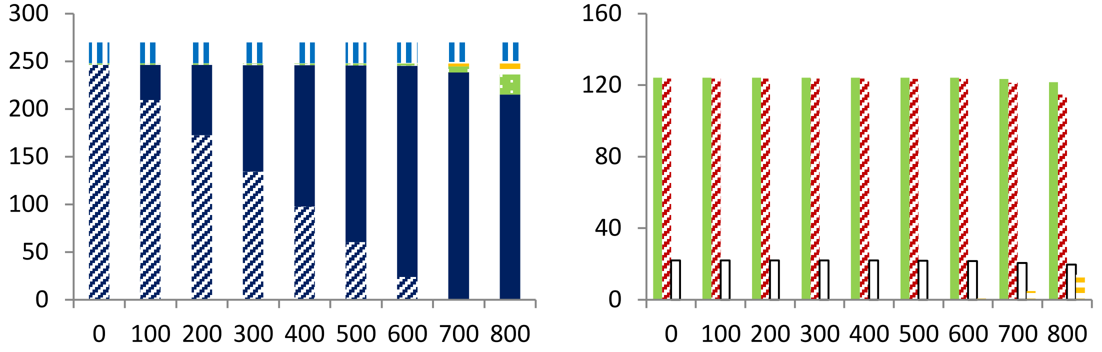
* X axis: Feedstock Supply 1000Mt, Y axis: 1000Ha

Figure 3-2. Crop Production Activities with Switchgrass Subsidy*

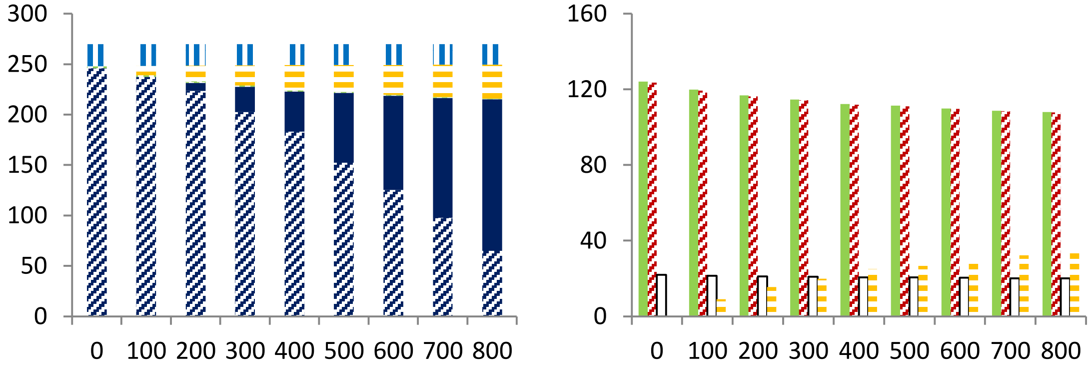
Baseline



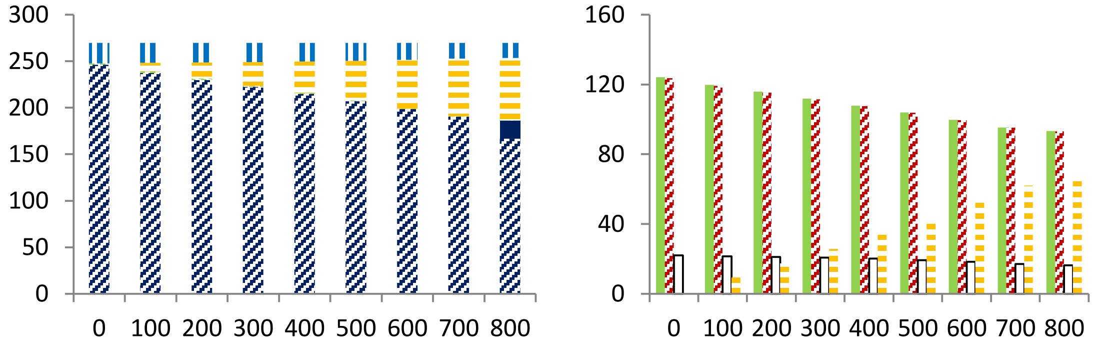
$40/Mt of Switchgrass Subsidy



$60/Mt of Switchgrass Subsidy



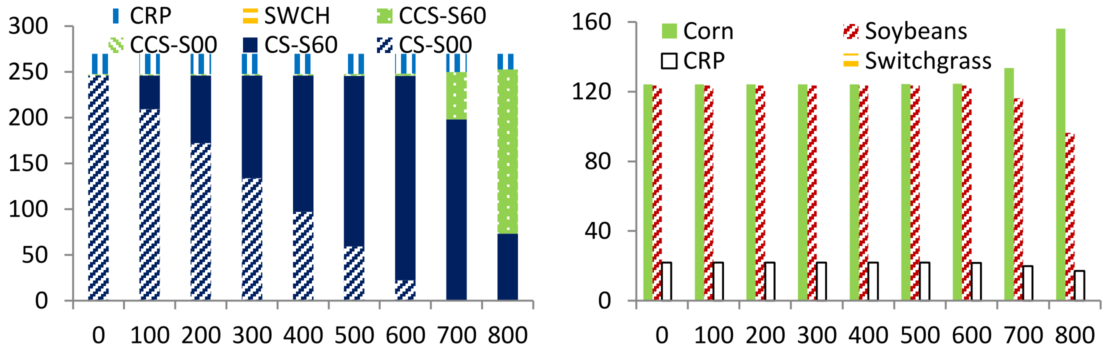
$80/Mt of Switchgrass Subsidy



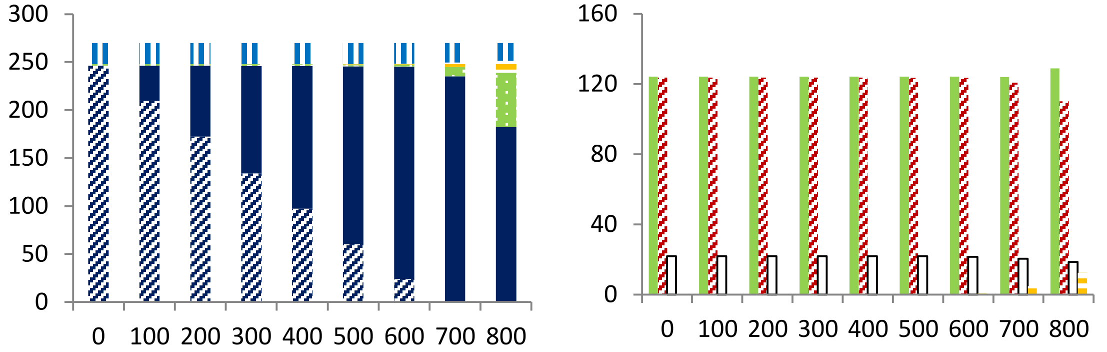
* X axis: Feedstock Supply 1000Mt, Y axis: 1000Ha

Figure 3-3. Crop Production Activities with Switchgrass Subsidy on Sloped Land*

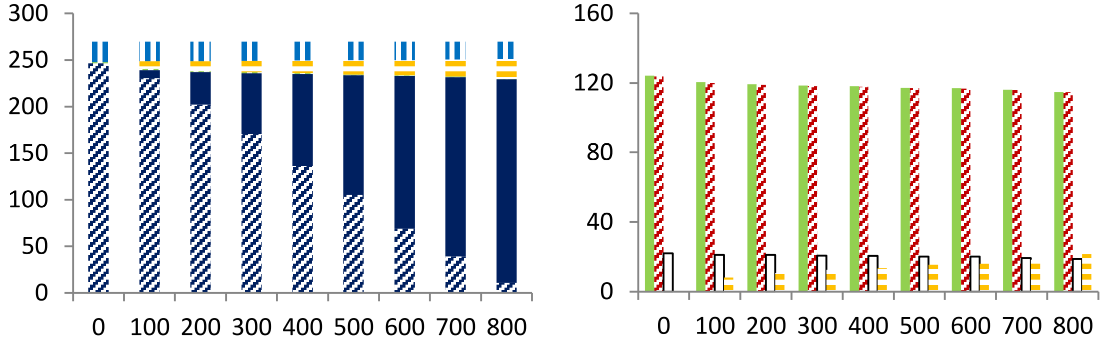
Baseline



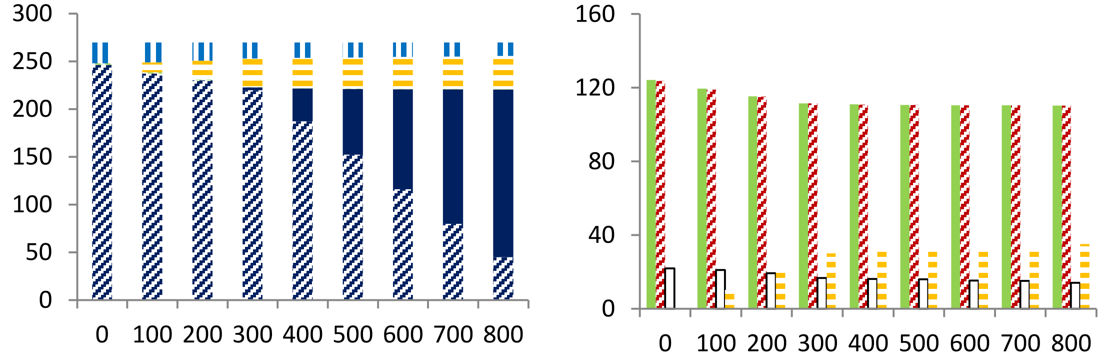
$40/Mt of Switchgrass Subsidy



$60/Mt of Switchgrass Subsidy

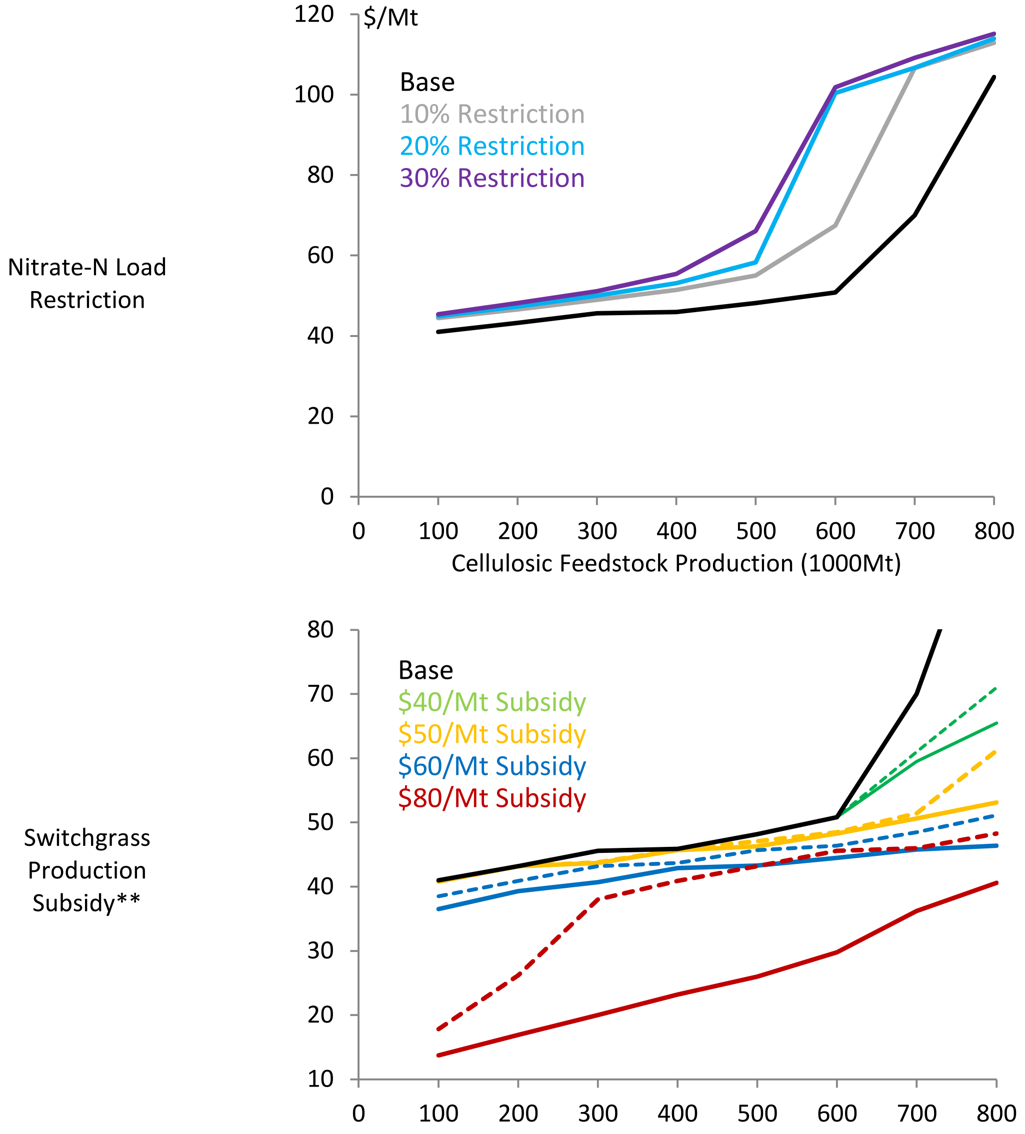


$80/Mt of Switchgrass Subsidy



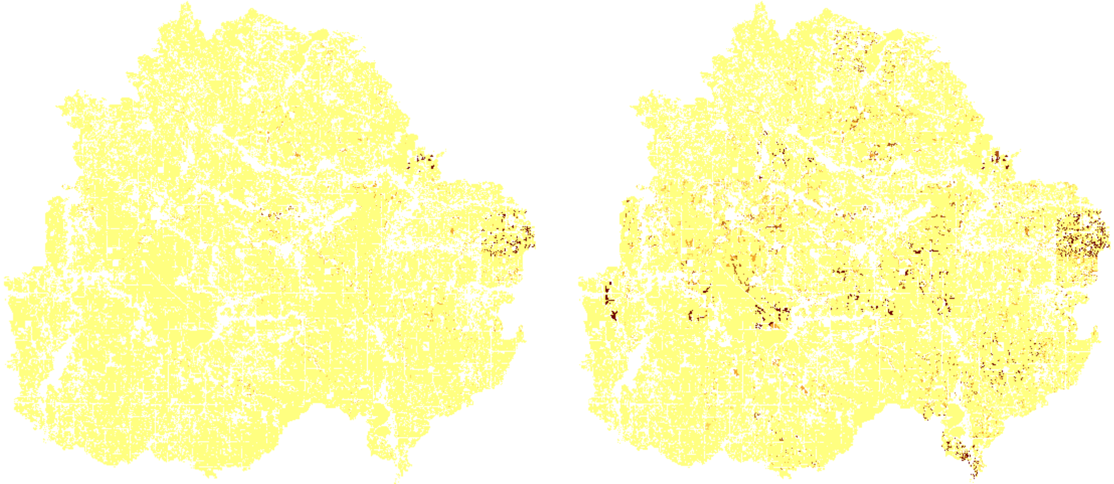
* X axis: Feedstock Supply 1000Mt, Y axis: 1000Ha

