THREE ESSAYS ON CLIMATE CHANGE MITIGATION POLICIES AND SUPPLY CHAIN ASSESSMENT FOR BIOFUEL PRODUCTION

A Dissertation

by

GUANNAN ZHAO

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Chair of Committee,	Bruce A. McCarl
Committee Members,	Edwin C. Price
	H. Neil Geismar
	Yu (Yvette) Zhang
Head of Department,	Mark L. Waller

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ABSTRACT

Greenhouse gas (GHG) emissions need to be reduced in order to avoid dangerous climate change. There are a number of ways of achieving emissions reductions and agriculture can play an important role. Some involve reducing emissions and enhancing sequestration from agricultural production and yet others involve substituting low emitting products for higher emitting products. In this dissertation we will investigate agricultural mitigation strategies in terms of a countrywide INDC and later in terms of replacing petroleum-based fuels with biofuel produced from agricultural feedstocks. In the latter case we will focus on efficiency enhancement by investigating the key logistics questions involved with moving bulky feedstocks to facilities.

In the first essay, a framework is employed that can provide a sector level evaluation and suggestion for agricultural mitigation policies in INDCs (Intended Nationally Determined Contributions), taking into account strategy interactions and food market effects by building a quadratic, price endogenous programming model. In the case study of Vietnam, the model provides the optimal portfolios of the INDC options across different mitigation targets/incentives. Significant differences between economic and technical potential of mitigation policies are discovered. According to the assessment of mitigation policies on food market prices, Vietnam’s agriculture can accomplish unconditional contribution claimed in the INDC with modest impacts on its food markets.

The results also suggest that delaying mitigation effort will increase the total costs of achieving the INDC commitments especially when the total amount of mitigation is not large.

In the second essay, we turn to the issues of supply chain efficiency in moving agricultural feedstocks from points of production to biorefineries. The literature is overviewed and synthesized on economic concerns involved within biofuel supply chain. Opportunities and challenges emerge from feedstock production, prepossessing, storage and transportation in the biofuel supply chain systems are discussed.

Following the conclusions from the second essay, the third essay quantitatively examines supply chain efficiency. In doing this we develop a mixed integer nonlinear programming (MINLP) model which integrates feedstock production, preprocessing, storage and biorefining as well as biofuel market effects. A case study is carried out at the level of the state of Texas for a variety of scenarios in terms of total amount of cellulosic biofuel produced then the model choice of supply chain elements is analyzed. Finally, we examine the value of including or omitting key supply chain elements considering the use of multiple feedstocks, preprocessing and feedstocks produced on marginal land.

DEDICATION

To my family

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I love this world.

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CHAPTER I

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas (GHG) emissions need to be reduced in order to avoid dangerous climate change (Fifth Assessment Report 2014). In this context, the 19th Convention of the Parties on Climate Change (COP19) in Poland in 2013 called upon all parties to develop "Intended Nationally Determined Contributions" (INDCs), containing plans for GHG emissions reductions. Almost all of the countries that were parties to the agreement have submitted their INDCs and many of these contain emissions reductions arising from agriculture. There are a number of ways of achieving emissions reductions and agriculture can play a role. Some involve reducing emissions and enhancing sequestration and yet others involve substituting low emitting products for higher emitting products (e.g., using agricultural feedstocks to produce liquid fuel replacing petroleum). In this dissertation we will investigate strategies that reduce emissions and/or enhance sequestration first in terms of a countrywide INDC and later in terms of replacing liquid fuels with biofuel produced from agricultural feedstocks. In the latter case we will focus on efficiency enhancement by investigating the key logistics questions involved with moving a bulky feedstock to a facility.

1.1 Background on INDCs and Vietnam

As stated above under the Paris Accord countries need to lay out plans for emissions reductions in the form of an INDC. Many countries have done so and many of these involve an agricultural component although for the most part the INDC is conceptual in nature based on technical concerns but not an economic and practical implementation one. Here we will investigate how realistic the Vietnam INDC is, what the best mix of mitigation strategies in it would be and what type of monetary incentive would need to be offered to stimulate adoption.

Vietnam is a representative developing country striving to make ambitious yet realistic contributions to GHGs mitigation. In forming its INDC Vietnam recognizes that agriculture sector is a large emitter of GHGs and also has substantial potential for offsetting emissions at a low cost. However, there is some uncertainty about those agricultural opportunities in terms of their competitive, economic potential in Vietnam. The evidence is lacking on the optimal sequence and combination of mitigation options over time and under different mitigation incentives. Secondly, large-scale country wide mitigation efforts in agriculture are likely to have effects in food markets altering agricultural production and consumption. Such actions could possibly threaten food security as well as increase farmers' opportunity costs of implementing agricultural GHG emissions reductions and thus affect mitigation opportunity desirableness and in turn adoption. Interactions between strategies also have largely been ignored.

In this study, we try to consider all of these factors discussed above simultaneously and employ a framework that can provide a sector level evaluation and suggestion for agricultural mitigation policies that would aid in implementing the INDC, taking into account strategy interactions and food market effects. We will carry out this study by building a quadratic, price endogenous programming agricultural sector model for Vietnam.

1.2 Background Fossil Fuel Replacement and Logistics

In addition and as part of many INDCs, countries are endeavoring to replace fossil fuels with domestically produced and lower GHG emitting biofuels particularly in the transportation sector. Biofuels produced from agricultural biomass have been proposed as part of the solution to climate change as they replace high GHG emitting fossil fuels while also enhance a country’s energy security. Such biofuels are attractive because in many countries the biomass feedstock can be produced renewably from a variety of domestic sources, and the production and use of bioenergy/biofuel products have potentially lower environmental impacts than their petroleum counterparts.

Consequently, many countries have set national biofuels targets and provide incentives and policy support to accelerate the growth of bioenergy industry. Considering the case in the United States of America, currently most biofuels in the U.S. are made from corn starch, which is the major type of first generation biofuel. However, a large dependence on corn as the biofuel feedstock has led to the debate about food versus fuel when the cultivated lands are used for energy production as opposed to traditional commodities.

These concerns have stimulated the development of second-generation biofuels. Cellulosic biofuel, which is produced from lignocellulosic biomass. However such feedstocks are bulky and early implementations have had issues in terms of logistics with today‘s cost apparently being substantially more than the fuel price as manifest in the high value of the RIN (Renewable Identification Number) compliance instrument (Figer 2011; Jones et al. 2017; Lim and Ouyang 2016). Therefore, improving the economic efficiency of the total farm to biorefinery system is a critical issue to large-scale commercialization.

An extensive amount of research is currently focusing on improving biomass productivity and designing the most efficient production through conversion system. However, the management of the feedstock production to biofuel processing facility supply chain is a less studied endeavor (An, Wilhelm, and Searcy 2011). The biofuel supply chain has many specific features compared with highly standardized grain feedstock or petroleum fuel supply chains. Total system planning in terms of land use change, storage, preprocessing, seasonality, transportation, biofuel market and other logistical issues are largely ignored by previous studies.

1.3 Plan of Dissertation

The work done in this dissertation will be reported through three essays. Chapter II presents agriculture sector component of a proposed Intended Nationally Determined Contributions employing a case study in Vietnam. Chapter III identifies the key research challenges and opportunities in designing and assessing biomass-to-bioenergy supply chains. Chapter IV examines biomass to bioenergy supply chain design and the value of utilizing various components.

CHAPTER II

ECONOMIC INVESTIGATION OF AGRICULTURE SECTOR IN INTENDED NATIONALLY DETERMINED CONTRIBUTIONS: A CASE STUDY OF VIETNAM

2.1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas (GHG) emissions need to be reduced in order to avoid dangerous climate change (Fifth Assessment Report 2014). In this context, the 19th Convention of the Parties on Climate Change (COP19) in Poland in 2013 called upon all parties to develop “Intended Nationally Determined Contributions” (INDCs), containing plans for GHG emissions reductions. Almost all of the countries that were party to the agreement have submitted their INDCs and many of these contain emissions reductions arising from agriculture.

Many studies have broadly discussed agricultural greenhouse gas mitigation potential from a global perspective (Smith et al. 2007; Smith et al. 2008). However, previous assessments are limited in scope neglecting major elements of the problem which we list below.

Firstly, the studies referenced above have covered the full domain of possible practices in general but not specific nationwide mitigation policies being implemented or proposed in a developing country. Trying to evaluate the INDCs in specific countries is valuable especially since INDCs are starting to be implemented. Moreover, even though the INDCs include information on contribution objectives, timeline, implementation scope, assumptions and approaches, they are often still brought discussions and are not totally clear on the exact pathway to be used to achieve the final target. In particular, the evidence is generally lacking on the sequence and combination of mitigation options to be employed over time and the specific design of any mitigation incentives is needed to facilitate private parties in choosing to follow the plan. Also, the INDC actions still need to be assessed as implementation proceeds in order to verify that the contributions are on target and do not face major implementation obstacles as the original plans are not totally appropriate in the country context.

Secondly, the estimates of the emissions quantity reduced via the mitigation options proposed are often based on small-scale implementations or experiments along with theoretical calculations without considering market implications. However, large-scale, countrywide implementations are likely to have market place effects in turn altering agricultural production patterns, market prices, resources available and consumption plus having further effects on emissions across the country and even in competitor countries. Such actions can increase farmers’ opportunity costs of adopting the agricultural GHG net emission reduction practices and thus affect mitigation option desirableness and performance. McCarl and Schneider (2001) found that when considering such forces the economic potential is much lower than the technical potential showing that increasing levels of compensation are necessary to procure higher levels of GHG mitigation from the activities. Additionally, Murray et al (2005) found market effects can stimulate offsetting leakage. Thus mitigation options should be evaluated within not only project content but also should also consider the total market and consumption system plus the global effects on emissions.

Thirdly, most mitigation strategy effectiveness studies only examine a single option without considering competition with other strategies for resources. Following arguments in Murray et al (2005) the competition between options that draw from a common resource base needs to be considered. For example, a single piece of land could not be simultaneously used for afforestation, dedicated bioenergy crop feedstock production and altered tillage. It is also possible that simultaneous implementation of multiple strategies can exploit complementarities to lower costs.

In this study, we evaluate the agricultural component of the Vietnam INDC. In doing this we try to consider all of the factors discussed above. Namely we do the evaluation in a modeling framework that considers the multiple strategies simultaneously at the sector level taking into account strategy interactions and market effects. Subsequently, we report on the optimal portfolios of strategies that generate various agricultural GHG emission contributions to a total county reduction and the resultant agricultural commodity market effects.

2.2 Background on Vietnam’s INDC

Vietnam has embedded the INDC into the long-term national Green Growth Strategy policy framework, which is a comprehensive, integrated part of national planning. The plan elements prioritize GHG emission reduction efforts (MARD 2015). In forming its INDC Vietnam recognized that agricultural sector is a large emitter of GHGs contributing about 39% of Vietnam's total carbon dioxide equivalent (CO_2eq) emissions. In terms of non-CO_2 GHGs agriculture releases about 68% of Vietnam's methane emissions and 73% of its nitrous oxide (UNFCCC, 2010). Furthermore, international assessments have identified agriculture as a sector with substantial potential for offsetting CO_2 emissions through augmented carbon sequestration. Murray et al. (2005) found in the U.S. setting that agricultural opportunities are available at a much lower cost per ton, compared with non-agricultural contributions.

Vietnam’s INDC consists of conditional and unconditional contributions to reducing GHG emissions. Unconditional contributions are those that can be implemented using domestic resources, while conditional contributions require international financial, technical and capacity building support. The total INDC specified mitigation goal from agriculture is 46.2 $MtCO_2$eq (million-ton carbon dioxide equivalent) at the maximum level of unconditional and conditional contributions. Vietnam in its planning gives the highest priority to the implementation of the unconditional contributions and sets an ambitious but also realistic mitigation target of 6.4 $MtCO_2$eq. In particular, even though the INDC is a commitment for the post-2020 period implementation actions are already underway through linked policies such as NAMA (Nationally Appropriate Mitigation Actions). Such actions are considered as an entry point for determining the feasibility of achieving the INDC. We do not emphasize on the differences between INDC with NAMA in this study, since a country's INDC acts as a general guideline while NAMA clarifies necessary actions.

However, there is some uncertainty about the GHG mitigation potential for those agricultural opportunities in Vietnam. Therefore, studies are needed on how the agriculture sector could contribute and respond to GHG reduction policies as an input to suggestions for implementing nationwide INDC. Designing a good plan in the early phase of implementation is important and urgent since Vietnam is heading to become reclassified as an industrialized country by 2020 upon which the financial support mechanism currently in place is still not strong enough to reduce GHG emissions.

2.3 Conceptual Model

A quadratic, price endogenous programming model, VASMGHG, will be used. This model is structured in the manner discussed in McCarl and Spreen (1980) as was implemented in the U.S. as Agricultural Sector Model (ASM) model (Adams et al. 2005; Baumes 1978; Beach and McCarl 2010). This model also includes GHG accounting as implemented in Schneider (2000) and McCarl and Schneider (2001). The approach simulates a perfectly competitive equilibrium within the agricultural sector in the presence of carbon pricing via the solution of an optimization problem whose first order conditions specify attainment of a competitive market equilibrium under a given set of supply and demand conditions (Ohrel et al. 2010). In particular, under the assumption that producers and consumers exist in a perfectly competitive market, their behavior can be simulated by maximizing producers' and consumer's surplus. The model incorporates constraints representing land, water, and labor endowments, commodity production technologies, supply and demand balances, trade balances, crop mix balance and also relevant policies.

Mathematically the model is as follows. Total agricultural surplus variable (*WELF*) is to be maximized. In Equation (1) *WELF* is set equal to the area under the commodity demand curves (denoted by function P_D) for multiple products (denoted by variable Z_h) less the area under the factor supply functions (denoted by function P_S) for inputs (denoted by variable X_i). In this case the area under the factor supply curves constitutes the total cost of production ($C_i(X_i)$). We also add in the area under export demand curves less that under the import supply curves. The consequent model has exogenous factor supply and product demand curves, but implicit factor demand and product supply.

Because of data requirements and information limitations in the Vietnam case, we specify the demand functions in a linear form, $P_{Dh} = \alpha - \beta Z_h$. Considering that the study focuses on the agricultural sector in Vietnam which is small in the context of global production and consumption we will use the small country assumption and use fixed, exogenous import and export prices (denoted by P_{IMh} , P_{EXh} respectively).

$$WELF = \sum_h \int_0^{Z_h} P_{Dh}(Z_h)dZ_h - \sum_i \int_0^{X_i} P_{Si}(X_i)dX_i = \sum_h Z_h(\alpha - 0.5\beta Z_h) - \sum_i C_i(X_i) + \sum_h P_{EXh}EX_h - \sum_h P_{IMh}IM_h \quad (1)$$

Agricultural production and food processing technologies are represented by Leontief production possibilities specifying fixed quantities of multiple inputs and outputs. In particular, for crop production, total factor use for factor *i* (X_i) will equal the per unit production use (a_{ik}) times the associated land use $Land_k$ (for crop *k*) summed over all crops.

$$-X_i + \sum_k a_{ik} Land_k \leq 0 \quad \text{for all } i \quad (2)$$

Another set of constraints addresses aggregation related aspects of farmers' decision process. These constraints force producers' land allocation ($Land_k$) to fall within the historical minimum and maximum level for each crop *k*.

$$Land_k \leq Max_k \text{ ; } Land_k \geq Min_k \quad \text{for all } k \quad (3, 4)$$

For raising livestock and poultry of animal type *j* (variable $Live_j$), a given amount of crop feedstuffs of type *k* (n_{kj}) are needed to provide sufficient nutrients.

$$Feed_k \geq \sum_j n_{kj} Live_j \quad \text{for all } k \quad (5)$$

Also the model includes a supply demand balance for crops where a crop of type *k* is either sold to food market ($Crop_k$) or used as feed ($Feed_k$) with this being less than or equal to total crop production which is computed as crop yield (y_k) times land use ($Land_k$).

$$Feed_k + Crop_k \leq y_k Land_k \quad \text{for all } k \quad (6)$$

Supply and demand balance equations for the food market form an important constraint set in the model, which link agricultural activities to output markets. Specifically, the total amount of crop commodities disseminated in Vietnam domestic food market through consumption (Z_{h-crop}) plus exports (EX_{h-crop}) cannot exceed domestic crop production level for food $Crop_k$ with processing technologies $c_{h-crop,k}$ plus imports (IM_{h-crop}). Livestock commodities (i.e., meat, dairy, egg, etc.) follow similar rules with processing technologies $l_{h-livestock,j}$ for livestock raising $Live_j$. Note that *h-crop* and *h-livestock* are subsets of commodities *h*. Equation (7) and (8) shows the set of commodity supply and demand balance equations employed in the model, which is indexed over commodities.

$$Z_{h-crop} + EX_{h-crop} \leq \sum_k c_{h-crop,k} Crop_k + IM_{h-crop} \quad \text{for all } h\text{-}crop$$

$$Z_{h-livestock} + EX_{h-livestock} \leq \sum_j l_{h-livestock} Live_j + IM_{h-livestock} \quad \text{for all } h\text{-}livestock \quad (7, 8)$$

In our study, we also consider food stuffs to meet nutritional requirements. The domestic consumption Z_h is constrained to exceed the minimum nutritional requirement per capita ($Nutri_h$) times population (*Pop*). Note that $Nutri_h$ is a commodity based measurement. Any policy intervention is restricted by the minimum food consumption per capita.

$$Z_h \geq Nutri_h * Pop \quad \text{for all } h \quad (9)$$

We constrain the model so that no more than certain share (R_h) of food can be imported from international sources reflecting a food security concern regarding the degree of dependence on imports.

$$IM_h \le R_h * Z_h \quad \text{for all } h \quad (10)$$

Since we are analyzing Vietnam's INDC it is essential that the model portrays agriculturally based net greenhouse gas (GHG) emissions. To facilitate this task, VASMGHG includes GHGs accounting equations by gas as shown in Equation (10), where e_{gk} is net emissions of gas g when planting one hectare of crop k and e_{gj} is net emissions when raising one animal of type j.

$$EMIT_g = \sum_k e_{gk} Land_k + \sum_j e_{gj} Live_j \quad \text{for all } g \quad (11)$$

There are also resource availability equations that limit the total use of natural or human resources to be at or below given regional endowments b_w. The main resources covered are labor, water and land endowment. Note that the natural and human resource index w is a subset of the production factor index i.

$$\sum_k a_{wk} Land_k \le b_w \quad \text{for all } w \quad (12)$$

Finally, all the decision variables are forced to be nonnegative.

The above model structure covers the basic structure of agricultural production and markets, and now we need to add GHG mitigation possibilities. In doing this we need to include production alternatives that enhance sequestration or reduce emissions. Therefore, production variables are expanded so they have an additional dimension related to mitigation options. Decision variable $Land_k$ will become $Land_{km}$ and $Live_j$ will become $Live_{jm}$.

McCarl and Schneider (2001) showed that different portfolios of mitigation activities arise as the volume of offsets rise or as the carbon price rises. Consequently in looking at the INDC we followed McCarl and Schneider (2001) in developing a supply curve of possible agricultural mitigation that varies depending on the size of the contribution agriculture would make at the national level. Given an agricultural mitigation target we will simulate the optimal mix of mitigation options chosen. In doing this there are *m* possible alternatives with each having GHG consequences and a pattern of costs and resource usages ($indc\_cost_m$). The production decision variables for crop and livestock management are $Land_{km}$ and $Live_{jm}$ and each has a projected emission reduction coefficient for the k^{th} cropping activity and the j^{th} animal activity ($INDC_{km}$, $INDC_{jm}$), which give the amount of net greenhouse gas reduction when applying particular crop and livestock production possibilities. The equation imposing the target (T) on GHG net emissions reductions will be

$$\sum_{k,m} INDC_{km} * Land_{km} + \sum_{j,m} INDC_{jm} * Live_{jm} = T \quad (13)$$

Upon solution, the shadow price on this equation is the marginal cost of developing an offset and corresponds to a carbon dioxide equivalent price.

