Studies on Cost Minimizing Cellulosic Biofuel Supply Chain Design

A Dissertation

by

Yuanyao Stanley Lee

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chairs of Committee	Bruce A. McCarl
	Stephen W. Searcy
Committee Members	Reid Stevens
	Ximing Wu
Head of Department,	Mark Waller

May 2019

ABSTRACT

A two-stage stochastic MIP model is developed and implemented that represents a multi-feedstock ethanol supply chain under feedstock yield uncertainty. The model minimizes expected cost by determining both strategic and tactical decisions. Two regional case studies based on Texas were conducted to examine the consequences of alternative supply chain design and the incorporation or omission of yield uncertainty along with the impact of using a high-resolution sub county regional resolution versus a lower resolution county level portrayal.

The results from the study demonstrated that incorporation of yield uncertainty is an important factor and uncertainty affects the need for feedstock contracting, the amount of excess feedstock dumping costs and tactical supply chain operation. In both case studies, more land for biomass feedstocks was contracted under uncertainty as a safety margin to keep the refinery running when yields are low. When comparing only using a single feedstock as opposed to multiple feedstocks scenario, the results indicated that the use of multiple feedstocks is superior particularly when there is inherent seasonality of the biomass feedstocks. If there is a year-round availability of freshly harvested feedstocks, then the model chooses not to add any storage and operates a “Just in time” supply chain system which in turn reduces the ethanol production cost significantly. Furthermore, in the presence of pellet export possibilities that remotely located storage depots with associated pellet plants provide options that allow the exploitation of geographically stranded feedstocks that are not near enough to biorefinery locations to be moved directly. Our results in the Texas High Plains case study show the corn Stover collection area goes from an 80 km radius to a 200 km one when pellets can be exported at a $150/mg price. Finally, the results of the experiment showed that transportation cost, in both cases, was affected as the geographic scale changed due to the altered precision of feedstock density portrayal. Thus,

we conclude that the biofuel supply chain design and logistic decisions are sensitive to geographic scale and that more precise data will improve the supply chain design.

TABLE OF CONTENTS

ABSTRACT i
TABLE OF CONTENTS iv
LIST OF FIGURES vii
LIST OF TABLES viii
CHAPTER I INTRODUCTION 1
Objectives 4
Methodology 5
Case Studies 6
Thesis Organization 7
CHAPTER II LITERATURE ON THE ECONOMICS OF BIOFUEL SUPPLY CHAINS 8
Research Scope 8
Modeling of Biofuel Supply Chains 9
Modeling of Biofuel Supply Chains with Uncertainty 14
CHAPTER III SUPPLY CHAIN DESIGN MODEL 19
Deterministic model development 20
Problem Scope and Statement 21
Structure of the Mixed Integer Problem 23
Mathematical Formulation 25
Incorporating Yield Uncertainty – the Stochastic Model 32
Development of a Probability Distribution for Crops Yields 32
Spatial Representation of the Availability of Feedstock 41
GIS Data Site Selection and Resolution Scheme 41
CHAPTER IV REGIONAL SUPPLY CHAIN MANAGEMENT CASE STUDY: TEXAS HIGH PLAINS 44
Introduction 44
Problem Statement 46
Case Study 47
Study Region and Potential Sites for Facilities 47
Biomass Considered in the Study 50
Land Use Constraint and Contract Scheme 51
Harvest Cost 53
Storage Cost 54

Size Reduction Option(Pelleting) 56
Feedstock Preprocessing and Handling at Biorefinery 59
Modeling Uncertainty in Biomass Yield 64
Model Analyses and Results 65
Effects of Including and Excluding Yield Uncertainty 66
Effects of eliminating decentralized storage and Pellet Plants 72
Impacts of Conversion Rate Improvement on Supply Chain Design 80
Impacts of Pellet Price on the Supply Chain Design under Stochastic Model 86
Experiments with Geographic Scale 95
Summary and Discussion 97
Conclusions 100
CHAPTER V REGIONAL SUPPLY CHAIN MANAGEMENT CASE STUDY: EAST TEXAS 103
Introduction 103
Case Study 105
Study Region and Potential Sites for Facilities 105
Biomass Considered in the Study Region and its Availability 107
Procurement Cost of Biomass 110
Storage Cost 112
Size Reduction Option(Pelleting) 114
Biomass Transportation and Handling 116
Preprocessing and Handling at Biorefinery 117
Yield Uncertainty Considerations 118
Analysis Results 121
Comparison of Multiple and Single Source of Feedstock Scenarios for the Results 129
Impacts of Ethanol Conversion Rate Improvements 137
Impacts of Alternative Pellet Prices 142
Impacts of Increases in Accessible Forest Area 147
Experiments with Geographic Scale 151
Summary and Discussion 152
Conclusions 155
CHAPTER VI CONCLUSION 158
REFERENCES 165
APPEENDIX A LIST OF SYMBOLS 170

LIST OF FIGURES

Figure 1Conceptual framework of a biofuel supply chain.. 21
Figure 2 Basic framework of the model 23
Figure 3 Texas High Plains study region.. 49
Figure 4 Potential locations for biorefinery, storage and pellet plants 49
Figure 5 Formation of the indoor storage 55
Figure 6 Biochemical and thermochemical conversion processes 60
Figure 7 Optimal locations in deterministic and stochastic model.. 66
Figure 8 Feedstock land contracted in the deterministic and stochastic models 70
Figure 9 Inventory level in the deterministic and stochastic models... 71
Figure 10 Monthly processing by feedstock type in the deterministic and stochastic solutions .. 72
Figure 11 Optimal locations of facility at no-pellet and central storage...................................... 73
Figure 12 Source of each biomass in the base, no-pellet and centralized only storage scenarios 78
Figure 13 Monthly inventory levels in the no-pellet scenario and central facility scenario......... 79
Figure 14 Comparison of process level in no-pellet central scenario.. 80
Figure 15 Optimal locations for improved conversion rate scenarios... 81
Figure 16 Source of each biomass under different conversion rates scenarios 85
Figure 17 Monthly inventory level in different conversion rate scenarios.................................. 85
Figure 18 Process level of conversion rate improvement scenarios.. 86
Figure 19 Optimal locations for different price scenarios 88
Figure 20 Source of each biomass at different pellet prices 93
Figure 21 Monthly inventory level at different pellet prices 94
Figure 22 Monthly biomass processed level of different pellet price scenarios........................... 95
Figure 23 Optimal facilities in different geographic scales... 96
Figure 24 East Texas study region... 106
Figure *25* Potential storage/pellet locations... 107
Figure 26 formation of the indoor storage 113
Figure 27 optimal locations in deterministic and stochastic model.. 123
Figure 28 Source of each biomass in deterministic and stochastic models 127
Figure 29 Monthly biomass process level of deterministic and stochastic model..................... 128
Figure 30 The optimal locations of facilities for single and multiple feedstock cases 130
Figure 31 Amount of each biomass harvested in no storage and storage scenario.................... 136
Figure 32 Monthly biomass process level of multiple and single source scenarios 136
Figure 33 Source of each biomass in different conversion rate scenario 141
Figure 34 Monthly biomass process level of different conversion rates scenarios 142
Figure 35 Optimal locations for different price scenarios 143
Figure 36 Source of each feedstock under different pellet price scenarios 147
Figure 37 Monthly biomass processed level of different pellet price scenarios......................... 147
Figure 38 Source of each feedstock under different forest access rates scenarios 150
Figure 39 Monthly biomass processed level of different forest access rates scenarios............. 151

LIST OF TABLES

Table 1 Empirical Probability Distribution of States of Nature 34
Table 2 Top Ten Counties with Most Available Biomass in The Study Region.......................... 48
Table 3 Equipment and Cost Estimates for Corn Stover And Switchgrass................................. 54
Table 4 Storage Cost of Corn Stover and Switchgrass 56
Table 5 Capital Cost of a Pellet Plant 57
Table 6 Variable Cost of Producing Pellet 58
Table 7 Capital Cost of Biorefinery... 61
Table 8 Summary of Key Parameters Used in The Model 62
Table 9 Probability of Working Days in the Study Region 63
Table 10 Empirical Probability Distribution of States of Nature 65
Table 11 Expected Costs of Each Component in Deterministic and Stochastic Model 67
Table 12 Summary of the Key Decisions from Deterministic and Stochastic Model 68
Table 13 Key Parameters of Central Facility, No Pellet and Base Cases.................................... 73
Table 14 Expected Costs for No-Pellet, Central Storage and Base Scenarios............................. 75
Table 15 Summary of the Key Decisions under the Base, No-Pellet and Centralized Storage Scenarios 76
Table 16 Expected Cost of Each Component in Different Conversion Rate Scenarios 81
Table 17 Summary of the key decisions of different conversion rates scenarios 83
Table 18 Expected Cost of Each Component at Different Pellet Price 89
Table 19 Summary of the Key Decisions of Different Pellet Prices Scenarios............................ 90
Table 20 Expected Cost of Each Component at Different Geographic Scale 96
Table 21 Average Cost of Each Scenario with and without the CWC Incentive 100
Table 22 Estimated Woody Residues in The Study Region 109
Table 23 Equipment and Cost Estimates for Switchgrass 112
Table 24 Storage Cost of Switchgrass 114
Table 25 Capital Cost of a Pellet Plant 115
Table 26 Variable Cost of Producing Pellet 116
Table 27 Capital Cost Components for Building a Biorefinery 118
Table 28 Switchgrass Yield Level's State of Nature.. 119
Table 29 Probability of Working Days 120
Table 30 Key Parameters Used in The East Texas Case Study... 121
Table 31 Expected Costs of Each Component in Deterministic and Stochastic Model 124
Table 32 Summary of the Key Decisions from Deterministic and Stochastic Model 125
Table 33 Expected costs of each component multiple and single source models 132
Table 34 Summary of the key decisions from multiple and single source feedstocks models... 133
Table 35 Expected Costs of Each Component in Different Conversion Rates Scenarios 138
Table 36 Summary of the Key Decisions of Different Conversion Rates Scenarios 140
Table 37 Expected Costs of Each Component in Different Pellet Prices Scenarios 144
Table 38 Summary of the Key Decisions of Different Pellet Prices Scenarios.......................... 145
Table 39 Expected Costs of Each Component in Different Forest Accessible Rate Scenarios.. 148
Table 40 Summary of the Key Decisions of Different Forest Access Rates Scenarios 149
Table 41 Costs Comparison between County Level and Hexagon Level Data in East Texas ... 152

CHAPTER I

INTRODUCTION

The US Congress has set up a goal for renewable fuel production under the Energy Independence and Security Act reflecting a desire to increase energy security and reduce the environmental impacts of using gasoline. The Renewable Fuel Standard(RFS) requirement under that Act aspires to have renewable fuel blending at the level of 136 Billion Liter Per Year (BLPY) by 2022. Within that targeted level, no more than 56.7 BLPY can be made from corn starch. Also, 60.5 BLPY and 19 BLPY will come from cellulosic biofuel and advanced biodiesel, respectively.

Such a goal implies that lignocellulosic feedstocks are expected to be a major input to many biorefineries. Yet, widespread use of lignocellulosic biomass feedstocks at high volumes would raise substantial logistical challenges. For example, a 30-million-liter plant at 100-liter ethanol per Mg conversion rate would need 300,000 Mg of material or equivalently, 500,000 large square bales to ensure the production process. Due to the low energy density and dispersed distribution of lignocellulosic biomass, bio-refineries will experience large costs of collecting and transporting lignocellulosic biomass. Additionally, most lignocellulosic biomass feedstocks such as switchgrass or corn stover are not equally available throughout the year exhibiting strong seasonality and thus, storage facilities are likely needed. The form of storage is also an issue as feedstock deterioration can happen raising feedstock needs and costs. Finally, agricultural commodities are highly weather dependent and exhibit substantial yield fluctuation and thus the total supply chain needs to be designed to assure an adequate feedstock supply plus deal with excesses. Careful design of a total farm to refinery supply chain must evolve a chain that accommodates uncertain supply, seasonality, feedstock energy density, and possible pretreatments among other factors. Cost reducing designs may be a major factor in making the industry viable. Previous studies have pointed out that the high logistics cost within supply chains are a critical factor which impedes the growth of the renewable fuel industry (Osmani and Zhang 2013; Osmani and Zhang 2014; Wang 2013). Estimates in that work indicate that logistics cost can be as much as 40% of the cost of the final product. Studies have also indicated that improved supply chain design could potentially reduce the logistical costs cost by 50% (An and Searcy 2012). Additionally, use of feedstocks that exhibit strong seasonality in terms of feedstock availability will inevitably require storage to smooth out feedstock supply, but poor storage schemes could lead to high deterioration of biomass and increase the total supply chain cost. Kim(2011) studied deterioration rates of corn stover under alternative storage methods. He pointed out that the indoor storage method, although costing more than outdoor storage, could effectively reduce the deterioration of corn stover. Additionally, if the carbon dioxide equivalent price becomes higher than $200/ton, he found indoor storage methods can be more cost-effective means of reducing GHG emissions than outdoor storage. Thus, by improving storage facilities, the loss of biomass can be effectively controlled. Moreover, the biomass loss, storage cost and transportation cost could be further lowered by employing methods such as pelleting for densifying and moisture removal (Mani et al. 2006).

While many studies have been done on individual components covering part of the total biofuel supply chain, none of them have covered the full chain while considering uncertain yields. Most previous studies tackled yield uncertainty by estimating the cost impacts of select yield outcomes like a low productivity year. While understand the impacts of yield uncertainty is important, this does not tell how to design the supply chain for improved system reliability plus deal with the issue of excess supply when yields are good.

Another important question this study tries to answer is the impact of data scale on the design of supply chains. Many previous studies have addressed design of cellulosic ethanol supply chain (Osmani and Zhang 2013; Alex Marvin et al. 2012; Gold and Seuring 2011; Chen and Fan 2012; Gebreslassie, Yao and You 2012; Cundiff, Dias and Sherali 1997).Yet, most of these studies were limited to the regional or county scale due to either data availability or computational capacity. However, use of only regional or county level data omits crucial information that is need for developing low cost logistics within the cellulosic ethanol industry namely information on distribution, location and spatial density of biomass. Ignoring such information can cause the design to fail to reflect the true costs and reducing the effectiveness of supposed "optimal" designs.

This study addresses optimal design and the value of omitting or including key components, doing single versus multiple feedstock processing, including yield uncertainty and incorporating geographic specificity versus doing the analysis at the county level. To do this a comprehensive supply chain optimization model is developed that integrates spatial information and yield uncertainty. The spatial information is introduced to help better reflect the distribution and location of each biomass along with transportation corridors. The developed model along with high resolution data are then used to examine the consequences of adding and excluding storage and pelleting components and the impacts of other key parameters in two case studies. The study will begin with identifying major potential components of the supply chain and their associated costs and operating characteristics. Then, a conceptual model integrating both choice of components and their operation under stochastic supply will be developed and set up over two case studies in distinctly different areas. A case study in the Texas High Plains region where there is substantial potential herbaceous biomass and another case study in East Texas where a mix of wood residues and herbaceous biomass are possible.

Objectives

The basic thrust of this study is to lower the cost of lignocellulosic based renewable fuel by efficient design of a location specific supply chains. In doing this several activities will be pursued:

- First, we will develop a conceptual and operational framework that can be adapted to local characteristics that helps assess supply chain design under yield uncertainty. This model will choose optimal location of facilities and feedstock production considering centralized or decentralized storage, pelleting, transportation, and conversion processes.
- Implement the model in the context of study regions in the Texas High Plains and in East Texas taking into account the regional characteristics, diverse feedstocks, and yield uncertainty.
- Use the model to investigate questions regarding the total supply chain design

The proposed study carries out analysis and modeling of regional lignocellulosic biofuel supply chains involving the locations for facilities, feedstock production, storage (central and remote), transportation, pelleting, feedstock mix and yield uncertainty. This study intends to answer the decision questions of a supply chain relating to

- The optimal locations of the biorefinery, its capacity and basic technology,
- The optimal feedstock production locations,

- The optimal strategy of handling feedstocks involving collection, storage, seasonality, and pelleting,
- Optimal locations of storage and pelleting that are determined jointly with biorefinery and feedstock location.
- The potential savings in estimated delivery cost of feedstock and biofuel under alternative supply chain designs considering whether remote storage and pelleting are possible
- The optimal feedstock mixes over the analysis period
- The most favorable storage and pelleting scheme
- The impact of uncertain supply on the proposed supply chain design
- The optimal strategy to respond to yield uncertainty

Methodology

A mixed integer, two stage stochastic, linear programming models will be developed to assess the feasibility of potential lignocellulosic biofuel biorefinery and implemented with case studies in both East Texas and the Texas High Plains. The model will minimize the annualized cost of constructing and operating the supply chain while meeting a production goal of a given volume of bioethanol. In particular, given the parameters such as availability of biomass, yield variability, capital costs of facilities, production, harvesting, storing and transportation costs as well as the transportation modes available, the current model attempts to develop cost minimizing decisions on: i) the location of biorefinery, ii) whether to use central storage, remote storage depots and pelleting facilities and if so their optimal location , iii) the area of supply region contracted and where is the region to do the contracting, iv) the amount of biomass harvested, v) the movement of feedstocks through the selected distributed system of feedstock handling and possible storage depots plus pelleting plants, vi) the amount of pellets produced,

vii) the amount of feedstocks transported in different segments of the supply chain, viii) choice of thermochemical versus biochemical conversion; ix) quantity to store, place of storage and months to store feedstocks and pellets and x) handing of feedstock yield shortfalls and excesses. We will also investigate the cost implications of including or excluding various system components

Case Studies

Once the conceptual model is developed, two case study implementations will be pursued. These will be located in, East Texas and one in the Texas High Plains are chosen to represent different feedstock compositions and spatial distribution. The model will be set up to reflect regional biomass yields, potential lands available, alternative feedstock possibilities, handling equipment, moisture content, yield uncertainty, transport mode availability, storage losses, pellet export prices and conversion technology. It will be applied to examine supply chain design and operation plus component inclusion and exclusion. In East Texas, wood residues and switchgrass will be considered as the main feedstocks while agricultural residues from corn and sorghum production along with switchgrass and energy sorghum will be considered in the Texas High Plains region. Additionally, to reflect potential land availability for energy crops only certain types of land will be used to produce feedstocks. In the East Texas case, switchgrass can only be grown on available pasture land and forest residues can only be drawn from thinning or harvest residues on current regional forested land. In the Texas High Plains region switchgrass and energy sorghum can only be grown on available dryland areas and corn residue is harvested from regional lands now in irrigated cropping.

Thesis Organization

The study is presented in six chapters. Chapter 2 gives a background literature review. Chapter 3 formally introduces the conceptual model to be used. Chapters 4 and 5 present the case studies in East Texas and Texas High Plains regions respectively. Finally, conclusions, limitations and comparisons of the results across these case studies will be presented in chapter 6.

CHAPTER II

LITERATURE ON THE ECONOMICS OF BIOFUEL SUPPLY CHAINS

In this chapter, previous studies related to lignocellulosic biofuel supply chain systems are reviewed. Here in reviewing prior studies we focus on the scope of study, the type of model used, and the basic findings.

There is substantial interest in expanding production of lignocellulosic biofuel. So far, total ethanol production has rapidly increased from 6.04 billion liters in 2000 to 55.9 billion liters in 2015 (EIA, 2016). However, the expansion has almost exclusively involved starch-based or generation one ethanol and biodiesel with the lignocellulosic industry component or generation two quantity lagging expectations. The Energy Independence and Security Act of 2007 (EISA) contemplated production levels of 11.35 Billion Liter Per Year (BLPY) in 2015 while actual 2015 production was only 540.55 Million Liter Per Year(MLPY) much of which involves landfill gas converted to liquids (EPA, 2016). Given the actual cellulosic ethanol production level is significantly behind the goal, study on the supply chain has emerged to help fill the gap and boost the cellulosic biofuel industry.