Figure 3-4. Marginal costs of Feedstock



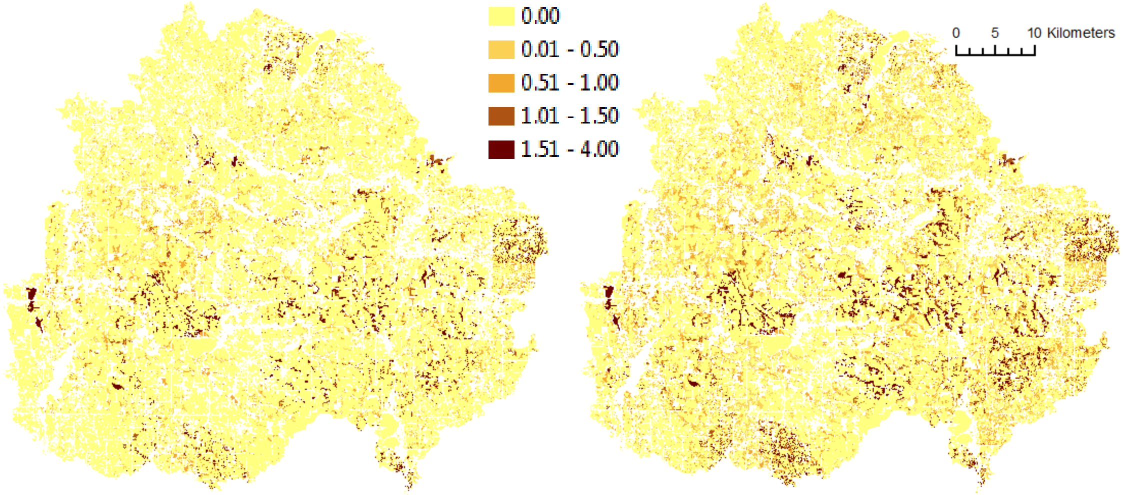
* Dashed lines represent the scenario when the switchgrass subsidy is targeted to sloped land only.

Figure 3-5. Change in Switchgrass Production at Various Levels of Switchgrass Subsidy* (Unit: 1000 Mt)



$20/Mt of Switchgrass Subsidy

$40/Mt of Switchgrass Subsidy

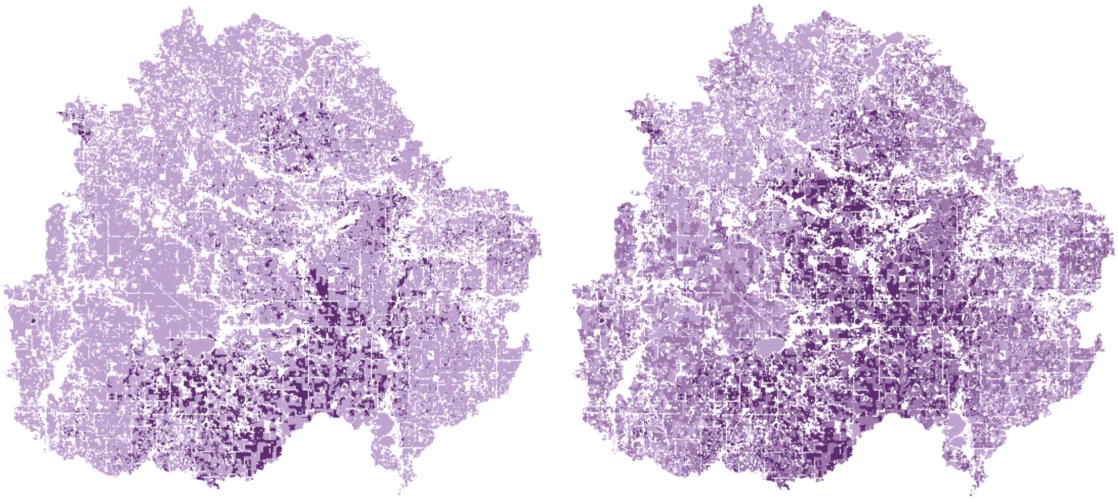


$60/Mt of Switchgrass Subsidy

$80/Mt of Switchgrass Subsidy

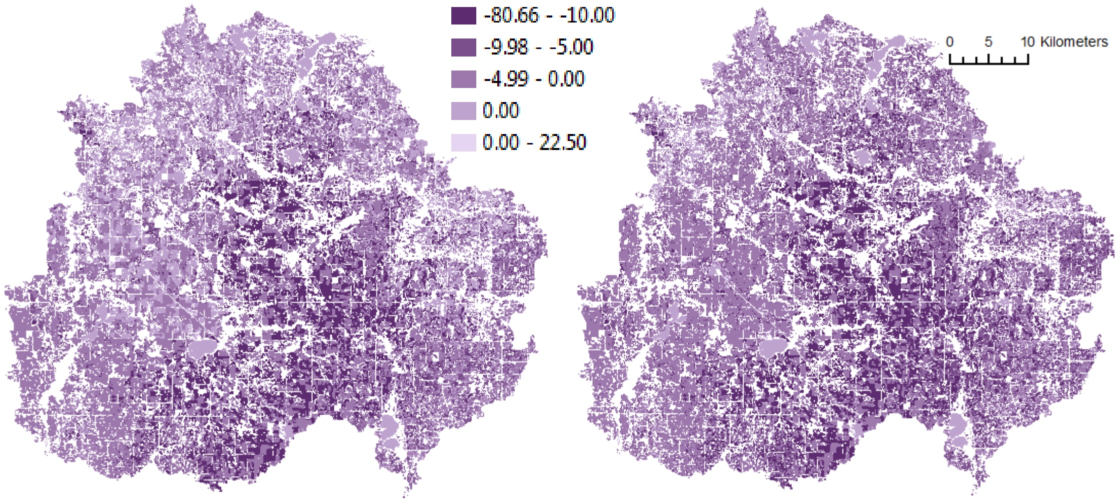
* Assuming 800 thousand Mt of cellulosic feedstock production

Figure 3-6. Change in Nitrate-N Losses at Various Levels of Switchgrass Subsidy, Relative to Zero Switchgrass Subsidy* (Unit: Kg/Ha)



$20/Mt of Switchgrass Subsidy

$40/Mt of Switchgrass Subsidy

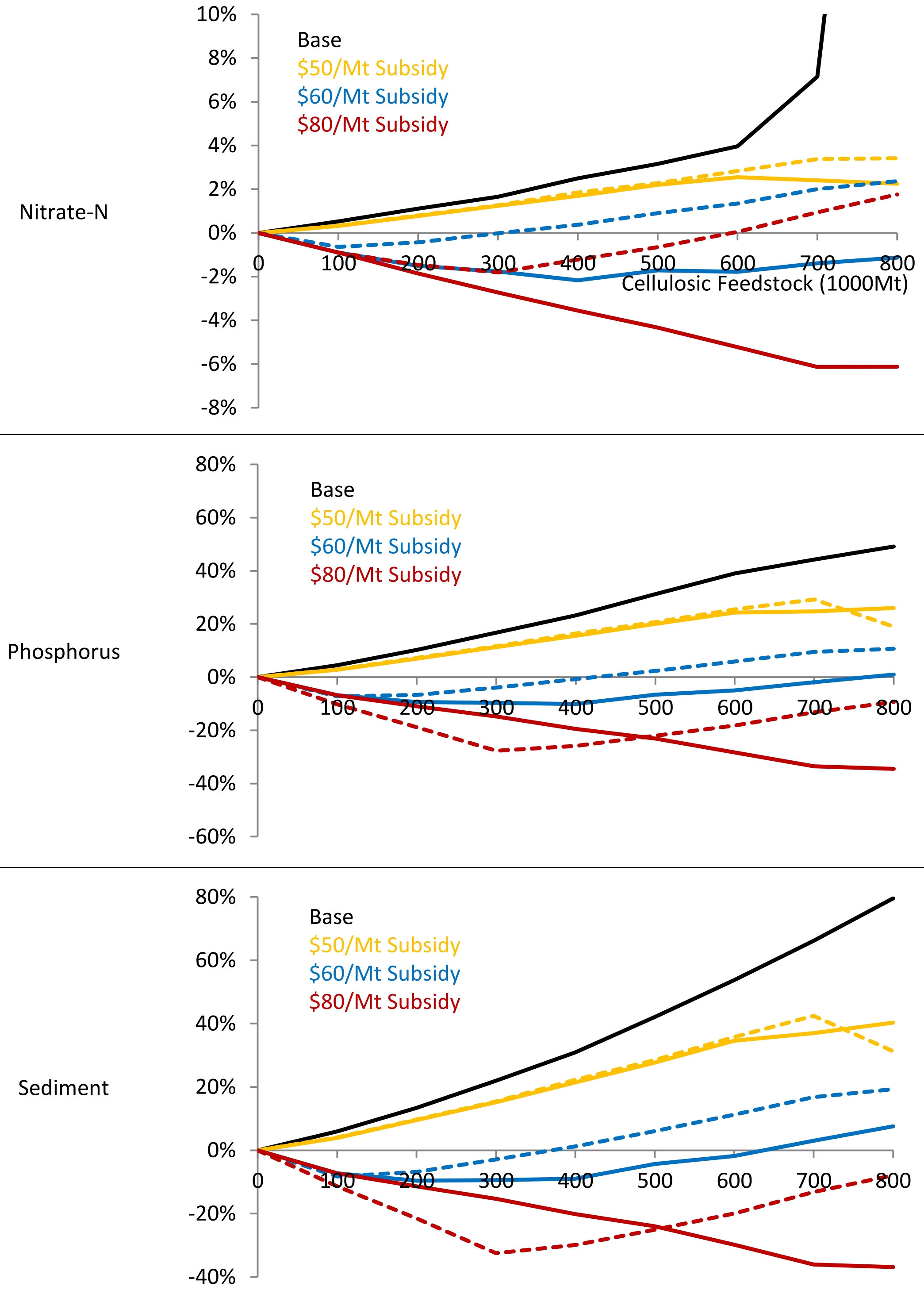


$60/Mt of Switchgrass Subsidy

$80/Mt of Switchgrass Subsidy

* Assuming 800 thousand Mt of cellulosic feedstock production

Figure 3-7. Percentage Change in Effluent Losses under Switchgrass Subsidy Scenario Compared to Scenario Limiting Subsidy to Sloped land*



*Percentage change in nutrient losses and sediment yield from zero feedstock production in baseline and dashed lines represent the scenario when the switchgrass subsidy is targeted to sloped land only.

Chapter 4. Emissions Trading with Timing and Uncertainty

4.1. Introduction

Recent movement towards market-based and incentive-based regulation has been spurred by the desire to attain environmental objectives at lower cost. Emissions trading (or cap-and-trade) is one type of market-based environmental regulation. Examples of emissions tradings programs include the acid rain program in Title IV of the 1990 Clean Air Act Amendments that set up a cap-and-trade systems to reduce emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x); the Regional Greenhouse Gas Initiative (RGGI) created in 2005 to regulates the carbon dioxide emissions in 10 Northeastern and Mid-Atlantic states; and the European Union Emissions Trading Scheme (EU ETS), which was established in 2005 and has been the largest multi-national emissions trading program for greenhouse gases.

In a cap-and-trade program, the regulator sets an overall cap on emissions and must allocate responsibility for achieving the cap to individual sources, termed "allowances" to emit. The trade component allows entities to sell their unneeded emission "allowances," while emission sources that emit more than their allowances may comply by buying additional allowances. Cap-and-trade programs allow flexibility in who makes the required emission reductions.

It is a well-known result that emissions trading can attain environmental goals at minimum cost (Montgomery, 1972). This result is based on a static model and assumes that there is complete information about abatement costs, perfect competition, and no transactions costs. In reality, emissions markets do not necessarily attain environmental goals at minimum cost because of various market imperfections (Taschini, 2010). For example, when firms have market power (Hahn, 1983; Misiolek and Elder, 1989) or there are transaction costs in emissions trading (Stavins, 1995) then emissions trading may not yield an efficient result.