Also, there are constraints limiting the adoption of the mitigation alternatives to a given limit (Cap_{mk} and Cap_{mj}) for GHG mitigation option on each crop and livestock.

$$Land_{mk} \le Cap_{mk} \text{ for all } m,k\,;\; Live_{mj} \le Cap_{mj} \quad \text{for all } m,j \quad (14, 15)$$

2.4 Data

This section presents discussion on the scope and empirical specification of the VASMGHG model. It covers domestic production, imports and exports for 15 commodities. The commodities included are the most critical food categories in Vietnam (Table 1). The 15 commodities arise from 7 crops and 6 livestock raising activities with the use of inputs categorized into land, fuel, fertilizer, pesticide, labor and other. The main data sources are the 2013 FAOSTAT database and other studies in the literature. The food processing input-output ratio is the ratio of food items produced via a processing channel divided by raw material consumption using data from FAOSTAT tables on Food Balance and Production. The maximum and minimum shares of land use for each crop are based on historical data since 2000 from FAOSTAT. Food consumption per capita from FAOSTAT Food Balance is used for deriving nutritional constraints related to food security. For inputs data, due to limited information on Vietnam agricultural production, we use the data arising in the Philippines' agricultural datasets from Philippine Statistics Authority. Elasticities for the commodities are adapted from (Hoang 2009; Le 2008) Demographic and resource availability data were drawn from the General Statistics Office of Vietnam.

The INDC contains a number of suggested GHG mitigation strategies. Some of these can be implemented within the country without external help are called unconditional contributions. The others require foreign assistance and are called conditional contributions. Here we will focus on all but one of the unconditional options eliminating the consideration of whether external support can be obtained. However, even though the INDC classifies improving livestock diets (A11-LIVDIET) as a conditional option that addresses enteric fermentation, we still incorporate it in our study because it is the only option related to livestock herd management. Option A1-BIOGAS which involves increasing rural use of biogas for cooking is the only option we do not consider among the unconditional options and is omitted since it is not closely related to food production and consumption. The potential mitigation strategies included in the model are listed in Table 2 including data on estimated greenhouse gas offset per unit and the maximum amount of the strategy that can be implemented.

Table 1. Data Collection Summary

Alternatives	**Notation in the Model**	**Elements**
Crops	K	paddy, corn, sugarcane, cassava, soybean, groundnut, sweet potato
Livestock	J	beef cattle, dairy cow, sheep, pig, poultry for egg, poultry for meat
Commodities	H	rice, corn, sugar, cassava, soybean, soybean oil, shelled groundnut, groundnut oil, sweet potato, beef, lamb, pork, poultry meat, egg, milk
Inputs	I	land, fuel, fertilizer, labor, fertilizer, others
GHG	G	CO_2; N_2O; CH_4
Data	**Notation in the Model**	**Source**
Crop yield	y_k	FAOSTAT-Production
Inputs	a_{ik}	FAOSTAT-Input, Literature (Heffer 2009; Khai and Yabe 2013; Young et al. 2002), Philippine Statistics Authority
Human nutrition	$Nutri_h$	FAOSTAT-Food Balance
Livestock nutrition	n_{kj}	FAOSTAT-Food Balance
Food processing	c_{hk} ; l_{hj}	FAOSTAT-Production, FAOSTAT-Food Balance
Import and Export Prices	P_{EXh} ; P_{IMh}	FAOSTAT-Trade
GHG Emissions from Production	e_{gk} ; e_{gj}	FAOSTAT-GHG Emissions
Demand Function	$\alpha; \beta$	Literature (Hoang 2009; Le 2008)
Endowments	b_w	FAOSTAT

Table 2. Mitigation Options for Agriculture Sector in Vietnam's INDC

Option	**Description**	**Mitigation Potential**	**Maximum Units to Which This Can be Applied**
A1-BIOGAS	Increased use of biogas	3.17 MtCO_2eq in total	*NA*
A2-ORGFERT	Reuse of agricultural residue as organic fertilizer	0.103 tCO_2eq/ha	6.3 million ha
A3-RICEWD	Alternate wetting and drying, and improved rice cultivation system	4.682 tCO_2eq/ha	1.7 million ha
A4-BIOCHAR	Introduction of biochar	5.370 tCO_2eq/ha	3.7 million ha
A5-RICEICM	Integrated Crop Management (ICM) in rice cultivation	0.500 tCO_2eq/ha	1.0 million ha
A6-ANNICM	Integrated Crop management (ICM) in annual crop cultivation	0.300 tCO_2eq/ha	2.0 million ha
A11-LIVDIET	Improvement of livestock diets	0.080 tCO_2eq/cattle	22.0 million cattle

2.5 Results

2.5.1 Model Baseline

The estimation of a baseline is an important first step for this study, because the amount of realized mitigation is the consequent difference between the emissions with the INDC program and the emissions without it. The emissions without the program are commonly called the baseline emissions.

The baseline 2013 GHG emissions as simulated with the model appear in Figure 1 for the agriculturally relevant mitigation categories. The major agricultural emission categories are:

- Methane produced from rice cultivation.
- Emissions from agricultural soils mainly in the forms of soil carbon release and nitrous oxide emissions from fertilizer use.
- Emissions from livestock via enteric fermentation and manure management which are the smallest of the three categories as of 2013 but are expected to increase by 2030 due to alterations in diet and income.

The model derived estimates for these emission categories are within 5% of the amounts estimated by the Vietnam Ministry of Natural Resource and Environment (MONRE) except in the livestock category. This arises since the optimal number of livestock suggested by the model is less than herd size assumed by MONRE. The model chooses to use the land to produce and export rice and then import meat instead of raising livestock and livestock feed in Vietnam. We feel these model results provide an adequate baseline for the subsequent INDC analysis.

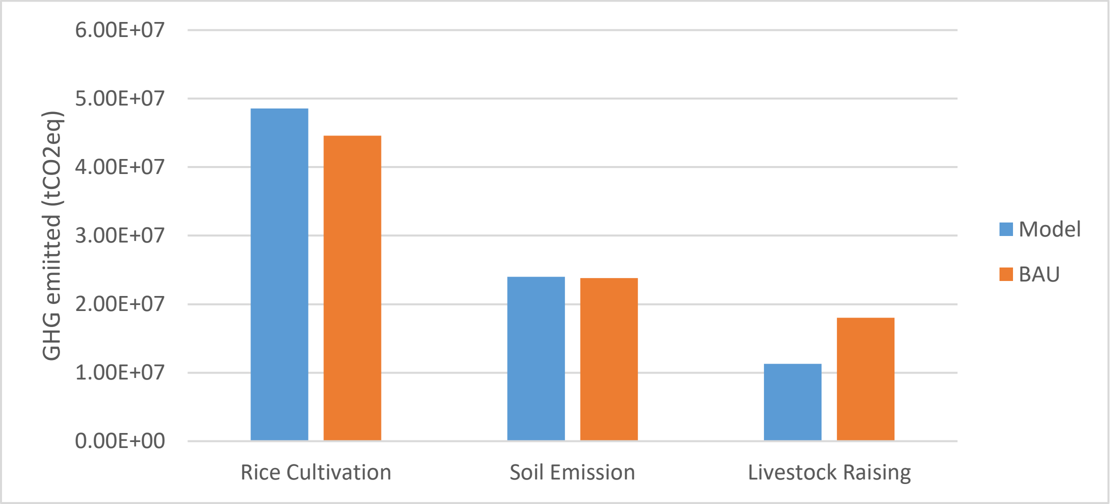


Figure 1. GHG Emissions: Model Baseline vs. BAU from MONRE

2.5.2 Mitigation Option Adoption and Potentials

2.5.2.1 Abatement Curve

Next we wished to examine the optimal portfolio of agricultural options used at various offset targets. To do this VASMGHG was run under different mitigation targets ranging from 1 to 27 million metric tons which correspond to 2% to 60% percent of stated maximum intentions in Vietnam's INDC. The resultant portfolio of mitigation options chosen and their relative contributions are graphically summarized in Figure 2 and listed in Table 3. The prices reported in the table are the shadow prices from the abatement target constraint and are reported in $/tCO_2eq.

Results show that at low carbon prices/offset quantities, strategies that are highly complementary with current production are used. These are:

- Agricultural residues as an organic fertilizer supply in crop fields (A2-ORGFERT),
- Integrated crop management for rice crops that reduces fertilizer use and methane emissions from rice cultivation (A5-RICEICM),
- Integrated crop management for non-rice crops that reduces the use of including fertilizer and fossil fuels in annual crop cultivation (A6-ANNICM) and
- Improvement of livestock diets by reducing roughage and substituting grains (A11-LIVDIET).

At higher prices/emission offset quantities the dominant strategy involves the introduction of biochar on existing croplands (A4-BIOCHAR) which enhances soil carbon sequestration. Additionally the Option A3-RICEWD that alters the irrigation schedule to incorporate midseason drying so as to reduce methane emissions does not appear in the portfolio until the price is much higher falling above \$70/tCO_2eq for around 20 million metric tons of agricultural emissions reductions.

Much as in McCarl and Schneider (2001) we find the portfolio of chosen options varies with the size of the effort measured either in the magnitude of the price or the quantity of offsets to be achieved. The composition of this portfolio gives information on strategies to utilize in order to meet a given agricultural mitigation goal. Initially at modest offset levels or as the project is just beginning the most desirable options for use are (A2-ORGFERT, A5-RICEICM, A6-ANNICM and A11-LIVDIET) which are relatively inexpensive and do not really alter major production practices. These options are the same ones utilized as we move toward the larger goal or choose to allocate more emissions to agriculture. Then to achieve a larger quantity of emissions we begin to use the more expensive and disruptive options A3RICEWD and A4BIOCHAR which will require greater levels of incentives.

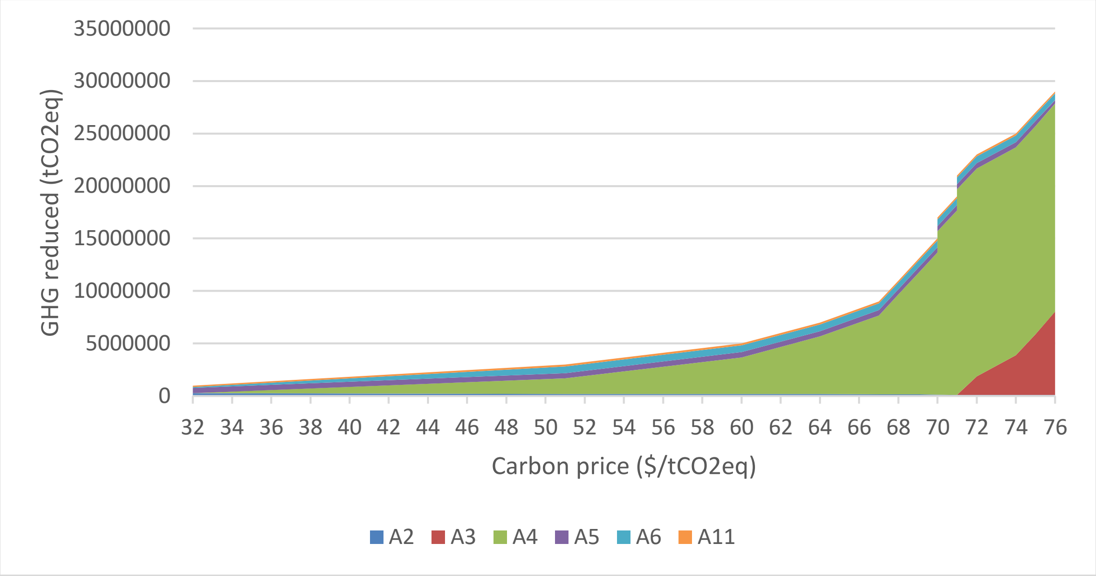


Figure 2. GHG Abatement Curve

2.5.2.2 Competitive Economic Potential of Mitigation Options

Many estimates for the emission abatement potential of selected strategies consider a strategy only in isolation ignoring resource competition and effects on agricultural markets. Also technical potential estimates state the total amount of the mitigation options are applied on all possible lands, or to all possible animals giving an ultimate quantity which ignores the cost of achieving that level of abatement. This may generate misleading results as argued in McCarl and Schneider (2001). In particular we expect an increasing amount of abatement the larger the price even within particular options due to resource competition and the use of higher cost lands as the abatement effort grows. To demonstrate the importance of such economic considerations, we use our model to compute competitive economic potential for each of the major agricultural strategies and compare with the levels of technical potential reported in the Vietnam INDC submission to UNFCCC (Figure 3).

Figure 3 shows GHG reductions achieved for each option as prices increase. The figure also includes a dotted green line which gives the technical potential for each option. As shown in Figure 3, programs on improving soil sequestration and crop cultivation (A3-RICEWD, A4-BIOCHAR, A5-RICEICM and A6-ANNICM) can ultimately approach the technical potential cited in the INDC document but slightly fall short of it when they take high carbon prices. For most of mitigation options, the amount of each strategy used keeps increasing with price until it reaches capacity. Among these options, the way of reducing GHG emissions via rice cultivation management (Option A5 in Figure 3) is the strategy that comes closest to the technical potential even considering the influences from other mitigation options and market conditions. Its supply of GHG reduction is inelastic to carbon price and is also consistent with technical potential. On the other hand the adoption of the A3-RICEWD and A6-ANNICM needs larger and larger carbon prices or incentive levels to achieve higher levels of abatement. Both A6-ANNICM and A11-LIVDIET reach their upper bound around \$50/tCO_2eq, but with different marginal contributions. Therefore, promoting integrated crop management (A6-ANNICM) would seem to merit usage before 2020 because of large marginal mitigation potential over a wide price range. In contrast, mitigation efforts from improving livestock diets are far below technical potential because of large opportunity costs generated from the food market because of the nutritional requirements for meat. There even exists significant mitigation reversion by using agricultural residue as organic fertilizer (A2-ORGFERT) when competing with other options**.** Its contribution significantly becomes smaller when other options are possible as incentives keep increasing. The lesser levels from this practice are driven by the fact that, the increasing marginal cost of mitigation from A2 is higher compared to others when considering the food market especially when A2 is applied to crops which have elastic demand such as corn and sugarcane.

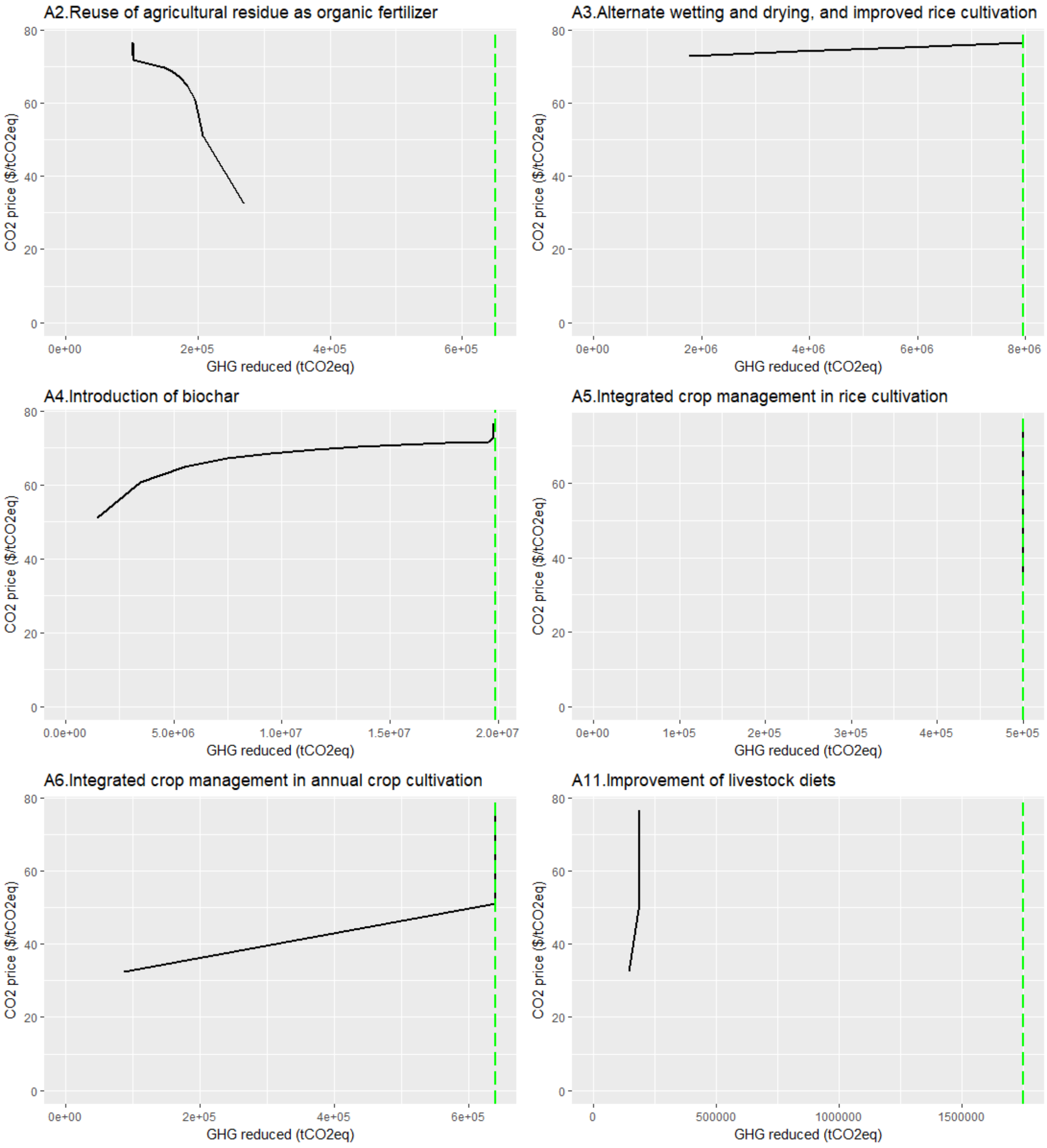


Figure 3. Individual Behavior of Different Mitigation Options

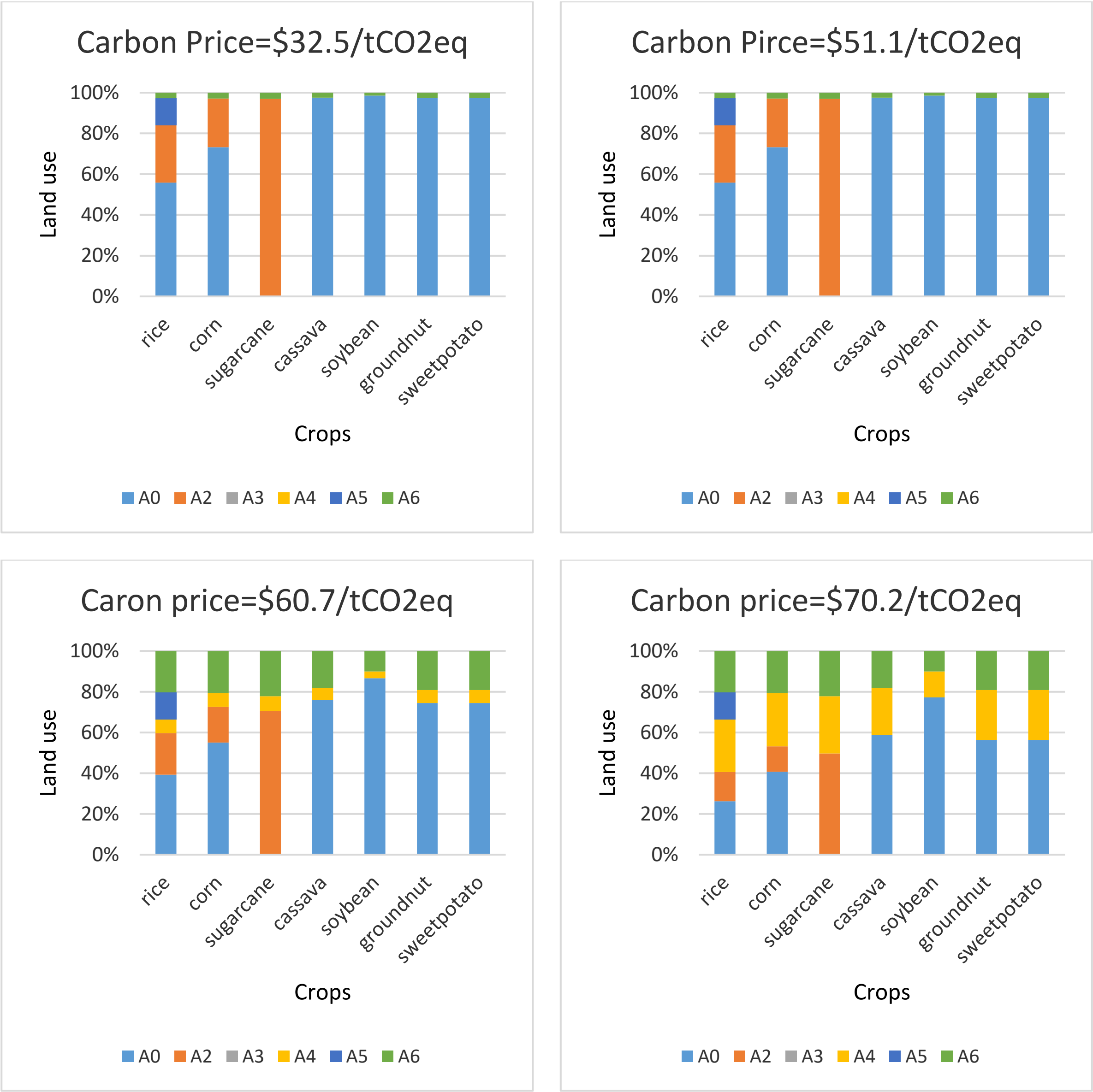
Finally, not only do mitigation strategies compete with each other, but also they displace traditional food production raising market prices and decreasing food consumption as also found in McCarl and Schneider (2001).The analysis also shows that Vietnam cannot satisfy the total INDC specified mitigation goal from agriculture (46.2

$MtCO_2eq$) by only using unconditional mitigation strategies since food demands slow down the implantation of some options. The upper bound of GHG reduction is calculated in the model without violating the constraints on food security. This bound is 29.2 $MtCO_2eq$ and amounts above that do not result in enough food to achieve country food security. Therefore, the unconditional requirement (6.4 $MtCO_2eq$) set by INDC can be easily satisfied, while extra international support is needed in order to provide Vietnam with enough incentives to reduce the amount more than 29.2 $MtCO_2eq$.