Research Scope

Gold and Seuring (2011) pointed out that the main reasons for careful design of biofuel supply chains are to: a) keep feedstock cost competitive; and b) ensure continuous supply of feedstock. To achieve these goals, supply chain designs need to determine: a) the locations and capacity of biorefineries, storage depots, and pellet plants, b) the amount of contracted biomass supply area, c) whether to use single versus multiple feedstocks; and d) the type of refining technology to use. On the other hand, the chain design also needs to incorporate tactical issues that may vary from year to year like: a) the amount of feedstock being harvested, stored/preprocessed, pelletized and shipped; b) modal choice; c) the level of biofuel being produced and d) the manner where feedstock shortfalls and excesses are handled (Gold and Seuring 2011; An and Searcy 2012; Park et al. 2017; Dal-Mas et al. 2011; De Meyer, Cattrysse and Van Orshoven 2015).

Given the cellulosic biofuel supply chain require large amount of lignocellulosic biomass, problems such as biomass feedstock seasonality and sourcing of biomass makes operating the cellulosic biofuel supply even more challenging. These considerations confirm the high relevance of supply chain and logistics design issues for the implementation of bio-energy production systems.

Modeling of Biofuel Supply Chains

When evaluating bio-energy supply chains, a systems perspective has to be taken encompassing biomass resources, harvest, movement, storage, and conversion. Yet, local characteristics and the large number of possible combinations of these components makes direct comparisons between different bioenergy systems difficult (Mccormick and Kaberger 2007). One common way to analyze and compare different biofuel supply chain designs is to apply Mixed Integer Program (MIP) optimization modeling to simultaneously identify facility locations, logistic decisions and system cost. For example, Marvin et al.(2012) utilized a MIP model to find out the optimal supply chain design in 9 mid-west states. The major components considered in the study included biomass supply region, storage and biorefinery. Besides, agricultural residues from five different grains were considered as the feedstock source and the supply of each agricultural residue was constant over the analysis period. According to the results of their study, the high availability of agricultural residue makes Midwest region a place to produce 17.7 BLPY ethanol. Besides, the proposed model helps determine the location and capacity of biorefineries across the study region. Note that this study did not consider possible supply variation due to weather and the possible use of prepossessing procedure to utilize the strand biomass.

MIP model was also frequently used to compare different settings of supply chain. Kim (2011) studied the effect of greenhouse gas prices and storage losses for corn stover under alternative storage methods on the best storage method. He found that indoor storage although more costly than outdoor storage, could cost effectively reduce the deterioration of corn stover. Additionally, he also found that with high carbon dioxide equivalent prices (over $200/ton), the indoor storage method is more cost efficient and would profitably reduce GHG emissions relatively to outdoor storage methods. The analysis of this study was conducted using county level spatial data, and all the biomass was assumed to be supplied at the county center. The assumption fails to reflect the biomass distribution condition within the county and lead to bias on estimates of transportation costs.

Kim et al. (2011) developed a MIP model and used it to compare the profits of centralized and distributed handling systems. The proposed supply chain contained two major components: choice of supply region and location of biorefinery. Besides, multiple woody biomasses were considered, and the yield of feedstocks was assumed constant at all time. Based on the results, they found out that a distributed system generated higher profits and was more flexible when facing varying demand than was the centralized system. No prepossessing procedure was considered in this study to discuss the possibility of exporting pellet to external market. Besides, county level spatial data was used in the analysis, and all the biomass distribution condition and transportation activity within the county were ignored.

Ekşioğlu et al. (2010) developed a deterministic MIP model to identify the impacts of adding an intermodal facility within biofuel supply chain and to estimate the total production cost of the corn-base ethanol supply chain. The yield of corn was assumed to be constant all time and the major components included in the supply chain consisted of supply region, storage and biorefinery. The results from their study indicated that the inclusion of an intermodal facility affects the optimal location of the biorefinery and reduces the overall production cost compared to single mode supply chains. This study did not consider possible supply variation due to weather and the possible use of prepossessing procedure to utilize the strand biomass. Besides, the study did not consider any prepossessing procedure and the possibility of exporting pellet to external market. Furthermore, rather than using a finer resolution spatial data, county level data was used in this study.

Zhang et al.(2016) developed a multi-transport-mode MIP model to addressing supply chain design problem in Michigan. Choice of supply region, amount/location of local storage and the biorefinery location were the major components of the proposed supply chain. Multiple woody biomasses were used as the main feedstocks and the supply of each biomass was assumed constant. The results of the study identified the optimal number, capacity, location of biorefineries and storage depots. They also provided the information of harvesting plans, transportation mode in each route, the amount of biomass shipped between different nodes in each period, and the inventory level changing over time. No prepossessing procedure was considered in this study to discuss the possibility of exporting pellet to external market. Besides, county level spatial data was used in the analysis, and all the biomass distribution condition and transportation activity within the county were ignored.

Park et al.(2017) developed a MIP model to examine supply chain issues in the context of a switchgrass-based biorefinery with a possible multi-modal transportation system in North Dakota. The optimal supply chain involved a chosen supply region plus the location of storage depots and the biorefinery. Besides, the yield of the sole feedstock switchgrass was assumed constant. They found that the average delivered cost of switchgrass could be significantly lowered when using the multimodal transportation system. The cost can be lowered from 0.705($/L) to 0.505 ($/L) when moving from a truck only system to a mixed rail and truck system. Their study also demonstrated the optimal transportation system involved the feedstock first being transferred from supply region to intermediate storage depots by truck and then shipped from these depots to a biorefinery using rail. This study only considered single source of biomass feedstock and did assumed no yield variation. County level spatial data was used in the analysis, and all the biomass distribution condition and transportation activity within the county were ignored.

In addition to MIP model, Khanna et al. (2011) examined the economically viable supply of agricultural biomass at different biomass price and the region production patter for each feedstock in the United States. This study applied a dynamic, multimarket equilibrium, nonlinear mathematical programming model to determine land location, crop production, and biofuel price in the market. Corn stover, wheat straw, switchgrass and Miscanthus are the major inputs in the model. They found that 617 to 923 million Mg of biomass can be produced in 2030 at a feedstock price of $140/Mg and that 18 million ha of idle cropland or cropland pasture would be used to supply this amount of biomass. Additionally, this study also pointed out the fact that the prices for biomass need to be very high to achieve anything like the often studied BTS production goal. This study focused on the availability of biomass and did not provide information of biofuel supply chain design. County level spatial data was used in the analysis, and all the biomass distribution condition and transportation activity within the county were ignored.

Most of the studies reviewed above used MIP or other optimization models to wholly or partial address the biofuel supply chain issue. The results of these studies indicated that using multiple biomass sources, decentral storage depots, multiple transportation modes and indoor storage can help reduce ethanol production cost. However, several issues are unresolved and merit further work. First, these studies generally assume certainty in factors such as biomass supply. Second, pelleting has been mentioned as a potential way to improve the use of stranded biomass by DOE; but, none of the studies we found considered its use. Finally, all these studies applied county level representations in their analysis and assumed all the biomass arose from the center of county. This ignores regionally heterogeneous biomass distribution and biases the data on the distance biomass needs to be transported within the county and in turn transportation cost.

Using finer scale data arising from Geographical Information Systems (GIS) is another method that can be used in characterizing cellulosic supply chain. Wang et al. (2017) used 6×6 km2 raster data to estimate the available corn stover in Ontario, Canada with fixed biorefinery and storage locations. With the estimates of corn stover in the region, the author then applied a simulation model to estimate biofuel supply chain delivery cost and required equipment. Panichelli and Gnansounou (2008) and Zhang et al.(2016) examined potential wood harvesting area and further estimated the availability of woody material in the study region given the biorefinery locations. Park et al.(2017) used GIS to calculate distances and to determine the optimal transport route for different transportation modes.

Gonzales and Searcy (2017) applied GIS methods to evaluate the available herbaceous biomass in Texas. Specifically, instead of assuming all the biomass are all located in the center of each county which, in turn, implies a centroid has a very high yield, this study proposed a way to allocated county level data into smaller spatial resolution unit to reflect the biomass density. Specifically, the biomass contained in each pixel is determined by the ratio of suitable land in the pixel and that in the county. The study then applied the estimates and compared the total available biomass within the collect region of each potential facility locations to determine the optimal location of biorefinery, storage and pellet plant.

Although the GIS provide an alternative way to help determine the distribution of biomass and the facilities locations, the method usually did not provide detailed information of tactical decisions such as the monthly inventory level, process level and amount biomass transported for each biomass since the focus of this type of approaches is on processing spatial data. Thus, GIS approaches usually need to link to other methods such as optimization to determine the solution to the tactical decisions to provide complete information to the decision makers.

Modeling of Biofuel Supply Chains with Uncertainty

Another key component need to be considered in the biofuel supply chain analysis is uncertainty. The works reviewed in the previous section assumed that the supply of each biomass feedstock was deterministic. However, the supply of biomass is usually uncertain and subject to the weather conditions Therefore, even though these studies identified some key factors affecting the objective, the results, if not interpreted correctly, may lead to problematic decisions when design a supply chain. Thus, given that large amount of biomass feedstock is required to satisfy commercialized level biorefinery, how to incorporate the uncertainty into the analysis framework plays a crucial role in providing accurate information on supply chain setup, logistics decisions as well as the cost estimate. Here the literatures examined the effects of uncertainties on configuration of the biorefinery supply chain and close relative to this study are reviewed below. Cundiff et al. (1997) did the earliest work we found on the issue. Their study used an approach that minimized the expected delivery and capacity expansion costs of switchgrass under yield uncertainty for a biorefinery location in Virginia. They examined optimal logistic decisions under four different switchgrass yield conditions. Specifically, the model was solved for four different switchgrass availabilities, and the results show that the total cost of delivering switchgrass ranged from $13 to $15/dry Mg with included an average of $8 to $10/dry Mg transportation cost, $3/dry Mg loading cost, and $2/dry Mg storage cost. The study did not consider land contracting, biomass pre-processing, or ethanol conversion techniques. Although the results provide solution to the decision under different biomass supply, their approach inevitable suffered from problems of dimensionality and certainty. Thus, in addition to solve model multiple time, a multiple stage optimization model should be considered

Chen and Fan(2012) developed a stochastic, two stage MIP that utilized multiple waste products for feedstocks. The whole supply chain from biomass production to biofuel supply was considered. The main analyses in the study addressed the comparative performance between stochastic and deterministic model versions ignoring or considering demand and supply uncertainties. The results of their study showed that the production cost of ethanol can be as low as $0.32/L through optimal planning of the entire biofuel supply chain. The study was done at a county/city level centroid. For uncertainty, instead of using an empirical distribution from historical data, the probability used to reflect the feedstock supply fluctuation was assumed to be equal over different states of nature which would amplify the occurrence of extreme outcomes and lead to questionable analysis results.

Gebreslassie et al. (2012) built a MIP model that accounts for uncertainties in both feedstock supply and demand as well as consideration of financial risk. The results from the study identified the optimal number, capacity, location of biorefinery and the selection of conversion technologies in the state of Illinois. Agricultural residue, woody materials and energy crops are considered as inputs for biorefinery in the study. Besides, the study considered feedstock supply region, storage and biorefinery as the essential components in the proposed supply chain. Although the study provides information on the selecting the biorefinery sites and managing the risk, the study assume that the storage will be built at the same spot of biorefinery and did not consider remote depot or pellet plants for capturing stranded biomass.

Azadeh et al.(2014) developed a stochastic MIP to simulate the supply and transportation of multiple types of biomass to the biorefinery. The source of uncertainties in their study were market price of biofuel and the yield fluctuation of biomass supply. In addition, risk preference was included in the study. Their model considered only three components of biofuel supply chains: supply region, biorefinery, and ethanol demand points (e.g. biofuel blender). And the major inputs used in this study included agricultural residues, woody materials, and municipal wastes. The results of the study identified the optimal locations of biorefinery and storage and they also provided solutions to the logistics decisions such as inventory level and transportation routes at optimality. Yet, this study did not consider the uncertain supply in their analysis which in turn did not account for the situation where shortfall of biomass occurred.

Works by Osmani and Zhang(2014; Osmani and Zhang 2013) proposed a two-stage stochastic MIP which maximizes the annualized profit of a supply chain while minimizing GHG emissions using three feedstocks: switchgrass, corn stover and wheat straw. Uncertainty was introduced on crop yields and ethanol prices. The components included in the study were supply region, preprocessing station and biorefinery and storage was included in the preprocessing station. Besides, the crop yield uncertainty was represented via a probability distribution based on historical data of energy crops. The supply of corn stover and wheat straw was assumed to have a negative correlation with the yield of switchgrass. When the switchgrass yield is high, less crops residues was used and vice versa. The study found out that mean value of the stochastic parameters has significant impacts on the second stage decisions. They did find that biorefinery location was insensitive to the uncertainties. The study again was done at the county or city centroid level

Mohammad et al. (2014) developed a MIP model to address the biodiesel supply chain design by minimized the delivery costs of biodiesel and carbon footprint under stochastic biomass supply and technology improvement. Sludge was the major input for producing biodiesel and this study take into account sludge supplier, biocrude plant, diesel plant and customer as the main components of the proposed supply chain. The results of this study identify the number, capacity and locations of biocrude plants as well as the optimal transportation route for sludge and biodiesel. The study was conducted at the county level scale which again could lead to biased solution of the logistic system due to the missing link to the biomass distribution.

Zhao (2017) studied design issues for cellulosic biofuel supply chains. In doing this he developed a stochastic, two-stage mixed integer model was used to identify biorefinery, storage and preprocessing facility locations across Texas. Specifically, he considered corn stover, switchgrass and woody biomass as feedstocks where the model operated at the county level scale. The results showed that biorefineries were optimally located in dense feedstock production areas. He also found use of multiple feedstocks decreased the impact of seasonality and the need for storage. The study was conducted at the county level scale which again could lead to biased solution of the logistic system due to the missing link to the biomass distribution. For uncertainty, instead of using an empirical distribution from historical data, the probability used to reflect the feedstock supply fluctuation was assumed to be equal over different states of nature which would amplify the occurrence of extreme outcomes and lead to questionable analysis results.

The studies reviewed above used MIP models and accounted for uncertainties in addressing the biofuel supply chain issue. Again, few of these studies considered pelleting as a way to improve the use of stranded biomass by reducing the size and moisture content of the feedstocks. Additionally, these studies were conducted at the county level ignoring within county heterogeneity in biomass distribution situation and needed transportation Furthermore, most of the studies derived looked at single feedstock uncertainty in yield distributions with the distributions formed by regression over historical records or by simple assumption such as a uniform distribution. When multiple feedstocks present in the study, no study address the joint distributions including correlations between crops.

To extend the prior work, this study develops an MIP model based on a sub-county GIS based feedstock supply and examines the impact of key factors of uncertainty, pelleting, storage, and conversion technology on the optimal supply chain design, logistics decisions and system cost. Additionally, this study derives an empirical joint feedstock yield uncertainty distribution based on the historical data which reflects the correlation of crops. Also pelleting possibilities were added into the model to examine economic feasibility as well as its impact on the optimal supply chain design, logistics decisions and total cost.

CHAPTER III

SUPPLY CHAIN DESIGN MODEL

In this chapter, a model is developed for supply chain design considering a number of elements including:

- Multiple feedstocks or restrictions to single ones
- GIS based land for feedstock harvest availability at the county and subcounty level
- Monthly feedstock supply by GIS region
- Land use for type of feedstock by GIS region
- Feedstock yield uncertain states of nature inclusion or non-inclusion
- Historically based Joint probability distribution of yields
- A priori contracting for some feedstocks at a per acre basis
- Ex-post payment for contracted feedstock removal on a per ton basis under states of nature
- Harvest timing windows
- Harvest levels by month under states of nature
- Dumping at a cost of contracted excess feedstock under states of nature
- Optimal feedstock movement by month under states of nature
- Monthly choice of feedstock to refine under states of nature
- Monthly feedstock disposition to storage, pelleting, refinery input by type under states of nature
- Pellet exports at a sale price

- Storage deterioration month to month under states of nature
- Location of storage depots, biorefinery and pelleting plats
- Capital and operating cost of facilities
- Rate of conversion feedstock to ethanol

In setting these items the model minimizes total production plus annualized capital cost of the system. The model will be first set up under deterministic conditions then will be expanded into a two-stage stochastic model to consider strategic decisions independent of yield states of nature and operating decisions under a state of nature. The chapter will also cover the empirical method used to develop yield distributions that represent the joint uncertainty in the yields of the multiple feedstocks.

Additionally, estimating lands that could be employed and the available feedstock thereon plus the associated feedstock movement and facility placements can be challenging. Most previous studies have performed their analysis at the county scale. Here using a Geographic Information System (GIS), we will conduct a more detailed analysis at sub-county scale. The GIS data and procedures used are introduced in the end of this chapter.

Deterministic model development

A Mixed Integer Programming (MIP) model, which contains both continuous (material handling) and discrete (facility construction) variables, will be developed to represent the supply chain and investments in facilities. The MIP model will minimize the total capital plus operating costs across the whole biofuel supply chain while delivering a given volume of feedstock. The solution to the MIP model identifies optimal location of the biofuel refinery, along with the location and capacity of storage and pelleting facilities. It also identifies feedstock growing locations, feedstock mix, feedstock resource location and type, monthly harvest, storage additions/withdrawal, pelleting use, and the level of feedstock being transported between the harvesting area and the storage/pelleting/bio-refinery sites.

Problem Scope and Statement

Figure 1 adapted from (Ekşioğlu et al. 2010) depicts the potential full design of the supply chain allowed in this study.

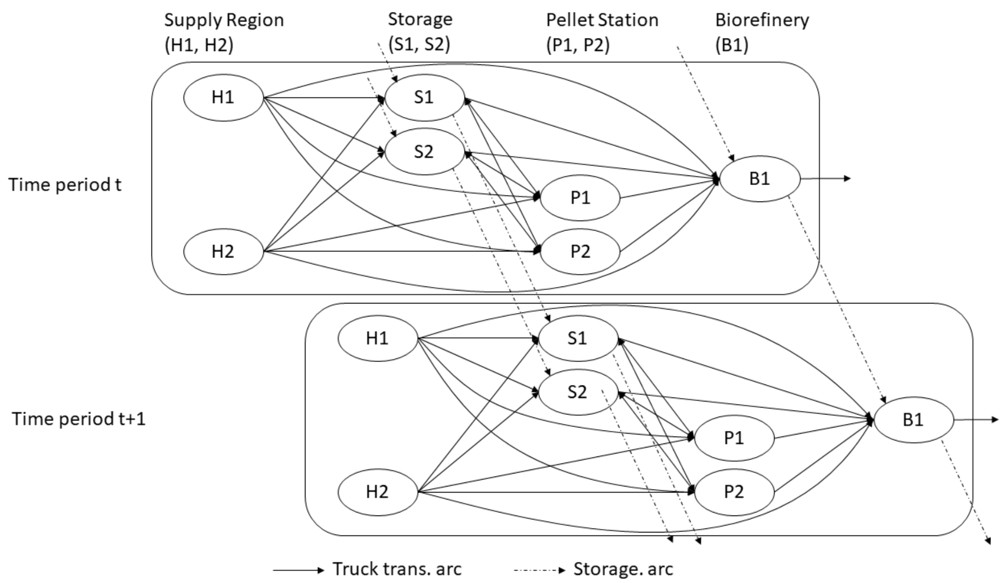


Figure 1Conceptual framework of a biofuel supply chain

The lignocellulosic ethanol supply chain in the current study is represented by an annual equilibrium model with monthly disaggregation where the chain is composed of four fundamental components: feedstock supply locations, intermediate storage depots, pelleting stations, and biorefinery possibly integrated with storage and pelleting.

In terms of feedstock supply the supply chain operator first decides the strategic decision of what lands need to be contracted to produce biomass. This will involve per ha and per ton removed payments. Then, the operational decision will be made on how much and where harvesting is done for each type of biomass per month when the month is in the harvest window. Depending on the biomass, different harvesting and collection systems will be used. The biomass, once harvested, will be moved to the edge of the fields and then transported to either remote storage depots for later use, pelleting stations to reduce size and moisture plus improve storage capability or will be shipped directly to the biorefinery site for refining, storage or pelleting.

In terms of storage first storage locations are chosen. Then monthly volume stored is determined. Most herbaceous biomass can be harvested in a short period of time due to timing of crop maturity, weather conditions and field operation constraints, and, thus consideration of timing is important as storage may be required to ensure year-round supply of feedstock to the biorefinery. For example, switchgrass, depending on the region, is usually harvested from December to the February. Another decision then is how much feedstock to store in raw or pelleted form to assure year-round feedstock supply. Additionally, biomass can deteriorate in storage with the rate dependent on form and storage method. method. Biomass stored on the edge of the field without any cover suffer losses of up to 30% while covered storage lowers the loss to 3% - 5% and pelleting eliminates deterioration (Darr and Shah 2012).