Uncertainty is another factor the standard model of Montgomery (1972) does not address. Uncertainty may occur stochastic factors such as equipment malfunctions, technological development, weather impacts that shift demand or performance, or energy costs, can cause actual emissions to differ from initially planned emissions. Any particular realization of these factors may make it easier or harder to meet the cap. For example, cold weather will cause energy utilities to increase production of energy to meet the increased demand, which will increase emissions – this will make it more difficult and costly to meet the cap. More rapid technology development of reducing emissions could reduce abatement costs. In addition, there are numerous decision points within the capped period when an entity can revise its strategy. If the cap is given for a year, the entity can decide on a daily or weekly basis how to revise actions based upon new information.

Consideration of both uncertainty and dynamics raises the following questions: 1) What is the optimal strategy for emissions sources faced with a cap on emissions under stochastic factors that affect emissions and abatement costs? and 2) Does the order of firms' decisions about permit purchase and emissions have an effect on the equilibrium?

The purpose of this paper is to analyze how stochastic factors in emissions trading affect the optimal dynamic strategy of emission sources when the order of firm's decision is considered. The contribution of this paper is to introduce a model of how uncertainty and dynamics affect the behavior of emissions sources by considering the order of moves in choosing emissions and permit purchases in emissions trading.

Though the dynamics of emissions trading are examined with emissions banking and borrowing in previous papers (Rubin, 1996; Schennach, 2000), the order of decision on choosing emissions and permit purchases has not been analyzed previously.

The paper is organized as follows. Section 2 reviews how uncertainty in emissions trading has been analyzed in previous studies. Section 3 develops stochastic models in emissions trading. Section 4 contains concluding remarks.

4.2. Literature Review

Crocker (1966) and Dales (1968) develop the idea of using transferable discharge permits to allocate the pollution-control burden among sources. Montgomery (1972) shows that efficient market equilibrium exists for permits trading scheme. Montgomery obtains his formal results from strong assumptions, such as perfect competition with perfect information and hence no uncertainty.

Many papers examine other factors that can adversely affect the performance of marketable permit systems. Hahn (1983) and Misiolek and Elder (1989) consider when firms have power in the permit market. Bohi and Burtraw (1992) show how the benefits from emission trading can be affected by regulatory rules and Keeler (1991) focuses on the degree of monitoring and enforcement of marketable permits. Stavins (1995) examines the presence of transaction costs in the market.

Dynamics of emissions trading are examined with emissions banking and borrowing. Cronshaw and Kruse (1996) extend the work of Montgomery to discrete T periods and examine utility firms subject to profit regulation with an upper bound on the profit. They show firms will bank permits only if the permit price increases with the rate of interest without profit regulation. If a firm’s profit is regulated then the model shows that permit market may not achieve emissions targets at least cost. The paper is based on competitive permit market and does not consider uncertainty about future emissions due to random demand for power.

Rubin (1996) adds both borrowing and banking in the continuous-time model by means of optimal control theory. It explores the problem of minimizing inter-temporal cost of pollution reduction in the presence of emissions permits that are tradable across firms and through time. Necessary conditions for optimization derive that firm trades permits until the discounted marginal cost of a permit in its bank account is equals to the discounted price of a permit. Rubin shows that each firm equates marginal cost of pollution abatement with the price of an emission permit and the permit price path follows Hotelling's rule. Then the present value of marginal abatement costs is constant when each firm can freely bank and borrow emissions. Though Rubin provides general treatment of emissions trading, it is based on the certainty of emissions and price.

Schennach (2000) examines the economics of allowance banking program which does not allow emissions permits to be borrowed from future allocation such as Sulfur Allowance Program, Title IV. Unlike Rubin (1996), Schennach considers uncertainty of emissions in continuous time and infinite time horizon model. The paper shows that the evolution of the firms' behavior over time can be separated into two periods: a banking period where units save part of their annual permit allocation for future use. This is followed by a period where banking stops and the stock of banked permits is drawn down. The introduction of uncertainty in the model indicates that the expected path of price can rises at a rate less than the discount rate even when the bank is not expected to be empty but the model does not provide an exact analytical solution of the price path.

Various papers address the issues of uncertainty in emissions trading without consideration of the order of moves that emissions sources can choose. Ben-David et al. (2000) examine the impact of permit price uncertainty and firm's risk aversion on the SO_2 market. They formulate an analytical model and test theoretical results in an experimental setting. The model results show that risk averse sellers of permits reduce their emissions less under uncertainty than under certainty while risk averse permits buyers abate more under uncertainty. That leads to inward shifts of supply and demand curve together.

Zhao (2003) analyzes the effects of cost uncertainties on firm's incentive to invest in abatement technologies or capital under permits trading and emissions charges. The author finds that cost uncertainties make firm's incentive for investment more decreased under emissions charges than under permits. Therefore, tradable permits help maintain firms' investment incentive under uncertainty.

Hennessy and Roosen (1999) investigate the effects of uncertainty on emissions trading. They have determined some of the impacts of tradable pollution rights when the magnitude of pollution is a stochastic event. The model of perfectly competitive markets suggests that the existence of uncertainty tends to reduce production activities of the regulated firm relative to the situation of nonstochastic pollution with the same mean rate of emissions.

Gupta and Maranas (2003) analyze the decision of a firm that can choose three market based pollution abatement instruments; permit, option and combination of option and permit. The paper includes uncertainty from emissions demand in a firm and permit market price. Given uncertainty, the firm was modeled to choose technology that can minimize total cost of emissions. Using uniform distribution of market and demand uncertainty in numerical modeling, the study finds that minimum total cost is incurred under combined use of the permit and option scenario.

Mrozek and Keeler (2004) show that emissions trading achieves better overall compliance when emissions have a stochastic component. The paper compares emissions standards (given permit limits) and Transferable Discharge Permit (emissions trading) regulation by modeling a permit market with two periods. They show that firms will choose lower levels of deviation from exact compliance, and expected overall emissions will be closer to target levels, under a TDP system than emissions standards. The greater the number of firms participating in the TDP market, the greater extent to which individual and aggregate emissions approach their permitted levels.

4.3. Emissions Trading Model under Stochastic Environment

4.3.1. Notation

There are n polluting firms (i=1, 2, …, n). Firm i is allocated allowable emissions, a_i. E_i is the initial emissions without any costly abatement activity by firm i. Let the abatement level by firm i be q_i and the resulting emissions by firm i be $e_i = E_i - q_i$. The abatement cost function for firm i is given by $C^i(q_i)$. It is assumed that the abatement cost function is twice continuously differentiable, increasing in emissions abatement ($C^i_q = \partial C^i(q_i) / \partial q_i > 0$) and convex ($C^i_{qq} = \partial C^i_q / \partial q_i > 0$). Firms can buy and sell emissions permits. Let b_i be the net purchase of permits with b_i > (<) 0 when firm i is a permit buyer (seller). Let P be the price of a permit. The model assumes that firms are price takers in the permit market.

Each firm has a single choice of the level of abatement (emissions) and net purchases of permits. If firm i has permits (the sum of initial allocation and net purchase of permits) greater than or equal to emissions ($a_i + b_i \geq e_i$), then firm i is in compliance and is not subject to paying a penalty. If, however, emissions exceed permits, $a_i + b_i < e_i$, then firm i has to pay a penalty, $\phi \cdot (e_i - a_i - b_i)$ where ϕ is the penalty per unit of emissions exceeding the number of permits. It is assumed that unit penalty fee is so high that $C^i_q < \phi$ for $0 \leq q_i \leq E_i$. Permit price is endogenously determined by permit market equilibrium. Firms trade permits to point where marginal costs of abatement are equalized and the permit price is determined. The objective of each firm is to minimize cost for emissions abatement, permit purchase and penalty. The cost to the firm i is defined as:

$$\Pi_i = C^i(E_i - e_i) + P \cdot b_i + I_i \cdot \phi \cdot (e_i - a_i - b_i)$$

$$\text{where } I_i = 1, \text{ if } e_i - a_i - b_i \geq 0, \text{ Otherwise } I_i = 0.$$

The third term is positive only when firm i has emissions more than permits on hand.

4.3.2. Modeling approach

In reality, there are stochastic factors that affect emissions, or the cost of reducing emissions to certain levels. For example, unexpected change in product demand can affect emissions. Let actual emissions be defined as the sum of expected emissions and stochastic emissions: $e_i = m_i + \varepsilon_i$ where m_i equals expected emissions and ε_i is a random variable. It is assumed that ε_i and ε_j are independent for all $i \neq j$. As in Mrozek and Keeler (2004), it is assumed that ε_i is uniformly distributed over the range $[-\psi, \psi]$ with $E(\varepsilon_i) = 0$.

If the highest possible emissions are lower than the permits the firm holds ($m_i + \psi \leq a_i + b_i$), the firm is certain that it will not face a penalty cost. If the lowest possible emissions are greater than the permits the firm holds ($m_i - \psi \geq a_i + b_i$), then firm will have to pay a penalty with certainty.

However if the number of permits is between the range of possible emissions, $m_i - \psi < a_i + b_i < m_i + \psi$, then there is uncertainty whether or not the firm will be in compliance. The expected penalty, $E(F_i)$ is defined as:

$$E(F_i) = \phi \int_{a_i+b_i-m_i}^{\psi} \left[(m_i + \varepsilon_i - a_i - b_i)\left(\frac{1}{2\psi}\right)\right] d\varepsilon_i$$

where the first term in parentheses is the amount that emissions exceed permits and the second term in parentheses is the probability density of ε_i. The lower bound to the integral is $a_i + b_i - m_i$ because the firm is in compliance when $e_i = m_i + \varepsilon_i = a_i + b_i$. Expansion of the integral yields:

$$E(F_i) = \left(\frac{\phi}{4\psi}\right)(\psi + m_i - a_i - b_i)^2. \tag{4.1}$$

There are three potential cases to analyze in terms of the timing of events. First, firms trade permits and then choose abatement (case 1). Firms choose abatement and then trade in the other two cases. In one case, firms choose trade with unknown emissions (case 2) because trade occurs before the value of the random variables are realized, or firms trade with known emissions (case 3) because trade occurs after the value of the random variables are realized. Because emissions are stochastic, firms choose abatement which determines expected emissions.

Because each case has two stages of decision, there are two subgames. The model is solved for pure strategy subgame perfect Bayesian Nash equilibrium. A subgame perfect Bayesian Nash equilibrium requires that the firms' strategies constitutes a Nash equilibrium in every subgame (Selten, 1965) given beliefs, and that beliefs satisfy Bayes' Rule. Backward induction is used to find a subgame perfect equilibrium.

4.3.3. Firms trade permits and then choose abatement

If the number of permits held is between the range of possible emissions as above, firm i in the second stage chooses expected emissions, m_i to minimize the sum of abatement cost and expected penalty:

$$\min_{m_i} \; C^i(E_i - m_i) + \left(\frac{\phi}{4\psi}\right)(\psi + m_i - a_i - b_i)^2$$

Using $C^i(q_i) = \frac{1}{2}\alpha_i q_i^2$, the first order condition yields:

$$\alpha_i(E_i - m_i) = \left(\frac{\phi}{2\psi}\right)(\psi + m_i - a_i - b_i).$$

Then expected emissions are derived,

$$m_i = \frac{2\psi\alpha_i E_i - \phi(\psi - a_i - b_i)}{2\psi\alpha_i + \phi}. \tag{4.2}$$

In the first stage, the firm chooses the level of permit purchase with m_i from (4.2)

$$\min_{b_i} \; E\Big(C^i(E_i - m_i)\Big) + P\cdot b_i + \left(\frac{\phi}{4\psi}\right)(\psi + m_i - a_i - b_i)^2.$$

The first order condition after plugging (4.2) into objective function generates the net purchase of permits, b_i:

$$b_i = E_i + \psi - a_i - P\left(\frac{2\psi\alpha_i + \phi}{\alpha_i\phi}\right). \tag{4.3}$$

Using $\sum_{i=1}^n b_i = 0$ in (4.3), the permit price is

$$P^* = \frac{\sum_{i=1}^n (E_i + \psi - a_i)}{\sum_{i=1}^n \left(\frac{2\psi\alpha_i + \phi}{\alpha_i\phi}\right)}. \tag{4.4}$$

Applying (4.4) into (4.3) yields the solution for net permits purchased:

$$b_i^* = E_i + \psi - a_i - \left(\frac{\sum_{i=1}^n (E_i + \psi - a_i)}{\sum_{i=1}^n \left(\frac{2\psi\alpha_i + \phi}{\alpha_i\phi}\right)}\right)\left(\frac{2\psi\alpha_i + \phi}{\alpha_i\phi}\right). \tag{4.5}$$

To simplify, assume α_i= 1 for all i and every firm has same ψ so that $\sum_{i=1}^n \psi = n\psi$. Then total expected emissions ($\sum_{i=1}^n m_i = M$) are derived from (4.2):

$$M = \sum_{i=1}^{n} m_i = \sum_{i=1}^{n} \frac{2\psi\alpha_i E_i - \phi(\psi - a_i - b_i)}{2\psi\alpha_i + \phi} = \frac{2\psi E - \phi n\psi + \phi A}{2\psi + \phi}. \qquad (4.6)$$

Using (4.6), it is possible to compare total allowable emissions ($\sum_{i=1}^{n} a_i = A$) and total expected emissions:

$$A - M = \frac{\psi(2A - 2E + \phi n)}{2\psi + \phi}. \qquad (4.7)$$

where $\sum_{i=1}^{n} a_i = A$, $\sum_{i=1}^{n} E_i = E$.