2.5.2.3 Distribution of Options among Crops

In addition to demonstrate the optimal portfolios of mitigation options according to varied carbon prices (mitigation targets), the distribution of each strategy among crops can also be illustrated. The application percentage based on land use for each crop is presented in Figure 4 with four mitigation targets simulated. Therein A0-NOMIT represents land use without applying any options.

Compared with those four mitigation scenarios in Figure 4, rice cultivation adopts most mitigation options. This occurs because of the large share of rice production in Vietnam plus the fact that certain options (A3-RICEWD and A5-RICEICM) are designed for rice only along with the substantial food demand for rice. The choices of corn mitigation options are applied in a form that is quite similar to that for rice because of the large fertilization requirements. Most of the production decisions on cassava, sweet potatoes, soybean and groundnut choose to not do any mitigation at low carbon prices. The participation for these crops is still moderate when higher carbon prices occur.


Carbon Price=$32.5/tCO2eq

Carbon Pirce=$51.1/tCO2eq

Caron price=$60.7/tCO2eq

Carbon price=$70.2/tCO2eq

Figure 4. Mitigation Strategy Use by Crop at Alternative Carbon Prices

As a cash crop, the percentage of strategies applied for sugarcane are significantly different from other two groups mentioned above. Sugarcane cultivation is highly affected by mitigation target starting at low carbon prices. The option A2-ORGFERT dominates for sugarcane due to the relative elastic demand for sugar and its low implementation cost. The options applied on sugarcane change significantly as carbon prices increase since A4-BIOCHAR and A6-ANNICM can provide large marginal mitigation potential after carbon price is over \$50/tCO$_2$eq.

2.5.3 Agricultural Market Impacts

The impacts of adopting the mitigation options on the commodity markets are also worthy of discussion and are summarized in Figure 5 and Table 3. It should be mentioned that a significant change in domestic food consumption is not allowed due to the constraints on nutritional requirements and self-sufficiency. In looking at the results we will examine an index of commodity prices under different incentives (mitigation targets). The price index calculation uses the Fisher Ideal Price Index to calculate price change under mitigation scenario s from the baseline (s_0). Also in this case h is the set of commodities considered in the model.

$$P = \sqrt{\frac{\sum_h (p_{hs} q_{hs_0})}{\sum_h (p_{hs_0} q_{hs_0})} \times \frac{\sum_h (p_{hs} q_{hs})}{\sum_h (p_{hs_0} q_{hs})}} \quad (15)$$

The price index results in Table 3 are not significantly changed when the carbon price is lower than \$51/tCO$_2$eq or the agricultural mitigation target is 3.0 MtCO$_2$eq, which is labeled the end of stable prices phase as shown in Figure 5. Then there is a moderate price increase stays up to \$67/tCO$_2$eq where agriculture mitigates is 9.0

$MtCO_2eq$ and prices increase by 4.5%. For targets above that commodity prices increase significantly. This means if agricultural mitigation targets exceed 9.0 $MtCO_2eq$, this will harm food security particularly of the urban poor who would not benefit from the higher prices while rural parties might benefit from sales income at higher prices plus any incentives that are given to get farmers to adopt mitigation practices.

As to agriculturally sector related welfare change without considering the positive externality from reducing GHGs, the economic surplus (Table 3) keeps decreasing for increasing mitigation target without any incentives or subsidies paid by the government to stimulate practice adoption. The impacts on economic surplus grow as the targets become more stringent particularly when the mitigation target is above 20$MtCO_2eq$. Achievement of an unconditional contribution in the INDC (6.4 $MtCO_2eq$) with a 2% price increase results in a 16% welfare reduction.

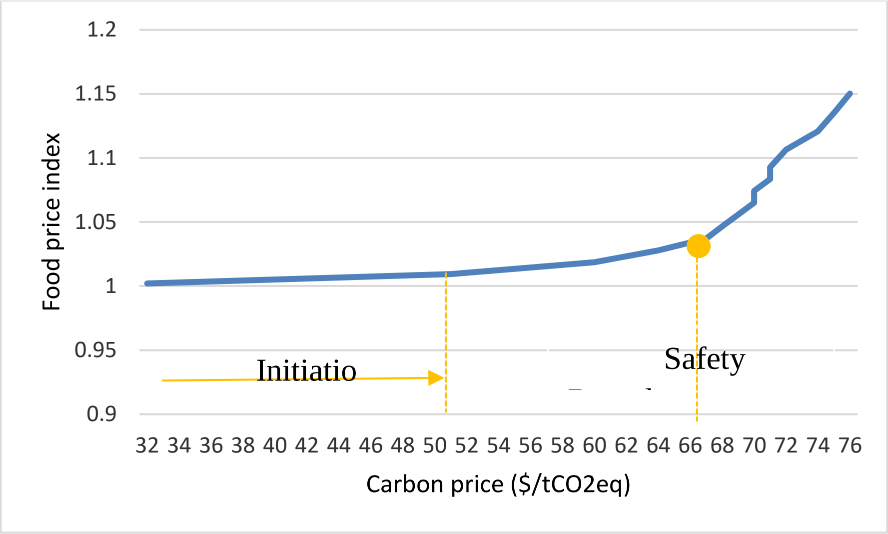


Figure 5. The Impacts of Mitigation Options on Food Market

2.5.4 Examining Future Effects of Mitigation Policy

Even though the model is static, we can investigate the effects of adopting an INDC portfolio for a future date with projecting technological progress and consumption growth.

We constructed a yield for the year 2020, where between 2013 and then crop yield is projected to grow at an annual rate of 1.2% per year while the population is projected to grow 1% per year as discussed in (Rutten et al. 2014; Smith et al. 2007). We also project that nutrition intake from meat, egg and milk will increase by 57% compared with food consumption in 2013, while the quantities of staple food consumed per capita remain stable. In turn given these assumptions we examine the implications of six mitigation targets with the results in Table 4.

Therein we find the not unexpected result that reducing one ton of CO_2eq becomes more expensive as time goes on. It indicates that 'wait' is not a good strategy because of increased mitigation costs. In the case of Vietnam, the mitigation cost per tCO_2eq grows more significantly overtime since food prices and land opportunity costs go up. Therefore, it is rational to begin mitigation actions as soon as possible while additional conditional mitigation actions can wait until international financial, technical and capacity building support becomes available and the agricultural target is over 7.0 $MtCO_2eq$.

The optimal portfolio of mitigation options is also changed due to the evolution of agricultural productivity and food demand growth. The emission reduction from improving cattle diet (A11-LIVDIET) increases in importance because of the increased demand for beef and the consequent larger herds. There is also increased reliance on the altered irrigation schedule for rice cultivation (A3-RICEWD) given the population induces increased demand for staple food.

The role of biochar and integrated rice management (A4-BIOCHAR and A5-RICEICM) in both cases reaching their respective capacity when aggressive mitigation targets are imposed. Contributions from substituting chemical fertilizer with agricultural residues (A2-ORGFERT) become more significant, however, that strategy still loses competitiveness with higher prices/mitigation targets due to competition with other strategies as found in the 2013 case. All mitigation options except A6-ANNICM are used to greatest extent because of the yield and demand growth. The reason leading to the distinct behavior of A6-ANNICM is that there exists a relatively elastic demand for food produced from crops other than rice and hence the opportunity cost increases more significantly in 2020 compared with rice and livestock production. Therefore, one can support A4-BIOCHAR and A5-RICEICM consistently and increase the implementation scale gradually over time for A3-RICEWD and A11-LIVDIET. For option A6-ANNICM, extra care should be taken because of a sensitive reaction to the change of market conditions. In scenario 2013, A6-ANNICM is quickly adopted and ultimately reach its maximum capacity whereas it disappears from the optimal portfolio in scenario 2020 mainly because it is applied to crops with high demand elasticity. The mitigation option distribution between different crops is similar with the scenario of 2013 except for the absence of option A6-ANNICM in mitigation scenarios. This relatively stable structure indicates the best set of climate mitigation policies does not vary greatly over time.

Finally, in terms of impacts on the food market, we find the price index effects are larger than the 2013 results as would be expected given the demand shifts, but these increases are small being less than 0.1%. The magnitude of negative impacts on welfare do not change a lot when GHG reductions are below unconditional contributions, however, the negative effect is largely reduced within conditional mitigation range due to the support from agriculture production development.

Table 3. Mitigation Efforts and Agricultural Market Shifts: Scenario 2013

Year 2013	**Carbon price in \$ per tCO_2eq**					
	32.5	51.1	60.7	64.8	70.2	75.1
GHG abatement by individual strategy ($MtCO_2eq$)						
A2. Reuse of agricultural residue as organic fertilizer	0.2696	0.2078	0.1962	0.1846	0.1382	0.1021
A3. Alternate wetting and drying, and improved rice cultivation system	0.0000	0.0000	0.0000	0.0000	0.0000	5.7769
A4. Introduction of biochar	0.0000	1.4662	3.4778	5.4894	13.5358	19.7950
A5. Integrated Crop Management in rice cultivation	0.5000	0.5000	0.5000	0.5000	0.5000	0.5000
A6. Integrated Crop management in annual crop cultivation	0.0869	0.6400	0.6400	0.6400	0.6400	0.6400
A11. Improvement of livestock diets	0.1435	0.1860	0.1860	0.1860	0.1860	0.1860
Total GHG emission abatement ($MtCO_2eq$)	1	3	5	7	15	27
Agricultural market shifts						
Crop prices index	1.0020	1.0094	1.0187	1.0279	1.0650	1.1350
Changes in agricultural economic surplus (Billion \$)	-0.031	-1.1807	-1.3309	-1.4810	-2.0816	-3.0571

Table 4. Mitigation Efforts and Agricultural Market Shifts: Scenario 2020

Year 2020	**Carbon price in \$ per tCO_2eq**					
	35.9	60.3	66.2	68.8	72.1	76.4
GHG abatement by individual strategy ($MtCO_2eq$)						
A2. Reuse of agricultural residue as organic fertilizer	0.3494	0.3384	0.3268	0.3152	0.2688	0.2353
A3. Alternate wetting and drying, and improved rice cultivation system	0.0000	0.0000	0.0000	0.0000	0.0000	6.2282
A4. Introduction of biochar	0.0000	1.9201	3.9317	5.9433	13.9897	19.7950
A5. Integrated Crop Management in rice cultivation	0.4091	0.5000	0.5000	0.5000	0.5000	0.5000
A6. Integrated Crop management in annual crop cultivation	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
A11. Improvement of livestock diets	0.2415	0.2415	0.2415	0.2415	0.2415	0.2415
Total GHG emission abatement ($MtCO_2eq$)	1	3	5	7	15	27
Agricultural market shifts						
Crop prices index	1.0021	1.0111	1.0203	1.0296	1.0666	1.1378
Changes in agricultural economic surplus (Billion $)	-0.051	-0.1971	-0.3472	-0.4973	-1.0979	-2.0793

2.6 Conclusion

Herein we reported on an examination of the potential role of agricultural GHG mitigation efforts included in Vietnam's INDC submitted to the UNFCCC process. Results show that Vietnam agriculture can implement strategies that do not require much international funding support with modest impacts on the food market if the mitigation target is relatively small being less than 9.0 $MtCO_2eq$. Furthermore, with substantial likely international financial support the agriculture sector can further contribute up to 29 $MtCO_2eq$.

For low agricultural mitigation shares or low GHG prices, prevalent strategies are reduced chemical fertilization, integrated cultivation management, and improved livestock diets. At higher carbon prices, most of the emission abatement comes from introducing biochar which enhances carbon sequestration. The best portfolio of mitigation strategies varies depending on the size of the agricultural mitigation target.

Through comparing estimates of abatement potential we find significant differences between economic and technical potential estimates. Our study suggests that the INDC overstates the potential of some strategies like reduced fertilization as it apparently omits considerations of interactions of mitigation policies and effects in the food market. The results also show the implementation of mitigation options varies between crops.

The effects of mitigation on food market prices are modest at low levels of agricultural offsets with only a 2% price increase associated with achievement of the unconditional contributions (6.4 $MtCO_2eq$).

The 2020 results suggest that delaying mitigation effort will increase the total costs of achieving the INDC commitments especially when the total amount of mitigation is not large. There is a different optimal mix of mitigation strategies compared with those in 2013, the results indicate how a nation-wide policy will adjust mitigation practices over time until 2030. Furthermore, the impacts on food market are relatively insensitive to the timing of mitigation efforts.

Several important limitations and uncertainties are present in this study. First, the findings presented here reflect technologies for which data were available. For example, most of the data from the traditional agricultural sector are based on FAOSTAT data with some needed transformations done to fit them into the model. Thus, the reliability of the estimates depends on the quality of the FAO data. Second, several potentially relevant factors are not considered due to limited information and these are the magnitude of needed implementation incentives, additional transaction costs involved in assembling farmers and monitoring their compliance with agreements and the potential yield increases and other benefits that would occur because from GHG mitigation is undertaken. Third, the time path of carbon sequestration rates and their eventual saturation are not considered herein because of the static setup of the model.

CHAPTER III

SUPPLY CHAIN DESIGN AND ASSESSMENT FOR CELLULOSIC BIOFUEL PRODUCTION: A LITERATURE REVIEW

3.1 Introduction

In conjunction with mitigation efforts and in pursuit of energy security many countries are endeavoring to replace fossil fuels with domestically produced and lower greenhouse gas (GHG) emitting biofuels particularly transportation fuels. Agricultural biomass-derived liquid transportation fuels and energy products have been proposed as part of the mitigation and energy security solution because the biomass feedstock can be produced renewably from a variety of domestic sources. Furthermore, the production and use of bioenergy/biofuel products have potentially lower environmental impacts than their petroleum counterparts including lesser GHG emissions (Granda, Zhu, and Holtzapple 2007; Yue, You, and Snyder 2014; You et al. 2012). Consequently, many countries have set national biofuels targets and provide incentives and policy support to accelerate the growth of bioenergy industry.

Currently most biofuels in the U.S. are made from corn starch, which is the major type of first generation biofuel. Corn ethanol production grew from around 8 million gallons in 1981 to more than 14 billion gallons in 2016, taking advantage of the fact that corn is the largest U.S. crop with more than 90 million acres of land planted to corn in 2016 (U.S. Bioenergy Statistics, USDA). Although corn production is increasing over time and corn ethanol production is commercialized maturely around the world, there is debate about food versus fuel when the cultivated lands are used for energy production.

Specifically, some studies (Babcock 2012) claimed that it is indisputable that biofuels contributed to increased agricultural commodity prices because the biofuel industry represents a large and growing share of corn consumption with 41.9% and 38.1% of total U.S. production in 2015 and 2016 respectively. The situation may get worse with food demand growth and weather related supply problems.

These concerns have stimulated the development of the second-generation biofuels. Cellulosic biofuel, which is produced from lignocellulosic biomass, is a representative second generation biofuel. Lignocellulosic biomass can come from residual, non-edible parts of food crops (e.g., stems, leaves and husks) as well as other non-food crops (e.g., switchgrass; jatropha; energy sorghum; fuelwood, industrial waste such as wood residues, skins and pulp from fruit pressing). Additionally several other second-generation biofuels are under development, including biohydrogen, biomethanol, 2,5-dimethylfuran, biodimethylether, biohydrogen diesel, mixed alcohols and wood diesel (An, Wilhelm, and Searcy 2011).

The usage of a lignocellulosic biomass is attractive from a food competition consideration. The expanded Renewable Fuel Standard program under the Energy Independence and Security Act of 2007 (EISA) reflects this in its renewable fuel standard provisions (called RFS2). That legislation mandates that starting in 2016, all of the increased blending in renewable fuels counting toward the RFS2 requirements must be met with second generation or other advanced biofuels, including cellulosic biofuel, biomass-based diesel, and other biofuels from other than starch grains. The targeted goals for 2022 are for 15 billion gallons per year (BGY) of conventional renewable transportation fuel (such as corn grain based fuel) and 21 BGY of advanced biofuels.

However, due to constraints in the fuel market to accommodate increasing volumes of ethanol, along with the low production of second generation renewable fuels and high production costs, the volume targets for cellulosic ethanol have not been achieved. Some companies have now brought cellulosic ethanol facilities online, but with widely varying costs. The lowest projected minimum ethanol selling price is $2.17 per gallon while a capital-intensive $500 million facility has the highest price of $4.55 with feedstock and logistics cost emerging as the most critical variable (Biomass Magazine 2016). Economic viability is clearly a critical issue hindering large-scale commercialization. An extensive amount of research is currently focusing on improving biomass productivity and designing the most efficient production through conversion system. However, the management of the feedstock production, storage and movement to biofuel processing facility supply chain is a less studied endeavor (An, Wilhelm, and Searcy 2011).

The biofuel supply chain has many different features than the highly standardized grain feedstock or petroleum fuel supply chains. Feedstocks are bulky, heavy with moisture, seasonably available, subject to large yield fluctuations, perishable in storage and easily combustible. It has been estimated that the logistics cost will account for more than 30 percent of the biofuel cost. Furthermore, the industry is still currently relying upon pilot plants and the logistics details that are not fully worked out, whereas conventional agriculture and petroleum based supply chain are well established. In addition, potential outcomes and impact of alternative biofuel supply chain designs are in flux within this industry and have caused some industrial failures with only one of a number of near commercial scale facilities operating today. In order to improve the overall economic profitability and social benefits, systematic modeling and optimization frameworks are required to simultaneously assess and identify the sustainable solutions for the design and operation of biofuel supply chains (You et al. 2012).

To accelerate the transition towards the large-scale and sustainable production and use of biofuels and bioenergy products, this study will identify the key research challenges and opportunities in designing and assessing biomass-to-bioenergy supply chains then feed them into an analytical exercise in this study.

In doing this we firstly describe the key components of the biomass-to-biofuels supply chains and their major characteristics, along with a comprehensive overview and classification of the existing contributions on these key components. In particular, we will cover important components of feedstock production, preprocessing, storage and transportation. We further demonstrate the important role of multi-scale modeling and optimization, which allows the integration across multiple logistics components. The exiting contributions are classified by deterministic and stochastic models. At the end of this study, we address the sustainability issues in biofuel supply chains, concerning environment, society, and economy respectively.

3.2 Key Supply Chain Components

A supply chain constitutes the activities involved in moving a product or service from supplier to customer, including procurement, conversion, possible storage, facility location and all logistics management activities. A study (Hess, Wright, and Kenney 2007) indicates the feedstock supply chain costs encompass 8% of the total grain-based ethanol production costs. In contrast, the supply chain for cellulosic biofuel has been estimated to account for 35-65% of the total production cost (Fales et al. 2007, Kumar and Sokhansanj 2007). Logistical costs that exceed 25% of the total biomass value may leave very little room for profit for biomass producers and biorefineries (Hess, Wright, and Kenney 2007).