For pelleting, the biomass can be sent to pellet station where excess moisture is removes and the size is reduced increasing energy density. Also, it is important to note the desirability of pelleting needs to weigh its lower transport cost per unit energy (occurring because of lower weight with water removed and its denser energy content) versus the capital and operating costs of the pelleting plant. Finally, all the biomass transport to the depots/pelleting station/biorefinery is assumed to be by truck following assertions that trucking is more efficient for short distance hauling(Park et al. 2017; Zhang et al. 2016).

Structure of the Mixed Integer Problem

The proposed model uses integer variables to depict facility location and a linear programming component to simulate transporting, storing, pelleting and processing feedstocks. Figure 2 represents a basic framework of the model.

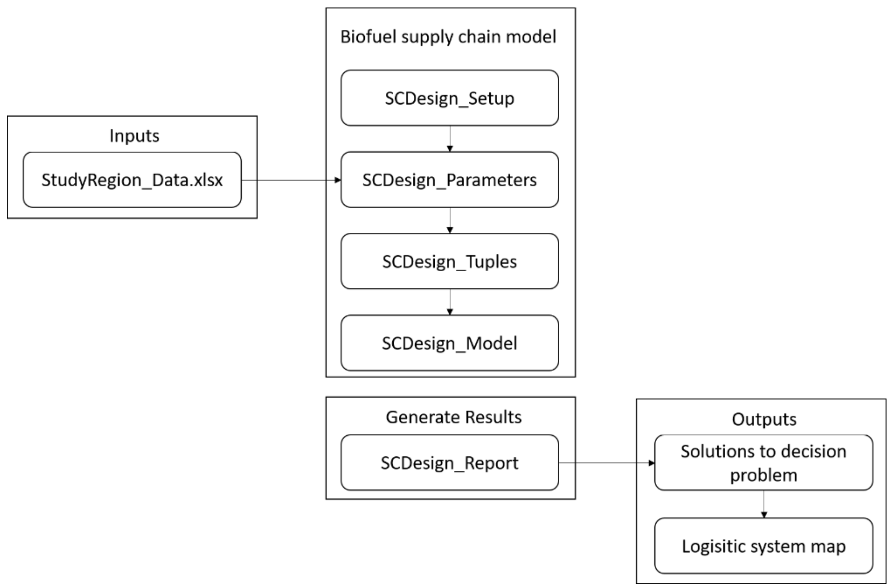


Figure 2 Basic framework of the model

The MIP biofuel supply chain model is programmed in GAMS and includes five components: sets, parameters, tuples, model and report writing.

- the sets identify all subscripts contained in the model,
- the parameters specify the data inputs into the model,
- the tuples define the potential locations of feedstock production and available shipment routes in the region,
- the model component specifies the variable and equations both naming them and in algebraic form.

- The report script compiles the optimal solutions into a set of reports that informs an analyst on the aspects of the solution.

The linear programming model component models production on the contracted lands, amount of each feedstock harvested, the amount of feedstocks being sent to intermediate storage depots, amount of feedstocks being sent to pelleting plants, seasonal storage additions/withdrawals, seasonal pelleting activity, seasonal export sales of pellets outside the region, monthly feedstock use for biorefining, amount of ethanol being produced, and the transportation movements of feedstocks by type in raw and pelleted form. The model minimizes total costs associated with construction of storage, pelleting and the biorefinery, feedstock contracting and the variable costs of production, storage, pelleting, feedstock conversion and transportation. In other words, given the parameters such as: a) feedstock production/harvest costs and land availability for energy crops and crop residues; b) land opportunity costs in other crops; c) availability of timber residues; d) amortized capital costs of facility construction for storage depots, central storage, remote pelleting, central pelleting and biorefinery technology plus potential locations; e) costs of monthly storage and capacity by feedstock type and form plus cost of storage loading and unloading; f) cost of and capacity for pellet manufacture, g) transportation availability by mode and transport cost for both raw feedstocks and pelleted ones for shortest routes identified by GIS between feedstock production locations, potential storage depots, potential pelleting sites, and potential biorefinery locations; h) costs of ethanol manufacturer from raw feedstocks and pellets; and i) where relevant, revenues from pellet export.

In turn, the model solves for: i) the location of biorefinery, storage depots and pelleting sites, ii) the area of energy crops, crop residues and other locally available feedstocks in the supply region contracted, iii) the amount of biomass harvested, iv) the usage of feedstocks in refining; v) seasonal storage by type of feedstock and pellets in the depots plus centrally, v) the amount of pellets produced, vi) the amount of feedstocks and pellets transported between different supply chain components and vii) the volume of pellets exported.

Mathematical Formulation

A list of model sets, parameters, and decision variables is given in Table 1. As said above the first model version discussed will assume deterministic biomass supply and will meet a given level of ethanol production. The objective function minimizes the annual total capital and operating cost of the supply chain involving 1) contracting cost for the energy crops and crop residues, CLC, 2) biomass production cost, CBP, 3) storage holding cost CST, 4) pelleting cost, CPL, 5) transportation cost CTP, and 6) capital cost of constructing facilities at the biorefinery, pelleting site and storage depots, CAP. The total objective function including all these components is expressed in Eq. (1).

$$Min\ CLC + \text{CBP} + CST + CPL + CTP + CAP \tag{1}$$

Each component is mathematically set up as follows.

$$CLC = \sum_{i,b} c_{ib} M_{ib} \tag{2}$$

$$CBP = \sum_{i,b,t} \alpha_b a_b N_{bit} \tag{3}$$

$$CST = \sum\nolimits_{b,k,t} \beta_b Q_{bkt} \tag{4}$$

$$CPL = \sum\nolimits_{b,l,k,j,t} \gamma R_{blt} \tag{5}$$

$$CTP = \sum_{ijbt} \left(\delta_b + \epsilon_b \times D_{ij}\right) OBR_{bijt} \tag{6}$$

$$+ \sum_{ikjbt} (\delta_b + \epsilon_b \times D_{ik}) OST_{bikt}$$

$$+ \sum_{iljbt} (\delta_b + \epsilon_b \times D_{il}) OPL_{bilt}$$

$$+ \sum_{bkjt} \left(\delta_b + \epsilon_b \times D_{kj}\right) PBR_{bkjt}$$

$$+ \sum_{bklt} (\delta_b + \epsilon_b \times D_{kl}) PPL_{bklt}$$

$$CAP = \sum_{j} \eta_j X_j + \sum_{k} \rho_k Y_k + \sum_{l} \phi_l Z_l \tag{7}$$

Equation 2 computes the total cost of contracting land that is paid on a per ha basis where c_{ib} represents the per hectare cost of contracting land at location i for feedstock type b. In this study c_{ib} is set equal to the sum of land rent as a measure of land opportunity cost and the establishment cost of establishing energy crop b per hectare land at location i. In the case of wood and corn stover c_{ib} is defined as the per hectare payment to the land owner that establishes the option of later collecting crop/woody residues. M_{ib} is the amount of land in hectares being contracted for supply of feedstock b at location i.

Equation 3 adds up the cost of feedstock harvest. The cost of each ton of feedstock type b is α_b , and is assumed to be invariant by location and time of year. The variable N_{bit} is gives the metric tons of feedstock type b being harvested at location i in month t while a_b is the yield of the feedstock.

Equation 4 adds up the total cost of storing of biomass where β_b is the per ton cost of storing feedstock type b and is assumed to be invariant by storage depot location and month. Here Q_{bkt} is the amount of feedstock b being stored at storage location k in month t.

Equation 5 adds up the total cost of pelleting biomass. Note that γ is the pelleting cost per Mg of raw feedstock that is pelleted and is assumed to be invariant by pelleting location and month, R_{blt} is the tons of feedstock b that are pelleted at location l in month t.

Equation 6 adds up the transportation cost within the supply chain where OBR_{bijt} is the amount of feedstock b being moved from production location i to biorefinery location j in month t. D_{ij} is the travel distance from production location i to biorefinery location j, σ_b is the cost of loading and unloading feedstock b and δ_b is the transportation cost for feedstock b per Km traveled. OST_{bikt} is the amount of feedstock b being moved from production location i to storage location k in month t. D_{ik} is the travel distance from production location i to storage location k. OPL_{bilt} is the amount of feedstock b being moved from production location i to pelleting location l in month t. D_{il} is the travel distance from production location i to pelleting location l. PBR_{bkjt} is the amount of feedstock b being moved from storage location k to biorefinery location j in month t. D_{kj} is the travel distance from storage location k to biorefinery location j. And, finally, PPL_{bklt} is the amount of feedstock b being moved from storage location k to pelleting location l in month t. D_{kl} is the travel distance from storage location k to pelleting location l.

Equation 7 adds up the annualized fixed capital costs incurred in constructing supply chain facilities where η_j, ρ_k, and ϕ_l are the annualized capital cost of building a biorefinery at potential biorefinery location j, a storage at potential storage location k, and a pellet plant at potential pellet plant location l, respectively. X_j, Y_k, and Z_l are binary decision variables which indicate whether a biorefinery, a depot and a pellet stations is built at location j, location k and location l or not correspondingly.

The model is optimized subject to a set of constraints which are portrayed within equations 8 to 18.

$$\sum_{bt} N_{bit} \leq M_{ib} \quad for\ all\ b, i \tag{8}$$

Equation 8 limits the amount of biomass harvested of type b, month t to be less than or equal to the amount of land contracted in region i. In the equation N_{bit} is the land area of feedstock b harvested in supply region i in month t, M_{ib} is the total amount of land contracted in supply region. Algebraically we sum across the energy crop possibilities b and the appropriate possible harvest time periods (t) requiring across all of those to be less than or equal to the amount of contracted land.

$$\sum_{j} OBR_{bijt} + \sum_{k} OST_{bikt} + \sum_{l} OPL_{bilt} \leq a_b N_{bit}\ for\ all\ b, i, t \tag{9}$$

Equation 9 ensures that for each feedstock b transported out of this supply region i the amount sent has to be less than the volume of feedstock b harvested in supply region i during harvest month t. In this study, the on-production-site storage location is precluded, and biomass will be sent to another segment of the supply chain once harvested. The variables OBR_{bijt}, OST_{bikt}, and OPL_{bilt} represent the amount of feedstock b being transported from supply region i to the places where it is used or stored covering biorefinery location j, storage location k, and pellet location l respectively.

$$Q_{b,k,t} + (\sum_j PBR_{bkjt} + \sum_l PPL_{bklt})_{b \neq pellet} \le (1 - \omega_b) Q_{bk,t-1} + \sum_i OST_{bikt} + (\sum_l PLST_{blkt})_{b=pellet} \quad for\ all\ b\ ,k,t \tag{10}$$

Equation 10 balances storage by month. Specifically, for storage location k the amount of feedstock b retained in storage from month t to month t +1 plus that shipped out from storage location k at t and the biomass stored at storage location k at month t must not be greater than the amount of storage carried over from last month adjusted for the storage loss (ω_b) plus the new incoming supply. Outgoing shipments can go to either the biorefinery location j or to the pelleting location l. The variable PBR_{bkjt} gives the volume of feedstock be going from storage location k to biorefinery location in month t. Similarly, PPL_{bklt} gives the volume of feedstock b transported from storage location k to pelleting location l in month t. Storage of feedstock b at storage location k that is held over from last month is represented by $Q_{bk,t-1}$while $Q_{bk,t}$ is the material placed in storage that will be held over to next month. Incoming shipments of feedstock b coming from supply location i to storage location k during the month t are represented by OST_{bikt}. $PLST_{blkt}$ represents the shipment of pellet from pellet plant plant l to storage k during month t. Additionally, there is a deterioration rate, ω_b, that reduces the amount of carryover storage.

$$Q_{bj,t} + S_{bjt} \le (1 - \omega_b) Q_{bj,t-1} + (\sum_i OBR_{bijt})_{b \neq pellet} + (\sum_k PBR_{bkjt} + \sum_l PLBR_{pellet,ljt})_{b=pellet} \quad for\ all\ b\ ,j,t \tag{11}$$

Equation 11 is a similar supply demand balance constraint for the feedstocks at refinery location j. There the refinery usage of biomass b during the month t plus the amount stored, must be less or equal to the carry over storage from the previous month adjusted for loss plus the incoming shipments of feedstock b from supply point i and storage location k plus. Here $Q_{bj,t-1}$ represents the storage of feedstock b at biorefinery location j carried over from month t-1 and $Q_{bj,t}$ the current amount stored into next month. S_{bjt} is the volume of feedstock b being used for processing at biorefinery location j during month t, and the incoming transport is represented by OBR_{bikt}, $PBR_{bkjt}$and $PLBR_{bljt}$1which give the amount of feedstock b being sent to biorefinery location j from supply region i, from storage location k, and from pelleting location l, respectively, at month t.

$$\left(\sum_{ib} OPL_{bilt} + \sum_{k} PPL_{bklt}\right) \times (1-\kappa_a) \geq (\sum_{k} PLST_{lkt} + \sum_{j} PLBR_{ljt} + PLEX_{lt)}) \;\; for\ all\ \ l,t \tag{12}$$

Equation 12 is a supply demand balance for feedstock b at pelleting location l during month. It limits usage to be less than or equal to the available supply and specifies that feedstock used for pellets being shipped out must be less than the sum of the feedstock in times the pelleting yield. Here 1-κ_a is pelleting yield, OPL_{bilt} is the incoming volume of feedstock b sent from supply region i to pelleting location l, PPL_{bklt} is the incoming amount of feedstock b transported from storage location k l, $PLST_{lkt}$ is the volume of pellets sent out from pelleting location l to storage location k, $PLBR_{ljt}$ represents the amount of pellets shipped from pelleting location l to biorefinery location j at time t, and $PLEX_{lt}$ represents the amount of pellets being exported from pelleting location l at time t if export is allowed.

$$U_{jt} \leq \sum_{b} \lambda_b S_{bjt} \;\; for\ all\ b,j,t \tag{13}$$

[1]Here b represents the amount of pellet being sent to biorefinery

Equation 13 is the ethanol balance constraint at biorefinery location j and it limits the ethanol manufactured and sold to be less than or equal to the amount produced from the various feedstocks shipped in. Here U_{jt}represents the amount of ethanol required to be produced at biorefinery location j during month t. The amount of processing activity is represented by S_{bjt}, for biomass feedstock b, and conversion rates is given by λ_b .

$$G_t X_j \leq \sum_{bj} U_{bjt} \;\; for\ all\ \ t \tag{14}$$

Equation 14 specifies that the minimum volume of ethanol that has to be produced in each month. Where G_t is the minimum requirement in month t, U_{bjt} is the amount of ethanol produced at biorefinery location j from feedstock b2 at time t and X_j is the binary variable indicating whether the biorefinery at location j is built or not.

$$\sum_b Q_{bkt} \leq F_k Y_k \; for\ all\ k, t \tag{15}$$

$$\sum_b Q_{bjt} \leq F_j X_j \; for\ all\ j, t \tag{16}$$

Equations 15 and 16impose capacity constraints on the available storage. Namely the sum of feedstock b stored at a location which an equation 15 is storage location k and in 16 is biorefinery location j. The storage capacities in these locations are F_k and F_j, respectively and these are multiplied by integer variables as to whether storage location K and biorefinery location jR in fact constructed.

$$H_t \leq \sum_b Q_{bjt} \;\; for\ all\ j, t \tag{17}$$

[2] Here feedstocks refer to both raw biomass and pellets

Equation 17 imposes a required amount of backup supply kept in storage at each biorefinery where H_t is the minimum required storage at any biorefinery in time t.

$$\sum_{j} X_j \leq 1 \tag{18}$$

Equation 18 limits the number of bio refineries constructed to one.

Incorporating Yield Uncertainty – the Stochastic Model

Yield uncertainty has been neglected in many of the previous studies. This is certainly questionable given the high degree of yield variability exhibited by agriculture. Clearly, the solutions of the deterministic model would likely downwardly bias the amount of feedstock acreage needed to be contracted plus would not deal with the situation where excess feedstock is produced. Simply put the design of the biofuel supply chain must be accommodating of yield fluctuation and have planned procedures for handling shortages and surpluses. (Gebreslassie et al. 2012), argue that a deterministically-based supply chain design may not work under conditions of shortage and are likely to generate suboptimal, poorly performing, supply chains. Here we extend the above deterministic model to account for yield uncertainty. Note other uncertainties could also be built-in but for now yield uncertainty is the only one we will address.

Development of a Probability Distribution for Crops Yields

The first step in developing the stochastic, yield uncertainty accommodating, model involves construction of a probability distribution for biomass yield. This was done based on historical yields that we will de-trend using a simple regression model. Yields over time generally exhibit a trend due to technical progress, climate change and other factors evolving over time. Regression will be used to estimate that trend then it will be removed with the variation around the trend used to form the yield uncertainty probability distribution. Namely, the residuals from the regression equation estimated over historical yield will be interpreted as equally likely crop yield variations from a yield expectation. The regression estimates appear in Equation 19.

$$A_{bt} = \beta_{0\mathrm{b}} + \beta_{1\mathrm{b}} t + e_{\mathrm{bt}} \tag{19}$$

Where A_{bt} is the historical reported yield for feedstock b or a related proxy crop in year t. The ratio of the error term (ebt) to the regression projection for each year is calculated to reflect the proportional deviation of crop yields from their predicted values. Based on the range of deviation, we then arrayed these proportional deviations from low to high and grouped them into intervals each with a probability equaling the count of observations falling into that interval divided by the number of historical observations. The mean of each interval was then used as representative of the observations falling into that interval. However, this procedure forms a single feedstock distribution, but multiple feedstocks are presented so a joint distribution needed to be formed.

The joint probability distribution was again formed using the historical observations. To do this the yield distributions for each feedstock we divided into four yield intervals: bad, low, fine, and good. The bad yield level for corn stover referred to any year with its shock worse than 20.4% below its expected yield level, while the low yield level referred to the years with their deviation falling between 20.4% and 9% below the mean. Similarly, the fine yield level referred the deviation between 9% below and 2.3% above the mean, and the good yield level referred to the cases when the yield was better than +2.3%. In turn the joint distribution was developed by categorizing each historical year in terms of the combination of the shocks for each of the feedstocks. In the high plains case studied in chapter 4 there were three crops and when each has 4 possibilities we get 43 or 64 joint possibilities. In turn we sorted the historical observations into these 64 buckets eliminating those that never occurred. The probability of each state of nature was then estimated through dividing the counts of observation falling into each bucket by the total observations. Table 10 below lists the probability of each states of nature used in the High Plains case model.

Table 1 Empirical Probability Distribution of States of Nature

	cornstover	switchgrass	energysorghum	sorghumstover	frequency	Prob
State of Nature 1	bad	bad	bad	bad	1	0.02
State of Nature 2	bad	low	bad	bad	1	0.02
State of Nature 3	bad	low	low	low	2	0.04
State of Nature 4	low	low	low	low	16	0.36
State of Nature 5	fine	low	low	low	2	0.04
State of Nature 6	fine	fine	low	low	3	0.07
State of Nature 7	fine	fine	fine	fine	16	0.36
State of Nature 8	good	fine	fine	fine	2	0.04
State of Nature 9	good	good	fine	fine	1	0.02
State of Nature 10	good	good	good	good	1	0.02

Mathematical Formulation of Stochastic Model

Now we form a two-stage stochastic MIP model that minimizes the expected cost of the biofuel supply chain in the face of the feedstock yield joint distribution. The model will follow the classic Dantzig two stage aircraft scheduling model. The first stage will contain state of nature independent strategic decisions like facility construction, feedstock land contracting and crop choice. The second stage represents tactical, state of nature informed decisions that given a yield outcome depict feedstock harvest, movement, storage, refining and other disposition.