Total allowance is greater than total expected emissions if the numerator in (4.7) is positive:

$$A - M > 0, \text{if } \frac{\phi}{2} > \frac{(E - A)}{n}. \qquad (4.8)$$

In the symmetric setup, $\frac{(E-A)}{n} = E_i - a_i$. In the case with certainty, firms will set $e_i = a_i$, which means that abatement i$q_i = E_i - a_i$s. Assuming, $C^i(q_i) = \frac{1}{2}\alpha_i q_i^2$ and $\alpha_i = 1$, the marginal cost of abatement with $q_i = E_i - a_i$ is simply $E_i - a_i$. Under uncertainty, the firm chooses to set emissions where the marginal cost of abatement equals the expected marginal penalty. Setting abatement at the same level under uncertainty as under certainty yields the same marginal cost of abatement $(E_i - a_i)$ and faces a probability of a fine of 50%, since $q_i = E_i - m_i - \varepsilon_i$ and there is a symmetric distribution of ε_i around 0, so that the expected penalty is $\frac{\phi}{2}$. If the expected marginal penalty is greater than the marginal cost of abatement, the firm will choose to reduce emissions and abates more under uncertainty as shown in (4.8). Then the permit price, which equals the marginal cost of abatement, will be higher. If the expected marginal penalty is less than marginal cost of abatement, the firm will increase emissions and reduce abatements:

$$\mathrm{A} - \mathrm{M} < 0, \text{if } \frac{\phi}{2} < \frac{(\mathrm{E} - \mathrm{A})}{\mathrm{n}}.$$

Total allowance and total expected emissions are same only if expected marginal penalty is same as marginal cost of abatement at the level of abatement under certainty:

$$\mathrm{A} = \mathrm{M}, \text{if } \frac{\phi}{2} = \frac{(\mathrm{E} - \mathrm{A})}{\mathrm{n}}.$$

4.3.4. Firms choose abatement and then trade

If firms trade permits after choosing emission, there are two cases. One case is where firms trade permits before emissions are realized. The other case is where firms trade permits after emissions are realized.

4.3.4.1 Firms choose trade before emissions are realized

In this case at the second stage, the firm minimizes the sum of permit purchase cost and the expected penalty. The objective function in the second stage is

$$\min_{\mathrm{b_i}} \; \mathrm{P} \cdot \mathrm{b_i} + \left(\frac{\phi}{4\psi}\right)(\psi + \mathrm{m_i} - \mathrm{a_i} - \mathrm{b_i})^2.$$

The first order condition is $\mathrm{P} = \left(\frac{\phi}{2\psi}\right)(\psi - \mathrm{a_i} - \mathrm{b_i} + \mathrm{m_i})$. Each firm selects net permit purchase:

$$\mathrm{b_i} = \psi - \mathrm{a_i} + \mathrm{m_i} - \mathrm{P}\left(\frac{2\psi}{\phi}\right). \tag{4.9}$$

Using $\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{b_i} = 0$, the permit price is

$$\mathrm{P}^* = \frac{\phi(\mathrm{n}\psi - \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{a_i} + \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{m_i})}{2\mathrm{n}\psi}. \tag{4.10}$$

Plugging (4.10) into (4.9),

$$b_i^* = m_i - a_i + \frac{1}{n}\sum_{i=1}^{n}(a_i - m_i). \tag{4.11}$$

In the first stage, each firm chooses expected emissions to satisfy the following:

$$\min_{m_i} \; E\big(C^i(E_i - m_i) + P \cdot b_i\big) + \left(\frac{\phi}{4\psi}\right)(\psi + m_i - a_i - b_i)^2. \tag{4.12}$$

Applying (4.10), (4.11) and $C^i(q_i) = \frac{1}{2}\alpha_i q_i^2$ into (4.12),

$$\min_{m_i} \; \frac{1}{2}\alpha_i(E_i - m_i)^2 + \frac{\phi(n\psi - \sum_{i=1}^{n} a_i + \sum_{i=1}^{n} m_i)}{2n\psi}\left(m_i - a_i + \frac{1}{n}\sum_{i=1}^{n}(a_i - m_i)\right)$$

$$+ \left(\frac{\phi}{4\psi}\right)\left(\psi - \frac{1}{n}\sum_{i=1}^{n}(a_i - m_i)\right)^2.$$

Then the first order condition is

$$\begin{aligned} -\alpha_i(E_i - m_i) + \frac{\phi}{2n\psi}\left(m_i - a_i + \frac{A - M}{n}\right) + \frac{\phi(n\psi - A + M)}{2n\psi}\left(1 - \frac{1}{n}\right) \\ + \frac{\phi}{2\psi}\left(\psi - \frac{A - M}{n}\right)\frac{1}{n} = 0. \end{aligned} \tag{4.13}$$

Total expected emissions, M is derived by summing (4.13) over all i with assumptions of $\alpha_i = 1$ and same ψ for every firm:

$$M = \frac{2\psi E - \phi n\psi + \phi A}{2\psi + \phi}. \tag{4.14}$$

(4.14) is same as total expected emissions in case 1, (4.6). Therefore the relationship between total allowable emissions, A, and total expected emissions, M, is the same as (4.7). As shown in the appendix, using (4.14) into (4.13) yields expected emissions, m_i:

$$\mathrm{m_i} = \frac{2\mathrm{n}\psi \mathrm{E_i} + \phi \mathrm{a_i} - \phi\psi \mathrm{n} + \frac{\phi\psi(\mathrm{n}-1)(2\mathrm{A} - 2\mathrm{E} + \phi \mathrm{n})}{\mathrm{n}(2\psi + \phi)}}{2\mathrm{n}\psi + \phi} \tag{4.15}$$

(4.14) is also plugged into the permit price (4.1) and permit purchase (4.11). Then it can be shown that the permit price is also the same as the permit price in cases 1 under the assumptions of $\alpha_i = 1$ and same ψ for every firm:

$$\mathrm{b_i} = \frac{2\psi(\mathrm{nE_i} - \mathrm{na_i} + \mathrm{A} - \mathrm{E})}{2\mathrm{n}\psi + \phi}$$

$$\mathrm{P} = \frac{\phi(\mathrm{n}\psi - \mathrm{A} + \mathrm{E})}{\mathrm{n}(2\psi + \phi)}.$$

4.3.4.2 Firms choose trade after emissions are realized

The objective function in the second stage where firm i chooses permit purchase is:

$$\min_{\mathrm{b_i}} \ \mathrm{P} \cdot \mathrm{b_i} + \mathrm{I_i} \cdot \phi \cdot (\mathrm{e_i} - \mathrm{a_i} - \mathrm{b_i})$$

where $\mathrm{I_i} = 1$ if $\mathrm{e_i} - \mathrm{a_i} - \mathrm{b_i} \geq 0$, otherwise $\mathrm{I_i} = 0$.

The second stage equilibrium is function of total excess demand of permits, X:

$$\mathrm{X} = \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{e_i} - \mathrm{a_i} - \mathrm{b_i}) = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{e_i} - \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{a_i}.$$

There are three cases of X. When X = 0, total emissions just equals the number of permits. If one firm has emissions above permits this is just balanced by others firm having more permits than emissions. There exists permit market equilibrium where demand and supply of permits are equal. Then net purchase of permits is defined as $\mathrm{b_i} = \mathrm{e_i} - \mathrm{a_i}$. The objective function becomes $\mathrm{P} \cdot (\mathrm{e_i} - \mathrm{a_i})$ and equilibrium permit price is $\mathrm{P} \in [0, \phi]$.

When X > 0, there is an excess demand for permits. There is at least one firm i for which emissions are greater than sum of allowances and permit purchase ($\mathrm{I_i} = 1$), so that the first order condition of that firm is P = ϕ. The level of permit purchase is not determined because each firm is indifferent between paying the penalty and buying permits with price equal to the penalty.

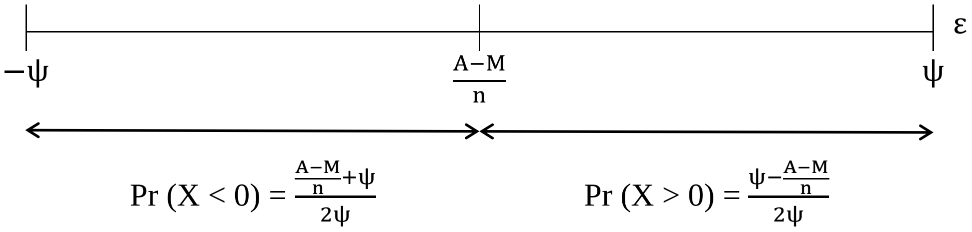
When X < 0, there is an excess supply of permits. There is at least one firm i for which emissions are less than the sum of allowances and permit purchase ($\mathrm{I_i} = 0$), so that the first order condition of the firm is P = 0. Like the excess demand case, the level of permit purchase for an individual firm is not determined because each firm is indifferent between selling permits at zero price and holding unneeded permits.

Let excess demand for emissions in firm i be $\mathrm{x_i = m_i + \varepsilon_i - a_i - b_i}$ and each firm has same shock for uncertain emissions as $\sum_{\mathrm{i=1}}^{\mathrm{n}} \varepsilon_{\mathrm{i}} = \mathrm{n}\varepsilon$. Then total excess demand of permits, X can be expressed as:

$$\mathrm{X} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{x_i} = \sum_{\mathrm{i=1}}^{\mathrm{n}} (\mathrm{m_i} + \varepsilon_{\mathrm{i}} - \mathrm{a_i} - \mathrm{b_i}) = \mathrm{M} + \mathrm{n}\varepsilon - \mathrm{A} \qquad (4.16)$$

Whether there is excess demand for permits depends on whether $\varepsilon > \frac{\mathrm{A-M}}{\mathrm{n}}$ or not (4.16). Pr (X > 0) = $\frac{\psi - \frac{\mathrm{A-M}}{\mathrm{n}}}{2\psi}$, as shown in figure 4-2. There is excess supply of permits (X < 0) with Pr (X < 0) = $\frac{\frac{\mathrm{A-M}}{\mathrm{n}} + \psi}{2\psi}$ and probability of X = 0 is zero.

Figure 4-1. Distribution of ε and probability of X



There are three cases for the cost of permit trading and penalty by the sign of X (table 4-1). When $X > 0$, the cost of permit trading and penalty fee is $\phi\cdot(m_i+\varepsilon_i-a_i)$ because $P=\phi$. When $X = 0$, there is no fine and only trading cost exist as $P(m_i+\varepsilon_i-a_i)$ because of $b_i=e_i-a_i=m_i+\varepsilon_i-a_i$. When $X < 0$, there is no fine and trading cost is also zero because the permit price is zero.

Table 4-1. The cost of trading and penalty fee

$X > 0$	$X = 0$	$X < 0$
$\phi\cdot(m_i+\varepsilon_i-a_i-b_i)+Pb_i$ $=\phi\cdot(m_i+\varepsilon_i-a_i)$	$Pb_i=P(m_i+\varepsilon_i-a_i)$	$Pb_i=0$

Now the firm chooses expected emissions in the first stage:

$$\min_{m_i}\ E\left(C^i(E_i-m_i)\right)+\phi\int_{\frac{A-M}{n}}^{\psi}\left[(m_i+\varepsilon_i-a_i)\left(\frac{1}{2\psi}\right)\right]d\varepsilon_i \tag{4.17}$$

Using $C^i(q_i)=\frac{1}{2}\alpha_i q_i^2$, the objective function is

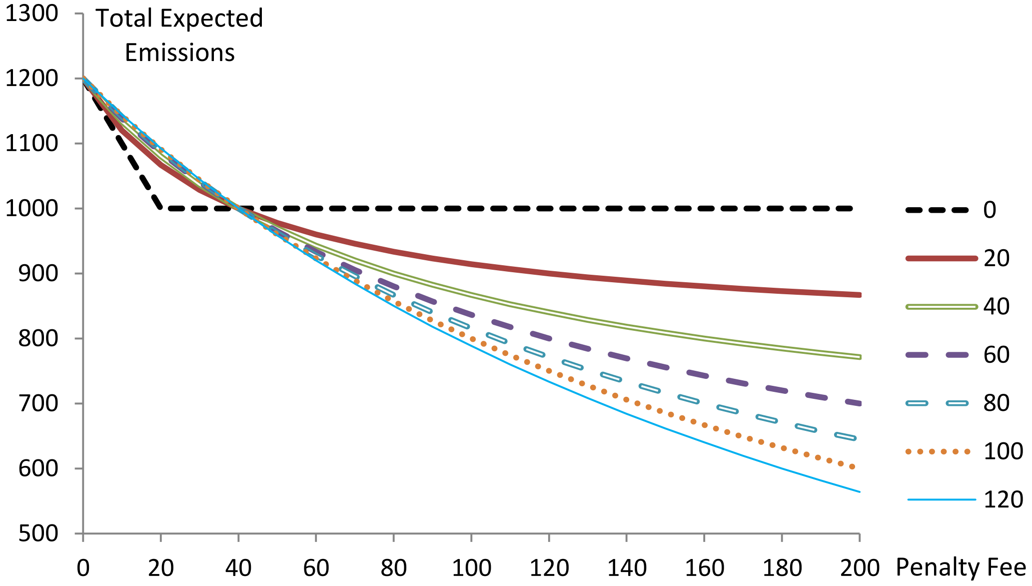
$$\min_{m_i}\ \frac{1}{2}\alpha_i(E_i-m_i)^2+\phi\int_{\frac{A-M}{n}}^{\psi}\left[(m_i+\varepsilon_i-a_i)\left(\frac{1}{2\psi}\right)\right]d\varepsilon_i. \tag{4.18}$$

From the first order condition, total expected emissions, M and expected emissions in each firm, m_i are derived. Note they are the same as (4.14) and (4.15) as shown in appendix (3).

4.3.5. Simulation results of total expected emission

Figure 4-2 shows how total expected emissions are affected by uncertainty and penalty fee. This numerical example is based on 10 emissions sources (n=10), 1200 units of total initial emissions, E, and 1000 units of total allowance emissions, A, with $C^i(q_i) = \frac{1}{2}q_i^2$ and $\sum_{i=1}^{n} \psi = n\psi$. Uncertainty of emissions is displayed by changing ψ from 0 to 120. Total expected emissions are calculated from (4.14).