Due to the characteristics of cellulosic biomass, several issues related to the movement from farm to consumers must be considered and dealt with to achieve an economically viable and efficient supply chain system. These issues have significant impacts on supply chain design and associated outcomes, and also interact with each other. All of these problems and the corresponding relationship will be discussed below. One should note that the supply chain issues are highly correlated but are separated here for convenience of discussion.

3.2.1 Feedstocks

3.2.1.1 Cellulosic Feedstock Types

One cellulosic feedstock appraisal is in the Billion-Ton Study (*Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*). That analysis addressed whether the conterminous U.S. agriculture and forestry resources had the capability to produce at least one billion dry tons of sustainable biomass annually to displace 30% or more of the nation’s present petroleum consumption. The first edition of the report (2005 BTS) was an estimate of “potential” biomass based on numerous assumptions. A major limitation of the 2005 BTS is that the identified biomass was not restricted by cost including logistics, and some of the potentials would likely be too expensive relative to other renewable feedstocks under current and prospective technological changes. Therefore, the Billion Ton Updated (BT2) in 2011 contained attempts to estimate biomass supply costs and quantities.

Estimates were made at a county level and summarized in this report as national totals. The BT2 categorized the potential feedstock based on the sectors (i.e. agriculture, forestry, energy crops). We will review the most representative biomass types among which are feedstock candidates for supply chain models. More importantly, BT2 handles most of concerns when designing the feedstock layer such as spatial availability for each feedstock and economic competition within crops.

3.2.1.1.1 Agricultural Biomass

Agricultural biomass mainly refers to crop residues including corn stover (stalks, leaves, and cobs), sorghum stubble, and straw from small grains (wheat, oats, and barley). Crop residues are desirable feedstocks for bioenergy applications because of their low cost, immediate availability, and relatively concentrated location in the major grain growing regions. In the BT2, supplies of crop residues were estimated simultaneously with energy crops like switchgrass since they may compete with energy crops for land and any changes in land use affect estimated quantities. More importantly, county-level supply curves of crop residues were estimated. A number of factors were taken into account when estimating available crop residues to make the result more reliable. The price of these residues included the collection costs, a payment to the grower based on the nutrient value of the residue, and a profit for economic consideration but nothing on logistics. Furthermore, sustainability was also taken into account with requirements for residue retention to control soil erosion and soil organic matter content. In addition, estimates were made for a baseline and a high-yield scenario which provide the possibility to operate scenario analysis for supply chain system.

3.2.1.1.2 Forest Biomass

Forest biomass and wood waste resources considered mainly include forest residues, unused primary and secondary mill processing residues, urban wood wastes and conventionally sourced wood. Forest residues refer to logging residues and thinnings from forest operations. Total logging residue and other residue in the United States currently amount to nearly 93 million dry tons annually—68 million dry tons of logging residue and 25 million dry tons of other removal residue (Smith et al. 2009). Most of this residue is left onsite because its small diameter size makes it unsuitable and uneconomic for the manufacturing of forest products. However, as markets for bioenergy feedstocks develop, a significant fraction of this residue could become economically feasible to remove, most likely in conjunction with conventional harvest operations where the costs of extraction (i.e., felling and skidding) are borne by the conventional forest product.

The other categories of harvest (saw and pulp logs) are not treated as feedstock candidates according to the following reasons. Wood that has commercial uses other than fuel (e.g., pulpwood and lumber) will cause unexpected competition within different industries which is not a desirable direction for the development of biofuel. As for urban wood wastes plus construction and demolition wastes, estimating how many of these resources that could move into bioenergy production is difficult and speculative, not mention that woody waste is impossible to treat in a uniform fashion to some extent. Also in reality, the BT2 study argues that only the pulpwood-sized round wood would be used for biomass. Although the processing of conventional forest products generates significant quantities of bark and mill residues, these forest products industry residues are currently used in the manufacture of forest products or for heat and power production, and valuable chemicals are recovered from pulping liquors.

3.2.1.1.3 Energy Crops

Typically, energy crops include perennial grasses (e.g.,switchgrass, miscanthus, etc.), woody crops (e.g., poplar, willow, southern pine, eucalyptus) and annual energy crops (e.g., high-yield sorghum).

In the BT2, an agricultural policy simulation model (POLYSYS) was used to assess the economic competitiveness of energy crop production and determined how much cropland and pastureland could possibly shift to energy crops. Unlike other feedstocks, the feature that energy crop must compete with traditional agricultural land use should be carefully dealt with. For example, implementing switchgrass-based bioenergy production systems requires converting marginal land from pasture, conservation plantings or annual row crops to switchgrass. By varying prices offered for biomass feedstocks, POLYSYS estimated potential energy crop supplies and changes in land use, including acreage changes among crops and conversion of cropland and pastureland to energy crops. Furthermore, potential production of different biomass at various years and farm gate prices were estimated. It also illustrated corresponding state shares of woody biomass, energy crops and agricultural residues at different farm gate prices.

Even though BT2 gives a comprehensive review of various feedstocks production and prove potentially sufficient availability, especially addressing the economic competition between traditional agricultural use and energy crop as well as energy crop competition with each other. However, the estimated amount and proportion of feedstocks availability for each state (county) still cannot reflect the real supply chain structure and costs since the report does not consider logistics or the downstream of supply chain such as biorefinery requirement. It leads us to discuss those factors in next section.

3.2.1.2 Issues on Feedstock Production in Supply Chain

The economic viability of the supply chain is primarily based on the availability and associated price of cellulosic feedstock, since biomass competes for land with conventional crops and pasture, including corn for ethanol. Namely, considerations for supply chain (logistics) begin with the profitability of feedstock production for farmers, which should at least exceed the breakeven price of foregoing conventional production on diverted cropland/pastureland. Many factors (climate, land attributes, productivity, etc.) will influence the magnitude of profit and also its uncertainty. Obviously, those factors vary and correlate with each other spatially which results in geographically dispersed or concentrated feedstock production. Hence, distance from the facility becomes a major issue with cost rising under geographically dispersed feedstocks or falling under concentrated production. In addition, cellulosic feedstock can come from various types of feedstock (agricultural residues, perennial grasses, woody residues, etc.) and downstream biorefineries may have an incentive to use a portfolio of these to avoid risk and seasonal differences given seasonal supply and raw material price/quantity fluctuation but this trades off against increases in processing and facility cost that are required to handle multiple feedstocks. So supply chain design should take care of feedstock production density and possible diversification.

Furthermore, second generation biomass production possibilities also compete with each other not only based on net revenue of cultivation but also in delivered cost including logistics cost. For example, woody crops have potentially less complex supply chains. In its simplest form, a woody crop can be harvested, chipped, and transported directly to the conversion facility and may not need storage. Furthermore, woody crops can be stored on the stump, with increasing volume, until needed at the conversion facility. Perennial grasses, annual energy crops, and crop residues have limited harvest and/or collection seasons and will require storage for use outside of the harvest season. This complicates the supply at a facility as a source of feedstock is needed year round and reliance on seasonal feedstocks can cause large storage needs and possibly storage losses. These herbaceous feedstocks also require more handling operations and are much bulkier than corn.

Another feature worth mentioning here is the low density and significant moisture content of agricultural feedstocks, which result in inefficient transportation per unit energy content as well as a need to dry or handle water in the biofuel conversion process. Moreover, raw material deteriorates over time due to this proportion of water. As a result, the industry may well need distributed preprocessing and storage with appropriate material flow scheduling within the logistics system. More considerations of designing supply chain system to deal with these specific characteristics will be discussed in the next section.

To sum up, farm gate analysis for the biofuel industry can distort the relative competitiveness of different sources and one must consider logistics design. Given the huge amount of possibilities from the supply side, deriving a comprehensive supply system to determine the production locations and associated logistic system for different types of feedstock is crucial. In addition, the value of using multiple feedstocks should be emphasized.

3.2.1.3 Using Multiple Feedstocks

The problems introduced by the seasonality and uncertainty of biomass availability plus the need for storage may be reduced, when the multi-biomass approach is applied to smooth supply fluctuation (Rentizelas, Tolis, and Tatsiopoulos 2009).

The research performed on the multi-biomass concept is very limited to date. For example, the simultaneous use of straw and reed canary grass was investigated (Nilsson and Hansson 2001). The conclusion was that the specific combination led to a total system cost reduction of about 15–20% compared to a single-biomass case, despite the increased production cost of reed canary grass compared to straw. Another interesting study (Epplin et al. 2005) was applied in the case of the state of Oklahoma to determine optimal combinations of feedstock from among grasses produced on Conservation Reserve Program (CRP) land, crop residues (maize stover and wheat straw), perennial grasses (indigenous grasses from native range and introduced grasses from pastures) and dedicated feedstock such as switchgrass (Panicum virgatum). Results indicated, among others, that restricting harvest to CRP acres imposed a rather substantial cost on the industry. For a 2000-t/day biorefinery, limiting feedstock production to CRP land would increase the expected cost to deliver a ton of cellulosic biomass to US$69 compared with a cost of US$33 for the multiple feedstock model.

Moreover, multiple feedstock supply could also reduce risk. Feedstock concentrated production ties total yield to environmental conditions such as precipitation, drought, heatwaves or forms of extreme weather. A multiple feedstock supply system can alleviate the variation in total supply when one feedstock is disrupted. For example, the study of Kou and Zhao (2011) showed that the risk of bankruptcy for a single-feedstock biorefinery was 75% with extreme weather condition while the risk for a multi-feedstock biorefinery was zero.

3.2.2 Preprocessing and Storage Facilities in Supply Chain

3.2.2.1 Preprocessing

Two particular features of the cellulosic feedstocks are that they have low density and contain substantial moisture. Preprocessing to densify and reduce moisture comes into the list of considerations if one wants to improve supply chain efficiency.

Biomass bulk density has a major impact on material handling, transportation, storage, processing efficiency, labor requirements and energy requirements (Sokhansanj et al. 2002). For example, truckloads of baled biomass are limited by volume rather than weight, resulting in high delivery costs (transportation and handling) per unit energy. In order to reduce delivered biomass costs, research primarily focuses on preprocessing biomass close to the point of harvest into a higher density, stable, standardized, and easily transportable form. Carolan et.al (2007) proposed the development of regional preprocessing centers (RBPC) that would be a part of the supply chain feeding into a biorefinery as a way to address dry matter losses, high transportation costs, and other potential logistical issues. The key question with this approach is whether the potential saving in storage and transportation costs could at least offset the fixed costs of the investment in preprocessing technologies. This economic variability of preprocessing was discussed by Larson et al. (2010) considering a preprocessing facility for densification and packaging before feedstock was placed in on-site storage at the conversion facility. Results suggested that the preprocessing system outperformed the conventional bale harvest methods in the delivered costs of switchgrass under the assumption of a given biorefinery size of 25 million gallons per year and a feedstock draw area of 50 miles. Similarly, Yu et al. (2011) evaluated the potential value of including preprocessing in the biomass feedstock supply chain for a biorefinery in East Tennessee. The results showed that stretch-wrap bale preprocessing technology could reduce the total delivered cost of switchgrass for large-scale biorefineries.

After harvesting, biomass must typically be preprocessed to reduce moisture content before it is processed at a biorefinery to produce biofuel, while stored biomass continues to degrade until converted. The benefit of preprocessing to reduce moisture can be integrated with storage method and dry matter loss reduction approaches. However, models are needed to manage the trade-off between storage methods and the capacity of preprocessing facilities. Larger capacities would allow preprocessing facilities to process biomass more quickly and create a denser item, so that less storage capacity would be required. However, capacity is expensive and it may be more economical to build plants of lesser capacities and incur the costs of providing storage facilities and of biomass degradation (Rentizelas, Tolis, and Tatsiopoulos 2009). In addition, the level of moisture that is acceptable depends on the conversion method utilized (An, Wilhelm, and Searcy 2011).

One densification method, pelletization, should be mentioned here since this technology gives the possibility to store feedstock for a long time (more than one year) and ship it nationally or internationally since pellets are easy to handle and exhibit reduced transportation costs in comparison to less condensed chips or bales (Hamelinck, Van Hooijdonk, and Faaij 2005). A study by Mani et al. (2006) mentioned that lignocellulosic biomass in its original form usually has a low bulk density of 30 kg/m3 and a moisture content ranging from 10% to 70%. Pelleting increases the specific density of biomass to more than 1000 kg/m3. Pelleted biomass has low moisture content and standard format. Forest and sawmill residues, agricultural crop residues, and energy crops can be densified into pellets. More importantly, the study estimated capital and operating cost of the pelleting plant at several plant capacities. Pellet production cost for a base case plant capacity of 6 tons/hour was about $51/ton of pellets. Pellet plants with a capacity of more than 10 tons/hour decreased the costs to roughly $40/ton of pellets. Raw material cost was the largest cost element of the total pellet production cost followed by personnel cost.

3.2.2.2 Storage

One characteristic of biofuel supply chain is that feedstocks (e.g., herbaceous crops) are harvested seasonally. Because feedstock availability is limited during some months of one year in addition to limited refinery capacity and risk consideration, storage is required.

Firstly, several broad categories of storage locations can be used individually or jointly. Feedstock can be stored in the field, in intermediate storage locations, or at the biorefinery. Three most frequently used biomass storage methods (storage enclosed in a warehouse, a covered storage facility and ambient storage) were analyzed and applied in a case study to come up with tangible comparative results by Rentizelas et al. (2009).

Specifically, the costs of these types of storage were calculated separately and cost allocation in the whole logistics under each storage scenarios were compared.

Some early studies contributed to the estimation of dry matter loss based on different storage methods and durations. For example, a large round bale may have an advantage over a large rectangular bale with respect to dry matter losses when stored outdoors (Cundiff and Grisso 2008). However, a large rectangular bale system, which has a larger throughput capacity than a large round bale system, may have harvest, handling, and storage economies of size advantages over large round bales (English, Larson, and Mooney 2008; Thorsell et al. 2004). In terms of storage loss, Larson et al. (2010) using data from a switchgrass storage experiment, estimated storage dry matter loss for a rectangular bale of switchgrass that was covered with a tarp and stored outdoors was 30 percent after 360 days in storage under Tennessee conditions. By comparison, the estimated storage dry matter losses after 360 days in storage for round bales of switchgrass wrapped with twine and stored outside with and without a tarp cover were 9 and 13 percent, respectively. The storage dry matter loss estimated in the study for uncovered switchgrass round bales is similar to the losses reported in a limited set of other studies addressing this issue (Johnson et al. 1991; Sanderson, Egg, and Wiselogel 1997; Wiselogel et al. 1996).

A comprehensive study by Kim (2011) estimated various biomass commodities (i.e., agricultural residuals, woody biomass and energy crops) storage cost adjusted by dry matter losses for both indoor and outdoor storage. In detail, the amortized cost of building and keeping storage for one unit of feedstock, the cost of moving one unit of feedstock in and out of storage, and the cost of maintaining one unit of the feedstock for one month were estimated separately. This study also highlighted the number of months of peak storage, the number of months an average ton was stored for different feedstocks.

Last important issue is the determination of the safety inventory level to overcome uncertainty. However, there are few articles addressing this. In a specific case study by Rentizelas et al. (2009) it was simply assumed that there was biomass inventory in the storage facility equal to the one required for 20-day full load operation of the biomass plant. In terms of carbon sequestration Kim and McCarl (2009) derived a safety margin. Like the storage issue, the quantity of sequestered carbon may need to be discounted to avoid liabilities from carbon sequestration quantity shortfalls because stochastic factors make the quantity of carbon generated under a sequestration project uncertain. They presented a potentially applicable uncertainty discount and the variance in historical crop yields across geographical areas was used to form this discount.

3.2.3 Transportation

Transportation unifies farm level supplies of feedstock, preprocessing, storage depots and biorefinery into a complete supply chain system. Alternatives for feedstock transportation include roads, railways, waterways, and/or a mix. And also two major factors influencing the transportation cost are the location of the facilities discussed above and the density of the feedstock. Because transportation problem is highly reliant on other elements in supply chain, few research focuses on this single issue.

Various transportation methods were examined with influencing factors such as travel distance and speed (Kumar and Sokhansanj 2007). Also geographical conditions such as the slope of road, the access of highway were all found to influence the hauling speed and cost (Yu, et al., 2011). In terms of calculation of hauling cost from farmgate to roadside, French (1960) derived that the average hauling distance given a rectangular road system, density of biomass production, demand of biomass, and yield per acre. Following French, McCarl et al. (2000) estimated crop specific hauling costs per ton per trip.

Although several studies address and evaluate important elements in supply chain, the conclusions may be distorted if those alternatives are not considered within a system. Therefore, next section will review the design of supply chain system and associated elements configuration.

3.3 Supply Chain Modeling and Optimization

3.3.1 Deterministic Models

The literature on the biomass-biofuel supply chain is developing rapidly. Several studies with different prospective published in a variety of journals. Below, we present a review of the related literature from a wide range and discuss their advantages and disadvantages that need works to explore further.

Firstly, two review papers are mentioned that give us the direction of effort. An et al. (2011) classified prior research on biofuel supply chain based on decision time frame (i.e., strategic, tactical, operational, and integrated) as well as levels in the supply chain (i.e., upstream, midstream, and downstream), noting that most of the studies in the field focus on the upstream supply chain (from farm to conversion plant). Finally, An et al. (2011) emphasized unique needs to support decisions that integrate the farm with commercial levels (e.g., storage, preprocessing, refining, and distribution) and identified fertile avenues for future research on the biofuel supply chain. They argued operations research models are needed to help assure the economic viability of the biofuel industry and that such models can be used by growers, processors, and distributors to design and manage an integrated system and by the government to inform policies needed to stimulate the growth of the industry and, perhaps, subsidize it.

Secondly, Sharma et al.,(2013) summarized the research on developing mathematical models for biofuel supply chain design and management. The majority of the research works reviewed involved developing mixed-integer linear programming models with decision making capability ranging from strategic to operational-level. Commonly used quantitative performance measure for biofuel supply chain (BSC) models were cost minimization or profit maximization. New approaches for modeling BSC were also introduced such as state-task-network, spatially explicit, multi-stage, multi-echelon, time-staged multi-commodity, multi-objective/multi-period, two-stage linear programming, and techno-economic system model. These approaches increased BSC decision making capabilities, and also addressed some of the critical issues and complexity associated with the BSC system. The main goal of these models developed for BSC involved considering sources of variability due to process and environment into the models for better management.

For some representative studies addressing different issues in biofuel supply chain design are summarized next.

Bowling et al. (2011) presented a model for a three level upstream network (from farm to biorefinery) that aimed to maximize total system profit considering overall sales and the costs for the feedstocks, transportation costs, capital costs for the facilities, and the operational costs for the facilities. The optimal solution determined the preprocessing and biorefinery facility locations only in a single period with a single biomass type. Only six locations with specific feedstock availabilities were considered. And there were two locations to install the central facilities and also two locations to install preprocessing hubs. The results showed that dispersed facility locations usually yield better solutions.

Huang et al. (2010) developed an optimization model containing supply points, biorefineries, and end users that integrated spatial and temporal dimensions. The planning objective was to minimize the cost of the entire supply chain of biofuel from biowaste feedstock fields to end users over the entire planning horizon, simultaneously satisfying demand, resource, and technology constraints. However, the model did not allow for any depot collection facilities and end-of-period inventory holding. Authors conducted a case study in California in which 8 biomass types with a number of supply points (range from 14 to 57), 28 candidate biorefinery sites and 143 demand locations (cities) were considered. Moreover, three input parameters, transportation cost, maximum refinery capacity and feedstock availability, were altered and their effects on the system cost and design were found to be insignificant with exception that the decreased refinery capacities led to changes in system design. Finally they concluded that, through careful supply chain design, biowaste-based ethanol production could be sustained at a compatible cost around $1.1 per gallon.

Compared with the studies above, Zhu and Yao (2011) included storage facilities and analyzed the benefit of multi-feedstock to the supply chain model. By maximizing the system revenue from raw materials to final product, the model determined the collection and biorefinery locations along with production, inventory and transportation decisions for each time period. Capacity for biorefinery production and storage at collection facilities were also considered. In their case study, the authors considered an annual planning horizon with 12 month intervals, 3 biomass types with 14 supply locations, 3 candidate collection sites and 2 candidate biorefinery locations. Their analysis focused on the different impact between a single type of biomass (switchgrass) and multi-types on determining facility locations and biomass flows. It was concluded that, in the latter case, the total logistics cost became larger but the unit profit from biofuel increases, since multi-feedstock strategy smoothed the biomass production fluctuations due to seasonality.