The objective function gives the first stage capital and contracting costs plus summed probabilistically weighted tactical decision costs as in Equation 20.

$$Min\ CAPCON + \sum_{s} Prob_s \times (CBP(s) + CST(s) + CPL(s) + CTP(s)) \qquad (20)$$

Equation 20 includes terms for strategic decisions on capital and contracting ($CAPCON$), plus the state of nature (s) dependent tactical decisions of feedstock harvest and removal, biorefinery processing (CBP), storage(CST), pelleting(CPL) and transport (CTP). The component parts of this are formed as follows.

$$CAPCON = \sum_{j} \eta_j X_j + \sum_{k} \rho_k Y_k + \sum_{l} \phi_l Z_l + \sum_{ib} c_{ib} M_{ib} \qquad (21)$$

Equation 21 sums annualized fixed capital cost of refinery construction $\sum_j \eta_j X_j$ over the refinery alternatives (j) plus storage depot construction $\sum_k \rho_k Y_k$ over the storage depot alternatives (k) plus pellet plant construction $\sum_l \phi_l Z_l$ over the storage alternatives (l) and the land area contracting costs $\sum_{ib} c_{ib} M_{ib}$ across the land area alternatives (i) and biomass feedstock alternatives (b). Note these are all chosen independent of state of nature. In other words, these choices are made, and their costs locked in before the yield state is known and are irreversible and not modifiable under individual yield states. Thus, one cannot have a different amount or location of biorefineries, storage depots, pelleting plants or contracted lands under each state of nature rather the same is shared by all. Here η_j is the annualized capital cost of constructing biorefinery facility at j while ρ_k and ϕ_l is the annualized capital cost of constructing storage depot at alternative k and at pelleting plant alternative l. Additionally c_{ib} is the per unit land contracting cost for parcel i which is the sum of land rental rate (as a measure of land opportunity costs) and the establishment cost for an acre of feedstock type b. X_j, Y_k, and Z_l are binary decision variables which indicates whether a biorefinery, a depot or a pelleting location is built. M_{ib} represents amount of land being contracted for production of feedstocks and is also established independent of exact yield outcome.

Note that for the second stage variables, an additional subscript, s, is introduced to represent the yield outcome within the stochastic model and they are weighted by the probability (Probs).

$$CBP(s) \quad = \sum_{i,b,t} \alpha_b a_{bs} N_{bits} \tag{22}$$

Equation 22 adds up the harvest cost of biomass by state of nature. Therein α_b is the cost of harvesting one ton of type b biomass while a_{bs} is the yield of deestock b under state of nature s and N_{bits} is the amount of biomass b land that is harvested from parcel i in month t under state of nature s.

$$CST(s) = \sum_{b,k,t} \beta_b Q_{bkt}(s) \text{ for all s} \tag{23}$$

Equation 23 adds up the cost of storing feedstock under state of nature s where β_b is the cost of storing type b biomass and $Q_{bkt}(s)$ is the amount of feedstock b being stored at depot k in month t under state of nature s.

$$CPL(s) = \sum_{b,l,k,j,t} \gamma_b (R_{blt}(s)) \text{ for all s} \tag{24}$$

Equation 24 portrays the total cost of pelletizing feedstocks with γ_b giving the pelleting cost per ton and $R_{blt}(s)$ is the amount of pellets derived from feedstock b at pelleting location k in month t under state of nature s.

$$CTP(s) = \sum_{ijbt} (\delta_b + \epsilon_b \times D_{ij}) OBR_{bijt}(s) \tag{25}$$

$$+ \sum_{ikjbt} (\delta_b + \epsilon_b \times D_{ik}) OST_{bikt}(s)$$

$$+ \sum_{iljbt} (\delta_b + \epsilon_b \times D_{il}) OPL_{bilt}(s)$$

$$+\sum_{bkjt}(\delta_b + \epsilon_b \times D_{kj})PBR_{bkjt}(s)$$

$$+\sum_{bklt}(\delta_b + \epsilon_b \times D_{kl})PPL_{bklt}(s) \quad \text{for all s}$$

Equation 25 adds up the transportation cost within the supply chain under state of nature s where $OBR_{bijt}(s)$ is the amount of feedstock b being moved from production location i to biorefinery location j in month t under state of nature s. D_{ij} is the travel distance from production location i to biorefinery location j, σ_b is the cost of loading and unloading feedstock b and δ_b is the transportation cost for feedstock b per Km traveled. $OST_{bikt}(s)$ is the amount of feedstock b being moved from production location i to storage location k in month t under state of nature s. D_{ik} is the travel distance from production location i to storage location k. $OPL_{bilt}(s)$ is the amount of feedstock b being moved from production location i to pelleting location l in month t under state of nature s. D_{il} is the travel distance from production location i to pelleting location l. $PBR_{bkjt}(s)$ is the amount of feedstock b being moved from storage location k to biorefinery location j in month t under state of nature s. D_{kj} is the travel distance from storage location k to biorefinery location j. And, finally, $PPL_{bklt}(s)$ is the amount of feedstock b being moved from storage location k to pelleting location l in month t under state of nature s. D_{kl} is the travel distance from storage location k to pelleting location l.

The model is again optimized with respect to constraints which are expressed in Equations. (26) to (36).

$$\sum_{b,t} N_{bit}(s) \leq M_{ib} \ \ for\ all\ i, s \tag{26}$$

Equation 26 limits the acres harvested of feedstock type b in supply region i and month t under state of nature s to be less than the state of nature independent amount of contracted land for feedstock b (Mib).

$$\sum_j OBR_{bijt}(s) + \sum_k OST_{bikt}(s) + \sum_l OPL_{bilt}(s) \leq a_{bs} N_{bit}(s)\ \forall b, i, t, s \tag{27}$$

Equation 27 ensures that the amount of feedstock b transported out from supply region i to be less than the harvested land area of feedstock b at month t in supply region i under each of the state of nature times the state of nature dependent yield. Note both the transport and the yield are state of nature dependent.

$$\begin{aligned} Q_{b,k,t}(s) + \sum_j PBR_{bkjt}(s) + (\sum_l PPL_{bklt}(s))_{b\neq pellet} \\ \leq (1-\omega_b) Q_{bk,t-1}(s) \\ + (\sum_i OST_{bikt}(s)))_{b\neq pellet} \\ + (\sum_l PLST_{blkt}(s))_{b=pellet}\ \forall b, k, t, s \end{aligned} \tag{28}$$

Equation 28 balances the stored feedstock of type b in each month for each of state of nature at storage location k. Specifically, the sum of the storage retained plus that shipped out from storage location k of feedstock type b is less than or equal to that shipped in from production places plus pellets from the pellet plant (l) plus that retained from storage adjusted for spoilage (ω_b) again by state of nature.

$$Q_{bj,t}(s) + S_{bjt}(s) \leq (1-\omega_b)Q_{bj,t-1}(s) + (\sum_i OBR_{bijt}(s))_{b\neq pellet} + (\sum_k PBR_{bkjt}(s) + \sum_l PLBR_{ljt}(s))_{b=pellet} \;\; \forall b,j,t,s \tag{29}$$

Equation 29 similarly balances feedstock at the refinery. There at biorefinery location j the sum of feedstock b converted into ethanol in month t and the biomass stored into next month must be less than the sum of feedstock b transported into biorefinery location j from production locations plus that from remote storage depots and that from pelleting locations ($PLBR_{bljt}$) in month t and the biomass carried in from storage location k in the previous month adjusted for spoilage again for each state of nature.

$$\sum_k PLST_{lkt}(s) + \sum_j PLBR_{ljt}(s) + +PLEX_{lt}(s) \leq \; (1-\kappa_a) \times \left(\sum_{bi} OPL_{bilt}(s) + \sum_{bk} PPL_{bklt}(s)\right) \; \forall \; l,t,s \tag{30}$$

Equation 30 imposes a balance for pellets out versus feedstocks in at pelleting location l in month t and it specifies the pellets transported to the storage or biorefinery locations must be less than the sum of the feedstocks received at pelleting location l adjusted for the pelleting yield.

$$U_{jt}(s) \leq \sum_b \lambda_b S_{bjt}(s) \;\; \forall b,j,t,s \tag{31}$$

Equation 31 limits the ethanol produced at biorefinery location j to the ethanol yield from the raw biomass and pellets processed accounting for the associated conversion rate. This balance is imposed for each state of nature.

$$G_t X_j \leq \sum_j U_{jt}(s) \quad \forall \, j, t, s \tag{32}$$

Equation 32 requires production of a minimum amount of ethanol in each month that is equal for each state of nature at each potential biorefinery location.

$$\sum_b Q_{bkt}(s) \leq F_k Y_k \;\; \forall k, t, s \tag{33}$$

$$\sum_b Q_{bjt}(s) \leq F_j X_j \;\; \forall j, t, s \tag{34}$$

Equations 33 and 34 limits the sum of feedstock b stored at storage location k or biorefinery location j to be less than its capacity, F_k and F_j times an integer variable identifying whether or not the storage depot location or central storage at the biorefinery is constructed. This is imposed for each month and each state of nature although the capacity constructed is independent of state of nature representing the first stage consideration. Note the volume stored can vary by state of nature but not the capacity.

$$H_t \leq \sum_b Q_{bjt}(s) \;\; \forall \, j, t, s \tag{35}$$

Equation 35 imposes a minimum safety requirement for a given volume of storage required for biorefinery to prepare for emergency use at all time under all states of nature.

$$\sum_j X_j \leq 1 \tag{36}$$

Equation 36 is a configuration constraint which limits the number of biorefineries built to be one.

Spatial Representation of the Availability of Feedstock

The exact design of the biofuel supply chain is geographically dependent based on potential locations for production of feedstocks, feedstock yields and their uncertainty, transport routes and modes, potential storage, pelleting and biorefinery locations and other factors. A supply chain with the biorefinery located closer to feedstock production lowers logistic and fuel production costs. Yet a coarser representation of the region and the possible incidence of large modeled regions can potentially inaccurately represent possibilities and bias solutions. Furthermore, most previous studies have used the relatively coarse county level geographic representation. Here we use a finer scale representation using Geographical Information System (GIS) data when considering the supply chain for a biorefinery., Namely we break the region into 200 square Km grid cells. This yields a number of cells within the study region county's that varies from 10 to 20.

GIS Data Site Selection and Resolution Scheme

With respect to GIS use this study proceeded in two stages. First, we looked at county level herbaceous and woody crop feedstock availability in a large area in s general study region and then locate a multi county service region that can support a biorefinery. Then later we disaggregate the county level data into a finer spatial grid.

The GIS data processing scheme used to do this is depicted in Figure 3 below.

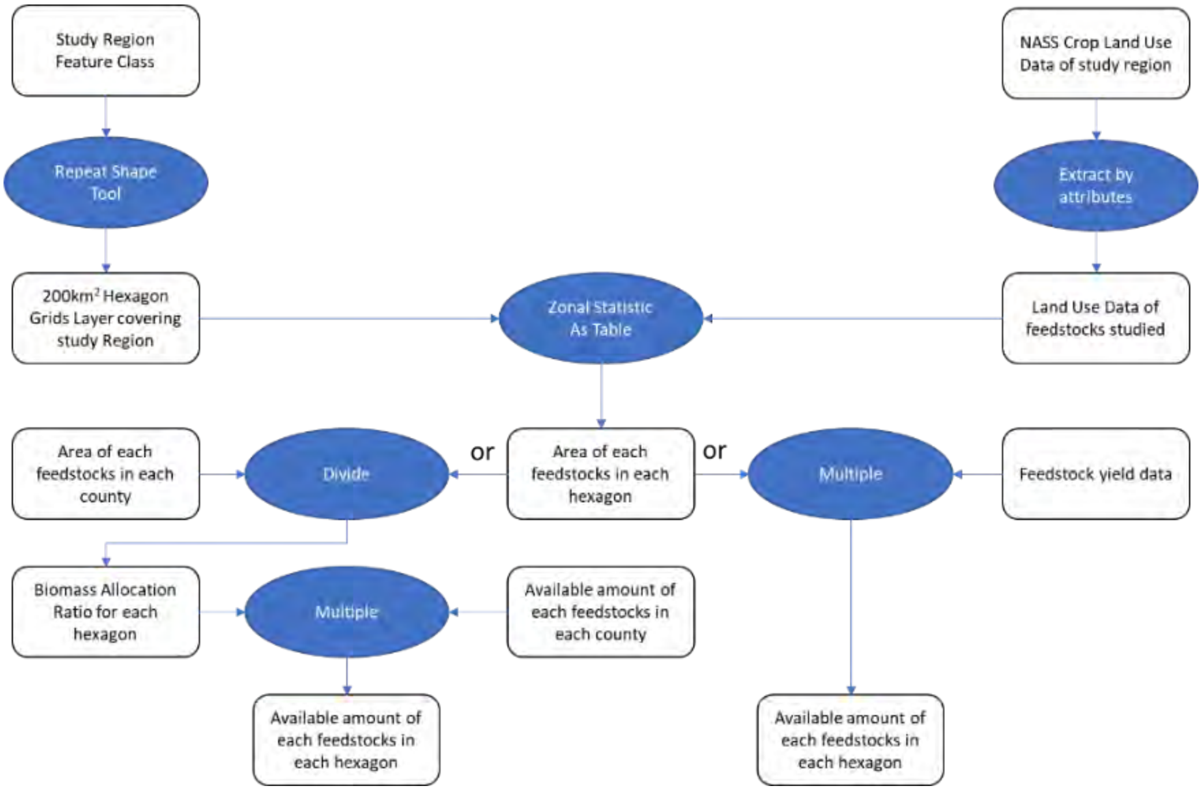


Figure 3. Conceptual framework of a biofuel supply chain

To implement this, we first chose two general study regions. One is in East Texas where there were both woody and herbaceous feedstocks are potentially available and the other is in North Texas where crop residues and energy crops could be utilized.

To hone in on exact locations first a 200 km2 hexagon layer was developed across a multi county region using the repeated shaping tool in ArcMap. Hexagons were used as they efficiently cover the study region without much sampling bias from edge effects and curvature plus they can cover the study region without overlap.

For the data GIS land use layers from the NASS Cropland Data Layer(CDL) (USDA 2018) were used. The available feedstock regions from other land uses were developed using the extracted by attributes tool from ArcMap. In East Texas used the tool to identify flat pasture land areas that could be used for feedstock production along with forested lands that were potentially available for harvest. In North Texas we used availability of irrigated corn land for potential crop residue harvest and the availability of dryland production for potential energy crop areas. Subsequently the hexagon grid layer and the feedstock distribution layer were then used in a zonal statistics tool as input to calculate the area in pixels of each land use in each hexagon. Here the pixels were 30m by 30m (i.e. 900 square meters). Then the available area of land use in a pixel was calculated by multiplying the count of pixels times the pixel size. For example, in in a hexagon there were 20 pixels where land use is classified as land in dryland sorghum then the sorghum area in the hexagon is set equal to 20 times 900.

CHAPTER IV

REGIONAL SUPPLY CHAIN MANAGEMENT CASE STUDY: TEXAS HIGH PLAINS

Introduction

There has been a growing interest in the production of the second-generation biofuels from agricultural residues, forest residues, energy crops and industrial waste. Relative to first generation biofuel processes, second generation biofuel feedstocks reduce energy-food competition through use of residues, higher yielding energy crops and or utilization of marginal land. Furthermore, the energy and greenhouse gas balances when producing the first-generation biofuel are not as favorable as those for second generation feedstocks (Wang et al. 2012; Wang et al. 2011; Humbird et al. 2011; Qin et al. 2006).

Based on the Renewable Fuel Standard (RFS) as laid out in the 2007 Energy Independence and Security Act indicates that the required blending of biofuel by 2020 would need to reach the level of 136,000 Million Liters Per Year(MLPY). Within this target, no more than 57,000 MLPY can come from first generation biofuel production, and at least, 61,000 MLPY is required from cellulosic based biofuels. However, the anticipated blending levels in that legislation have not been met. For example, in 2015, only 540.55 MLPY of cellulosic biofuel was produced as opposed to a target of 11,350 MLPY (EPA 2016). Additionally, a lot of this came from a reclassifying biogas from landfills, municipal wastewater treatment facility digesters, agricultural digesters as cellulosic biofuel and this in 2018 is expected to be 93% of the cellulosic biofuel (Hansen 2017) so via the earlier definitions production is quite small.

Reasons for why commercial production has not grown as fast as expected involve cost, logistics and large-scale conversion technology issues. Several studies have argued that technological challenges need to be solved in order to make lignocellulosic feedstock based biofuel price competitive relative to other means of ethanol production (Krishnakumar and Ileleji 2010; Hess, Wright and Kenney 2007).

One big challenge hindering cellulosic ethanol expansion is logistics cost. Previous studies (Hess et al. 2007; An and Searcy 2012; Park et al. 2017) argued that the logistics cost of cellulosic biofuel is substantial with results showing it can range from 30% to 50% of total production cost. This high cost arises due to the wide spatial distribution of biomass, it's low energy density and its high-water content. Moreover, logistics costs are also increased by the existence of short harvesting windows for some forms of biomass that in turn require additional labor, alternative harvest equipment and substantial storage investments plus storage operation.

Beyond those cost issues another development complicating logistics system design is the inherently uncertain nature of lignocellulosic biomass yields as the source crops are highly influenced by the weather conditions and thus yields vary from year to year.

All these things considered logistic system design can be complex, needing to deliver feedstocks at low costs throughout the year while accommodating yield uncertainties. In this chapter, a case study setting on logistics design under the factors above will be done in the High Plains of Texas.

The chapter is presented in the following order. First background on the study region and key case study assumptions are introduced. Second, we cover the steps used to derive a probability distribution for yields of multiple crops and the formation of a discrete set of yield states of nature. Third we study the logistical supply chain implications of considering and ignoring uncertainty. We will also study the consequence of having or eliminating remote storage and possible pelleting operations then do a sensitivity analyses on the impacts of conversion rate improvement and alternative pellet prices. Finally, an analysis will be done examining the effect of using high resolution spatial data versus county data.

Problem Statement

Conceptually a cellulosic biofuel supply chain consists of the following a) A set of feedstock production locations (e.g. H1, H2, …, Hi); b) multiple biomass feedstocks that can be produced, F1, F2, …, Fb, with alternative harvest seasons; c) a biorefinery located potentially at sites, B1, B2, …, Bj; d) possible locations for storage at sites, S1, S2, …, Sk and e) potential locations, P1, P2, …, Pl, for densifying the bulky biomass into small, dry and more energy dense pellets. In turn designing the supply chain involves choosing the optimal simultaneous choices of location and operation of feedstock production, biorefinery, storage and pelleting along with a monthly movement pattern that supplies an appropriate amount of feedstock to the refinery on a year-round basis. Additionally, provisions are needed to handle variation in feedstock yields.

A Mixed Integer Programming (MIP) model was developed that modeled the choice variables associated with the items above and minimized costs of investments and operations. The model minimized cost of making a given amount of cellulosic ethanol and in doing that manipulated variables for:

- The location of the biorefinery plant
- The location of biomass harvesting site(s) and the associated amount of each biomass produced
- The location of intermediate storage site(s) and the associated monthly storage levels for each biomass plus for pellets
- The location of pelleting plant(s) and the amount of pellets produced

- The amount of each biomass being transported, stored and pelletized between the units of the supply chain at each time of year under the uncertain distribution of yields.
- The disposition of pellets in terms of transport, storage, and possible export.

Case Study

Study Region and Potential Sites for Facilities

The study region was determined based on a spatial analysis of biomass availability in proximity to transport routes in a 45-county region in the Texas High Plains. Based on National Renewable Energy Laboratory (BREL) studies (Aden et al. 2002; Humbird et al. 2011), a biorefinery which can process at least 2000 dry Mg of biomass per day was assumed in turn yielding 189 million liters of cellulosic ethanol per year. Furthermore, we assumed that the biorefinery operated at full capacity during 8500 hours per year (around 95% of the time) and under an assumed yield of 264 liters per MG of feedstock. Given those assumptions the minimum annual feedstock requirement that needs to be collected from the current study region is about 730,000 Mg. Furthermore, the current study preselected a set of potential biorefinery locations making sure the selected locations had access to a major road or railroad and that each potential site would be away from cities to avoid environmental and traffic issues.

According to Aden et al.(2002), we used GIS to identify locations within an assumed collection radius of 80-km that could supply the 2,000 Mg per day design. Based on these criteria and the available biomass estimates from the Bioenergy Knowledge Discovery Framework (KDF) (Langholtz, Stokes and Eaton 2016) , the candidate biorefinery locations was narrowed down to the places where sufficient biomass was available. Table 2 below listed the top ten counties with most available biomass.