Figure 4-2. Effect of uncertainty and penalty on total expected emissions



In the certainty case ($\psi = 0$), total emissions are greater than allowable emissions if penalty fee is less than 20 units. With a penalty of less than 20, each firm will choose not be in compliance because the marginal cost of abatement will exceed the marginal penalty. If emissions are stochastic, total allowances and expected emissions are equal at a penalty of 40 because the expected penalty (40/2 = 20) and marginal cost of abatement are then equal with each firm abating 20 units. An increase in the penalty fee reduces the total expected emissions. Above a penalty of 40, the marginal cost of abatement is less than expected marginal penalty and firms abate more. An increase in uncertainty with a penalty of at least 40 will lead to a decrease in expected emissions.

4.4. Conclusion

This study examines how uncertainty in emissions trading affects the optimal dynamic strategy of emissions sources when the order of firm's decision is considered. Firms have two choice variables: abatement and net purchase of permits. Because firms have two stages of decision, the model analyzes whether the order of moves between abatement and trading permits affects equilibrium outcomes.

Three cases are analyzed when stochastic emissions are considered. The order of moves does not affect the outcome. All three cases have the same total expected emissions regardless of firm's decision order. Whether firms abate more with uncertainty as compared to a case with no uncertainty is dependent on the expected penalty cost and marginal abatement cost. If the expected marginal penalty cost is greater than the marginal abatement cost at the level of abatement chosen under conditions of certainty about emissions, the firm will choose to reduce emissions more and the permit price will be higher under uncertainty than with no uncertainty. Likewise, if the expected marginal penalty is less than marginal cost of abatement, the firm will increase emissions and reduce abatements.

The model shows that total expected emissions are affected by the level of unit penalty and uncertainty of emissions represented by the range of possible emissions given the capped period. An increase in the penalty fee reduces the total expected emissions under uncertainty. If the expected marginal penalty cost is greater than the marginal abatement cost at the level of abatement chosen under conditions of certainty about emissions, then an increase in uncertainty decreases expected emissions.

If actual abatement cost and emissions data are available, the empirical analysis can consider the impact of the penalty on abatement decisions of firms. This study can be extended to include banking and borrowing in emissions trading to consider the different order of firms' decision in permit purchase and abatement. The model also can be developed to examine how social welfare changes under uncertainty about emissions.

Chapter 5. Conclusion

Three essays in the dissertation analyze the impacts of cellulosic feedstock production and emissions trading. Chapter Two analyzes the economic impacts of cellulosic feedstock production in a major watershed of south-central Minnesota. A regional economic model of agricultural production in the watershed is constructed. Results indicate that intensive corn production for cellulosic feedstock production has negative impacts on nutrient losses and sediment yield. Switchgrass has environmental benefits relative to corn stover but high marginal cost of production causes switchgrass to cover small part of crop land. Results imply relevant policy options and production practices are important to handle tradeoffs between cellulosic feedstock production and water quality.

Chapter Three evaluates policy options to manage water quality from cellulosic feedstock production by extending the model of chapter two. Restricting nitrate-N loads increases the cost of cellulosic feedstock supply and in some circumstances makes switchgrass production an economical alternative. Switchgrass production subsidies, if sufficiently high can increase feedstock supply while reducing or eliminating the negative effects of feedstock production on water quality. Subsidy above $60 leads to a substantial decline in grain production and a sharp increase in subsidy payments. When subsidy is only provided to sloped land, subsidy can be increased without sharp increases in policy budget.

Optimal location of processing plants from a social perspective may be influenced by environmental considerations. The modeling approach used here, if applied to a broader geographic area, could include endogenous variables for plant location and size, so the impacts of environmental policies on the location, type and size of processing plants could be evaluated. Similarly, investments in infrastructure to improve water quality, such as energy crop buffer strips, or drainage or stream bank management structures, could be assessed as policy alternatives for reducing the environmental impacts of biofuels.

Chapter Four examines how uncertainty in emissions affects firms' decisions about permit purchase and abatement. The results show that whether firms abate more under uncertainty compared to a case with no uncertainty depends on the expected penalty cost and marginal abatement cost. If the expected marginal penalty cost is greater than the marginal abatement cost at the level of abatement chosen under conditions of certainty about emissions, the firm will choose to reduce emissions more and the permit price will be higher under uncertainty than with no uncertainty. Results show policy makers need to consider relevant level of penalty to make emissions sources reduce emissions closed to allowance. Emission trading well designed to consider the penalty and abatement cost of emissions sources can attain environmental goal more effectively.

References

Alig, R., M. Adams, McCarl, B. and P. J. Ince. 2000. Economic Potential of Short-Rotation Woody Crops on Agricultural Land for Pulp Fiber Production in the United States. *Forest Products Journal* 50 (5): 67-74.

Arnold, J. G., and N. Fohrer. 2005. SWAT2000: Current capabilities and research opportunities in applied watershed modeling. *Hydrol. Process.* 19(3): 563-572.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams.1998. Large-area hydrologic modeling and assessment: Part I.Model development. *J. American Water Resour. Assoc.* 34(1): 73-89.

Babcock, B.A., Gassman, P.W., Jha, M., and Kling, C.L. 2007. Adoption subsidies and environmental impacts of alternative energy crops: Iowa State University, Center for Agricultural and Rural Development (CARD) Briefing Paper 07-BP 50, 15 p.

Ben-David, S., Brookshire, D., Burness, S., McKee, M., & Schmidt, C. 2000. Attitudes toward Risk and Compliance in Emission Permit Markets. *Land Economics* 76 (4): 590-600.

Bohi, D. R., & Burtraw, D. 1992. Utility investment behavior and the emission trading market. *Resource and Energy Economics* 14: 129–153.

Brechbill, S. and Tyner, W. 2008. *The economics of biomass collection, transportation, and supply to Indiana cellulosic and electric utility facilities*. Working Paper #08-03, Department of Agricultural Economics, Purdue University.

Chen, X. and Ö nal, H. 2012. Modeling Agricultural Supply Response Using Mathematical Programming and Crop Mixes. *American Journal of Agricultural Economics* 94(3): 674-686

Crocker, T. D. 1966. The Structuring of Atmospheric Pollution Control Systems. In H. Wolozin, *The Economics of Air Pollution* (pp. 61-86). New York: W.W.Norton&Company.

Cronshaw, M. B. & Kruse, J.B. 1996. Regulated firms in pollution permit markets with banking. *Journal of Regulatory Economics* 9: 179-189.

Dales, J. 1968. *Pollution, Property, and Prices.* Toronto: University of Toronto Press.

Daniel G. De La Torre Ugarte and Daryll E. Ray 2000. Biomass and bioenergy applications of the POLYSYS modeling framework. *Biomass and Bioenergy* 18(4): 291-308.

Doering, O., Diaz-Hermelo, F., Howard, C., Heimlich, R., Hitzhusen, F., Kazmierczak, R., Lee, J., Libby, L., Milon, W., Prato, T., and Ribaudo, M. 1999. Evaluation of the economic costs and benefits of methods for reducing nutrient loads to the Gulf of Mexico: Topic 6 report for the integrated assessment of hypoxia in the Gulf of Mexico: Silver Springs, MD, National Oceanic and Atmospheric Administration Coastal Ocean Program, Decision Analysis Series No. 20, 137 p.

Duffy, M., 2010. Estimated costs of crop production in Iowa-2010. Iowa Cooperative Extension Service Bulletin No.FM 1712.

Egbendewe-Mondzozo, A., Swinton, S.M., Izaurralde, R. C., Manowitz, D. H. and Zhang, X. 2010. *Biomass Supply from Alternative Cellulosic Crops and Crop Residues: A Preliminary Spatial Bioeconomic Modeling Approach.* Staff Paper 2010-07, Dept. of Agricultural, Food, and Resource Economics, Michigan State University.

Eidman, V., Petrolia, D., Pham, L., Huang, H. and Ramaswamy, S. 2009. *The Economic Feasibility of Producing Ethanol from Corn Stover and Hardwood in Minnesota.* Staff Paper P09-3, Department of Applied Economics, University of Minnesota.

Fargione J., Hill J., Tilman D., Polasky S. and Hawthorne P. 2008. Land Clearing and the Biofuel Carbon Debt. *Science* 319: 1235–1238.

Farrell, A.E., Plevin, R. J., Turner, B.T., Jones A.D., O'Hare, M., and Kammen, D. M. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311: 506–508.

Folle, S. M. 2010. *SWAT Modeling of Sediment, Nutrients and Pesticides in the Le–Sueur River Watershed, South-Central Minnesota*. Ph. D. dissertation, University of Minnesota.

Gallagher, P., Dikeman, M., Fritz, J., Wailes, E., Gauther, W. and Shapouri, H. 2003. Supply and social cost estimates for biomass from crop residues in the United States. *Environmental Resource Economics* 24(4): 335–358.

Graham, R., R. Nelson, J. Sheehan, R. Perlack and L. Wright. 2007. Current and potential US corn stover supplies. *Agron. J*. 99:1-11.

Gupta, A., & Maranas, C. D. 2003. Market-Based Pollution Abatement Strategies: Risk Management Using Emission Option Contracts. *Industrial & engineering chemistry research* 42: 802-810.

Hahn, R. 1983. Market power and tradable property rights. *Quarterly Journal of Economics* 99: 753–765.

Hennessy, D. A., & Roosen, J. 1999. Stochastic Pollution, Permits, and Merger Incentives. *Journal of Environmental Economics and Management* 37 (3): 211-232.

Hoekman, S.K. 2009. Biofuels in the U.S.-Challenges and Opportunities. *Renewable Energy* 34:14-22.

Hill, J., Polasky, S., Nelson, E., Tilman, D., Huo, H., Ludwing, L., Neumann, J., Zheng, H. and Bonta, D. 2009. Climate change and health costs of air emissions from biofuels and gasoline. *Proceedings of the National Academy of Sciences* 106(6): 2077-2082.

Huang, H.-J., Ramaswamy, S., Al-Dajani, W., Tschirner, U. and Cairncross, R. A. 2009. Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis. *Biomass and Bioenergy* 33(2): 234-246.

Johannson, R.C., M. Peters and R. House. 2007. Regional Environment and Agriculture Programming Model (REAP). USDA-ERS Technical Bulletin TB-1916, March 2007

Johnson, J. M.-F., Reicosky, D., Allmaras, R., Archer, D., & Wilhelm, W. 2006. A matter of balance: conservation and renewable energy. *Journal of Soil and Water Conservation, 61*(4): 120A-125A.

Kaylen, M., Van Dyne D.L., Choi, Y. and Blasé, M. 2000. Economic feasibility of producing ethanol from lignocellulosic feedstocks, Bioresource Technology**.** *Biotechnology* 72: 19-32.

Keeler, A. 1991. Non compliant firms in transferable discharge permit market: Some extensions. *Journal of Environmental Economics and Management* 21: 180-189.

Khanna, M., Hochman, G., Rajagopal, D., Sexton, S., Zilberman, D. 2009. Sustainability of food, energy, and environment with biofuels. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 4 (028): 10 pp.

Khanna, M., H. Onal, X. Chen, and H. Huang. 2008. *Meeting Biofuels Targets: Implications for Land Use, Greenhouse Gas Emissions and Nitrogen Use in Illinois.* Paper Presented at the Transition to A Bioeconomy: Environmental and Rural Development Impact, Farm Foundation, St. Louis, MO.

Kurkalova, L.A., S. Secchi and P.W. Gassman. 2010. Corn Stover Harvesting: Potential Supply and Water Quality Implications. In Handbook of Bioenergy Economics and Policy. Vol. 33. Khanna, M., J. Scheffran and D. Zilberman(eds) pp. 307-323. New York. U.S.A: Springer.

Lazarus, W. F. 2010. *Minnesota crop cost and return guide for 2011*. University of Minnesota Extension: St. Paul, MN.

Malcolm, S. 2008. Weaning Off Corn: Crop Residues and the Transition to Cellulosic Ethanol. Paper Presented at the Transition to A BioEconomy: Environmental and Rural Development Impact, Farm Foundation, St. Louis, MO.

Mann, L., V. Tolbert and J. Cushman. 2002. Potential environmental effects of corn (zea mays L.) stover removal with emphasis on soil organic matter and erosion. Agriculture, *Ecosystems and Environment* 89:149-166.

Maung, T.A. and McCarl, B.A., 2008. *Economics of Biomass Fuels for Electricity Production: A Case Study with Crop Residues.* American Agricultural Economics Association Annual Meeting

McLaughlin, S., J. Bouton, D. Bransby, B. Conger, W. Ocumpaugh, D. Parrish, C. Taliaferro, K. Vogel and S. Wullschleger. 1999. Developing switchgrass as a bioenergy crop. In: J.J. Janick, Editor, Proceedings of the fourth national new crops symposium, ASHS Press, Alexandria, VA (1999), pp. 282–299.

Misiolek, W. S., & Elder, H. W. 1989. Exclusionary manipulation of markets for pollution rights. *Journal of Environmental Economics and Management* 16: 156-166.

Montgomery, W. D. 1972. Markets in licenses and efficient pollution control programs. *Journal of Economic Theory* 5: 395-418.

Morey, R.V., N. Kaliyan, D.G. Tiffany and D.R. Schmidt. 2009. A biomass supply logistics system. ASABE Paper No. 096660. St. Joseph, Mich.: ASABE.

Mrozek, J. R., & Keeler, A. G. 2004. Pooling of Uncertainty: Enforcing Tradable Permits Regulation when Emissions are Stochastic. *Environmental & Resource Economics* 29: 459-481.