Zhang et al. (2013) added more logistics alternatives. Especially, the tradeoffs in harvest costs, biomass storage costs with dry matter losses during storage and preprocessing cost were considered in determining the optimal multi-period supply chain. The objective was to minimize total system cost which included harvesting, storage, transportation, preprocessing and conversion costs by considering switchgrass as the biomass. A case study was conducted using the 53 counties in North Dakota with a year planning horizon (one month for each period). The results of the case study showed that loose chop preprocessed before going to the biorefinery was the optimal harvesting method for switchgrass as compared to traditional baling methods. The authors also claimed that biorefinery locations were insensitive to the annual variation in switchgrass yield.

Chen and Onal (2014) used a price-endogenous, dynamic, mixed-integer nonlinear programming (MINLP) model to determine the biofuel feedstock supply response in U.S. agriculture and future biorefinery locations that meet the mandated cellulosic biofuel production targets. Empirical results showed that: (i) the U.S. biofuel mandates would lead to a significant increase in food commodity prices; (ii) regional comparative advantage in producing biofuel feedstocks would be more important than proximity to biofuel demand locations when determining the optimum refinery locations; and (iii) incorporating biofuel refinery locations in land-use decisions would make a considerable difference in the regional biomass production pattern. Those results give us the motivation to consider a more comprehensive model to take care of more economic factor outside the typical supply chain model when including feedstock price.

The study by Eksioglu et al.(2009) considered both upstream and downstream decisions. Specifically, they modeled a four-level supply chain system, including biomass supply, collection facilities, biorefineries, and blending facilities, to determine collection facility locations and biorefinery location and capacity decisions. The model had a multi-period setting and includes harvesting, inventory, transportation and processing costs. The authors conducted a case study in Mississippi where they considered 45 counties as supply points.

3.3.2 Stochastic Models

Some studies in the literature consider uncertainty in problem parameters such as biomass supply, biofuel demand and biomass and biofuel prices. Different approaches including scenario-based optimization, stochastic programming and robust optimization, are utilized to incorporate these uncertainties.

Bai et al. (2012) examined relationships in the supply chain when facing uncertainty. This study incorporated the effects of biomass price on the biomass-biofuel supply chain network. A game-theoretic optimization model was introduced that designs the biomass-biofuel supply chain and determined farmers' and biofuel producer's decisions. The authors proposed two models: (i) a non-cooperative Stackelberg (leader and follower) model and (ii) a cooperative game model (centralized). In their Stacleberg model, each actor was assumed to try to maximize their individual profits, the cooperative model maximizes the system profit. The authors implemented both approaches on a case study in Illinois using networks with 20 farms, candidate biorefinery locations and local markets respectively. They observed that the system profit increased when there was cooperation between the biofuel producer and farmers. When cooperation existed, more biorefineries were open and more land was allocated to produce biomass.

Kim et al. (2011) presented a two-stage stochastic programming to illustrate the impact of uncertainty the overall profitability and design. The model included biomass supply locations and amounts, candidate sites and capacities for two kinds of fuel conversion processing, and the logistics of transportation from the locations of forestry resources to the conversion sites and then to the final markets. They determined the five most important uncertain parameters affecting the objective function which were: (i) the price of the final product, (ii)-(iii) the conversion yield ratios of the two conversion processes, (iv) maximum demand and (v) biomass availability. A total of 33 scenarios were generated by combining these five scenarios with their high and low values plus an expected value scenario. The authors implemented the robustness analysis and Monte Carlo sensitivity analysis to compare the multiple scenario design with the single scenario design.

Dal-Mas et al. (2011) proposed two alternative objective functions separately: (i) maximizing the system profit and (ii) minimizing the risk associated with the investment. The uncertainty came biomass purchase costs and biofuel market and were represented by a set of possible scenarios. A multi-echelon Mixed Integer Linear Program (MILP) was presented to help decision-makers and potential investors assessing economic performances and risk on investment of the entire biomass-based ethanol supply chain. The model allowed optimizing economic performances and minimized financial risk on investment by identifying the best network topology in terms of biomass cultivation site locations, ethanol production plant capacities, location and transport logistics. A case study of corn ethanol supply chain in Northern Italy was conducted and compare the different outcomes from two alternative objectives.

Osmani and Zhang (2013) presented models to design and optimize lignocellulosic based ethanol supply chains. Both papers introduced two-stage stochastic programs considering uncertainties in (i) supply (biomass yield), (ii) ethanol demand, (iii) biomass price and (iv) ethanol price.

Tay et al. (2013) presented a robust optimization approach for the synthesis of integrated biorefineries that dealt with uncertainties in raw material supply and product demand. This approach made use of a single-step mixed integer nonlinear programming, which was generated and solved with data from multiple biomass supply and product demand scenarios. Based on the optimized result, detailed allocation of biomass, intermediates, and final products was determined. The optimal capacity of each process technology was found. An illustrative case study was then used to demonstrate the effectiveness of the robust optimization approach with consideration of uncertainties.

Based on the review of represented papers, it can be concluded that even though each paper has particular understanding of supply chain design and authors address these concerns in each paper, a comprehensive model looking at all the factors simultaneously has not been done nor has it been used to study optimal design and the impact of adding or deleting components from the supply chain. This phenomenon drives us to conduct further study on this topic.

3.4 Modeling Sustainability Issues in Supply Chains

3.4.1 Socio-economic Effects of Supply Chain

3.4.1.1 Job Creation and Income

The generation and implementation of biofuel policies will consider a wide range of objects including energy security, environmental benefit, and also community development especially in terms of employment and income. Local communities also give the priority to these two issues regarding biofuel production. In general, biofuel industry has more impacts on rural development, since a biofuel plant is most likely to be set in rural area because of feedstock availability and byproduct consumption by livestock producers (Lambert et al. 2008). When studying on the impact of bioenergy sector on employment, terminologies and operational definitions should be clarified (i.e., direct employment vs. indirect employment; full-time employment vs. part-time employment) (Domac, Richards, and Risovic 2005). Therefore, the development of biofuel production in rural area may have positive effects on rural labor market by firstly introducing direct employment, and, secondly by supporting related industries and the employment therein. Considerable effort should also be made not only on the region under analysis but out of the specified region. It may give a distorted result and prediction about future employment and income if this leakage element is ignored. Furthermore, the duration of impact of biofuel production should also be paid attention (Domac, Richards, and Risovic 2005).

Parcell and Westhoff (2006) summarized the studies on economic effects on states and rural communities during the rapid growth period of ethanol production in the U.S.. And they claimed that given the production capacity around 2006, the ethanol production industry annually employed approximately 3500 workers, paid out nearly $132 million in worker salaries. For the entrance of an individual plant, a 60 gallon per year ethanol plant was projected to create a 54 direct and a 210 indirect jobs. Most of these studies used simulation approach such as input-output (IO) analytical process. According to Swenson's (2005) study, a 3.87 employment multiplier with a 40-employee ethanol plant will generate 155 job opportunities in total, and similarly, if income multiplier is 2.80, then an ethanol plant with 1 million payment to employees will generate the income effect of 2.8 million in total. For a most recent study conducted by Brown et al. (2013) using empirical approach, the employment impact was statistically significant, an ethanol plant leading on average to 0.9 percent increase in employment within the industries closed to ethanol production such as trucking and natural gas distribution. In particular, with a corn based ethanol plant, the average increase in local employment from all sources is 254 and 82 jobs are created within closed industries.

The horizontal comparison within energy industries may be desirable for local government and policy makers. Brown et al. (2013) considered three emerging energy industries including unconventional natural gas extraction, wind power, and corn-based ethanol production. The authors stated that the growth from the exploitation of unconventional sources made substantial contribution to employment growth, while the contribution from wind energy and ethanol plants were smaller. Also, from the perspective of vertical comparison, the potential economic effects of biofuel industries may vary from short term to long term. For example, the intensity of labor use may decrease with the technology development and appreciate logistics design. The results may also vary across studies, since the employment and income effects depend not only on the size of biofuel plant and biomass but also the socioeconomic status and other industries which may compete or cooperate with biofuel industry. For example, in developing countries, the wood-energy worker probably earns well below an average wage while the worker earns the equivalence to many other technically qualified jobs and has an average lifestyle. Therefore, many biofuel energy workers in developing countries would prefer other opportunities which can help them move up in the economic level (Domac, Richards, and Risovic 2005). In terms of impacts from other industries, biofuel industry may compete with other industries especially because of feedstock uses such as corn grain for food and corn for ethanol. Therefore, the expansion of biofuel production may lead to the increase in profitability of other industries, which will change the labor use and income within biofuel industry. The interaction between related industries with respect to employment and income effects remain largely understudied.

3.4.1.2 Welfare

Another concern when evaluating biofuel issues is welfare distribution. For example, subsidies and taxes usually alter the welfare distribution between consumers and producers. There are also other aspects involved with welfare changes such as externalities and international welfare.

Historically in the U.S. one major policy supporting biofuel was the $0.51 per gallon tax credit and the associated $0.54 per gallon tariff on imported ethanol. Rajagopal et al. (2007) found that the ethanol tax credit increased the welfare of gasoline consumers and corn producers, leading to an increase of social welfare of $17.4 billion. Taheripour and Tyner (2008) showed that the ethanol tax credit benefited corn producers. There are also studies that include estimates of environmental externalities. Vedenov and Wetzstein (2008) estimated that producing ethanol generated a $0.04 per gallon ($1.57/MT) environmental benefit.

Another important consideration is the international impacts. Studies showed that the RFS2 mandates cause some international consumer losses which lead to food security concerns but at the same time international producer gains (Ewing and Msangi 2009; To and Grafton 2015).

3.4.1.3 Market Implications

Biofuel production increases have influences on commodity markets. One significant agricultural market impact is altered commodity price due to increased commodity demand, affecting producers, consumers, and secondary processors. In 2005, 191 million tons corn were consumed by non-ethanol sources, whereas that number in 2012 was slightly over 145 million tons, a 30% decrease (NASS Database). Biofuel production creates a tighter supply environment, which raises prices. The prices received by farmers went up by 56% (17% in real terms) and hence land values also went up from 2001-2015 by 273% (in real terms by 201%). The high prices stimulated additional supplies with the 2001-16 period showing a 16% increase in corn planting, a 43% increase in total production, a 22% increase in yield per acre and an 85% increase in nominal price (35% adjusted for inflation). The supply increase has come from both intensification in the form of yield per acre and extensification through increased acreage. But this trend slowed dramatically in 2013 when the RFS2 ceiling and blend wall was reached with declining price and acreage but increasing crop yield. This portends a lower corn price future which we have seen since 2013.

Several studies have examined U.S. biofuel policy influences on commodity price and welfare. Babcock et al. (2011) simulated three ethanol policy scenarios; the full RFS2 mandate, a limited mandate of 9 billion liters (2.4 billion gallons) of RINs, and a full waiver (i.e. no mandate at all). The difference in corn price between having no biofuel mandate and the limited mandate was an extra $11.02/MT ($0.28 per bushel). Additionally, the difference between the limited mandate and the full mandate was an additional $35.82/MT ($0.91 per bushel) of corn with the total effect of the mandate being a $46.84/MT ($1.19 per bushel) increase in corn price.

3.4.2 Environmental Impact

The major issues of environmental sustainability and environmental consideration for certain policy or project are (1) GHG emission, (2) water resources quality (3) soil degradation and loss of biodiversity. Cellulosic ethanol has the potential to cut greenhouse gas emissions by up to 86% (Awudu and Zhang 2012). However, biofuel production especially its supply chain may have huge emissions, because fossil energy is used during the farming of biomass crops, delivering feedstocks, pretreat feedstocks and during biofuel production.

Since biofuel production results from environmental awareness, the study of environmental sustainability has received increasing attention in the past decades. Among the various approaches, life cycle assessment (LCA) methodology is one of the most successful tool for evaluating and analyzing the environmental impacts of product systems (Azapagic 1999). Therefore, the life cycle optimization framework was proposed in biofuel supply chain design (Gebreslassie et al. 2013; Gebreslassie, Waymire, and You 2013; Wang, Gebreslassie, and You 2013; Yue, Kim, and You 2013). This general modeling framework takes LCA methodology into account, allowing us not only to identify the optimal solution for economic concern but also evaluate the environmental impacts of alternative supply chain assignment. When other criteria (i.e., environmental impact) are considered at the same time, the life cycle optimization framework is transferred to perform multi-objective optimization. In this case, the results are often presented as a set of Pareto-optimal solutions, consisting of a Pareto frontier which reveals the tradeoffs in decision under multiple objectives. One can choose among these Pareto-optimal solutions based on the preference for the design and operation of potential biofuel supply chains.

Life cycle assessments (LCA) of biofuel production, however, still remained questionable, mainly because of the adoption of a traditional process analysis approach resulting in system boundary truncation and because of issues regarding the impacts of land use change and GHG emissions from processing and moving feedstocks.

3.5 Conclusion

Although ethanol and bio-diesel are the most worldwide recognized biomass-derived liquid transportation fuel products currently, it is foreseeable that in advanced biofuels such as cellulosic biofuel would experience rapid growth due to lower competition with food, potentially higher yields, lower GHG emissions, political expectations, economic promise, environmental impact reductions, and social benefits.

This study overviewed and synthesized the literature on economic concerns involved within biofuel supply chain. Opportunities for efficiency enhancement and challenges across the whole system from feedstock production, prepossessing, storage and transportation in the biofuel supply chain systems were discussed. Additionally, we reviewed methodologies for supply chain modeling and optimization work considering both deterministic and stochastic methods and summarized supply chain studies from different settings.

Finally, biofuel production has market, welfare, and local economy implications. Increased production affects land use, conventional commodity supply and prices plus alters the welfare distribution among agricultural producers and consumers both domestically and internationally. Biofuel facilities can also help create jobs and income for local communities. We also investigated issues associated with biofuel supply chains in the threefold aspects of sustainability—economy, environment, and society. From a life-cycle perspective, it is generally agreed that first generation ethanol crops have much higher GHG emissions than the second generation, although translation of this into product value has not yet been widely achieved. However, the potential environmental impacts, such as increased fertilizer application and GHG flux change, needs to be addressed carefully. Future study of biofuel production and supply chain needs to focus continuously on cost-efficient, uncertainty managing, feedstock supply chains.

CHAPTER IV

SUPPLY CHAIN DESIGN AND ASSESSMENT FOR CELLULOSIC BIOFUEL PRODUCTION

4.1 Introduction

Many countries including the U.S. is endeavoring to replace fossil fuels with domestically produced and lower greenhouse gas (GHG) emitting biofuels while also gaining energy security benefits. Ethanol is currently the main biofuel product and is a gasoline substitute in the transportation sector. Nearly all ethanol produced in the U.S. is derived from corn grain, taking advantage of the fact that corn is the largest U.S. crop with more than 90 million acres of land planted in 2016.

The large dependence on corn has led to the debate about food versus fuel when the cultivated lands are used for energy production as opposed to traditional commodities (Ferris and Joshi 2004; Fortenbery and Park 2008; McNew and Griffith 2005; Taylor et al. 2006; Searchinger et al. 2008; Hertel et al. 2010). Babcock (2012) argued that it is indisputable that biofuels contributed to increased agricultural commodity prices particularly during 2007-2012. This is because biofuel industry represents a large and growing share of corn consumption reaching a 40% share of total corn production.

The expanded Renewable Fuel Standard program (RFS2) under the Energy Independence and Security Act of 2007 (EISA) reflects the food versus fuel concern limiting conventional, corn-based, fuel blending that can be used in complying with the program to 15 billion gallons per year (BGY) starting from 2015. Today we are at that limit. To achieve the additional blending requirements under the RFS2 requires production and blending of so called "second generation" or "advanced biofuels", including cellulosic ethanol. Actual levels of second generation biofuels have substantially lagged the mandates, but as of 2017 several near production scale commercial cellulosic ethanol production facilities although facility construction is stagnant and only one remains in full operation. To date most of the research on this industry has focused on improving biomass productivity, designing the most efficient farm level production and improving performance of biorefinery level conversion systems. The link between the two -- the supply chain is still a less studied endeavor (An, Wilhelm, and Searcy 2011). Moreover, total system planning in terms of coordination across land use change, storage, preprocessing, seasonality, transportation, biofuel market and other logistical issues has not been extensively examined as argued in the previous essay. This study will focus on economic efficiency within the cellulosic ethanol supply chain although the results and approaches will also be relevant to other categories of bioenergy since the main features and issues are shared will be discussed in detail in next section.

4.2 Problem Statement

4.2.1 Feedstock Production and Land Use

The economic viability of cellulosic ethanol production is primarily based on the cheap availability of delivered cellulosic feedstock, since biomass may compete for land with conventional crops, including corn for ethanol. Namely, considerations for supply chain begin with profitability of feedstock production for farmers, which should at least equal to the opportunity cost of conventional production on diverted cropland. Few studies have explored the total supply chain for cellulosic ethanol including considerations of the opportunity cost of the land.

Cellulosic ethanol feedstock can come from various sources including agricultural residues, perennial grasses, short rotation woody crops, and woody residues. Biorefineries may have an incentive to use a portfolio of these to avoid yield risk, large storage requirements, raw material cost fluctuation plus accommodate seasonal differences. A portfolio of feedstock production possibilities can be designed so that the feedstocks complement one another not only based on production cost and land use but also logistics cost, seasonality and storage requirements. For example, woody crops have potentially less complex supply chains. In its simplest form, a woody crop can be harvested, chipped, and transported directly to the conversion facility just in time for use. In contrast, perennial grasses and crop residues typically have limited harvest seasons and require storage for use outside of that season.

However the above suggestions venture somewhat into unexplored territory. Research on multi-biomass feedstock biorefineries and associated supply chains is very limited to date. Nilsson and Hansson (2001) investigated the simultaneous use of straw and reed canary grass finding the combination led to a total system cost reduction of 15–20% compared to a single-biomass case. Epplin et al. (2005) examined optimal combinations of feedstock in Oklahoma considering grasses produced on Conservation Reserve Program (CRP) land, crop residues (maize stover and wheat straw), perennial grasses (indigenous grasses from native range and introduced grasses from pastures) and dedicated energy crops such as switchgrass (panicum virgatum). Results indicated that restricting harvest to CRP acres imposed a rather substantial cost on the industry. For a

2000-t/day biorefinery, limiting feedstock production to CRP land would increase the expected cost to deliver a ton of cellulosic biomass to US$69 compared with a cost of US$33 for the use of multiple feedstocks.

4.2.2 Logistics Alternatives Decision

Beside feedstock production consideration discussed above, other features influencing delivered cost are low feedstock energy density and significant moisture content. These factors raise transportation cost per unit energy as well as the need to dry and densify before processing, transport and storage. In particular feedstocks deteriorate over time when they have high water content. As a result, a biorefinery may well need distributed preprocessing to densify the energy content lowering the cost per unit of potential energy transported along with actions to lower water content avoiding transporting a lot of heavy water. Additionally, seasonality is a factor with a need to store feedstocks from time of harvest until they are needed. This also potentially raises the possibility of distributed storage and preprocessing as a means of reducing storage losses and cost. Fixed costs for these logistics alternatives can be large so that the benefits from them should be accurately evaluated and compared with operations in their absence. Logistics components including technology choice as well as production, preprocessing, storage, biorefinery capacity and location decisions are highly interrelated and therefore coordination is needed.