Table 2 Top Ten Counties with Most Available Biomass in The Study Region

FIPS	County Name	Available biomass (Mg)
48421	Sherman	4,734,719
48069	Castro	4,483,805
48279	Lamb	4,364,005
48341	Moore	4,215,060
48189	Hale	3,943,240
48205	Hartley	3,931,930
48233	Hutchinson	3,848,703
48437	Swisher	3,368,894
48369	Parmer	3,315,179
48111	Dallam	3,210,686

Among all the counties in the study region, Castro, Lamb and Sherman counties contained the most biomass and were considered as the potential counties where a biorefinery could be located. In total, 45 counties in Texas, New Mexico and Oklahoma which fell within 80-km radius of Castro, Lamb and Sherman counties were selected as the total potential feedstock supplying region. Of those counties, Texas contains 39 which are in USDA crop reporting districts one and district two. Six counties are included from adjacent areas in the bordering states of New Mexico and Oklahoma.

Figure 3 below shows the study region.

Once the study region boundary was determined, a more detailed spatial analysis was conducted to identify the suitable locations for the biorefinery within each candidate county. This was done by breaking the whole study region broken into 200 square km hexagons which is a geographic area we judge to can reflect the heterogeneity of biomass distribution without significantly degrading model solution time. The potential biorefinery locations were also considered to be candidates for location of one or more storage depots and or pellet plants. Additionally, hexagons in the outlying counties which fell within the 80-km radius periphery of potential biorefinery, had access to both rail and road transportation, and were away from the towns and cities were considered as the potential locations for distributed storage and pelleting plants. Figure 4 below depicts the potential locations of storage and pelleting plants in the present study region.

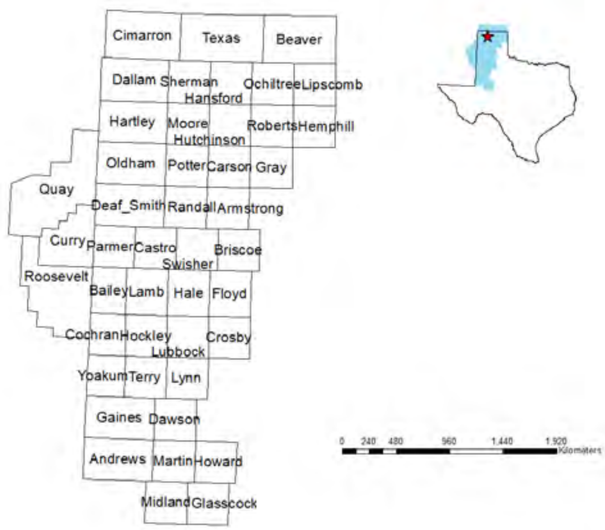


Figure 3 Texas High Plains study region

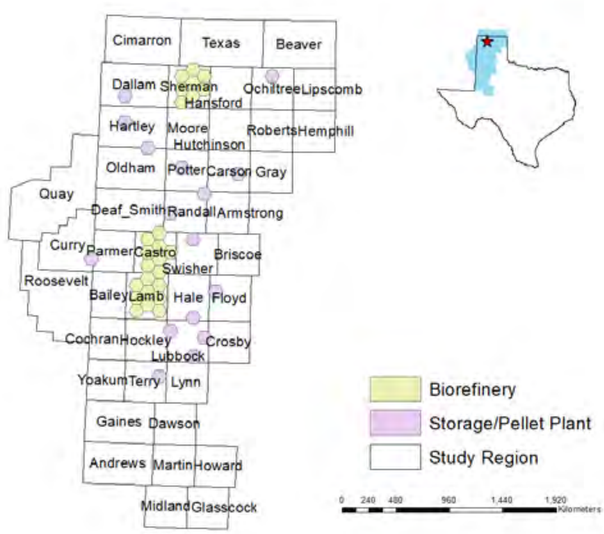


Figure 4 Potential locations for biorefinery, storage and pellet plants

Biomass Considered in the Study

Four types of lignocellulosic biomasses were considered as sources of cellulosic feedstock: corn stover, sorghum stover, switchgrass and energy sorghum. Among these biomass types the DOE 2016 Billion-Ton Study (Langholtz et al. 2016) estimates that corn stover is currently the most abundant biomass in the region with a potential supply of 75 to 112 million dry Mg. Given the harvest window for corn grain in the current study region lasts from early September to early November (Texas Corn Producer, 2018), we assume the harvest window for corn stover coincided with that for harvesting corn grain which made the window October to November. Moreover, the yield of corn stover used in the study was assumed proportional to the yield of corn grain. Based on 2016 Billion-Ton Study (Langholtz et al. 2016), a bushel of corn (or 25.4 Kg) is associated with 0.0237 ton corn (or 0.0215 Mg) stover. Then following Wilhelm et al. (2007) we assumed stover is retained on the land to prevent wind and water erosion amounted to 4.84 Mg/ha. Then given an assumed regional typical corn grain yield of 504.7 bushel/ha3 (USDA NASS, 2017), the corn stover yield used in the study is assumed to be average 6.01 Mg/ha.

Sorghum also is a candidate feedstock in the region. Sorghum is a productive, drought-resistant species, and different types can be used to produce ethanol depending on the conversion technology applied. In the present study, two types of sorghum were considered: 1) sorghum residues from conventional sorghum grain production and 2) high biomass sorghum varieties grown as an energy crop and referred here as energy sorghum. The harvest window for energy sorghum was assumed to be identical to that for sorghum grain which begins in November and

[3] Given the yield in the NHP is 203.9 Bu/acre or 504.7, the yield of corn stover in Texas High Plains is 10.85 Mg/ha. After deducting the amount need to be left on the farm, the actual corn stover available is

ends in December and the harvesting windows for sorghum stover was assumed to be from December to February. The yield of energy sorghum was set at 14.4 Mg/ha based on Rooney et al. (2007). As for the sorghum stover, its yield is also assumed proportional to the grain yield. Based on the 2016 Billion-Ton Study, a bushel (25.4 Kg) of sorghum grain can provide 0.0241-ton sorghum stover, and the resultant yield of sorghum stover is 5.41 Mg/ha considering the yield of sorghum in the High Plains region is 247.5 bushels per ha based on the FASOM model developed by McCarl et al. (2018). Following the assumption made above and assuming 4.84 Mg/ha of the sorghum stover is left for erosion control, 0.57 Mg/ha was used as the yield of sorghum stover in this study.

In addition, switchgrass was also a possible feedstock in this study. Qin et al. (2006) conducted a feasibility analysis of replacing coal with switchgrass in power generation examining environmental, energy and economic aspects. They pointed out that a high yield switchgrass can be price competitive with other feedstock sources and reduce GHG emissions. Due to its ability to be adapted to various environments, switchgrass has been recommended by the U.S. Department of Energy (USDOE) as one of the biofuel species for combustion, gasification, and liquid fuel production (USDA-Natural Resources Conservation 2011). The harvesting window for switchgrass in the region is assumed to begin in December and end in February, and the yield of switchgrass used in the study was 10.02 Mg/ha (McCarl et al., 2018).

Land Use Constraint and Contract Scheme

To ensure sufficient year-round feedstock supply, the biofuel supply chain needs to contract lands with land owners before receiving any biomass. Several types of land were considered in the model to produce biomass: previous dryland cotton and wheat fields that could be used for switchgrass, dryland sorghum for energy sorghum, and existing dry and irrigated sorghum or corn fields for stover recovery. The different choices here are chosen so as to not expand agricultural water consumption. Thus, the crop residues can be collected from both irrigated and non-irrigated land while energy crops were only allowed to be grown and harvested on dryland.

The contracting schemes used for agricultural residues and energy crops were assumed to be setup as follows: the biorefinery will pay a fixed per hectare fee and a per Mg removed fee.

The per hectare fee consisted of the annualized establishment cost for energy crops plus the costs of replacing nutrients cost that are removed when the crop residue is removed plus the land opportunity cost. Later we will also discuss a per Mg removed payment. The per hectare cost of energy crops, following Griffith et al. (2010), is composed of the amortized cost of establishing and maintaining switchgrass. Specifically, $576 /ha cost was used to establish and maintain switchgrass, and, thus, $58.25/Mg cost was applied in the study considering the yield for switchgrass was 9.9 Mg/ha By the same token, the establishment and maintenance cost of energy sorghum4 was $ 491.1/ ha and the mass cost used in the study was $33.91/Mg considering the yield of energy sorghum on the dryland is $14.5/ha.

The nutrients replacement cost for agricultural residue follows the estimated from Sawyer (2018). Specifically, the cost of removing the nutrients provided by a Mg corn stover can be estimated by the cost of replacing the nutrients by adding additional fertilizer. Given prices for P_2O_5 and K_2O are $ 0.84 and $ 0.53 per Kg respectively, completely removing 9.79 Mg corn stover from a hectare of land needs 34.8 Kg. P_2O_5 and 149.3 Kg. K_2O. Thus, the cost of

[4] Given the similar structure, this study uses the budget of sorghum grain on dryland in district 2 built by Texas AgriLife. (2017) as an approximation for energy sorghum. Moreover, the acreage cost is divided by the 14.5 mg/ha since all parts of energy sorghum can be use instead of just the grain.

removing all the corn stover from a hectare of land is $37.29 and the cost of compensating the loss of per Mg corn stover used in this study was $3.8/Mg. For simplicity, this study assumed the per Mg cost of collecting sorghum stover is identical to corn stover[5]. in addition to the establishment cost/nutrient replacement cost, land rent in the study region was used to reflect the opportunity cost of land. Given that energy crops can be only planted on the dry land, $24/acre or $59.4/ha rental rate (USDA NASS Quick Stats 2017) was used in the study region.

Harvest Cost

The harvesting and collection method and associated costs (i.e. the per Mg cost) used were based on DOE uniform-format feedstock supply system (Hess et al. 2009). For the corn stover, the harvesting and collection process begins right after grain harvesting. A tractor and flail shredder with windrower is used to windrow the standing stubble, cobs, husks, leaves and tops (i.e. stover) left on the ground. Once the moisture content of the windrowed stover is sufficiently low[6], a large square baler pulled by a tractor creates 1.2-meter-wide × 1.2-meter-high×2.4-meter-long large square bales (i.e. 3'×3'×8'), and the square bales are then picked up and moved to edge of the field by a self-propelled stacker. For simplicity, this study assumed that the harvesting and collection process for corn stover and sorghum stover were identical.

Switchgrass, unlike crop residues, does not need to be harvested after extracting the grain, and uses different equipment compared to stover. To harvest switchgrass, a self-propelled windrower with a disc header is assumed to be used to cut the switchgrass. The cut and conditioned switchgrass is then deposited on the field forming a windrow. Then later, a square

---

[5] Based on O'Brien et al.(2010), the N-P-K contains in one ton value for corn and sorghum grain is 6.86 Kg N, 1.62 Kg P2O5, 20.2 Kg K2O, and 1.35 Kg S

[6] Consider the weather condition in the High Plains region, this study assumes that the water content of crop/residues is 25%

baler and self-propelled stacker are used to bale and move switchgrass. Note that the conditioning process which crushes the stem of switchgrass is used to speed up drying and reduce dry matter loss.

Table 3 lists the equipment and estimated costs of harvest and collection operations.

Table 3 Equipment and Cost Estimates for Corn Stover And Switchgrass

Logistics processes	Grain Harvest Condition & Windrow	Baling	Collect& moving biomass	Dry Matter Loss	Total Costs
Corn-Stover					
Equipment	180 hp tractor and flail shredder with windrower	275 hp tractor and large square baler	Self-propelled stacker		
Bulk DM Density	1.14 Mg/300 windrow-meter	0.52Mg/bale			
Cost($/DM Mg)	4.58 ± 0.71	12.02±1.22	2.08±0.35	5.02±2.10	23.89±2.69
Switchgrass					
Equipment	Self-propelled windrower with disc header	275 hp tractor and large square baler	Self-propelled stacker		
Bulk DM Density	1.14 Mg/300 windrow-meter	0.58Mg/bale			
Cost($/DM Mg)	3.31±0.78	10.77±1.06	1.87±0.308	0.48±0.231	16.44±1.59

Source:(Hess et al. 2009)

Storage Cost

When paced in storage the biomass needs be protected and preserved to avoid deterioration and fire danger. Here we assume this involves covered storage in a hoop barn. Figure 5 shows the setup of the storage facility assumed in the present study. Given the weight of each large bale is around 0.52 Mg, each hoop barn can hold around 1000Mg of biomass7. Stacks within a hoop barn are separated with 2 meters between then and hoop barns are assumed to be placed 15 meters away to help prevent loss from fire and to ensure access for fire-fighting equipment and when using a hoop barn for storage the biomass loss per year is assumed to be 3%(Darr and Shah 2012).

[7] Given the mess of each bale is 0.52/ Mg, the total mess of each stack can be calculated as 4*8*30*0.52= 499.2 Mg. therefore the mess contained in a hoop barn is around 1000Mg

In this study, each depot is assumed to have a 100,000 Mg capacity which means it is composed of 100 hoop barns. This study further assumes that the hoop barns of biomasses are placed in a 10 by 10 configuration with a setback distance of 18 meters between barns (Darr and Shah 2012) (ISU 2017). Thus, a land area of with dimensions of 392 by 532 meter would be needed or 20.85 hectares. In terms of cost we follow Darr and Shah(2012), and assume the one time construction cost of a hoop barn was $120 per square meter and the consequent fixed cost of building the depot with 100 hoop barns is $27,377,280 and we assume an 20 year life resulting in an annualized cost of $2,584,000. In addition, suppose the storage facility is located on pasture land and the land rent for pasture land is $18.1/ha, with a cost of $318 one year for the total depot.

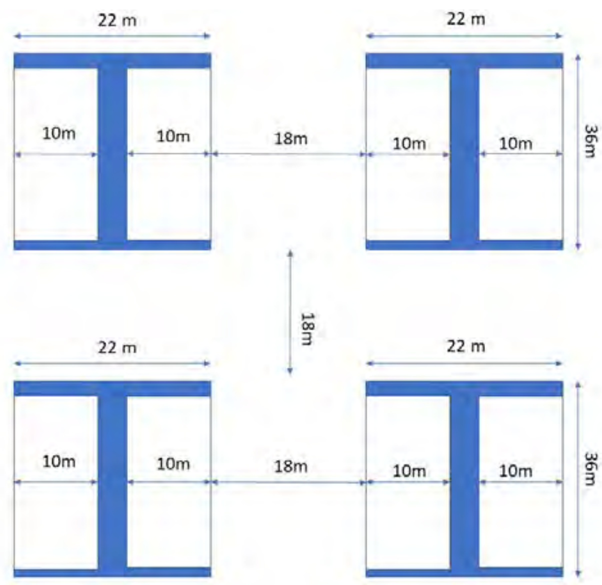


Figure 5 Formation of the indoor storage

There is also a variable cost of moving bales in and out. This includes the costs of stacking, and storage. The storage equipment for stacking the switchgrass, energy sorghum and residues is assumed to be identical per Mg.

In terms of bale movement in the facility a Telehandler is assumed to be used to pick up large square bales from the truck and stack them in the formation mentioned above at a rate of 80 bales per hour. Table 4 below listed the assumed variable storage costs per bale.

Table 4 Storage Cost of Corn Stover and Switchgrass

Logistics processes	stacking	Storage	Dry Matter Loss	Total variable Costs
Equipment	Loader (Telehandler)	Land rent & stack maintenance		
Cost(Corn stover) ($/DM Mg)	1.003±0.1	0.11±0.01	1.58±0.48	2.693
Cost(Switchgrass)($/DM Mg)	0.904±0.132	0.11±0.01	1.17±0.35	2.184

Source: (Hess et al. 2009)

Size Reduction Option(Pelleting)

The current study also considered pelleting as a means of densifying the biomass to reduce volume, transportation cost and deterioration plus potentially allow exports of excess production. Following Hoque et al.(2006) and Mani et al.(2006), we assume that a pellet plant could be built at the same location as the storage depots where it would use biomass to produce pellets. Pelleting usually consists of three main stages: drying, size reduction and densification. The pellet process begins with size reduction. Specifically, a telehandler removes a square bale from a stack and load it onto a conveyer which feeds the bale into the grinder. The ground biomass is then sent to a rotating drum dryer to reduce moisture content. After drying, the biomass passes through a hammer mill which further reduces the biomass to finer particles and the resultant biomass is then sent to the pressing mill to form pellets. Finally, the cooled and screened pellets are moved by conveyer to a truck or train and then are wither transported to biorefinery, placed in a storage bin for later use or exported to another location.

Here, a pellet plant is assumed produce 13.4 Mg of pellets per hour with an annual production capability of 100,000 Mg of pellets. During the pelleting 5% of the biomass is assumed to be lost. The plant is assumed to operate 24 hours a day for 310 days a year. The construction cost is estimated at $3,278,954 (Hoque et al. 2006) as detailed in table 4 with the plant lasting 20 years for an annual cost of $309,486. The variable costs include the raw biomass cost, operation and maintenance costs for each processing stage, personnel cost and land opportunity costs in the form of land rental rate. The biomass cost was dropped from the operating cost in this study as it is covered elsewhere in the model and the adjusted estimated operating cost is as detailed in Table 6 and equals $21.42/Mg of pellets produced.

Pellet storage was also considered. The assumed pellet storage processes are moving the pellet to storage bin along with labor costs as also detailed in Table 6. The resultant variable cost and the operating cost was $2.51 per Mg of pellets produced.

Table 5 Capital Cost of a Pellet Plant

Item	Purchase cost ($)	Installation cost ($)	Annuity
Solid fuel burner	184,545	92,272	37,611
Rotary drum dryer	566,813	340,088	93,377
Drying fan	49,766	19,906	9,466
Multiclone	49,766	19,906	9,466
Hammer mill	95,881	38,352	18,238
Pellet cooler	51,050	38,288	9,198
Screen shaker	38,352	23,011	8,337
Packaging unit	138,380	30,863	22,994
Storage bin	38,352	23,011	5,350
Misc. equipment	170,112	68,045	32,358
Front end loader	200,000		27,174
Fork lift	164,000		22,282
building	72,051		6,282
Total	2,329,829	949,125	

Source:(Hoque et al. 2006)

Table 6 Variable Cost of Producing Pellet

Description	Annual cost($/year)	Unit cost($/Mg)
Producing pellet		
Drying	657,090	6.54
Hammer mill	27,531	0.27
Pellet mill	63,135	0.63
Pellet cooler	9,841	0.1
Screening	2,531	0.03
Miscellaneous equipment	16,475	0.16
Personnel cost	617,000	6.17
Maintenance and land rent	2,401	0.02
Operating cost of pelleting		21.42
Storing pellet		
Packaging	64,210	0.64
Storing	1,000	0.01
Personnel cost	186,880	1.86
Total cost of storing		2.51

Source: (Hoque et al. 2006)

Biomass Transportation and Handling

The transportation and handling operations involve loading/unloading feedstock and moving it from a supply region to one of intermediate storage, pelleting or the biorefinery. The cost of transportation and handling operations includes a fixed cost for loading and unloading and a variable cost which is a function of distance. Given the transportation distance in this study was relatively short, truck transport was assumed.

To compute cost, we assume use of a 2.4-meter-wide by 16-meter-long 3-axle flatbed trailer to move the large square bales(1.2×1.2×2.4-meters). This means 26 large square bales can be loaded and moved in a load. A Telehandler was used to load/unload the semi-trailer at a rate of 80 bales per hour, and the total fixed loading/unloading cost per truck load is $55/truckload. Given the weight of each bale is about 0.52 Mg or 13.52 Mgs per truckload, the loading and unloading cost is $4.06 per Mg or $5.41 per Mg under an assumed 25% moisture content (Hess et al. 2009).

The variable cost, on the other hand, following Mahmudi and Flynn (2006) is assumed proportional to the distance traveled. Based on their study assuming the feedstock moisture content is 25%, the estimated variable cost of truck transportation is $0.148/Mg-km. For pellets, based on the study by Ortiz et al.(2011), the total cost for loading the pellets using augers and unloading by opening gates and dumping is $2.74 per Mg. For the variable cost of transporting pellets we use the average transport rate which according to Ortiz et al.(2011) is $0.07/Mg-Km .