National Research Council, Committee on Water Implications of Biofuels Production in the United States (eds.). 2008. Water Implications of Biofuels Production in the United States. Washington D.C.: The National Academies Press.

Neitsch, S.L., Arnold, J.G., Kiniry J.R. and Williams, J.R. 2005. Soil and Water Assessment Tool Theoretical Documentation. Grassland, Soil and Water Research Laboratory, Agricultural Research Service.

Nelson R., Ascough J. and Langemeier M. 2006. Environmental and economic analysis of switchgrass production for water quality improvement in northeast Kansas *Journal of Environmental Management* 79: 336–347.

Perlack R.D. and Turhollow A.F. 2003. Feedstock cost analysis of corn stover residues for further processing. *Energy* 28: 1395-1403.

Petrolia D.R. 2008. The economics of harvesting and transporting corn stover for conversion to fuel ethanol: a case study for Minnesota Producers. Biomass and *Bioenergy* 32(7): 603-612.

Rabotyagov, S., Campbell, T., Jha, M., Gassman, P., Arnold, J., Kurkalova, L., et al. 2010. Least-cost control of agricultural nutrient contributions to the Gulf of Mexico hypoxic zone. *Ecological Applications* 20 (6): 1542–1555.

Redfearn, D., K. Moore, K. Vogel, S. Waller, and R. Mitchell. 1997. Canopy architecture and morphology of switchgrass populations differing in forage yield. *Agronomy Journal* 89: 262–269.

Ribaudo, M. O., Heimlich, R., Claassen, R., and Peters, M. 2001. Least-cost management of nonpoint source pollution: source reduction versus interception strategies for controlling nitrogen loss in the Mississippi Basin. *Ecological Economics* 37(2): 183-197.

Ribaudo, M.O., J.A. Delgado, L. Hansen, M. Livingston, R. Mosheim, and J. Williamson. 2011. Nitrogen in Agricultural Systems: Implications for Conservation Policy. Economic Research Report No. (ERR-127). Washington, DC: USDA.

Rubin, J. D. 1996. A Model of Intertemporal Emission Trading, Banking, and Borrowing. *Journal of Environmental Economics and Management* 31: 269-286.

Runge, C.F. and Senauer B. 2007. How Biofuels Could Starve the Poor. *Foreign Affairs*. May/June.

Schmer, M. R., Vogel, K. P., Mitchell, R. B., & Perrin, R. K. 2008. Net energy of cellulosic ethanol from switchgrass. *Proceedings of the National Academy of Sciences* 105(2): 464-469.

Schennach, S. M. 2000. The Economics of Pollution Permit Banking in the Context of Title IV of the 1990 Clean Air Act Amendments. *Journal of Environmental Economics and Management* 40: 189-210.

Schnepf, R. 2010. Cellulosic Ethanol: Feedstocks, Conversion Technologies, Economics, and Policy Options. Washington, DC: Congressional Research Service. Report for Congress R41460.

Secchi, S. and Babcock, B. 2007. *Impact of High Crop Prices on Environmental Quality: A Case of Iowa and the Conservation Reserve Program*. Center for Agricultural and Rural Development, Iowa State University: Ames, IA.

Secchi, S., Gassman, P.W., Jha M., Kurkalova L. and Kling C.L. 2008. *The Water Quality Effects of Corn Ethanol vs Switchgrass Based Biofuels in the Midwest.* Paper Presented at the Transition to A Bioeconomy: Environmental and Rural Development Impact, Farm Foundation, St. Louis, MO.

Selten, R. 1965. Spieltheoretische Behandlung eines Oligopolmodells mit Nachfragetragheit. Zeitschrift f ̈ur die gesamte Staatswissenschaft 121: 301–324.

Smil, V. 1999. Crop residues: agriculture’s largest harvest. BioScience 49(4): 299–308.

Smith D.J., Schulman C., Current D., and Easter, K.W. Willingness of Agricultural Landowners to Supply Perennial Energy Crops. Selected Paper at the Agricultural & Applied Economics Association Annual Meeting, Pittsburgh, Pennsylvania, July 2011.

Stavins, R. 1995. Transaction costs and tradable permits. *Journal of Environmental Economics and Management* 29: 133-148.

Taschini, L. 2010. Environmental Economics and Modeling Marketable Permits: A Survey. *Asian Pacific Financial Markets* 17 (4): 325-343.

Taylor, R. D., & Koo, W. W. 2010. *Optimizing Ethanol Production in North Dakota.* Fargo, North Dakota: Center for Agricultural Policy and Trade Studies, North Dakota State University.

Tiffany, D.G., B. Jordan, E. Dietrich and B. Vargo-Daggett. *Energy and Chemicals from Native Grasses: Production, Transportation and Processing Technologies Considered in the Northern Great Plains.* Staff Paper P06-11. University of Minnesota, Department of Applied Economics. June 2006.

Tilman, D., Hill, j., & Lehman, C. 2006. Carbon-Negative Biofuels from Low-Input High -Diversity Grassland Biomass. Science 314, 1598-1600.

U.S. Congressional Budget Office. 2007. *CBO TESTIMONY: Approaches to Reducing Carbon Dioxide Emissions.* WASHINGTON, D.C.

US Department of Agriculture – Agricultural Marketing Service. Ethanol Transportation Backgrounder. 2007.

US Department of Agriculture – Agricultural Marketing Service, Truck Transportation

http://www.ams.usda.gov/AMSv1.0/ams.fetchTemplateData.do?template=TemplateV&navID=AgriculturalTransportation&leftNav=AgriculturalTransportation&page=ATQuarterlyUpdatesArchive&description=Quarterly%20Updates%20Archive&acct=graintransrpt accessed July 2011.

Vogel, K.P. 1996. Energy production from forages (or American agriculture-back to the future). *Journal of Soil and Water Conservation* 51: 137-139.

Walsh, M. E., D. G. De La Torre Ugarte, H. Shapouri, and S. P. Slinsky. 2003. Bioenergy Crop Production in the United States: Potential Quantities, Land Use Changes, and Economic Impacts on the Agricultural Sector. *Environmental and Resource Economics* 24 (4): 313-333.

Whittaker G., 2005. Application of SWAT in the evaluation of salmon habitat remediation policy. *Hydrological Processes* 19(3): 839-848.

Williams, JR. 1995. The EPIC model. In: Singh VP (ed) Computer models in watershed

hydrology. Water Resources Publications, Highlands Ranch, pp 909–1000.

Woolsey, E. 1992. Switchgrass-back to the future. In *Switchgrass-back to the future*. Energy crops forum, Oak Ridge National Laboratory, Spring, 1992.

Wu, J., & Tanaka, K. 2005. Reducing Nitrogen Runoff from the Upper Mississippi River Basin to Control Hypoxia in the Gulf of Mexico: Easements or Taxes. *Marine Resource Economics* 20(2): 121-144

Zhao, J. 2003. Irreversible abatement investment under cost uncertainties: tradable emission permits and emissions charges. *Journal of Public Economics* 87: 2765–2789.

Appendix A. Appendix to Chapter 2

A.1. Equilibrium of Economic Model and Kuhn Tucker Condition

The equilibrium of the sector is solved by setting up the Lagrangian function as follows:

$$(6)\quad \mathcal{L}(X,Y,Z,T,\lambda,\mu,\theta)=\sum_{g=1}^{r}\sum_{i=1}^{n}a_iY_{gi}-\sum_{g=1}^{r}\sum_{h=1}^{r,h\neq g}\sum_{i=1}^{n}t_{ghi}T_{ghi}-\sum_{g=1}^{r}\sum_{k=1}^{m}c_kZ_{gk}$$

$$+\sum_{g=1}^{r}\sum_{i=1}^{n}\mu_{gi}\left[-Y_{gi}+\sum_{j=1}^{s}\sum_{u}e_{gjui}X_{gju}+\sum_{h=1}^{r,h\neq g}T_{hgi}-\sum_{h=1}^{r,h\neq g}T_{ghi}\right]$$

$$+\sum_{g=1}^{r}\sum_{k=1}^{m}\theta_{gk}\left[Z_{gk}-\sum_{j=1}^{s}\sum_{u}v_{gjuk}X_{gju}\right]+\sum_{g=1}^{r}\sum_{u}\lambda_{gu}\left[Q_{gu}-\sum_{j=1}^{s}X_{gju}\right]$$

Thus Kuhn-Tucker conditions are derived as:

$$(7)\quad \frac{\partial\mathcal{L}}{\partial Y_{gi}}=a_i-\mu_{gi}\leq 0$$

$$(8)\quad \frac{\partial\mathcal{L}}{\partial X_{gju}}=\sum_{i=1}^{n}\mu_{gi}\,e_{gjui}-\sum_{k=1}^{m}\theta_{gk}\,v_{gjuk}+\lambda_{gu}\leq 0$$

$$(9)\quad \frac{\partial\mathcal{L}}{\partial Z_{gk}}=-c_k+\theta_{gk}\leq 0$$

$$(10)\quad \frac{\partial\mathcal{L}}{\partial T_{ghi}}=-t_{ghi}+\mu_{hi}-\mu_{gi}\leq 0$$

$$(11)\quad \left[\frac{\partial\mathcal{L}}{\partial Y_{gi}}\right]Y_{gi}=[a_i-\mu_{gi}]Y_{gi}=0$$

$$(12)\quad \left[\frac{\partial\mathcal{L}}{\partial X_{gju}}\right]X_{gju}=\left[\sum_{i=1}^{n}\mu_{gi}\,e_{gjui}-\sum_{k=1}^{m}\theta_{gk}\,v_{gjuk}\right]X_{gju}=0$$

$$(13)\quad \left[\frac{\partial\mathcal{L}}{\partial Z_{gk}}\right]Z_{gk}=[-c_k+\theta_{gk}]Z_{gk}=0$$

$$(14)\quad \left[\frac{\partial\mathcal{L}}{\partial T_{ghi}}\right]T_{ghi}=[-t_{ghi}+\mu_{hi}-\mu_{gi}]T_{ghi}=0$$

$$(15)\quad Y_{gi},X_{gju},Z_{gk},T_{ghi}\geq 0$$

$$(16)\quad \frac{\partial \mathcal{L}}{\partial \mu_{gi}} = -Y_{gi} + \sum_{j=1}^{s}\sum_{u} e_{gjui}X_{gju} + \sum_{h=1}^{r,h\neq g} T_{hgi} - \sum_{h=1}^{r,h\neq g} T_{ghi} \geq 0$$

$$(17)\quad \frac{\partial \mathcal{L}}{\partial \theta_{gk}} = Z_{gk} - \sum_{j=1}^{s}\sum_{u} v_{gjuk}X_{gju} \geq 0$$

$$(18)\quad \frac{\partial \mathcal{L}}{\partial \lambda_{gu}} = Q_{gu} - \sum_{j=1}^{s} X_{gju} \geq 0$$

$$(19)\quad \left[\frac{\partial \mathcal{L}}{\partial \mu_{gi}}\right]\mu_{gi} = \left[-Y_{gi} + \sum_{j=1}^{s}\sum_{u} e_{gjui}X_{gju} + \sum_{h=1}^{r,h\neq g} T_{hgi} - \sum_{h=1}^{r,h\neq g} T_{ghi}\right]\mu_{gi} = 0$$

$$(20)\quad \left[\frac{\partial \mathcal{L}}{\partial \theta_{gk}}\right]\theta_{gk} = \left[Z_{gk} - \sum_{j=1}^{s}\sum_{u} v_{gjuk}X_{gju}\right]\theta_{gk} = 0$$

$$(21)\quad \left[\frac{\partial \mathcal{L}}{\partial \lambda_{gu}}\right]\lambda_{gu} = \left[Q_{gu} - \sum_{j=1}^{s} X_{gju}\right]\lambda_{gu} = 0$$

$$(22)\quad \mu_{gi}, \theta_{gk}, \lambda_{gu} \geq 0$$

and g=1…r, h=1…r, h≠g, i=1…n, j=1…s, k=1…m, l=1…q

Using (7), (11) and (15), $\mu^*_{gi} = a_i$, if $Y^*_{gi} > 0$. Thus μ^*_{gi}, dual variable related with the output constraint for product i, is equal to the equilibrium price of the product i when product i is consumed in the region. From (10), (14) and (15), $\mu^*_{hi} - \mu^*_{gi} = t_{ghi}$, if $T^*_{ghi} > 0$. It implies the difference in market prices of product i between any two regions g and h is equal to the unit transportation cost.

Regional equilibrium input prices are Lagrange multipliers associated with input constraints (2) and (3). If variable input k is used in region g, $Z^*_{gk} > 0$, then the equilibrium price of variable input, c_k, is equal to θ^*_{gk} by (9), (13) and (15). The duals of the fixed input constraints, λ^*_{gl}, are interpreted as the market prices of those inputs.

Conditions (8), (12) and (15) set up the equilibrium conditions for the aggregate production activities. The left-hand side of (8) implies the net marginal profit of production of activity j. When there is production activity j, $X_{gj}^{*} > 0$, the net profit is zero by (12) and (15).