Preprocessing can reduce logistics cost by (1) removing moisture in feedstock to minimize storage losses before conversion and/or transporting weight; (2) densifying the feedstock to reduce the volume transported and/or reduce storage space needed. Important questions are what proportion of the feedstock should be preprocessed and what alternative technologies should be used (e.g., cubing, pelletizing, drying, stretch-wrap, etc.). Simultaneously, the location and capacity of facilities should be decided and the fixed costs of those weigh against the logistic and processing cost savings. All of these depend on numerous factors. Feedstock production location will affect preprocessing facility location because ideally we desire the transportation distance for the most bulky, less dense energy form of the feedstock to be relatively short. Preprocessing decisions also should coordinate with storage duration, capacity and location. The economic viability of preprocessing was discussed by Larson et al. (2010) who considered a preprocessing facility for densification before feedstock was placed in on-site storage at the biorefinery. Results suggested that the preprocessing system outperformed the conventional bale harvest methods in the delivered costs of switchgrass under the assumption of a given biorefinery size of 25 million gallons per year and a feedstock draw area of 50 miles. The key question still remains to be solved is that to what extent preprocessing alternatives could reduce final product biofuel price. The potential saving on storage and transportation costs need to be evaluated but are typically ignored by previous studies on supply chain design. Moreover, one densification method that remains less studied is pelletizing. Pelleted biomass with low moisture content yields a product in a standard form and allows extended storage plus increases density for long distance shipping (Hamelinck, Van Hooijdonk, and Faaij 2005).

Storage adds value to the supply system by dealing with feedstock seasonality and to some extent supply uncertainty. Uncertain supply from farmland can be managed through a stored safety stock that buffers against feedstock shortages. Few studies examine the size of this safety stock in a biorefinery context. To deal with supply uncertainty in manufacturing industry, assuming the demand is normally distributed with mean μ, standard deviation σ and the ordering lead time is L, the optimal safety stock level to guarantee a service level α is $z_\alpha \sqrt{L}\sigma$, where z_α is a standard normal deviate such that $\Pr(z \le z_\alpha) = \alpha$ (You et al. 2008). However, the main source of uncertainty is feedstock yield variation since biofuel demand is relatively stable due to inelastic gasoline consumption, and the stock margin is not scale-free setting an obstacle to be applied directly in biofuel industry. In terms of carbon sequestration Kim and McCarl (2009) derived a scale-free safety margin considering coefficient of variation. This optimum level will be studied herein.

Research on alternative storage methods and corresponding storage loss (dry matter loss) have been covered by Thorsell et al. (2004), Cundiff and Grisso (2008), Rentizelas et al. (2009), Larson et al. (2010) and Kim (2011). Storage can occur in the field, in intermediate storage locations, or at the biorefinery. Stored items can be protected using options such as tarps or buildings. In general, low cost methods lead to high storage loss while negligible losses result from high cost preprocessing and/or storage methods in depots. Storage may be spatially dispersed which brings more complexity to logistics design. Capacity and location of storage depots are common variables in logistics design where these are coordinated with feedstock production and collection facility along with planning of the radius served by each facility.

4.2.3 Market and Logistics Component Evaluation

In this study we will examine optimal supply chain design and the value of utilizing various components. This will be done by altering the availability of some important alternatives like preprocessing, marginal land use and multiple feedstocks. In doing this we consider the spatial heterogeneity of corn yield and price as a factor in calculating the opportunity cost of cropland and supply chain design. Also, we will model cellulosic ethanol production in competition with first generation corn ethanol production both in land use and cost of final product.

4.3 Model Formulation

In this study we will use a mixed integer nonlinear programming (MINLP) model to represent build or not build decisions on storage, preprocessing, biofuel production facilities along with supply chain operation related to land use, transportation and production level of logistics components. The model will minimize total cellulosic-based bioethanol supply chain cost. It will consider the following supply chain/logistics decisions: (1) selection of feedstock cultivation sites *i* with choice of biomass type *b* to be produced on land type *l*; (2) possible use of preprocessing plus selection of feedstock preprocessing locations *j* and method *Preprotech*; (3) location *k* and size of feedstock storage plus choice of method *Stgtech*; (4) site selection for location of biorefineries *l;* (5) facility capacity level *cap* for preprocessing, storage and biofuel production facilities; (6) the amount of preprocessing, storage and production level by time period *t*; and (7) material flow between supply chain components in each period. The formulation (objective function and constraints) of the proposed model and related assumptions are presented next. A list of indices, sets and parameters used is given in Tables 1 and 2.

4.3.1 Objective Function

The objective function minimizes total annual cost. The total cost includes cellulosic feedstock production and harvest cost (i.e., purchase cost of feedstock at farm gate), preprocessing cost, transportation cost between facilities, operations cost at the biorefinery, bioethanol transportation cost from biorefinery to demand location, annualized fixed cost of preprocessing, storage facilities and biorefineries. The different terms will be explained below.

Eq. (1) gives the feedstock cost component. The first term in Eq. (1) gives the purchase cost of all types of feedstock in all supply zones, which is the sum-product of the price paid to the feedstock producer ($BiomassCost_b$) times the amount of feedstock shipped from supply site i to all destinations which are preprocessing location j , storage location k plus biofuel production facility location r.

The second term gives the opportunity cost of diverting cropland to energy crop production. Here we link feedstock market and biofuel market through corn price which is a function of cellulosic consumption volume ($\sum_t \text{Demand}_t$) and cropland diverted to energy crop (i.e., switchgrass) production ($\sum_i QtyLand_{i,'switchgrass','cropland'}$). Instead of dumping demand functions into the objective function, we simply assume that the market substitution of cellulosic biofuel will affect corn price by α in percentage for every one-million-gallon of fuel replaced. Moreover, if an energy crop is widely planted on cropland, an increase in corn price β will be generated because of reduced corn production. Such parameters can be found in the literature as discussed in next session. The gross crop value per acre is calculated as the product of corn price and crop yield ($Yield_{'corn'}$). Finally, the cash rent is determined as the opportunity cost, which is θ percent of gross crop value per acre. Land located in areas having higher yields generally has higher opportunity cost. Moreover, establishment cost for energy crop will be considered in the model as described in the fourth term.

$$\begin{aligned}&\sum_{i,b,t} BiomassCost_b * \Big(\sum_j \mathrm{Ship}_{i,j,'baled',b,t} + \sum_k \mathrm{Ship}_{i,k,'baled',b,t} + \sum_r \mathrm{Ship}_{i,r,'baled',b,t}\Big)\\ &+\theta * Cornpice_0 * \Big(1-\alpha\sum_t \mathrm{Demand}_t\Big) * \sum_i \big(Yield_{i,'corn'} * QtyLand_{i,'switchgrass','cropland'}\big)\\ &+\theta * Cornpice_0 * \Big(\beta\sum_i QtyLand_{i,'switchgrass','cropland'}\Big) * \sum_i \big(Yield_{i,'corn'} * QtyLand_{i,'switchgrass','cropland'}\big)\\ &+\sum_{i,l} E\mathrm{stablishmentCost}_{'switchgrass'} * QtyLand_{i,'switchgrass',l}\end{aligned} \tag{1}$$

This specification introduces the spatial dimension with varying opportunity cost, location of cultivation site, and feedstock yield. Consideration of these factors is necessary to optimally select cultivation sites in coordination with the supply chain design.

Eq. (2) contains the second part of the objective function which represents the operation cost of facilities in the supply chain including the preprocessing cost for feedstocks collected from farm gate and the biofuel refinery costs. Preprocessing cost is the sum of per unit cost ($PeproCost_{PreproTech}$) times the quantity preprocessed ($QtyPrepro_{j,PreproTech,b,t}$). Similarly, the operation cost of biorefinery is the sum of refining cost ($ProcessCost_b$) times the quantity refined ($EthQty_{r,b,t}$).

$$\sum_{j,PreproTech,b,t} PeproCost_{PreproTech} * QtyPrepro_{j,PreproTech,b,t} + \sum_{r,b,t} ProcessCost_b * EthQty_{r,b,t} \tag{2}$$

Eq. (3) shows the transportation cost component which incorporates the volume and weight characteristics of the cellulosic feedstock including moisture content. Feedstock density affects transportation cost since the size of the load is restrictive rather than the weight. Additionally, the water content of the feedstock increases the cost of transport since a greater weight is being moved. Thus cost equals the sum of distance between two facilities ($Distance_{m,n}$, where m, n is the union of i, j, k, r) times trucking cost per mile ($TransVarCost$) adjusted by the moisture content of feedstock in format f

($WeightRatio_{f,b}$, f is the union of '*baled' and PreproTech*). There is also a loading and unloading cost ($TransFixCost$) that depends on density of the feedstock in format *f* ($SizeRatio_{f,b}$). The final term is the transportation cost for ethanol shipped from the biorefinery *r* to demand zone *d*.

$$\begin{aligned}
&\sum_{m,n,f,b,t} TransVarCost * Distance_{m,n} * Ship_{m,n,f,b,t} * WeightRatio_{f,b} \\
&+ \sum_{m,n,f,b,t} TransFixCost * Ship_{m,n,f,b,t} * SizeRatio_{f,b} \qquad (3) \\
&+ \sum_{r,d,t} EthonalTransCost * Distance_{r,d} * Ship_{r,d,t}
\end{aligned}$$

Finally, amortized fixed costs of facility construction are added into the objective function, which are zero-one decision variables times a parameter giving amortized construction cost for the facility of a given capacity and technology (Eq. (4)).

$$\begin{aligned}
&\sum_{j,PreproTech,Cap} FixedCostPrepro_{PreproTech,Cap} * PreproContruct_{j,PreproTech,Cap} \\
&+ \sum_{j,StgTech,Cap} FixedCostStg_{StgTech,Cap} * StgContruct_{k,StgTech,Cap} \qquad (4) \\
&+ \sum_{r,Cap} FixedCostPlt_{Cap} * PltContruct_{r,Cap}
\end{aligned}$$

4.3.2 Constraints on the Model

The model also contains constraints as discussed below.

Eq.(5) ensures that in each supply site *i*, the allocated land use ($QtyLand_{i,b,l}$) for feedstock *b* production on each land type does not exceed the corresponding land availability ($AvailableLand_{i,l}$) associated with a land share parameter ($\lambda_{b,l}$) indicating the percentage of land type *l* in each supply location *i* can be diverted to grow feedstock *b*.

$$QtyLand_{i,b,l} \le \lambda_{b,l} * AvailableLand_{i,l} \qquad \text{for all } i,b,l \quad (5)$$

Eq. (6)-Eq. (8) represents supply demand balances for feedstocks at each stage of the supply chain including at the feedstock production site, the preprocessing facilities and the biorefinery. In Eq. (6), the amount shipped from the farms in a supply zone ($\sum_{m/i} Ship_{i,m/i,'baled',b,t}$) cannot exceed the acres of feedstock grown ($QtyLand_{i,b,l}$) times the corresponding yield ($Yield_{i,b,l,t}$). Here biomass yield is time dependent reflecting seasonality.

$$\sum_{m/i} Ship_{i,m/i,'baled',b,t} \leq \sum_{l} Yield_{i,b,l,t} * QtyLand_{i,b,l} \qquad \text{for all } i,b \quad (6)$$

Eq. (7) restricts the amount of biomass preprocessed ($\sum_{PreproTech} QtyPrepro_{j,PreproTech,b,t}$) to be equal to the quantity of each feedstock delivered to the preprocessing facility ($\sum_{i} Ship_{i,j,'baled',b,t}$) for each period. Similarly, Eq. (8) requires the amount of feedstock converted in each biorefinery ($EthQty_{r,b,t}$) equal to the amount received ($\sum_{m/r,f} Ship_{m/r,r,f,b,t}$).

$$\sum_{i} Ship_{i,j,'baled',b,t} = \sum_{PreproTech} QtyPrepro_{j,PreproTech,b,t} \qquad \text{for all } j,b \quad (7)$$

$$\sum_{m/r,f} Ship_{m/r,r,f,b,t} = EthQty_{r,b,t} \qquad \text{for all } r,b,t \quad (8)$$

Storage, preprocessing moisture removal and densification considerations are modeled in Eq. (9) to (12). Eq. (9) ensures that for each preprocessing facility and biomass type, the amount of densified feedstock sent to all biorefineries ($Ship_{j,r,PreproTech,b,t}$) and depots ($Ship_{j,k,PreproTech,b,t}$) by period equals the amount of baled feedstock preprocessed ($QtyPrepro_{j,PreproTech,b,t}$). It should be noted that the moisture content is altered by preprocessing. Therefore, the constrain balances dry matter reflecting reduction in moisture content ($moisture_{f,\,b}$).

$$(1\text{-}moisture_{'baled',b})*QtyPrepro_{j,PreproTech,b,t}$$
$$=\sum_{k}(1\text{-}moisture_{PreproTech,b})*Ship_{j,k,PreproTech,b,t}+\sum_{r}(1\text{-}moisture_{PreproTech,b})*Ship_{j,r,PreproTech,b,t}$$

for all *j, b, t, preprotech* (9)

Eq. (10) reflects storage ensuring that for each feedstock type and format, the amount retained in storage plus the amount of feedstock shipped out from a storage location in a period matches the amount of feedstock received from both farms and preprocessing facilities in that period plus the carryover storage from last period adjusted by dry matter loss ($StorageLoss_{b,\,f,\,StgTech}$) for feedstock form and storage method.

$$\sum_{r}Ship_{k,r,f,b,t}+\sum_{StgTech}QtyStg_{k,f,StgTech,b,t}$$
$$=\sum_{(i,j)}Ship_{(i,j),PreproTech,b,t}+\sum_{StgTech}(1\text{-}StorageLoss_{b,f,StgTech})*QtyStg_{k,PreproTech,StgTech,b,t\text{-}1}$$

for all *k, f, b, t* (10)

Eq. (11) requires a safety margin against the crop yield risk. An uncertainty discount ($\delta_b = z_\alpha * CV_b$) is adapted from Kim and McCarl (2009) where z_α is a distribution based multiplier reflecting the desired level of confidence (α) and CV_b stands for the coefficient of variation of yield for the feedstock. In this study, a normal distribution of feedstock yield is assumed and z_α =1.64 implies a one tailed 95% confidence level. The supply of feedstock in a storage facility after the uncertainty discount in each period sets the upper bound on shipments from that depot.

$$\begin{aligned}
&\sum_{r,f}(1\text{-}moisture_{b,f})*Ship_{k,r,f,b,t}\\
&\leq \sum_{f,StgTech}(1\text{-}moisture_{b,f})*(1\text{-}\delta_{b})*(1\text{-}StorageLoss_{b,f,StgTech})*QtyStg_{k,f,StgTech,b,t\text{-}1}\\
&+\sum_{i}(1\text{-}moisture_{b,'baled'})*(1\text{-}\delta_{b})*(1\text{-}StorageLoss_{b,'baled',StgTech})*Ship_{i,k,'baled',b,t}\\
&+\sum_{j,PreproTech}(1\text{-}moisture_{b,PreproTech})*(1\text{-}\delta_{b})*(1\text{-}StorageLoss_{b,PreproTech,StgTech})*Ship_{j,k,PreproTech,b,t}
\end{aligned}$$

for k, b, t (11)

The model also contains a biofuel flow balance at a biorefinery, where the amount of biofuel places in storage in a period plus the quantity of biofuel shipped out to meet market demand equals the sum of current period biofuel production and carryover storage from last period.

$$EthInvQty_{r,t}+\sum_{d}Ship_{r,d,t}=EthInvQty_{r,t-1}+\sum_{b}EthQty_{r,b,t} \quad \text{for all } r, t \quad (12)$$

Eq.(13) to (15) impose capacity constraints on facilities requiring the production level to be no more than the designated capacity by period. The capacity parameters are all expressed in weight units except for storage capacity which uses volume units so it can reflect densification.

$$\sum_{b}QtyPrepro_{j,PreproTech,b,t}\leq\sum_{cap}PreproLimit_{cap}*PreproContruct_{j,PreproTech,Cap}$$

for all $j, PreproTech, t$ (13)

$$\sum_{b,f}QtyStg_{k,StgMethod,b,t}*SizeRatio_{b,f}\leq\sum_{cap}StgCap,StgContruct_{k,StgMethod,cap}*StgLimit_{cap}$$

for all $k, StgMechod, t$ (14)

$$\sum_{b}EthQty_{r,b,t}=\sum_{cap}PltLimit_{cap}*PltContruct_{r,cap} \quad \text{for all } r, t \quad (15)$$

Eq. (16) to (18) constrains the zero one facility construction variables only allowing one facility to be situated at each candidate location across all capacity levels and technologies.

$$\sum_{PreproTech,Cap} PreproContruct_{j,PreproTech,Cap} \leq 1 \qquad \text{for all } j \quad (16)$$

$$\sum_{StgTech,\, Cap} StgContruct_{k,StgTech,Cap} \leq 1 \qquad \text{for all } k \quad (17)$$

$$\sum_{Cap} PltContruct_{r,\, Cap} \leq 1 \qquad \text{for all } r \quad (18)$$

Finally, Eq. (19) imposes a minimum level of ethanol to be shipped constraint which requires the amount of biofuel shipped out from the biorefineries to each demand point to be equal to the amount required at that location.

$$Demand_{d,t} = \sum_{r} Ship_{r,d,t} \qquad \text{for all } d,\, t \quad (19)$$

All decision variables need to be non-negative.

Table 5. Key Sets (Indices) in the Model

Set	Elements	Explanation
i	all counties in Texas	feedstock supply site
j	one county with the highest total biomass from each district in Texas	preprocessing candidate sites
k	one county with the highest total biomass from each district in Texas	storage candidate sites
r	Tracked sites with clean and renewable energy generation potential, EPA	biorefinery candidate sites
d	Harris, Texas	bioethanol demand site
b	corn stover, switchgrass, woody biomass	biomass type
f	baled, ground, pellet	biomass format
cap	small, large	facility capacity
PreproTech	ground, pellet	
StgTech	indoor, outdoor	
t	Jan, Feb,……,Dec	month

Table 6. Key Parameters and Data Sources

Item	Source	Note
yield (ton/acre)	USDA; NREL: the Biofuels Atlas	assume switchgrass productivity on marginal land is 70% of productivity on cropland
		corn grain to residue ratio=1:1, and sustainable removal rate=50%,
		assume woody biomass has 40% moisture
available land (acre)	USDA	
biomass cost ($/ton)	U.S. BILLION-TON UPDATE; Edward (2007)	biomass cost only includes harvest cost for switchgrass. switchgrass purchase cost=harvest cost ($/ton) + establishment cost($/acre) +opportunity cost($/acre)
		biomass cost of corn stover = nutrient payments+ harvest cost
		all of the woody residue resources can be harvested at less than $40 per dry ton roadside
preprocessing cost ($/ton) preprocessing capacity (ton/month) preprocessing fixed cost ($)	Lin et.al (2014)	
storage capacity (cubic meter) storage fixed cost ($)	Kim dissertation (2011)	

Table 6. Key Parameters and Data Sources (continued)

Item	Source	Note
ethanol production cost ($/dry ton)	Memisoglu dissertation (2014)	
biomass to ethanol ratio (gallon/dry ton)	Theoretical Ethanol Yield Calculator, DOE	
biorefinery capacity(gallon/month) biorefinery fixed cost biorefinery ethanol inventory capacity(gallon)	USDA; Wallace et.al (2010); Memisoglu dissertation (2014)	
transportation cost ($/ton)	Lin et.al (2013)	
monthly ethanol demand (galloon)	DOE	
harvesting percentage each month	USDA, Popp et.al (2013)	
size ratio, density	Lin et.al (2014)	baled corn stover as a benchmark; it affects storage cost and transportation fixed cost
moisture; the weight ratio; storage loss	Popp et.al (2013)	moisture affects variable transportation cost and storage losses, the weight ratio is calculated based on moisture content

4.4 Assumption and Data Preparation for Case Study

In order to demonstrate the model we will use a case study. This case study will examine the cellulosic bioethanol supply chain within Texas. Texas has potential to provide multiple types of cellulosic source (woody biomass, crop residue, and energy crop) plus a large percentage of fuel ethanol (around 10%) in the U.S. is used in blending in Texas.

The feedstock candidates will be corn stover, switchgrass and woody residues which are selected since these represent each of the major types of biomass (crop residues, energy crops and wood residues) that could be used. Corn is widely planted across Texas. The forest land is only located in East Texas. Most areas in Texas are suitable for switchgrass growth but exhibit varying yields. In order to address competition between first generation feedstock and cellulosic feedstock, it is assumed that switchgrass can be grown on cropland and a certain share of that cropland is engaged in corn production before. This land share is determined by crop mix ratio within a location, which is represented by land share parameter in Eq.(5). Since we allocate switchgrass across cropland used for different crops according to certain mix ratio, we avoid the possibility that corn will take a land share from other crops when switchgrass production divert land away from corn.