To calculate per ton costs for movements a distance matrix was determined and used. Specifically, ArcMap was first applied to identify the longitude and latitude of the centroid within each hexagon in the supply region. Given that the road system in the study region is close to rectangular, once the coordinates of centroid were specified, the Euclidean distance of any two points is multiplied by a winding factor 1.4 was used to approximate the actual travel distance following the study by Segebaden (1964).

Feedstock Preprocessing and Handling at Biorefinery

Figure 6 adopted from Mu et al. (2010) depicts the flow diagram of two biorefinery processes. The diagram on the top shows a biochemical process while the one at the bottom shows a thermochemical process. The study by Mu et al. (2010) indicates that the biochemical method will have a slight edge over the thermochemical method if the conversion efficiency of the biochemical process is improved as anticipated plus that this method has lower environment impact. Thus, in this study, biochemical conversion technology is assumed to be the main technology used in producing the ethanol.

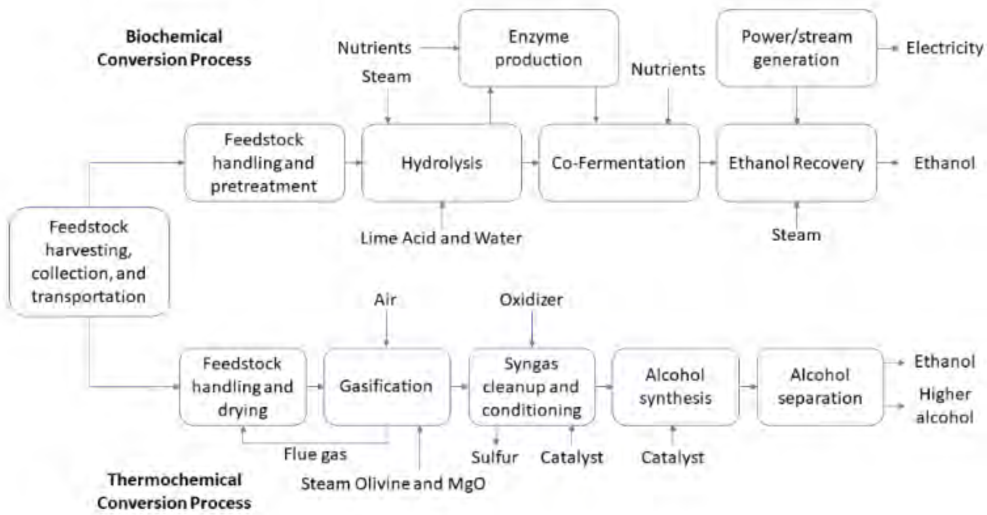


Figure 6 Biochemical and thermochemical conversion processes

Based on the figure, the biochemical process can be described as follows: Lignocellulosic biomass will be pretreated, hydrolyzed, fermented and, finally, distilled as it is transformed into ethanol (Mu et al. 2010; Foust et al. 2009; Wright and Brown 2007). To do this, telehandlers remove square bales from the stack and load them onto a conveyer which feeds the bale into a grinder where particle size is reduced. The ground biomass is then washed and loaded into a pretreatment stage where the hemicellulose part of the ground biomass is broken into simple sugars by adding diluted sulfuric acid. Other chemicals are also added to facilitate enzymatic cellulose hydrolysis. The mixed solids and liquids are then fermented and further converted into a liquid which contains ethanol and byproducts. The ethanol will be then separated through distillation. The lignin part which is not decomposed will be collected and used to generate heat and electricity for the process.

The capacity of the biorefinery was assumed to be 261.954 million liters per year and it was assumed to operate 24 hours a day for 310 days a year. The construction cost us detailed in Table 7 and is assumed to be $220.1 million with the plant lasting 20 years for an annual cost of

$24,504,403 The variable cost used in the study is composed of two parts: operating cost and enzyme cost. The resultant operating cost based on Huang et al. (2010), is $0.079 per liter with an enzyme cost of $0.068 per liter.

Table 7 Capital Cost of Biorefinery

Item	Cost($)
Pretreatment	22,700,000
Conditioning	9,400,000
Fermentation	11,200,000
Distillation and solid recovery	26,100,000
Wastewater treatment	3,700,000
Storage	2,400,000
Boiler	46,000,000
Utilities	5,500,000
Total installed cost	127,000,000
Misc. costs	93,100,000
Total cost	220,100,000

Source:(Aden and Foust 2009)

Table 8 summarizes the parameters used in the model, and all the costs were adjusted to 2017 dollars.

Table 8 Summary of Key Parameters Used in The Model

Input parameter	Original Value	Adjusted Value	Unit	Source
Biorefinery Capacity	21,735		1000 L/ mo.	Assumed
Storage Capacity	100		1000 Mg/mo.	Assumed
Pelleting Plant Capacity	100		1000 Mg /yr.	(Hoque et al. 2006)
Fixed Costs of Biorefinery	220,100(2009)	259,600	1000$	(Aden and Foust 2009)
Fixed Costs of Storage	27,377	27,377	1000$	(ISU 2017, Duffy 2007)
Fixed Costs of Pelleting Plant	3,278(2006)	4,011	1000$	(Hoque et al. 2006)
Operating Cost of biorefinery	0.15(2010)	0.17	$/L	(Huang et al. 2010)
Operating Cost of Storage				
Corn Stover	2.693(2009)	3.39	$/DM Mg	(Hess et al. 2009)
Switchgrass	2.184(2009)	2.75	$/DM Mg	(Hess et al. 2009)
Sorghum Stover	2.693(2009)	3.39	$/DM Mg	Assumed
Pellet	2.51(2006)	3.07	$/DM Mg	(Hoque et al. 2006)
Operating Cost of pelleting	21.42(2006)	26.21	$/DM Mg	(Hoque et al. 2006)
Minimum ethanol production	10396.04		1000 L/ mo.	Assumed
Loading/unloading Cost				
Large squared Bale	5.41(2009)	6.19	$/DM Mg	(Hess et al. 2009)
Pellet	2.74(2011)	2.99	$/DM Mg	(Ortiz et al. 2011)
Variable transportation cost				
Large squared Bale	0.148(2006)	0.18	$/DM Mg-Km	(Mahmudi and Flynn 2006)
Pellet	0.07(2010)	0.078	$/DM Mg-Km	(Ortiz et al. 2011)
Contract & establishment cost				
Switchgrass	323.21(2014)	358.66	$/ha	(Wang et al. 2014)
Energy Sorghum				
Corn stover	108.54		$/ha	Assumed
Sorghum stover	73.84		$/ha	Assumed
Harvesting Cost				
Switchgrass	16.44(2009)	18.82	$/DM Mg	(Hess et al. 2009)
Energy Sorghum				
Corn stover	23.89(2009)	27.35	$/DM Mg	(Hess et al. 2009)
Sorghum stover	23.89(2009)	27.35	$/DM Mg	Assumed
Yield				
Switchgrass	10.02		DM Mg/ha	FASOM
Energy Sorghum				
Corn stover	5.67		DM Mg/ha	(Langholtz, Stokes and Eaton 2016)
Sorghum stover	2.13		DM Mg/ha	(Langholtz et al. 2016)
Interest Rate	0.07			
Deterioration rate	0.03			
Water content	0.25			
Project life span	20		year	

Other Assumptions

The current study assumed the equipment capital costs are amortized into a constant payment. Eq. (1) was used to amortize the capital investments where the asset has a life span of n years and the interest rate is r %. This was applied assuming a 20-year life and a 7% discount rate.

$$\text{Amortized } Annual\ cost = \frac{(initial\ investiment)}{(1-(1+r)^{-n})} \tag{1}$$

Including these data into the model results in a cost minimizing objective function that represents a single years typical operating cost along with a typical year share of construction cost.

The planning horizon was one year divided into 12-time periods. We needed to reflect availability of equipment and labor and that needed to take into account probable working days. Based on the study of Soloranzo-Campos (1990) the number of good working days in each month in the study region is listed in Table 9. The resultant estimated working days available are as follows.

Table 9 Probability of Working Days in the Study Region

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
probabalility of working day	0.7	0.7	0.71	0.6	0.7	0.6	0.6	0.65	0.8	0.8	0.43	0.1
actual days available	23	19	22	19	20	18	19	20.2	24	24	12.9	3.1

Source: Soloranzo-Campos (1990)

Modeling Uncertainty in Biomass Yield

To simulate feedstock yield uncertainty, an empirical joint distribution was developed using historical Texas level data on yields for corn grain, sorghum grain and hay[8] from 1950 to 2016. Ten states of nature which reflect the yield fluctuation were constructed and implemented into stochastic model.

To derive the states of nature, this study first removed yield trends that are assumed to arise due to technological progress. This was done by regressing historical (USDA NASS 2017) data on yields of hay, sorghum and corn on time to find the trend then using the unexplained error (residuals) from that trend to form the yield deviations. Once the residuals were obtained, yield deviation proportions were formed as the ratio of the yearly residuals after trend removal to the regression projected yields for that year. The residuals were then applied to current High Plains yields to develop a distribution for a feedstock.

Since multiple feedstocks were available, joint states of nature were used to represent the multi-feedstock distribution of biomass yield deviations. The probability of these states of nature were derived based on the historical data. To keep the model size tractable, the deviations for each biomass were grouped into four yield levels: bad, low, fine, and good. For example, the bad yield level for corn stover referred to any year with a shock equal or less than 20.4% below the expected yield level, low yield level referred to the years with their deviation falling between 20.4% and 9%, below the projected yield level. Fine was recorded when the yield deviation was between 9% below and +2.3% above the projected yield, and good occurred when the yield was better than +2.3% above the mean. In turn to develop each state of nature we have to develop a

[8] Given that there is no record of switchgrass production during this period, the variation in hay yield is used as a proxy for the variation in switchgrass yield

joint distribution. This was done by categorizing each historical year in terms of the combination of the shocks for all three feedstocks resulting in a potential of 64 combinations. However, many of those combinations never occurred and were eliminated. The probability of each state of nature was then estimated through dividing the counts of observation falling into each joint state of natural by the total number of observations. Note that the yield deviations exhibited strong correlations across crops. This shows that certain key factors such as precipitation plays an important role influencing all the crop yields. For example, during the 2011 drought all the crops exhibited their lowest yield state. Table 10 below lists the states of nature used and their probabilities.

Table 10 Empirical Probability Distribution of States of Nature

	cornstover	switchgrass	energysorghum	sorghumstover	frequency	Prob
State of Nature 1	bad	bad	bad	bad	1	0.02
State of Nature 2	bad	low	bad	bad	1	0.02
State of Nature 3	bad	low	low	low	2	0.04
State of Nature 4	low	low	low	low	16	0.36
State of Nature 5	fine	low	low	low	2	0.04
State of Nature 6	fine	fine	low	low	3	0.07
State of Nature 7	fine	fine	fine	fine	16	0.36
State of Nature 8	good	fine	fine	fine	2	0.04
State of Nature 9	good	good	fine	fine	1	0.02
State of Nature 10	good	good	good	good	1	0.02

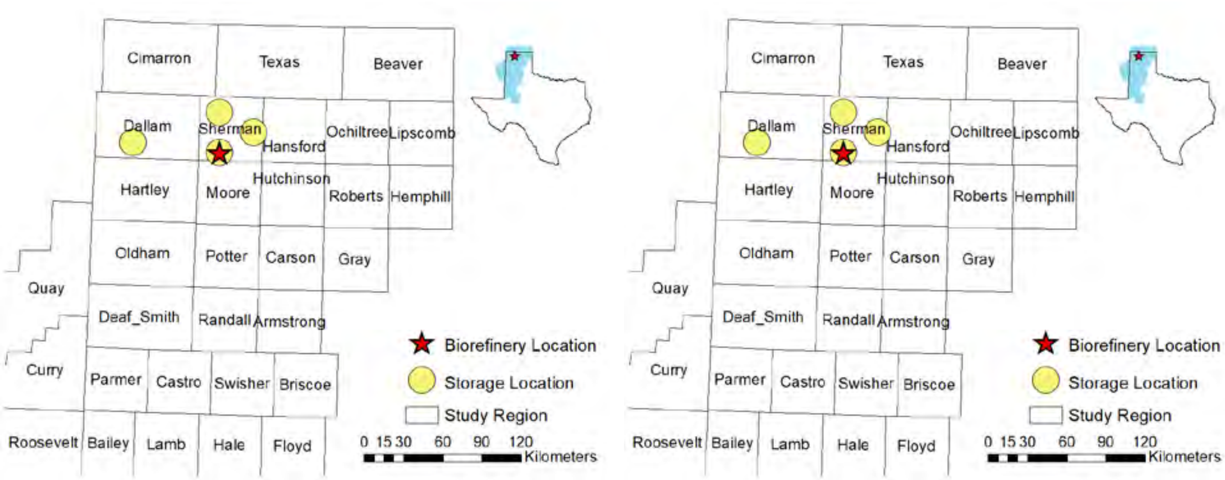
Model Analyses and Results

This section presents the results of analyses conducted in this study. The results of including and excluding yield uncertainty are considered first, followed by results on the impacts of including or excluding different supply chain designs, conversion rates and pellet prices. Then a set of results will be included on the effect of using higher resolution spatial data.

The model was executed using the General Algebra Modeling System (GAMS) software using CLPLEX as the solver with tolerance gap that terminates when the gap between the best possible integer solution and the realized objective falling at or below 0.1%.

Effects of Including and Excluding Yield Uncertainty

The first experiment involved running the model with and without the yield uncertainty. In the model without yield uncertainty the projected yields were used whereas in the stochastic model the above probability distribution was used. In turn Figure 7 depicts the resultant optimal facilities that arise from the deterministic and stochastic models. The results show the optimal locations of the biorefinery, storage depots and pellet plants were identical across the models. The biorefinery was located in southwest Sherman County, with five storage depots selected. Storage depots with pellet plants are located on the north, west and east sides of the biorefinery with another two depots co-located with the biorefinery.



(a)Deterministic model (b)Stochastic model

Figure 7 Optimal locations in deterministic and stochastic model

Table 11 presents the expected cost components in the two models. There we see that the objective value with the deterministic model is 1.54% lower than that under the stochastic model.

The stochastic model exhibits higher costs of contracting land, operating storage, and transporting biomass while simultaneously showing lower costs of harvesting and pelleting.

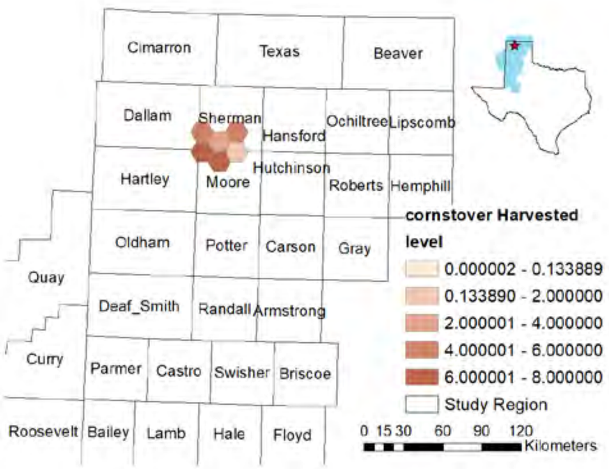
Table 11 Expected Costs of Each Component in Deterministic and Stochastic Model

Item	Determinisitc	Stochastic	Unit
Expected cost of supply chain	113,026.91	114,775.41	$1,000
Annualized cost of building biorefinery	24,504.40	24,504.40	$1,000
Annualized cost of building Storage	9,952.32	9,952.32	$1,000
Annualized cost of building Pellet Station			$1,000
Cost of contracting land	985.16	1,974.12	$1,000
Expected Cost of harvesting biomass	26,985.80	27,963.79	$1,000
Expected Cost of dumping biomass		17.61	$1,000
Expected Cost of storing biomass(offsite)	5,763.86	6,286.97	$1,000
Expected Cost of pelleting			$1,000
Expected Cost of producing ethanol	31,752.00	31,752.00	$1,000
Expected Cost of Transporting biomass	13,083.37	12,324.20	$1,000
Average cost of producing ethanol	0.59	0.60	$/L

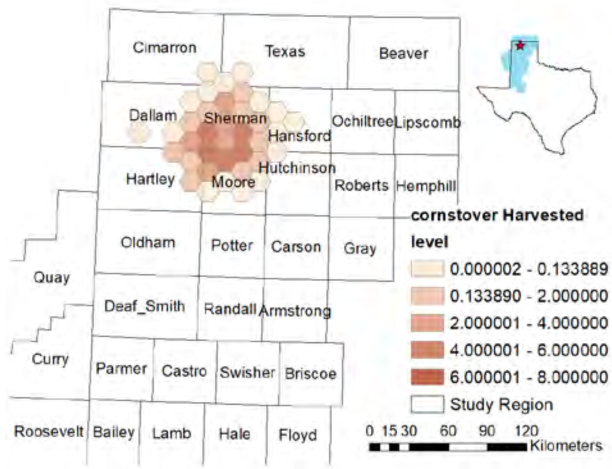
Table 12 summarizes the key decisions from the deterministic and stochastic models while Figure 8 depicts sources of biomass feedstocks. In the stochastic model, the investments and the land contracted are determined before uncertainty is resolved and the transport, storage pelleting, dumping and feedstock processing decisions are made under knowledge of the realized yield state. To reveal some of the resultant variation in decisions, the first column under the stochastic model represents the decisions made when the worst yield state of nature is realized, while the second column depicts the decisions under the best state of nature, and the third column shows the computed average level of decisions.