A.2. Crop Budget Description

Budget	Budget Description
CS-S-S00	soybeans in corn-soybean rotation with no stover harvest - base
CS-C-S00	corn in corn-soybean rotation with no stover harvest - base
CS-S-S10	soybeans in corn-soybean rotation with 10% stover harvest
CS-C-S10	corn in corn-soybean rotation with 10% stover harvest
CS-S-S30	soybeans in corn-soybean rotation with 30% stover harvest
CS-C-S30	corn in corn-soybean rotation with 30% stover harvest
CS-S-S60	soybeans in corn-soybean rotation with 60% stover harvest
CS-C-S60	corn in corn-soybean rotation with 60% stover harvest
CCS-S-S00	soybeans in corn-corn-soybean rotation with no stover harvest
CCS-C1-S00	first year corn in corn-corn-soybean rotation with no stover harvest
CCS-C2-S00	second year corn in corn-corn-soybean rotation with no stover harvest
CCS-S-S10	soybeans in corn-corn-soybean rotation with 10% stover harvest
CCS-C1-S10	first year corn in corn-corn-soybean rotation with 10% stover harvest
CCS-C2-S10	second year corn in corn-corn-soybean rotation with 10% stover harvest
CCS-S-S30	soybeans in corn-corn-soybean rotation with 30% stover harvest
CCS-C1-S30	first year corn in corn-corn-soybean rotation with 30% stover harvest
CCS-C2-S30	second year corn in corn-corn-soybean rotation with 30% stover harvest
CCS-S-S60	soybeans in corn-corn-soybean rotation with 60% stover harvest
CCS-C1-S60	first year corn in corn-corn-soybean rotation with 60% stover harvest
CCS-C2-S60	second year corn in corn-corn-soybean rotation with 60% stover harvest
SWCH-PLT	planting in switchgrass production
SWCH-MAT	maintenance in switchgrass production
SWCH-HVT	harvest in switchgrass production
CRP-PLT	planting prairie in CRP land
CRP-HVT	harvest prairie in CRP land (just cutting for weed)

A.3. Input Price

Input	Unit	Price ($)	Source
Corn Seed	LB	4.89	1
Soybean Seed	BU-S	49.70	2
Anhydrous Ammonia	LB	0.39	3
Diammonium Phosphate, 18-46-0	LB	0.35	3
Metolachlor	GAL	120.63	4
Acetochlor	GAL	69.60	2
Atrazine	GAL	17.30	2
Diesel	GAL	3.10	5
Switchgrass Seed	LB	11.00	5
UREA,	LB	0.54	5
Prairie Seed	LB	10.00	5

Source:

1: National, hybrid, 2: National, 3: Northcentral region, 4. 2006 year data inflated PPI chemcial index from USDA, NASS Agricultural Prices 2011 April.

5: Lazarus, W. F. 2010. Minnesota crop cost and return guide for 2011. University of Minnesota Extension: St. Paul, MN. : 5

A.4. Enterprise crop budget in the regional economic model

GAMS Text	Units	CS-S-S00	CS-C-S00	CS-S-S10	CS-C-S10	CS-S-S30	CS-C-S30	CS-S-S60	CS-C-S60	CCS-S-S00	CCS-C1-S00	CCS-C2-S00	CCS-S-S10
CORN SEED	LB	0.00	20.61	0.00	20.61	0.00	20.61	0.00	20.61	0.00	20.61	20.61	0.00
SOYBEAN SEED	BU-S	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	0.00	1.00
ANHYDROUS AMMONIA	LB	0.00	120.00	0.00	125.35	0.00	136.06	0.00	152.12	0.00	120.00	158.36	0.00
DIAMMONIUM PHOSPHATE 18-46-0	LB	0.00	163.00	0.00	163.00	0.00	163.00	0.00	163.00	0.00	163.00	163.00	0.00
METOLACHLOR	GAL	0.10	0.24	0.10	0.24	0.10	0.24	0.10	0.24	0.10	0.24	0.24	0.10
ACETOCHLOR	GAL	0.00	0.17	0.00	0.17	0.00	0.17	0.00	0.17	0.00	0.17	0.17	0.00
ATRAZINE	GAL	0.00	0.06	0.00	0.06	0.00	0.06	0.00	0.06	0.00	0.06	0.06	0.00
DIESEL FUEL	GAL	4.39	4.15	4.39	5.64	4.39	5.64	4.39	5.64	4.39	4.15	4.15	4.39
LUBRICATION COST	USD	1.36	1.29	1.36	1.75	1.36	1.75	1.36	1.75	1.36	1.29	1.29	1.36
CUSTOM HIRE	USD	14.00	17.00	14.00	17.00	14.00	17.00	14.00	17.00	14.00	17.00	17.00	14.00
CROP INSURANCE	USD	28.06	27.09	28.06	27.09	28.06	27.09	28.06	27.09	28.06	27.09	27.09	28.06
LABOR FOR FIELD OPERATIONS	USD	6.35	4.32	6.35	11.03	6.35	11.03	6.35	11.03	6.35	4.32	4.32	6.35
NON-FIELD OPERATION LABOR & MGMT	USD	41.93	51.90	41.93	51.90	41.93	51.90	41.93	51.90	41.93	51.90	51.90	41.93
OTHER VARIABLE OR OPERATING COST	USD	10.00	41.65	10.00	43.79	10.00	43.79	10.00	43.79	10.00	41.65	41.65	10.00
VARIABLE MACHINE COST	USD	28.37	30.36	28.37	40.66	28.37	40.66	28.37	40.66	28.37	30.36	30.36	28.37
FIXED MACHINERY COST	USD	19.55	16.61	19.55	26.43	19.55	26.43	19.55	26.43	19.55	16.61	16.61	19.55
OTHER FIXED OR OVERHEAD COST	USD	6.86	11.51	6.86	14.05	6.86	14.05	6.86	14.05	6.86	11.51	11.51	6.86
MISCELLANEOUS	USD	16.64	21.10	16.64	20.33	16.64	20.33	16.64	20.33	18.66	23.12	23.12	18.66

GAMS Text	Units	CCS-C1-S10	CCS-C2-S10	CCS-S-S30	CCS-C1-S30	CCS-C2-S30	CCS-S-S60	CCS-C1-S60	CCS-C2-S60	SWCH-PLT	SWCH-MAT	SWCH-HVT	CRP-PLT	CRP-HVT
CORN SEED	LB	20.61	20.61	0.00	20.61	20.61	0.00	20.61	20.61	0.00	0.00	0.00	0.00	0.00
SOYBEAN SEED	BU-S	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ANHYDROUS AMMONIA	LB	125.35	163.72	0.00	136.06	174.42	0.00	152.12	190.48	0.00	0.00	0.00	0.00	0.00
DIAMMONIUM PHOSPHATE 18-46-0	LB	163.00	163.00	0.00	163.00	163.00	0.00	163.00	163.00	0.00	0.00	0.00	0.00	0.00
METOLACHLOR	GAL	0.24	0.24	0.10	0.24	0.24	0.10	0.24	0.24	0.00	0.00	0.00	0.00	0.00
ACETOCHLOR	GAL	0.17	0.17	0.00	0.17	0.17	0.00	0.17	0.17	0.00	0.00	0.00	0.00	0.00
ATRAZINE	GAL	0.06	0.06	0.00	0.06	0.06	0.00	0.06	0.06	0.15	0.00	0.00	0.15	0.00
DIESEL FUEL	GAL	5.64	5.64	4.39	5.64	5.64	4.39	5.64	5.64	0.47	1.26	1.78	0.47	0.38
LUBRICATION COST	USD	1.75	1.75	1.36	1.75	1.75	1.36	1.75	1.75	0.15	0.39	0.55	0.15	0.12
CUSTOM HIRE	USD	17.00	17.00	14.00	17.00	17.00	14.00	17.00	17.00	45.00	0.00	0.00	45.00	0.00
CROP INSURANCE	USD	27.09	27.09	28.06	27.09	27.09	28.06	27.09	27.09	0.00	0.00	0.00	0.00	0.00
LABOR FOR FIELD OPERATIONS	USD	11.03	11.03	6.35	11.03	11.03	6.35	11.03	11.03	1.68	7.17	8.67	1.68	1.68
NON-FIELD OPERATION LABOR & MGMT	USD	51.90	51.90	41.93	51.90	51.90	41.93	51.90	51.90	20.00	20.00	20.00	20.00	20.00
OTHER VARIABLE OR OPERATING COST	USD	43.79	43.79	10.00	43.79	43.79	10.00	43.79	43.79	0.00	1.74	3.48	0.00	0.00
VARIABLE MACHINE COST	USD	40.66	40.66	28.37	40.66	40.66	28.37	40.66	40.66	6.68	18.44	23.29	6.68	3.26
FIXED MACHINERY COST	USD	26.43	26.43	19.55	26.43	26.43	19.55	26.43	26.43	6.14	11.86	12.56	6.14	2.41
OTHER FIXED OR OVERHEAD COST	USD	14.05	14.05	6.86	14.05	14.05	6.86	14.05	14.05	7.86	3.61	4.27	7.83	2.41
MISCELLANEOUS	USD	22.35	22.35	18.66	22.35	22.35	18.66	22.35	22.35	0.00	0.00	0.00	0.00	0.00
SWITCHGRASS SEED	LB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.00	0.00	0.00	0.00	0.00
NITROGEN FERTILIZER FOR SWITCHGRASS	LB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.50	45.50	45.50	0.00	0.00
PRAIRIE SEED	LB	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00

Appendix B. Appendix to Chapter 3

B.1. Crop Land Area by Corn-Soybean Rotation under Total Phosphorus Load Restrictions

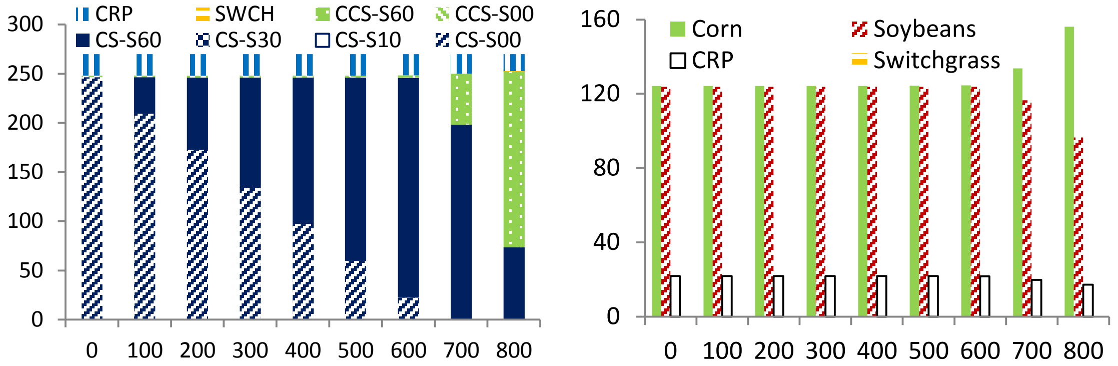
		Cellulosic Feedstock Production(1000Mt)								
Rotation	(Unit: 1000 Ha, %)	0	100	200	300	400	500	600	700	800
		---Baseline----------------------------------								
Two-Year	Total Area	246.2	246.2	246.1	246.0	246.0	245.8	245.6	198.2	73.4
	Stover Harvest Area	0.0	36.9	73.9	112.0	148.7	186.2	223.2	198.2	73.4
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%
Three-Year	Total Area	1.6	1.7	1.7	1.9	1.9	2.1	2.5	51.8	179.2
	Stover Harvest Area	0.0	0.0	0.1	0.5	0.5	1.3	2.2	51.8	179.2
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%
		----------------------10% Reduction in Nitrate-N Losses--------------------								
Two-Year	Total Area	239.8	237.3	234.6	227.8	209.7	173.1	135.0	110.0	105.8
	Stover Harvest Area	0.0	37.5	74.9	110.0	128.2	117.6	105.0	103.0	103.7
	Ave. Removal Rate	0%	60%	59%	57%	56%	57%	57%	58%	59%
Three-Year	Total Area	1.4	2.4	3.5	8.7	25.3	60.9	97.7	120.4	122.7
	Stover Harvest Area	0	0	1	6	23	59	96	119	122
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%
		----------------------20% Reduction in Nitrate-N Losses--------------------								
Two-Year	Total Area	233.0	231.2	225.9	209.5	176.9	149.7	128.2	111.7	102.8
	Stover Harvest Area	0.0	40.5	79.0	101.5	96.8	97.7	98.9	99.4	100.0
	Ave. Removal Rate	0%	55%	53%	52%	52%	53%	56%	58%	59%
Three-Year	Total Area	2.2	2.8	6.8	21.9	53.3	78.5	97.5	111.5	118.5
	Stover Harvest Area	0.0	0.5	4.4	19.3	50.8	76.2	95.9	110.5	117.7
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%
		----------------------30% Reduction in Nitrate-N Losses--------------------								
Two-Year	Total Area	225.3	219.3	203.7	183.9	163.8	147.8	136.3	126.9	117.0
	Stover Harvest Area	0.0	45.3	73.1	84.6	93.0	97.1	97.1	97.0	96.1
	Ave. Removal Rate	0%	41%	41%	44%	46%	49%	51%	53%	55%
Three-Year	Total Area	3.3	8.2	22.3	40.2	57.9	71.4	80.8	87.9	95.2
	Stover Harvest Area	0.0	5.3	19.5	38.1	56.4	70.5	80.1	87.4	94.5
	Ave. Removal Rate	0%	60%	60%	60%	60%	60%	60%	60%	60%

B.2. Land Type in CRP and Switchgrass Production under Phosphorus Losses Reduction (Unit: Ha)