We also assume that switchgrass can be grown on marginal land but restrict the maximum land availability so that only 10% of marginal land can be converted to switchgrass cultivation. Marginal land is land that is of little agricultural value because crops produced from the area would be worth less than any rent paid for access to the area. Therefore, these areas have been abandoned to crop and pasture. If switchgrass is decided to be planted on cropland, for the land used for corn production before, the upper bound is 30% which is the historical lowest share of corn planted for biofuel after 2010. It indicates corn ethanol can still make up the gap between cellulosic ethanol production and total consumption even substituting energy crop with corn on cropland. Some constraints reflexing land attribute are also assumed, among which switchgrass and corn stover cannot be produced from forest land where woody biomass is produced and vice versa. Also corn cannot be cultivated on marginal land.

The main data source for biomass yield comes from National Renewable Energy Laboratory (NREL) and the data sets related to land endowment can be accessed from United States Department of Agriculture (USDA). All information on feedstock cost were drawn from the Billon-Ton study Updated (Perlack et. al). These data include estimates of harvest cost (for corn stover, switchgrass and woody residue), costs of replacing lost nutrients (for corn stover). The corn residue pricing considers harvest cost as well as cost to replace the lost nutrients per ton of stover removed. For bioenergy crops (switchgrass) production competing land with corn, not only harvest cost measured by \$/ton is represented by $BiomassCost_b$, but also the opportunity cost of diverting the land away from food crop production and establishment cost is added in \$/acre.

The transportation cost along with feedstocks characteristics such as moisture and density as well as derived weight and size ratio are based on the findings in Lin et.al (2013). Other information relevant to facilities including candidate locations, operation and fixed cost are from multiple sources as shown in Table 2. In particular, each candidate preprocessing and storage facility is the county with the highest total biomass from each district. To determine candidate biorefinery locations, of all the candidate locations provided by EPA therein, we consider only the ones that are suitable for biorefinery construction with an “excellent" or outstanding" potential. The ethanol demand location is assumed in Harris County since ethanol distribution is out of our study scope. The model will consider Texas wide with subregions being counties.

4.5 Results

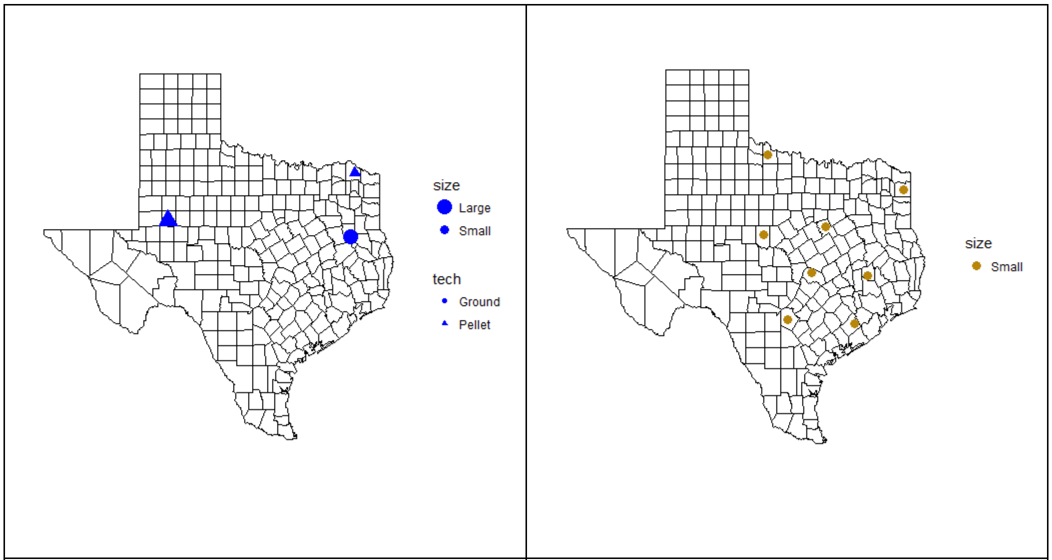
The MINLP model (Eq. (1)–(19)) is solved with different scenarios of cellulosic ethanol production level. The supply chain design and its outcome will be analyzed in this section including logistics component evaluation and tradeoff, land use change and feedstock and ethanol markets.

4.5.1 Logistics Components Chosen

In order to reduce transportation cost, the model chooses to preprocess the feedstocks produced in the counties which are far from the processing plant (Figure 1a). Therefore, preprocessing location is most affected by feedstock production site relative to biorefinery location, trying to reduce the hauling distance of baled feedstock. Ground and pelletized feedstock are two candidate preprocessing methods in our model. The longer the distance the more densified preprocessing format (pellet) is chosen. This is demonstrated by the installation of pelletization equipment in West Texas that is the region most far away from biofuel production site. One preprocessing facility the model locates in East Texas which has a long distance from the biorefineries adopts pelletization technology whereas the solution of closer facility is to use a grinding format. In terms of the type of feedstock preprocessed, only preprocessed woody residues are shipped to biorefinery directly (Figure 2b). However, only a small portion of woody residue is preprocessed since the forest land is close enough to biorefineries and it can be sent straight to the refinery any time within one year without storage (Figure 2a). Results also show that most of the feedstocks preprocessed are shipped to storage facilities (Figure 2c). It indicates the logistics design related to preprocessing facilities is heavily influenced by storage losses and cost.

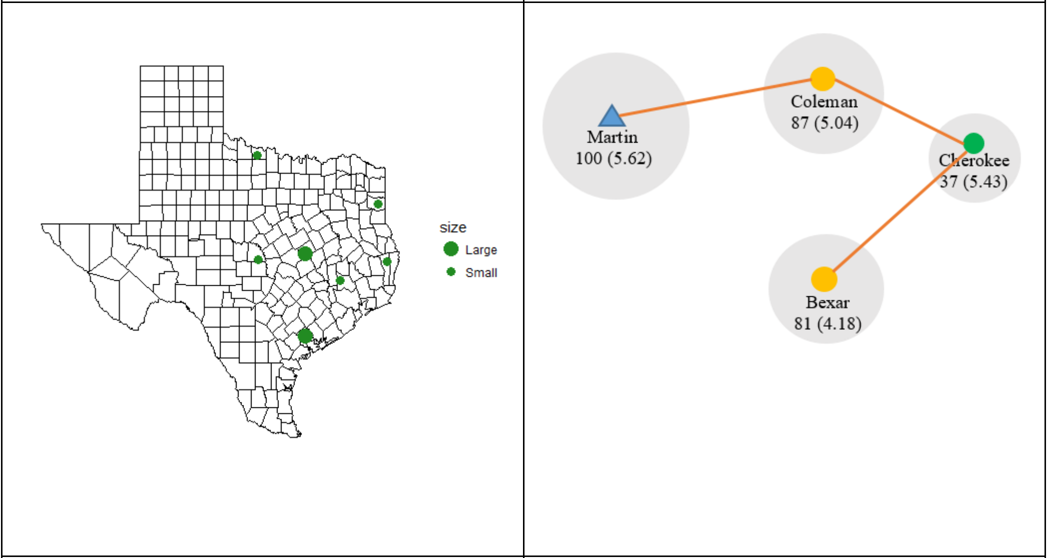
Storage facilities are more likely to be set next to biorefineries compared with preprocessing facilities (Figure 1b). Most places where a biorefinery is set also have a storage facility. Indoor storage is the strategy chosen even though it is 75% more expensive than the outdoor storage due to awaited storage loss. The logistics chooses to set more storage facilities instead of expanding individual storage capacity to handle huge amount of feedstock. The baled and pelletized switchgrass is shipped from storage facilities to biorefineries during the months of the year when biomass cannot be produced from farmland due to the timing of harvest (Figure 2c). The baled switchgrass is delivered firstly because of higher storage losses compared with pelletized switchgrass.

The biorefinery locations strike a balance between feedstock production locations. This leads to three facilities being located in East Texas. The reason for setting small capacity biorefineries in East Texas is they do not have to produce extra ethanol against seasonality because of the stable supply of woody residues. In contrast, the biorefineries in Central Texas tend to expand their capacity in order to handle a huge amount of feedstocks collected from most counties in Texas as well as deal with seasonality. The quantity of feedstock shipped from feedstock production locations to biorefineries reflects the seasonality of biomass harvest possibilities (Figure 2a). When corn residue and/or switchgrass are not available, woody residue is used. When corn residue and switchgrass become available, woody feedstock is not used likely because of the higher water content. Ethanol storage in biorefinery also provides buffer against feedstock seasonality but constant ethanol demand. The ethanol production is relatively stable except in June which is the last month of the unavailability of both corn residue and switchgrass (Figure 2d). The biorefineries produce more than demand when biomass is relatively sufficient.



a. Preprocessing location

b. Storage location

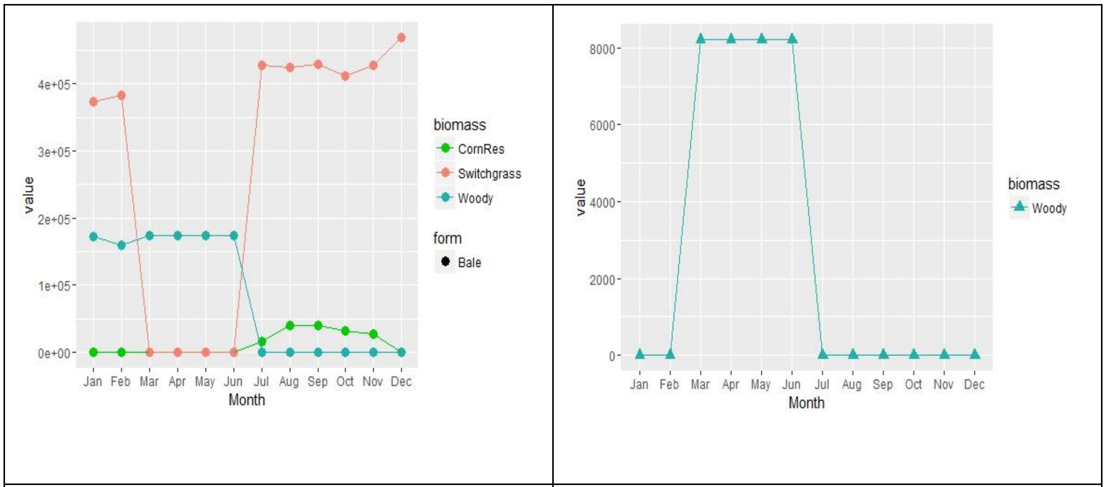


c. Biorefinery location

d. Collection radius of facilities

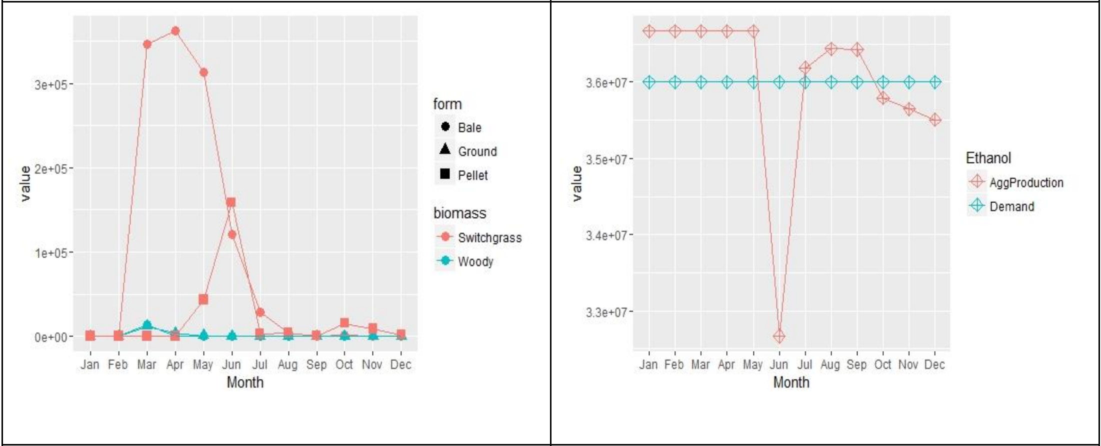
Figure 6. Assignment of Logistics Components

The Department of Energy's Office of the Biomass Program (OBP) currently considers a biorefinery capacity of 2,032 dry metric tons (or 2,000 dry matter tons (DMT)) per day to be approximately optimal for a conventional-bale supply system with an 81-km (50-mile) collection radius. This study embodies more details.



a. Feedstock production site to biorefinery (unit: ton)

b. Preprocessing to biorefinery (unit: ton)



c. Storage to biorefinery (unit: ton)

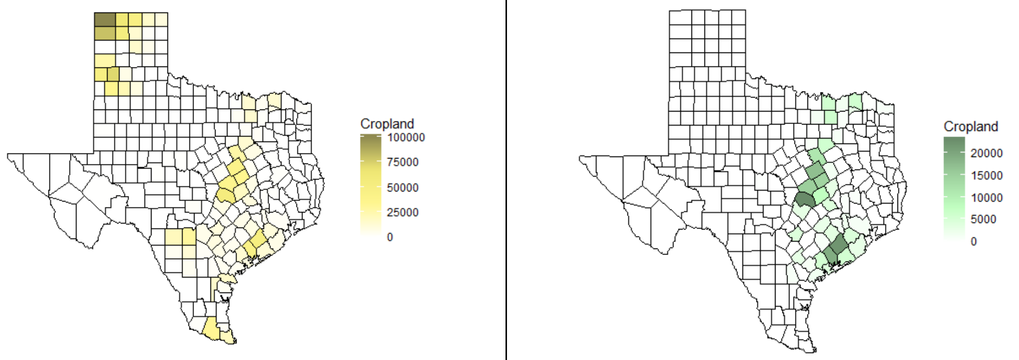
d. Ethanol production and demand (unit: gallon)

Figure 7. Material Flow between Logistics Components

Figure 1d represents the spatial structure of the supply chain where the grey circular elements on the map represent baled biomass delivered from harvesting sites to a facility in trucks and connecting lines represent the delivery between facilities. The number outside the parentheses represents the collection radius with the average yield per acre in parentheses. The connection between facilities with switchgrass collection radius will be illustrated as an example. The collection radius for each type of facility is primarily dependent on switchgrass yield with controlling planted acreage in each supply zone. One conveyance pathway is selected for demonstration since there exists a complete package of facilities including one preprocessing, two storage and one biorefinery. The collection radius decreases with the facilities approaching to downstream. The radius for preprocessing facility with 300 dry ton required per day in Martin reaches 100 miles even though the average yield within the area providing feedstock to the preprocessing facility is highest. The reason is that transportation cost is saved after feedstock preprocessed. The delivered distance between preprocessing facility in Martin and the storage depot in Coleman is the longest move in the solution, which indicates that the bulky baled feedstock is first pretreated near the production location then shipped when long distances are involved. For a depot with a capacity of 1750 dry ton for switchgrass, the hauling distance is 87 miles with a yield of 5.04 ton/acre. Another depot serving the biorefinery in Cherokee has a collection radius of 81 miles with switchgrass yield of 4.18 tons/acre on average. The reason of higher yield resulting in the longer hauling distance is that both depots supply feedstock to another biorefinery in Travis and Victoria respectively but feedstock requirement from the depot in Coleman is 8.7% higher because of capacity difference between two biorefineries in Travis and Victoria. Under the circumstances biomass yield is 5.43 tons/acre and the conversion rate of biorefinery is 70 gallons per dry ton, the collection radius of biorefinery is 37 miles when the daily switchgrass requirement is 1500 dry ton. After converting the result based on DOE assuming 2000 dry ton/day, it yields an equivalent number, yet biomass yield and conversion technology may change the conclusion.

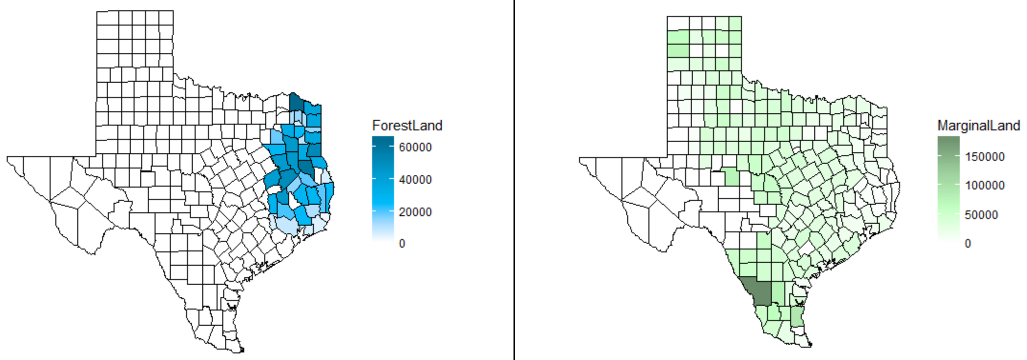
4.5.2 Land Use Change

Land use is an important but distinguished component in supply chain. The amount of land used to produce biomass in each area is primarily based on land endowment but not exactly consistent with it since downstream facilities (i.e., preprocessing, storage and biorefinery) also have an impact on land change decision. For demonstration purposes, the scenario of maximum ethanol production level is selected in which 27% of ethanol in the market is cellulosic ethanol with 376 million gallons produced annually. Corn residue production for biomass is located in North Texas mainly because of relatively high yield whereas coordination with the biorefinery location is the logic behind feedstock production site selection in Central Texas (Figure 3a). As for switchgrass production, cropland used for switchgrass production concentrates in the area where biorefineries are located in order to reduce hauling distance. In contrast, marginal land for switchgrass production is dispersed because of the lower conversion/opportunity cost even though disperse production results in higher transportation cost. Woody biomass production located in East Texas where forest land is concentrated.



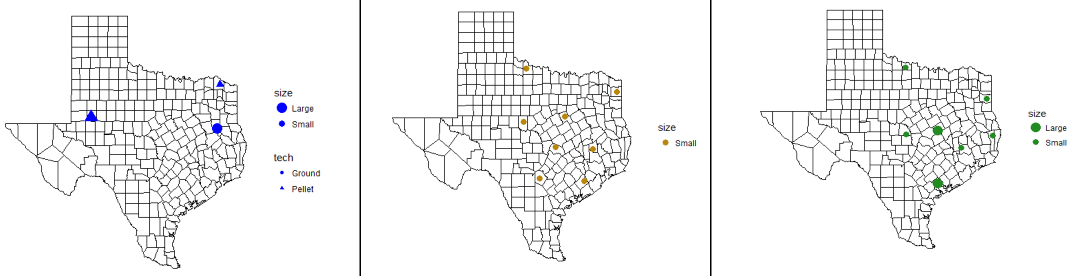
a. Cropland for corn residue

b. Cropland for switchgrass



c. Forest land for woody biomass

d. Marginal land for switchgrass



Preprocessing Location

Storage location

Biorefinery location

Figure 8. Land Use for Feedstock Production in Maximum Production Scenario

Stability of land use for biofuel feedstocks is also a concern when the portfolio may vary depending on production targets. It is presented by the share of available land for bioenergy purpose (Figure 4). Forest residues are the most stable source in any scenarios due to all year-round availability. However, woody feedstock does not show significant increase in utilization for large-scale biofuel production. It indicates woody residues play the most important role in mitigating seasonality but the high water content is still the main concern in supply chain even within the hauling radius from forest land to biorefinery in East Texas. Corn stover as a byproduct can be collected without disturbing current cropland assignment, leading to the high percentage of corn stover collection from cropland (99.4%) given that Texas has limited cropland for corn in total. The production of switchgrass on marginal land is firstly triggered with increasing demand because of negligible opportunity cost, whereas the decision of converting cropland to switchgrass plantation does not happen until we require that 17% of the Texas total fuel ethanol comes from cellulosic sources blending. The increase of marginal land use does not follow a straight-line pattern particularly the production level is between 5% and 13%, indicating the decision change of switching energy crop production from low yield marginal land to relatively high yield one.