Table 12 Summary of the Key Decisions from Deterministic and Stochastic Model

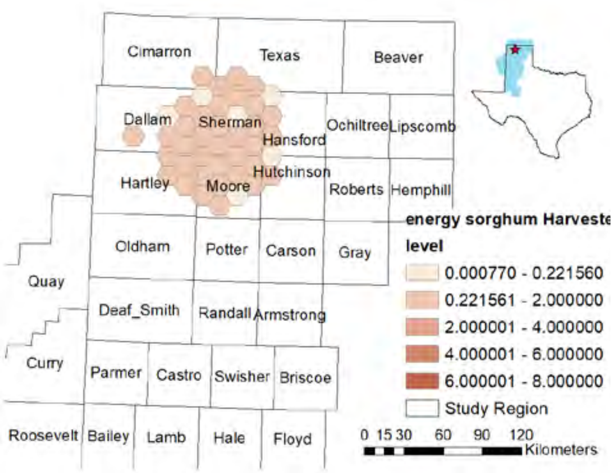
Item	Deterministic	Stochastic			Units
		Worst yie	Best yielc	Average	
First-stage decision					
Total land contracted for biomass	172.19	252.36	252.36	252.36	1000Ha
Corn stover	27.59	124.17	124.17	124.17	1000Ha
Energy sorghum	23.23	23.64	23.64	23.64	1000Ha
Sorghum stover	0.55	0.55	0.55	0.55	1000Ha
Switchgrass	120.82	103.99	103.99	103.99	1000Ha
Second-stage decision					
Total biomass harvested	735.11	743.29	736.89	736.67	1000Mg
Corn stover	109.25	406.65	54.62	184.36	1000Mg
Energy sorghum	135.89	95.71	111.20	135.97	1000Mg
Sorghum stover	0.63	0.44	0.86	0.63	1000Mg
Switchgrass	489.34	240.48	570.20	415.72	1000Mg
Total biomass dumpped		0.00	621.52	313.14	1000Mg
Corn stover		0.00	525.60	309.70	1000Mg
Energy sorghum		0.00	76.49	2.92	1000Mg
Sorghum stover		0.00	0.00	0.01	1000Mg
Switchgrass		0.00	19.42	0.51	1000Mg
Total biomass stored	1,918.02	2,589.60	1,786.13	2,107.42	1000Mg
Corn stover		1,337.47	0.00	301.55	1000Mg
Energy sorghum	243.05	246.58	0.00	294.30	1000Mg
Sorghum stover					1000Mg
Switchgrass	1,674.96	1,005.55	1,786.13	1,511.57	1000Mg
Total biomass processed	676.90	664.29	682.85	672.55	1000Mg
Corn stover	109.25	366.30	54.62	175.18	1000Mg
Energy sorghum	128.38	88.09	110.98	126.92	1000Mg
Sorghum stover	0.63	0.44	0.86	0.63	1000Mg
Switchgrass	438.65	209.46	516.39	369.82	1000Mg



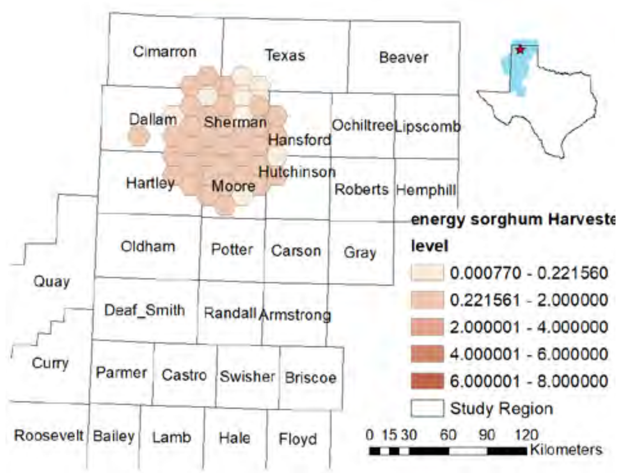
(a) Corn stover in deterministic model



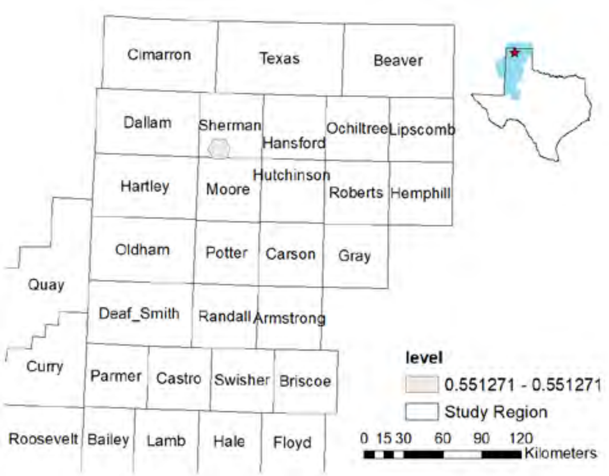
(b) Corn stover in stochastic scenario



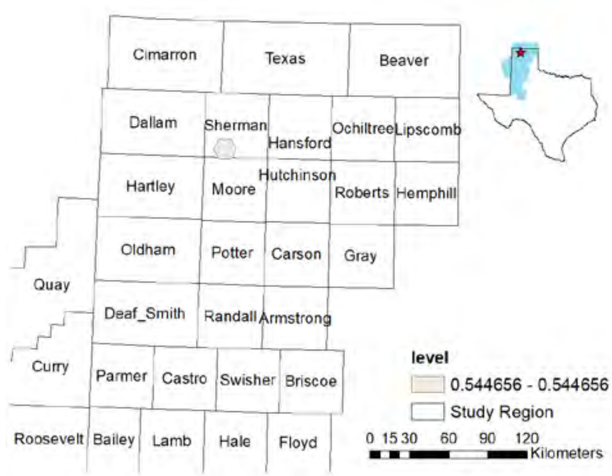
(c) Energy sorghum in deterministic model



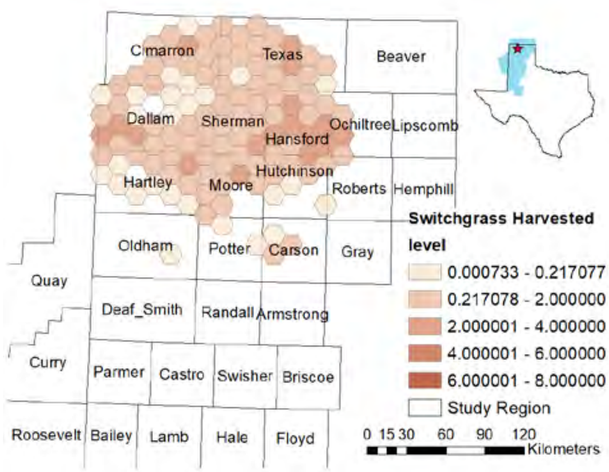
(d) Energy sorghum in stochastic scenario



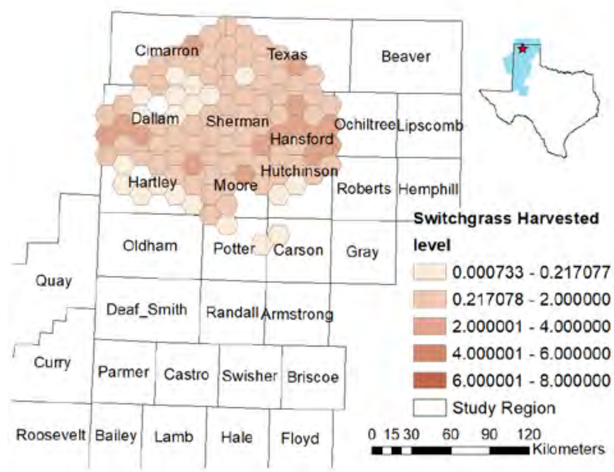
(e) Sorghum stover in deterministic model



(f) Sorghum stover in stochastic scenario



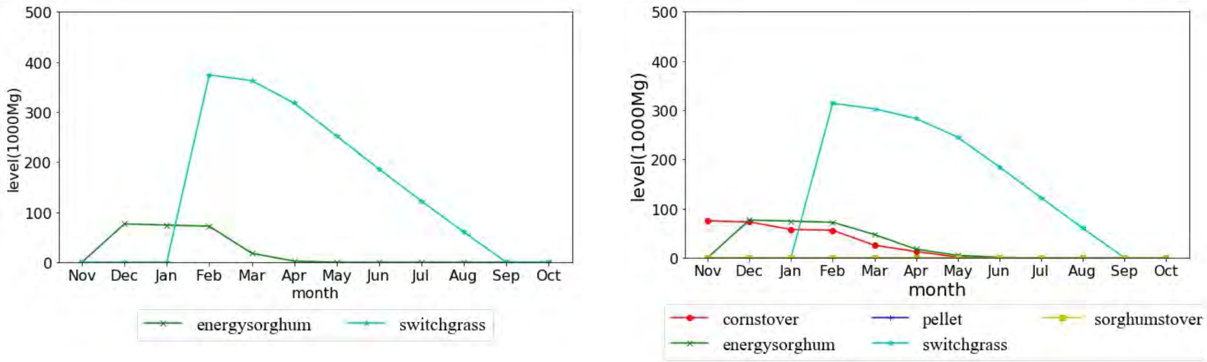
(g) Switchgrass in deterministic model



(h) Switchgrass in stochastic scenario

Figure 8 Feedstock land contracted in the deterministic and stochastic models

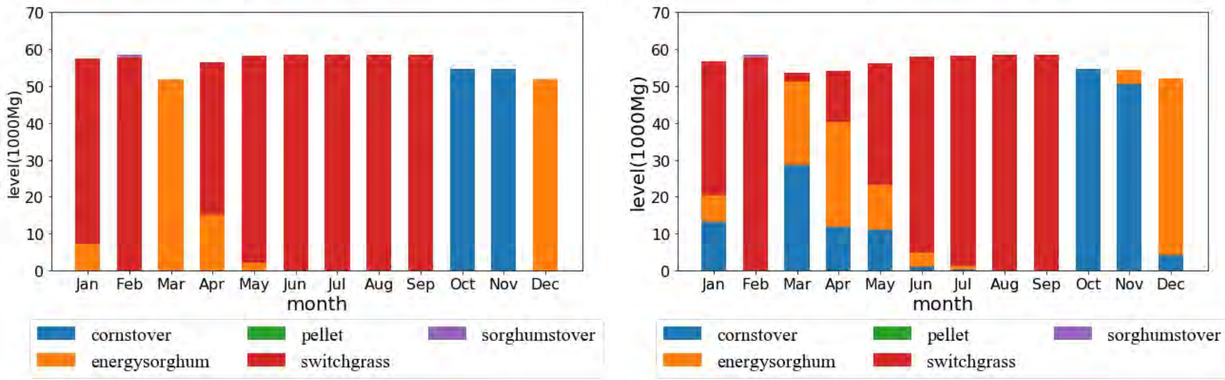
Here we see the amount of land contracted differs substantially when considering yield uncertainty. Namely nearly 46.5% more land was contracted in the stochastic model relative to the deterministic model. Consequently, the supply region increased from 15 km in the deterministic model to 60 km in the stochastic model for corn stover, remained at 60 km for energy sorghum and 15 km for sorghum stover, and slightly decreased from 90 to 80 km for switchgrass. The drastic increase in the land contracted for corn stover ensured the biorefinery had sufficient biomass when the low yields were realized. The amount of switchgrass harvested in the stochastic model was 15% lower likely due to the higher yield fluctuation relative to the other feedstocks while the amount of corn stover increased by 68.7%. Additionally, in the stochastic model, all the biomass harvested when the worst yield state of nature occurred was sent to storage or biorefinery with no biomass dumped. On the other hand, around 30% of the total biomass was dumped when the best yield state of nature was realized. Given the dumping cost for agricultural residues were low, almost all the biomass dumped was corn stover.



(a)Deterministic model (b)Stochastic model

Figure 9 Inventory level in the deterministic and stochastic models

The monthly storage inventory levels are shown in Figure 9. Under deterministic yields about 90,000 Mg of energy sorghum was placed in storage in February and then another 380,000 Mg of switchgrass in March. In the stochastic model, on average 90,000 Mg of corn stover was placed in storage in January and another 90,000 Mg of energy sorghum was added in February. Additionally, 310,000 Mg switchgrass was placed in storage and became the main inputs for the biorefinery later in the year. This shows when the yield is known in the deterministic model that more switchgrass was used due its low storage cost. But that less was used in the stochastic model due to the higher yield variability. Meanwhile, in both models, switchgrass was stored longer than was the other feedstocks given its relatively lower storage cost.



(a)Deterministic model (b)Stochastic model

Figure 10 Monthly processing by feedstock type in the deterministic and stochastic solutions

Figure 10 depicts the monthly amounts of feedstocks processed in the two models. In both cases, switchgrass was the dominant feedstock throughout most of the year. Specifically, under deterministic yields switchgrass was the dominant feedstock in January, February, and from April to September (constituting 70 to 100%) while energy sorghum and corn stover are dominant in their harvest windows: March, October and November. The average biomass processing under yield uncertainly generally follows the same pattern except there is more use of corn stover. Switchgrass again dominates in January, February, and from April to September but at a lower level (60%). Energy sorghum and corn stover are dominant in March, October and November. Corn stover use increased in January and from March to May to replace switchgrass which has relatively high yield fluctuation.

Effects of eliminating decentralized storage and Pellet Plants

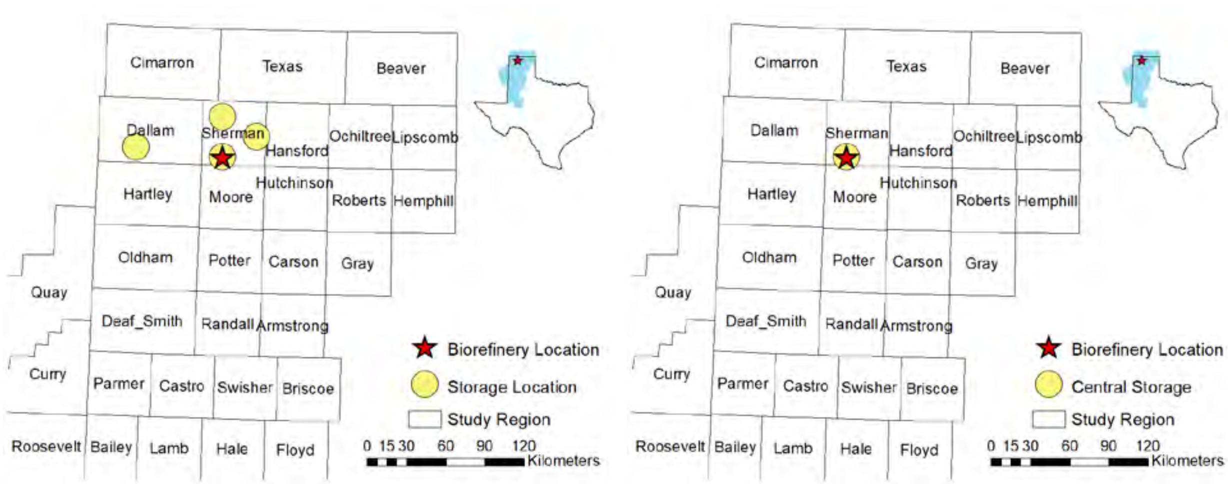
We now examine the impacts of different supply chain configurations. Two specific alternatives were studied and compared relative to the uncertain yield base case. These were a case with only central storage and potential pelleting facilities and a configuration without pelleting plants. The logistic decisions of these two scenarios along with the base scenario are summarized in Table 13.

Table 13 Key Parameters of Central Facility, No Pellet and Base Cases

	Central facility	No-Pellet	Base case
Storage capcity(1000Mg)	500	100	100
Fixed cost ($1000)	136,885	27,377	27,377
potential facility locations	Only available at potential biorefinery locations	Available at potential biorefinery locations plus additional intermediated storage location. No pellet plant available	Available at potential biorefinery locations plus additional intermediated storage/pellet plant locations

Note that when remote depots are not allowed then the centralized storage is five times larger than in the other cases.

Figure 11 depicts the optimal locations of facilities in no-pellet and central storage scenarios.



(a)Base case/No-pellet scenario (b)Central storage

Figure 11 Optimal locations of facility at no-pellet and central storage

At optimality, five smaller storages and one large capacity storage and were selected in the no-pellet and central storage only scenarios. The facility setup in the no-pellet scenario was identical to that in the remote storage permitted base case. In those cases, two storages were placed at the biorefinery location, two storages were located 15 km north and east of the biorefinery and one was to the west in Dallam County. For the central storage scenario, no pellet plant we chosen. Since the storage/pellet were limited at the same spot of biorefinery, all the biomass must be sent to the central storage in the baled form first and then processed later. Under this circumstance, the cost of pellet plant construction and operation plus the additional cost of transporting feedstocks to the biorefinery offset the advantages or reduced storage, storage loss and transport when pelleting remotely. Thus, no pelleting was done.

Table 14 summarizes the cost components for these cases. We find the total cost under the no-pellet and central storage scenario was not meaningfully different from that under the base case. The no-pellet and base case costs were identical, and the e central storage scenario expected cost was only 0.1% higher than the base scenario. The higher cost in the central scenarios mainly comes from an increased cost of contracting land and harvesting biomass as well as the additional cost of feedstock transport.

Table 14 Expected Costs for No-Pellet, Central Storage and Base Scenarios

Item	Base case	No-pellet	Central storage	Unit
Expected cost of supply chain	114775.41	114775.4113	114940.3074	$1,000
Annualized cost of building biorefinery	24504.404	24504.40352	24504.40352	$1,000
Annualized cost of building Storage	9952.3181	9952.318126	9952.318126	$1,000
Annualized cost of building Pellet Station				$1,000
Cost of contracting land	1974.1196	1974.119571	1998.550324	$1,000
Expected Cost of harvesting biomass	27963.794	27963.79434	28028.67306	$1,000
Expected Cost of dumping biomass	17.612456	17.61245565	15.67150985	$1,000
Expected Cost of storing biomass(offsite)	6286.9659	6286.965854	6299.717262	$1,000
Expected Cost of pelleting				$1,000
Expected Cost of producing ethanol	31,752.000	31752	31752	$1,000
Expected Cost of Transporting biomass	12324.197	12324.19744	12388.97357	$1,000
Average cost of a gallon ethanol	0.602	0.602	0.603	$/L

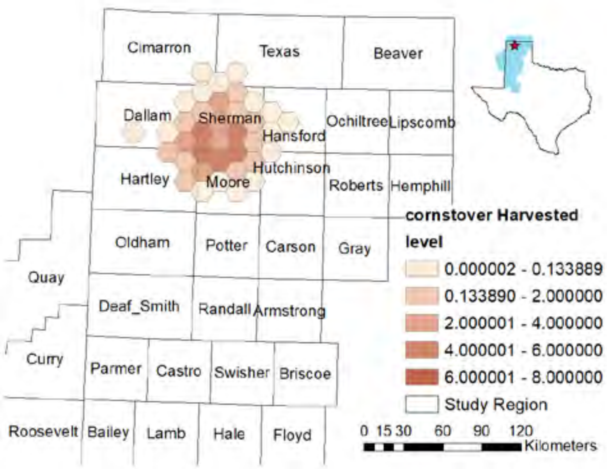
Table 15 lists key decisions in these three cases while Figure 12 depicts amount and area of each feedstock. The no-pellet scenario results were identical to the base case since it had no pelleting at optimality. The central storage and base cases only exhibited minor differences. Specifically, 0.1% more lands were contracted in the central storage scenarios with contracting increasing for all feedstocks excepting switchgrass. Specifically, the land used for corn stover and energy sorghum increased by 0.4% and 5% respectively. Simultaneously the land contracted for switchgrass dropped by 3%. Besides, the admittedly relatively smaller amount of land contracted for sorghum stover increased by more than four times in the central storage scenario.

Comparing to the base case, the central storage supply region was unchanged at a 60 km radius for corn stover. The supply region increased from 50 to 60 km for energy sorghum while it dropped from 90 to 80 km for switchgrass and the supply region for sorghum stover expanded to 15 km. The amount of biomass harvested generally followed the land contracted results. Under centralized storage only scenario, the amount of biomass harvested increased 2.5% for corn stover, 5.1% for energy sorghum and 436% for sorghum stover. On the other hand, the amount of switchgrass harvested dropped by 3%.

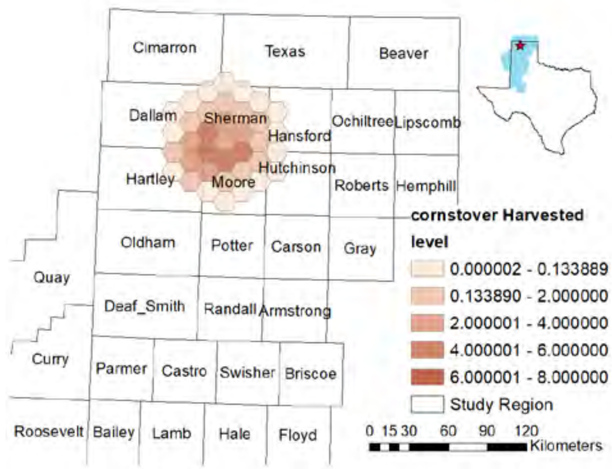
Meanwhile, the amount of biomass being dumped under the best yield state of nature slightly decreased (0.8%) under central only storage. The lower amounts of biomass dumped under central storage arise because of the decreasing use of the more variable switchgrass with more corn stover and energy sorghum contracted and harvested.