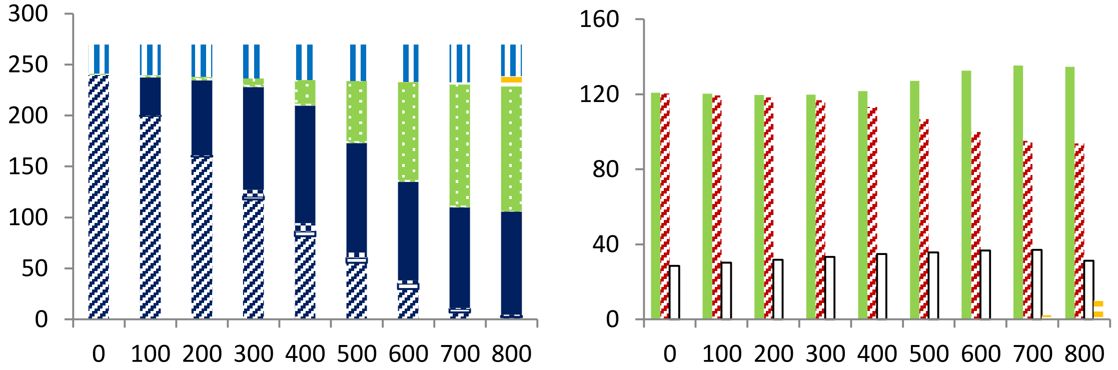
	Cellulosic Feedstock Production (1000 Mt)								
	0	100	200	300	400	500	600	700	800
	No Reduction(Baseline)								
CRP	21,931	21,931	21,931	21,931	21,931	21,848	21,643	19,790	17,168
Sloped	21,883	21,883	21,883	21,883	21,883	21,800	21,596	19,742	17,120
Critical	4,286	4,286	4,286	4,286	4,286	4,284	4,276	3,734	2,346
Low Yield	20,558	20,558	20,558	20,558	20,558	20,545	20,506	19,409	17,069
Switchgrass	0	0	0	0	0	0	0	0	61
Sloped									61
Critical									34
Low Yield									61
	10% Reduction in Phosphorus Losses								
CRP	28,516	30,132	31,686	33,233	34,771	35,724	36,673	37,096	31,271
Sloped	28,468	30,085	31,638	33,185	34,723	35,677	36,625	37,048	31,223
Critical	6,270	6,778	7,042	7,552	8,012	8,401	8,744	9,309	7,158
Low Yield	23,204	23,204	23,204	23,204	23,204	23,204	23,204	23,204	22,929
Switchgrass	0	0	0	0	11	84	429	2,235	10,041
Sloped					11	84	429	2,235	10,041
Critical					11	34	108	425	3,102
Low Yield									275
	20% Reduction in Phosphorus Losses								
CRP	34,545	35,706	37,042	38,291	39,379	40,839	41,890	40,928	36,887
Sloped	34,497	35,658	36,994	38,243	39,331	40,792	41,842	40,881	36,839
Critical	7,984	8,373	8,849	9,353	9,788	10,458	10,819	10,740	9,236
Low Yield	23,204	23,204	23,204	23,204	23,204	23,204	23,204	23,204	23,060
Switchgrass	0	0	16	49	148	667	2,162	5,568	11,580
Sloped			16	49	148	667	2,162	5,568	11,580
Critical				1	52	240	672	1,351	3,292
Low Yield									143
	30% Reduction in Phosphorus Losses								
CRP	41,125	42,217	43,551	45,251	46,769	46,682	43,978	40,513	36,604
Sloped	41,077	42,170	43,504	45,204	46,721	46,634	43,847	40,175	36,083
Critical	10,489	10,803	11,199	11,509	11,814	12,019	11,635	10,488	8,940
Low Yield	23,204	23,204	23,204	23,204	23,204	23,204	23,204	23,096	22,959
Switchgrass	0	36	189	404	1,216	3,801	8,710	14,463	20,945
Sloped		36	189	404	1,216	3,801	8,265	13,650	18,760
Critical		19	97	208	516	1,120	2,696	4,996	8,411
Low Yield								107	244

B.3. Crop Production Activities under Phosphorus Losses Reduction*

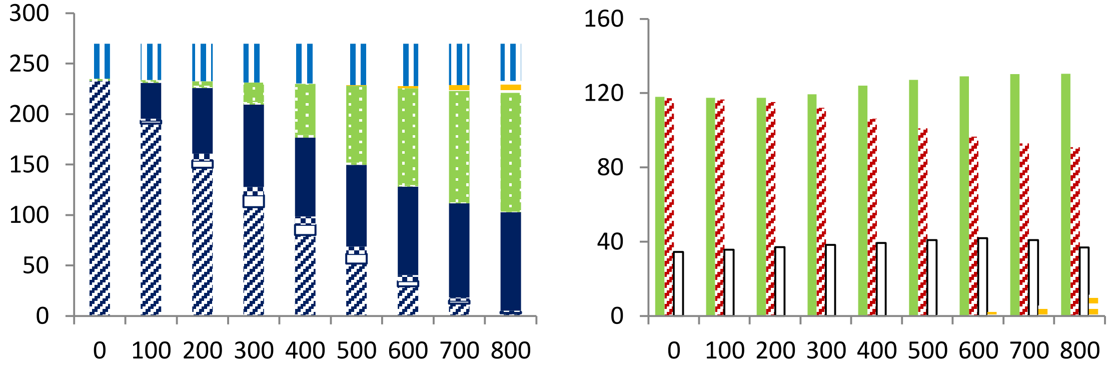
Baseline



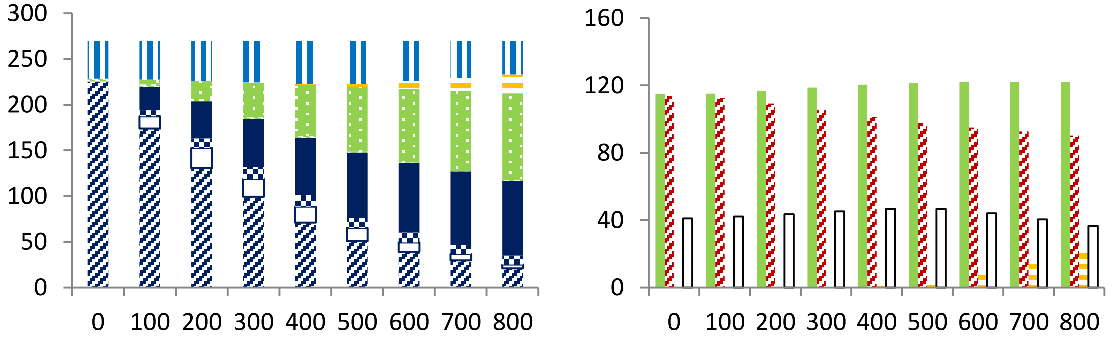
10% Reduction



20% Reduction



30% Reduction



* X axis: Feedstock Supply 1000 Mt, Y axis: 1000 Ha

Appendix C. Appendix to Chapter 4.

C.1. Derivation of (4.7)

$$P_u^* - P_c^* = \frac{\sum_{i=1}^{n}(E_i + \psi - a_i)}{\sum_{i=1}^{n}\left(\frac{2\psi\alpha_i + \phi}{\alpha_i\phi}\right)} - \frac{\sum_{i=1}^{n}(E_i - a_i)}{\sum_{i=1}^{n}\frac{1}{\alpha_i}}.$$

Let $\sum_{i=1}^{n} a_i = A$, $\sum_{i=1}^{n} E_i = E$, and it is assumed that α_i= 1 for all i and $\sum_{i=1}^{n} \psi = n\psi$.

$$P_u^* - P_c^* = \frac{E + n\psi - A}{n\left(\frac{2\psi + \phi}{\phi}\right)} - \frac{E - A}{n} = \frac{E + n\psi - A - \left(\frac{2\psi + \phi}{\phi}\right)(E - A)}{n\left(\frac{2\psi + \phi}{\phi}\right)}$$

$$= \frac{\phi E + \phi n\psi - \phi A - 2\psi E + 2\psi A - \phi E + \phi A}{n(2\psi + \phi)}$$

$$= \frac{\phi n\psi - 2\psi E + 2\psi A}{n(2\psi + \phi)}$$

$$\therefore P_u^* - P_c^* = \frac{\psi(\phi n + 2(A - E))}{n(2\psi + \phi)}$$

C.2. Derivation of (4.14) and (4.15)

When Firm chooses expected emissions in the first stage, first order condition (4.13) is

$$-\alpha_i(E_i - m_i) + \frac{\phi}{2n\psi}\left(m_i - a_i + \frac{A-M}{n}\right) + \frac{\phi(n\psi - A + M)}{2n\psi}\left(1 - \frac{1}{n}\right)$$
$$+ \frac{\phi}{2\psi}\left(\psi - \frac{A-M}{n}\right)\frac{1}{n} = 0.$$

where $\sum_{i=1}^{n} a_i = A$ and $\sum_{i=1}^{n} m_i = M$.

Summing (4.13) over i=1…n with assumption for α_i=1 for all i.

$$M - E + \frac{\phi}{2n\psi}(M - A + A - M) + \frac{\phi(n\psi - A + M)}{2\psi}\left(1 - \frac{1}{n}\right) + \frac{\phi}{2\psi}\left(\psi - \frac{A-M}{n}\right) = 0.$$

$$\rightarrow 2\psi(M - E) + \phi(n\psi - A + M)\left(1 - \frac{1}{n}\right) + \phi\left(\frac{n\psi - A + M}{n}\right) = 0.$$

$$\rightarrow 2n\psi(M - E) + \phi(n\psi - A + M)(n - 1) + \phi(n\psi - A + M) = 0.$$

$$\rightarrow 2n\psi(M - E) + \phi(n\psi - A + M)n = 0.$$

$$\rightarrow (2n\psi + \phi n)M = 2n\psi E - \phi(n\psi - A)n = 0.$$

$$\rightarrow (2\psi + \phi)M = 2\psi E - \phi(n\psi - A) = 0.$$

$$\therefore M = \frac{2\psi E - \phi n\psi + \phi A}{2\psi + \phi} \quad (4.14)$$

Expected emissions of firm i is derived by using (4.14) into (4.13):

First, let A−M = Z.

$$E_i - m_i = \frac{\phi}{2n\psi}(m_i - a_i) + \frac{\phi}{2n\psi}\frac{Z}{n} + \frac{\phi n\psi}{2n\psi}\left(1 - \frac{1}{n}\right) - \frac{\phi Z}{2n\psi}\left(1 - \frac{1}{n}\right) + \frac{\phi\psi}{2n\psi} - \frac{\phi Z}{2n\psi}\frac{1}{n}.$$

$$\rightarrow E_i - m_i = \frac{\phi}{2n\psi}(m_i - a_i) + \frac{\phi}{2}\left(\frac{n-1}{n}\right) - \frac{\phi Z}{2n\psi}\left(\frac{n-1}{n}\right) + \frac{\phi}{2n}.$$

$$\rightarrow 2n\psi(E_i - m_i) = \phi(m_i - a_i) + \phi\psi(n - 1) - \phi Z\left(\frac{n-1}{n}\right) + \phi\psi.$$

$$\rightarrow (2n\psi + \phi)m_i = 2n\psi E_i + \phi a_i - \phi\psi n + \phi\left(\frac{n-1}{n}\right)Z.$$

$$m_i = \frac{2n\psi E_i + \phi a_i - \phi\psi n + \phi\left(\frac{n-1}{n}\right)Z}{2n\psi + \phi}.$$

We know Z = A−M is same as (4-7):

$$A - M = \frac{\psi(2A - 2E + \phi n)}{2\psi + \phi}.$$

Therefore expected emissions of firm i is derived as

$$\therefore m_i = \frac{2n\psi E_i + \phi a_i - \phi n\psi + \frac{\phi\psi(n-1)(2A - 2E + \phi n)}{n(2\psi + \phi)}}{2n\psi + \phi}. \tag{4.15}$$

C.3. Derivation of $\mathbf{m_i}$ and M from (4.18)

Firm chooses expected emissions from the first order condition derived from (4.18):

$$-\alpha_i(E_i - m_i) + \frac{1}{n}\frac{\phi}{2\psi}\left(m_i + \frac{A-M}{n} - a_i\right) + \frac{\phi}{2\psi}\int_{\frac{A-M}{n}}^{\psi} 1\, d\varepsilon_i = 0.$$

$$\rightarrow -\alpha_i(E_i - m_i) + \frac{\phi}{2n\psi}\left(m_i + \frac{A-M}{n} - a_i\right) + \frac{\phi}{2\psi}\left(\psi - \frac{A-M}{n}\right) = 0.$$

Summing the first order conditions over i=1…n with assumption for α_i=1 for all i.

$$M - E + \frac{\phi}{2n\psi}(M + A - M - A) + \frac{\phi(n\psi - A + M)}{2\psi} = 0.$$

$$\rightarrow 2\psi(M - E) + \phi(n\psi - A + M) = 0.$$

$$\rightarrow M(2\psi + \phi) = 2\psi E - \phi(n\psi - A) = 0.$$

$$\therefore M = \frac{2\psi E - \phi n\psi + \phi A}{2\psi + \phi} \quad \text{that is same as } (4.14)$$

Firm's expected emissions are derived by using M above first order condition. Let A−M =Z.

$$E_i - m_i = \frac{\phi}{2n\psi}(m_i - a_i) + \frac{\phi}{2n\psi}\frac{Z}{n} + \frac{\phi}{2} - \frac{\phi}{2n\psi}Z$$

$$\rightarrow 2n\psi(E_i - m_i) = \phi(m_i - a_i) + \phi\frac{Z}{n} + n\psi\phi - \phi Z$$

$$\rightarrow 2n\psi(E_i - m_i) = \phi(m_i - a_i + n\psi) + \phi\left(\frac{1-n}{n}\right)Z$$

$$\rightarrow (2n\psi + \phi)m_i = 2n\psi E_i - \phi(n\psi - a_i) + \phi\left(\frac{n-1}{n}\right)Z$$

Using Z=A − M $= \frac{\psi(2A-2E+\phi n)}{2\psi+\phi}$, expected emissions of firm i is derived as

$$\therefore m_i = \frac{2n\psi E_i + \phi a_i - \phi n\psi + \frac{\phi\psi(n-1)(2A - 2E + \phi n)}{n(2\psi + \phi)}}{2n\psi + \phi}.$$