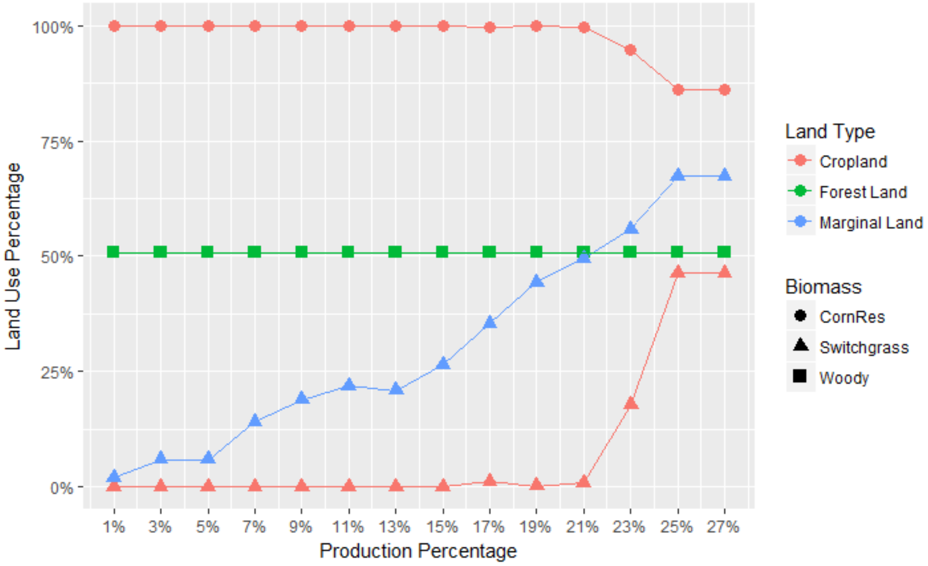


Figure 9. Land Use Portfolio of Feedstocks for Different Production Scenarios

4.5.3 Evaluation of Logistics Alternatives

This section will investigate the value of select supply chain components including whether preprocessing facilities can be employed, whether marginal land can be used and whether multiple feedstocks can be used. Three major cases will be analyzed. The first removes the use of preprocessing facilities. The second removes the potential use of marginal land and the third involves blocking the accessibility of biomass other than energy crop (switchgrass). For the baseline scenario without blocking any alternatives, the model suggests that at most 27% of total ethanol production can be replaced by cellulosic sources. Table 3 includes three production scenarios for each case where the last one is the maximum capacity. Cost allocation of selected production scenarios are also shown in Table 3 with all results being presented by the percentage change compared with the baseline scenario. Feedstock purchase cost is calculated based on Eq. (1) and cellulosic ethanol unit cost is from the value of objective function divided by total amount of ethanol produced. All the fixed costs are annualized numbers.

The preprocessing facilities decrease costs when a large amount of ethanol is to be produced. The threshold in Texas is 125 million gallons that is 5% of total fuel ethanol production. When the production level is below 5%, 3% as an example, model chooses to set fewer storage facilities but with larger capacity, leading to 33.33% cost decrease in fixed costs for storage. This design raises the transportation expenditure as its cost but still gains a biofuel cost equal to that in the baseline scenario. If the production exceeds the 5% threshold in the absence of preprocessing facilities, more storage facilities will appear in Northwest Texas and the capacity of biorefineries to produce ethanol in a month is increased in order to allow more ethanol storage. The model can mitigate the negative effect of blocking preprocessing facility by assigning more other types of facilities (i.e., storage and biorefinery) to decrease transportation cost when ethanol demand is not large as shown in the scenario of 9%. It reduces transportation variable cost and fixed cost by 20.36% and 4.84% respectively, resulting in a moderate final product cost increase. However, the benefit from this design decreases as the volume required becomes larger as shown in scenario 27%. Transportation variable cost increases by 10.57% even though the model still chooses to add more storage facilities and expand biorefinery capacity compared with the baseline. Comparing the last two scenarios regarding the cost share of setting depots, without preprocessing facility, ethanol production heavily relies on supply directly from farmland and the importance of storage is minor. Furthermore, land use structure and purchase cost of feedstocks are not sensitive to the availability of preprocessing. The final ethanol product price increases by 3% on average without preprocessing facility but allowing the adjustment of other facilities to minimize total cost. If the logistics decisions except preprocessing keep consistent with the baseline scenario, a 17% cost increase will occur on average.

The maximum capacity cannot reach 27% suggested by the baseline scenario in the case of disabling multiple feedstocks and marginal land use because of restriction on cellulosic sources. Switchgrass can be widely adopted on marginal land and become major cellulosic source contributing to at most 21% of fuel ethanol without using other biomass types. However, when blocking marginal land, the model does not choose to significantly expand switchgrass on cropland if considering opportunity costs of land use, resulting in only 7% at maximum. The cost of storage is largely reduced (-33.33% in scenario 5% and -66.67% in scenario 7%) since more feedstocks are shipped directly to biorefineries with capacity improvement but dramatic transportation cost rises correspondingly. This situation results from woody residue produced in East Texas becomes the major feedstock in this case. Woody residue is available all year around, leading to storage facilities being unnecessary. Corn stover seasonality drives biorefineries to increase their capacity in order to produce more ethanol during harvest season. Assigning cropland to switchgrass production causes a dramatic increase in purchase cost. The average cost goes up by 50% on average compared with the baseline scenario.

Multiple feedstocks seem slightly expensive compared with the result from only using switchgrass when the production target is below 9% due to cheap production cost of switchgrass on marginal land. For the scenario of 3%, the purchase cost decreases by 0.86% but this single feedstock strategy causes the slight raise of transportation cost (4.10%) because of disperse switchgrass production. When the production volume exceeds the threshold of 9%, the purchase costs are higher than the baseline since more switchgrass is cultivated on cropland but with decreasing transportation cost because of concentrated production. Moreover, more storage facilities in High Plains appear to deal with more severe seasonality resulting from single feedstock compared with diversified feedstock strategy in the baseline. It brings up to 350% more investment in storage facilities. When only one type of feedstock is considered, the results show that preprocessing becomes more important to reduce storage costs and losses. The ethanol production cost per gallon increases by 12.03% at maximum capacity and 8% on average.

4.5.4 Market Equilibrium

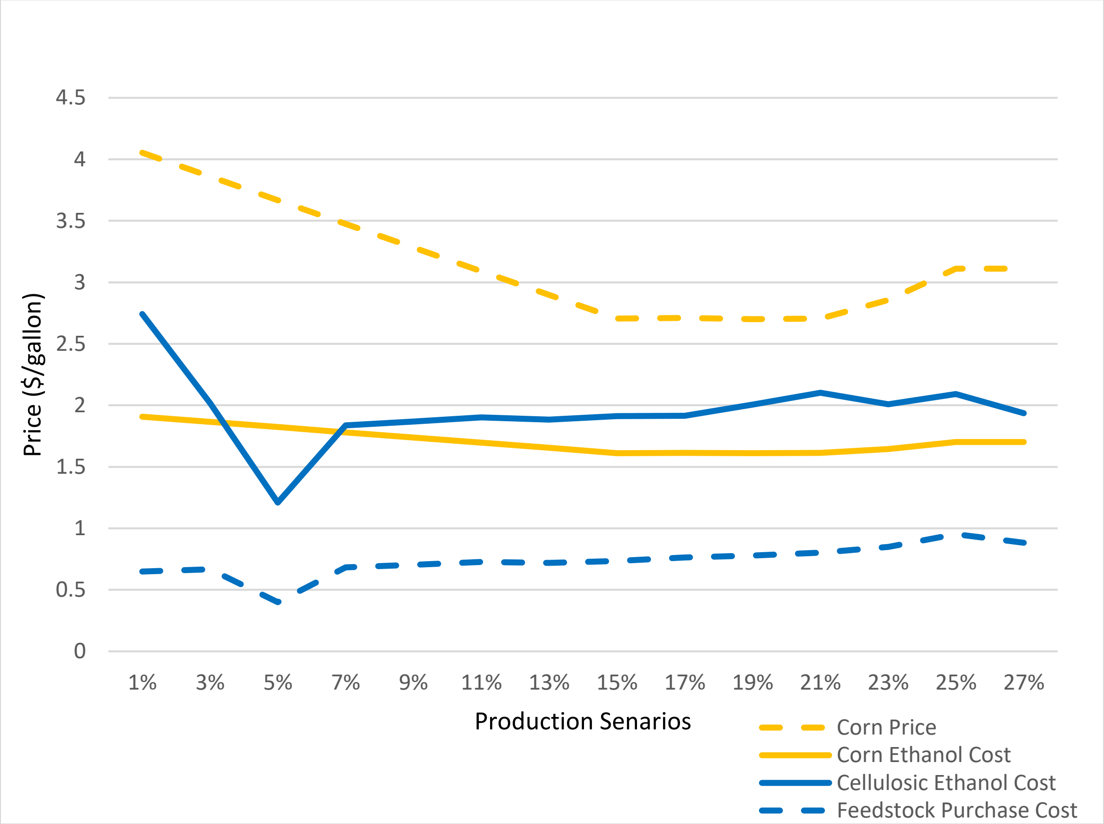


Figure 10. Market Price Variation for Different Production Scenarios

Texas annual fuel ethanol blending is 1.4 billion gallons. In order to discover biofuel market dynamics and equilibrium, this analysis we simulate cellulosic ethanol production amounts which represent alternative percentage shares for cellulosic ethanol of this 1.4 billion in total (Figure 5). The model suggests that at most 27% of total ethanol production can be replaced by cellulosic sources.

The variation pattern of the average cost of producing cellulosic ethanol and the feedstock cost (measured in dollar per gallon of cellulosic biofuel) remains similar across the different production levels. However, cellulosic feedstock price contributes less to the variation of final product cost than logistic costs at the initial stage (i.e., production is less than 7%). The average cost of final product decreases dramatically due to falling payments for feedstock acquisition as well as decreasing marginal cost of logistical movement when total production is lower than 69.8 (5%) million gallons. However, after production exceeds 69.8 (5%) million gallons, the cost goes up sharply mainly because of increasing cost brought by facility expansion. When production is over 97.7 (7%) million gallons, it can be found that an increase of 35% (from scenario 7% to 25%) in feedstock cost only leads to an increase of 11% in cellulosic ethanol cost. It is because an appropriate supply chain design can offset the negative effect of feedstock price increase through logistics component coordination.

The cellulosic feedstock price and corn price reflect the land competition derived by biofuel market. The supply of woody biomass and corn residue are relatively stable due to the attributes of forestry land which cannot be converted to other uses and corn stover as a byproduct of corn production. Therefore, cost variation mainly comes from introduction of switchgrass on cropland and marginal land. Although switchgrass plantation on marginal land generates lower yield than on cropland plus the profit from cropland falls due to saturation of cellulosic ethanol in biofuel market, the much lower opportunity cost of marginal land causes switchgrass is rarely planted on cropland until more than 17% of demand (200 million gallons) needs to be satisfied by cellulosic biofuel. Given the feedstock price is hardly affected by land competition with food crops before production capacity is beyond 200 million gallons (i.e., 17%), the fall and rise of marginal cost of switchgrass production on marginal land contributes to the behavior of feedstock price before production requirement is more than 17%. Two forces affect corn prices, one of which is the outcome of substitution between cellulosic ethanol and corn ethanol. Introduction of cellulosic ethanol to biofuel market leads to the reduction of corn demand along with its price if inelastic corn supply is assumed based on the phenomenon have been observed since 2015. After a significant capacity improvement of cellulosic ethanol production, the appearance of switchgrass on cropland will result in the raise of food crop price even the market share of corn ethanol keeps squeezing. It indicates the response from food market dominates that from biofuel market when altering cultivation assignment on cropland.

The corn ethanol price (cost) is calculated by corn price plus operation margin allocated to facilities supporting corn ethanol production (U.S. Bioenergy Statistics, USDA). Hence, the corn ethanol price shows the consequence of land use change from upstream. Without any subsidy or tax credit on biofuel production, the fuel ethanol market will reach the equilibrium when biofuel price from two sources are equal due to the homoscedasticity of two products. There exists two equilibrium where cellulosic biofuel production accounts for 3% or 7% of total production respectively. Cellulosic biofuel production can be more competitive in terms of market share by manipulating subsidy or tax credit.

4.6 Conclusion

This study examines efficiency improvement possibilities within the cellulosic ethanol total supply chain. We develop a mixed integer nonlinear programming (MINLP) model which integrates feedstock production, preprocessing, storage and biorefining as well as biofuel market effects. Then we use that model to design an optimal supply chain plus examine the value of including or excluding various supply chain elements.

A case study is carried out at the level of the state of Texas for a variety of scenarios in terms of total amount of cellulosic biofuel and inclusion or omission supply chain elements. In doing that, the value of including or omitting multiple feedstocks, preprocessing and use of marginal land is assessed. The solutions from the case study with the model yields a number of important insights about logistics components and their interaction.

In order to reduce transportation cost, the model chooses to preprocess the feedstocks near production sites. Furthermore, storage costs and losses are significantly reduced since most of feedstocks preprocessed are delivered to storage facilities limiting feedstock losses, lowering storage costs and supplying a seasonally even level of feedstock.

Storage facilities are more likely to be located next to biorefineries to provide sufficient feedstocks especially during the periods where feedstock harvest is unavailable. Feedstocks in raw form with high storage losses are firstly shipped from storage facilities.

The supply chain also prefers to add more storage facilities instead of capacity expansion when more feedstocks are needed.

Biorefineries are optimally located in dense feedstock production areas. Utilizing multiple feedstocks reduced the costs resulting from agricultural crop seasonality. Woody residue is a desirable addition as it is less seasonal in availability even though it has a high percentage of water content leading to increased transportation cost.

The collection radius for different logistics components (i.e., preprocessing, storage, biorefinery) was also investigated. The feedstock collection radius is primarily dependent on feedstock yield and varies with the facilities.

As to land use change for biofuel production, the amount of land used to produce biomass in each area is primarily based on land endowment but not exactly consistent with it since site selection needs to coordinate with other components in the supply chain. The production of switchgrass on marginal land is widely adopted because of negligible opportunity cost and the model does not choose to significantly promote switchgrass on cropland because of its high opportunity cost. Agricultural residue such as corn stover is also widely used where available since it is a byproduct of crop production. Therefore, it can be collected without disturbing crop mix. Forestry land usage is relatively stable because it is hard to be converted to other uses.

This study also investigates the value of select supply chain components including whether preprocessing facilities can be employed, whether marginal land can be used and whether or not multiple feedstocks can be used. The final ethanol product price increases by 3% on average without preprocessing facilities. The ethanol production cost per gallon increases by 50% when restricted to only a single feedstock and 8% when marginal land is not usable.

Moreover, the biofuel market effects regarding first and second generation feedstock and final product prices are also analyzed resulting from the saturation of cellulosic ethanol and the aggregated effects of energy crop planted on cropland. The appearance of switchgrass on cropland will result in the raise of food crop price even the market share of corn ethanol is replaced by cellulosic ethanol.

The equilibrium of biofuel market is discovered after introducing cellulosic ethanol. According to this study, there exists two equilibrium where cellulosic biofuel production accounts for 3% or 7% of total production respectively. Cellulosic biofuel production can be more competitive in terms of market share by manipulating subsidy or tax credit. It will provide a guideline to promote cellulosic biofuel production by manipulating subsidy or tax credit.

Table 7. Cost Change Compared with Baseline Scenario

	No preprocessing			No marginal land			No multiple feedstock		
Scenario	3.00%	9.00%	27.00%	3.00%	5.00%	7.00%	3.00%	9.00%	21.00%
Purchase cost	0.00%	0.00%	0.00%	41.33%	34.66%	51.93%	-0.86%	0.73%	46.74%
Fixed cost (preprocessing)	*NA*	*NA*	*NA*	0.00%	0.00%	0.00%	0.00%	0.00%	353.94%
Fixed cost (storage)	-33.3%	100.00%	25.00%	0.00%	-33.33%	-66.6%	0.00%	300.00%	350.00%
Fixed cost (biorefinery)	0.00%	31.25%	15.38%	25.00%	87.50%	15.38%	0.00%	12.50%	-5.88%
Transportation variable cost	1.91%	-20.36%	10.57%	106.25%	200.43%	57.22%	4.10%	-12.42%	-30.79%
Transportation fixed cost	0.00%	-4.84%	-3.37%	0.85%	41.75%	-0.86%	0.66%	0.76%	-4.48%
Cellulosic ethanol cost	0.00%	3.33%	3.64%	34.85%	112.24%	34.68%	0.09%	2.17%	12.03%

CHAPTER V

CONCLUSIONS

This dissertation conducts analysis pertaining to agriculturally based GHG mitigation possibilities examining the economics and GHG efficiency of multiple agricultural strategies. In particular modeling work and literature reviews were carried out in two settings. First, the optimal portfolio of strategies suggested in a country document in support of achieving the goals of the Paris Accord was examined along with their resultant GHG, and market effects in the context of Vietnam. Second, we examined mainly economic issues regarding achieving efficiency in the supply chain when replacing liquid fuels with biofuels produced from agricultural feedstocks. In the latter case we focused on efficiency enhancement in supply chain with a Texas based case study.

In the first essay we examined the characteristics and optimal mix of agriculturally based plans in the Vietnam "Intended Nationally Determined Contribution" document or the INDC for short. The examination was done using agriculture sector analysis and provided a sector level evaluation on the role of agricultural mitigation policies identified in the Vietnam INDC. This involved building a quadratic, price endogenous agricultural sector programming model for Vietnam. Then we used that model to generate an agricultural abatement curve across increasing quantities of agricultural contribution identifying at each contribution level with optimal portfolios of the INDC options. In doing this we found significant differences in the GHG effects of several strategies arising between the potential in our economic sector model and the stated technical potential in the INDC. In particular we found the role of using agricultural residue as organic fertilizer was substantially overstated in the INDC. Mitigation efforts from improving livestock diets are also far below technical potential because of large opportunity costs generated from the food market because of the nutritional requirements for meat. Overall in terms of potential agricultural contribution we found Vietnam agriculture can accomplish unconditional contribution claimed in the INDC with modest impacts on its domestic food market and prices. We also found that delaying mitigation effort will increase the total costs of achieving the INDC commitments especially when the total amount of mitigation is not large.

In the next two essays we turned to the issue of supply chain efficiency in moving feedstocks from point of production to the biorefinery while supplying a seasonally even flow of feedstock into the biorefinery. In the essay in Chapter III, the literature is overviewed and synthesized on economic concerns involved within biofuel supply chain. Opportunities and challenges emerge from feedstock production, prepossessing, storage and transportation in the biofuel supply chain systems are discussed. Additionally, we classified supply chain modeling and optimization work into deterministic and stochastic method and summarized supply chain studies from different scopes. We also investigated issues associated with biofuel supply chains in the threefold sustainability—economy, environment, and society. Out of this literature review we concluded that more studies of biofuel production and supply chain coordination are needed and that such studies need to focus on cost-efficient, uncertainty managing, feedstock supply chains.

In the third essay in Chapter IV we quantitatively examine supply chain efficiency. In doing this we developed a mixed integer nonlinear programming (MINLP) model which integrates feedstock production, preprocessing, storage and biorefining as well as biofuel market effects. The model minimizes the total annual cost of producing a given volume of cellulosic-based bioethanol and delivering it to locations for blending. A case study is carried out at the level of the state of Texas for a variety of scenarios in terms of total amount of cellulosic biofuel then the model choice of supply chain elements is analyzed. Finally, we examine the value of including or omitting key supply chain elements considering the use of multiple feedstocks, preprocessing and feedstocks produced on marginal land.

The solutions from the case study with the model yields a number of important insights about logistics components and their interaction. In order to reduce transportation cost, the model chooses to preprocess the feedstocks near production sites. Furthermore, storage costs and losses are significantly reduced since most of feedstocks preprocessed are delivered to storage facilities in a densified more storable form. Storage facilities are more likely to be located next to biorefineries to provide sufficient feedstocks especially during the periods where feedstock harvest is unavailable. Biorefineries are optimally located in dense feedstock production areas. Utilizing multiple feedstocks reduced the costs resulting from agricultural crop seasonality. As to land use change for biofuel production, the amount of land used to produce biomass in each area is primarily based on land endowment but not exactly consistent with it since site selection needs to coordinate with other component in supply chain. The production of switchgrass on marginal land is widely adopted because of negligible opportunity cost and the model does not choose to grow substantial amounts of switchgrass on cropland because of high opportunity cost of cropland.

This study also investigated the value of select supply chain components including whether preprocessing facilities can be employed, whether marginal land can be used and whether or not multiple feedstocks can be used. The final ethanol product price increases by 3% on average without preprocessing facility but allowing the adjustment of other facilities to minimize total cost. In the case of disabling multiple feedstocks and marginal land use because of restriction on cellulosic sources. The ethanol production cost per gallon increases by 50% and 8% on average respectively for these two cases. Moreover, the equilibrium of biofuel market is discovered after introducing cellulosic ethanol, which provides a guideline to promote cellulosic biofuel production by manipulating subsidy or tax credit.

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