Table 15 Summary of the Key Decisions under the Base, No-Pellet and Centralized Storage Scenarios

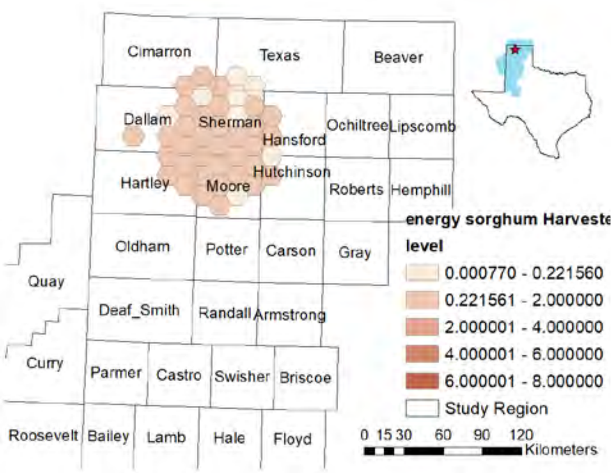
Item	Base scenario			No-Pellet sccenario			Central storage scenario			Units
	Worst yield	Best yield	Average	Worst yield	Best yield	Average	Worst yield	Best yield	Average	
First-stage decision										
Total land contracted for biomass	101.95	101.95	101.95	101.95	101.95	101.95	102.06	102.06	102.06	1000Ha
Corn stover	50.17	50.17	50.17	50.17	50.17	50.17	50.40	50.40	50.40	1000Ha
Energy sorghum	9.55	9.55	9.55	9.55	9.55	9.55	10.05	10.05	10.05	1000Ha
Sorghum stover	0.22	0.22	0.22	0.22	0.22	0.22	1.18	1.18	1.18	1000Ha
Switchgrass	42.01	42.01	42.01	42.01	42.01	42.01	40.43	40.43	40.43	1000Ha
Second-stage decision										
Total biomass harvested	743.29	736.89	736.67	743.29	736.89	736.67	743.05	736.91	736.03	1000Mg
Corn stover	406.65	54.62	184.36	406.65	54.62	184.36	408.59	54.62	189.14	1000Mg
Energy sorghum	95.71	111.20	135.97	95.71	111.20	135.97	100.73	111.20	143.03	1000Mg
Sorghum stover	0.44	0.86	0.63	0.44	0.86	0.63	2.32	4.55	3.37	1000Mg
Switchgrass	240.48	570.20	415.72	240.48	570.20	415.72	231.41	566.52	400.50	1000Mg
Total biomass dumpped	0.00	621.52	313.14	0.00	621.52	313.14	0.00	615.54	310.43	1000Mg
Corn stover	0.00	525.60	309.70	0.00	525.60	309.70	0.00	528.36	307.27	1000Mg
Energy sorghum	0.00	76.49	2.92	0.00	76.49	2.92	0.00	86.32	3.13	1000Mg
Sorghum stover	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	1000Mg
Switchgrass	0.00	19.42	0.51	0.00	19.42	0.51	0.00	0.86	0.02	1000Mg
Total biomass stored	2,589.60	1,786.13	2,107.42	2,589.60	1,786.13	2,107.42	2,594.65	1,786.13	2,122.84	1000Mg
Corn stover	1,337.47	0.00	301.55	1,337.47	0.00	301.55	1,325.57	0.00	277.47	1000Mg
Energy sorghum	246.58	0.00	294.30	246.58	0.00	294.30	296.32	0.00	330.77	1000Mg
Switchgrass	1,005.55	1,786.13	1,511.57	1,005.55	1,786.13	1,511.57	972.76	1,786.13	1,514.60	1000Mg
Total biomass processed	664.29	682.85	672.55	664.29	682.85	672.55	663.70	682.87	671.43	1000Mg
Corn stover	366.30	54.62	175.18	366.30	54.62	175.18	368.59	54.62	180.69	1000Mg
Energy sorghum	88.09	110.98	126.92	88.09	110.98	126.92	91.61	110.98	132.88	1000Mg
Sorghum stover	0.44	0.86	0.63	0.44	0.86	0.63	2.32	4.55	3.37	1000Mg
Switchgrass	209.46	516.39	369.82	209.46	516.39	369.82	201.17	512.72	354.50	1000Mg



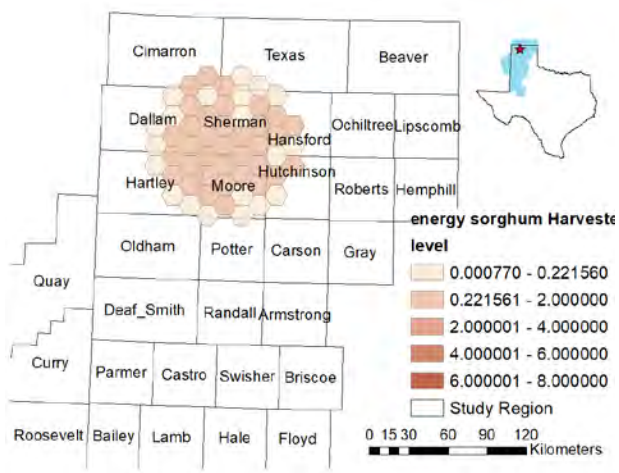
(a) Corn stover in base/no-pellet scenario



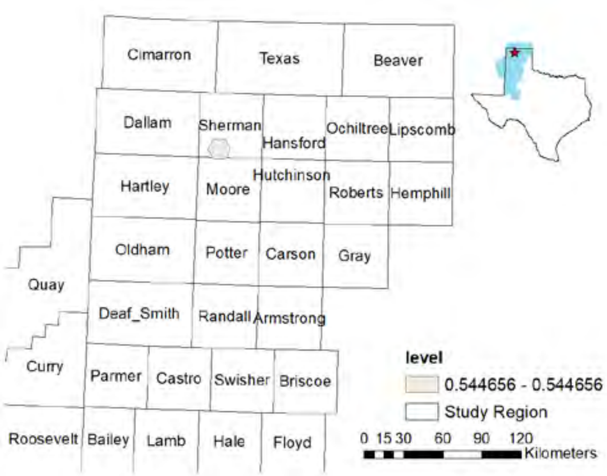
(b) Corn stover in central storage scenario



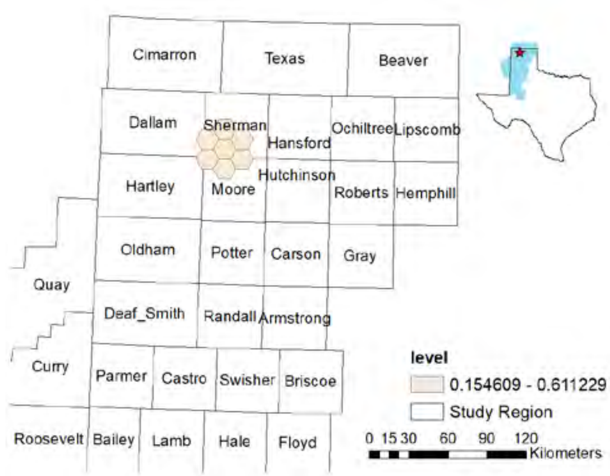
(c) Energy sorghum in base/no-pellet scenario



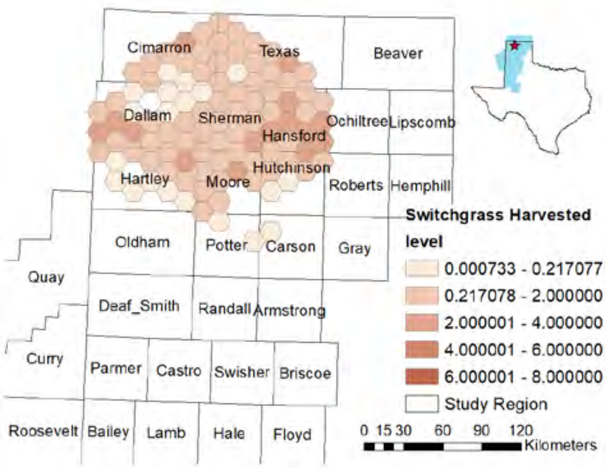
(d) Energy sorghum in central storage scenario



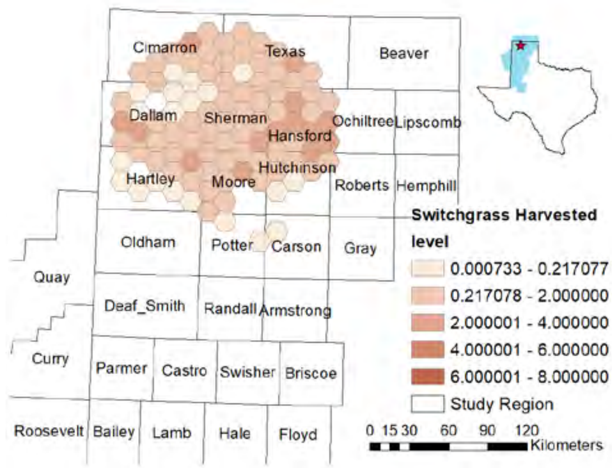
(h) Sorghum stover in base/central storage scenario



(h) Sorghum stover in central storage scenario



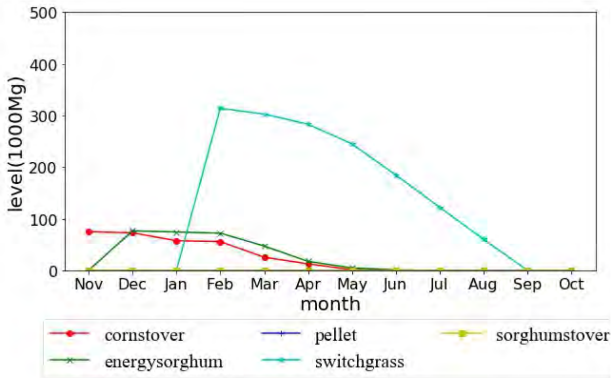
(h) Switchgrass in base/central storage scenario



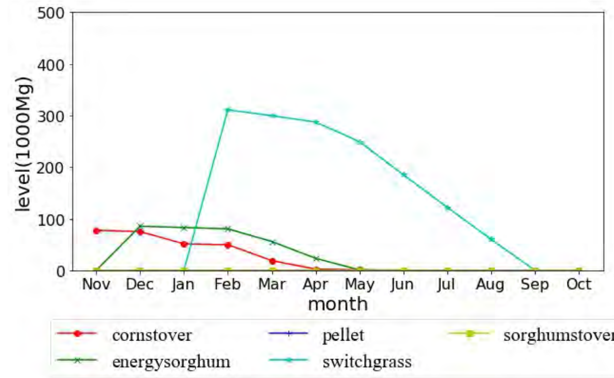
(h) Switchgrass in central storage scenario

Figure 12 Source of each biomass in the base, no-pellet and centralized only storage scenarios

Figure 13 depicts the storage inventory levels under the base case/no-pellet and central storage cases. There we see the inventory levels were similar. Switchgrass was used as the major source of feedstocks throughout the analysis periods reflecting its lower storage costs. Specifically, more than 300,000 Mg of switchgrass was placed in storage in February and then supplied to the biorefinery from February to September. The storage placements for corn stover was around 80,000 Mg in November and the corn stover last was used from November to April. The inventory level for energy sorghum was similar to that for corn stover. Around 85,000 Mg of energy sorghum was placed in storage and kept from December to April in all the scenarios.



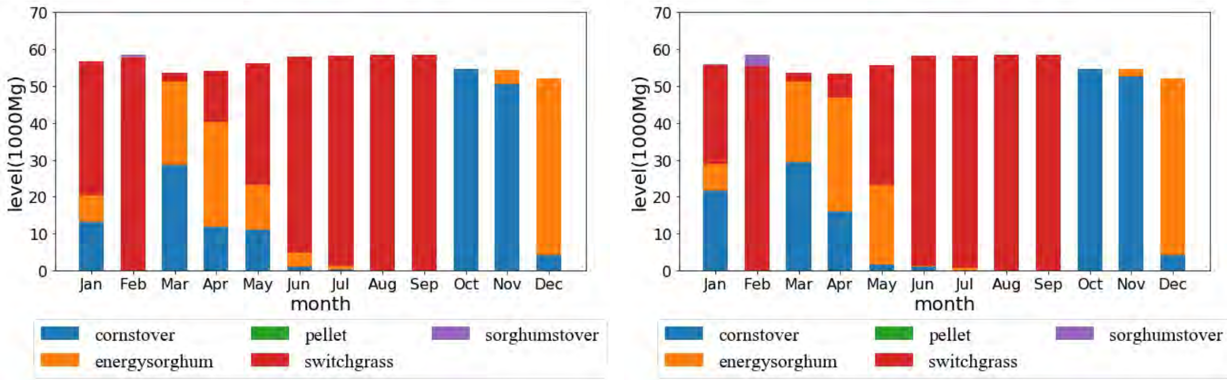
(a) Monthly inventory level in base/no-pellet scenario



(b) Monthly inventory level in central storage scenario

Figure 13 Monthly inventory levels in the no-pellet scenario and central facility scenario

Figure 14 below shows the amount of each biomass processed at the refinery by month. Again, the results from all three scenarios exhibit similar feedstock use. We find switchgrass used both within its harvest window and also stored then used as the major feedstock in most periods. In the central storage scenario, around 20% to 60% of biomass came from switchgrass in January, April and May while more than 80% of the processed biomass was switchgrass in February and from June to September. Additionally, the combination of corn stover and energy sorghum provided the necessary feedstock for the biorefinery in March, April and from October to December. Since the storage cost of these two-biomass feedstock was higher than that for switchgrass, they were generally harvested and sent directly to the biorefinery. Only small amounts were stored and processed in March and April.



(a) Biomass process level in no-pellet scenario (b) Biomass process level in central storage scenario

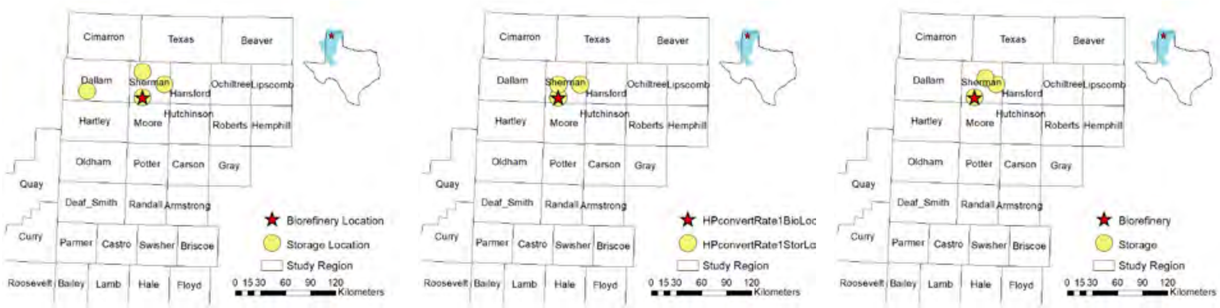
Figure 14 Comparison of process level in no-pellet central scenario

The analysis so far focused on the comparison of different supply chain designs versus the base-case. In the following sections, sensitivity analyses were conducted with the stochastic model to examine the impacts of altering biofuel conversion rates and the export price of pellets.

Impacts of Conversion Rate Improvement on Supply Chain Design

The conversion rates assumed ranged from 70 to 80 gal/Mg, and the current performance is limited since most of the lignin content of biomass is not utilized in the conversion process. However, based on Mu et. al (2010), there is a potential technological breakthrough that improves saccharification and fermentation efficiency raising yields to above 90 gal/Mg. To examine the impacts of conversion rate improvements we conduct a sensitivity analysis where we study 15% and 25% increases in conversion rates.

Figure 15 depicts the facility types and locations under different conversion rates. There we see higher biofuel conversion rates change the storage locations. With higher conversion rates the facilities moved closer to the biorefinery since a smaller supply region was needed. Additionally, no pellet plant was used to reduce the size of feedstock in both conversion rate scenarios since feedstocks now only need to be transported within a smaller supply region. The closer location and lower volume of feedstocks eliminated the need for the transport cost reductions under the pelleting process. Less (four as opposed to five) storage facilities were selected under both the medium and high improvement scenarios. Therein two storage facilities were placed at the biorefinery location and the other two were placed nearby the biorefinery and no pellet plant was used.



(a)Base case (b)Medium improvement (c)High improvement

Figure 15 Optimal locations for improved conversion rate scenarios

Table 16 summarizes the expected cost of each component under the alternative conversion rates. Expected cost decreases by 7.5% and 10.5% when conversion efficiencies increase, respectively.

Table 16 Expected Cost of Each Component in Different Conversion Rate Scenarios

Item	Base case	Medium improvement	High improvement	Unit
Expected cost of supply chain	114,775.41	106,155.71	102,626.09	$1,000
Annualized cost of building biorefinery	24,504.40	24,504.40	24,504.40	$1,000
Annualized cost of building Storage	9,952.32	7,961.85	7,961.85	$1,000
Annualized cost of building Pellet Station				$1,000
Cost of contracting land	1,974.12	1,682.52	1,546.88	$1,000
Expected Cost of harvesting biomass	27,963.79	24,147.52	22,225.55	$1,000
Expected Cost of dumping biomass	17.61	38.78	33.05	$1,000
Expected Cost of storing biomass(offsite)	6,286.97	5,384.30	5,002.87	$1,000
Expected Cost of pelleting				$1,000
Expected Cost of producing ethanol	31,752.00	31,752.00	31,752.00	$1,000
Expected Cost of Transporting biomass	12,324.20	10,684.34	9,599.48	$1,000
Average cost of a gallon ethanol	0.60	0.56	0.54	$/L

Table 17 summarizes the key decisions under the alternative conversion rates. Note in these results the study assumes an identical amount of cellulosic biofuel produced in all cases even when the conversion rates improve so less feedstock is needed. Alternatively, the biorefinery could collect the same level of feedstock as in the base case producing more ethanol but this was not considered here.

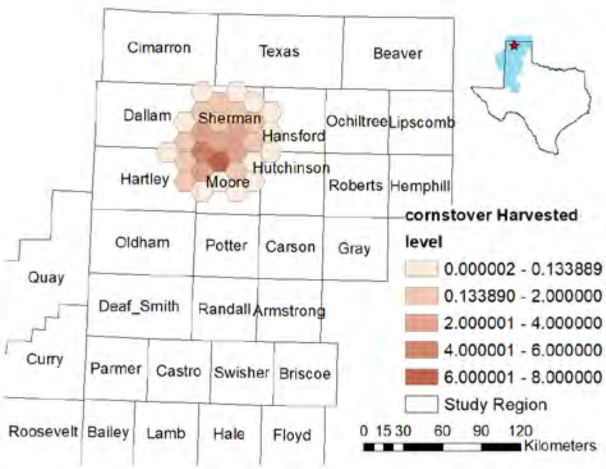
Figure 16 illustrates the supply regions by feedstock when different conversion rate scenarios are applied. This shows the land contracted drops by 12.1% and 19.3%, respectively. Land used for collecting corn stover reduced the most by 18.5% and 25.2%, while that for energy sorghum decreased by 11% and 15.9%, switchgrass area dropped by 4.9% and 13.1% and sorghum stover lands remained unchanged. The results also show the corn stover supply region slightly decreased from 60 to 50 km and 45 km in the medium and high improvement scenarios. The area for energy sorghum and sorghum stover collected remained at 50 km and 15 km radius across the scenarios. The supply region for switchgrass dropped from 90 to 70 and 60 km in the medium and high improvement scenarios.

Table 17 Summary of the key decisions of different conversion rates scenarios

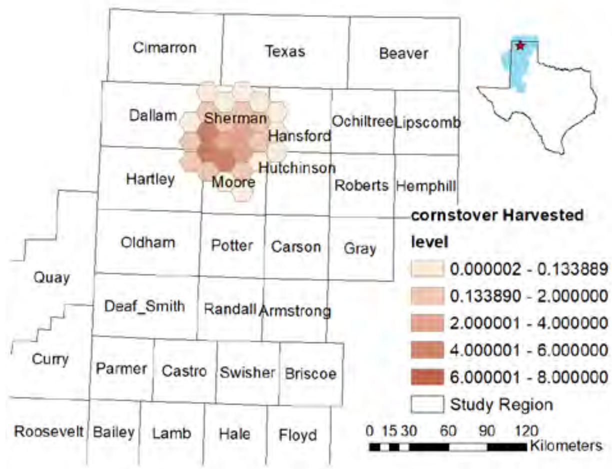
Item	Base scenario			Medium improvement			High improvement			Units
	Worst yield	Best yield	Average	Worst yield	Best yield	Average	Worst yield	Best yield	Average	
First-stage decision										
Total land contracted for biomass	252.36	252.36	252.36	221.67	221.67	221.67	203.60	203.60	203.60	1000Ha
Corn stover	124.17	124.17	124.17	101.20	101.20	101.20	92.91	92.91	92.91	1000Ha
Energy sorghum	23.64	23.64	23.64	21.03	21.03	21.03	19.87	19.87	19.87	1000Ha
Sorghum stover	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	1000Ha
Switchgrass	103.99	103.99	103.99	98.89	98.89	98.89	90.28	90.28	90.28	1000Ha
Second-stage decision										
Total biomass harvested	743.29	736.89	736.67	645.68	640.02	640.39	593.88	589.37	588.97	1000Mg
Corn stover	406.65	54.62	184.36	331.43	47.50	126.91	304.26	43.70	115.97	1000Mg
Energy sorghum	95.71	111.20	135.97	85.12	108.78	119.62	80.42	90.46	112.93	1000Mg
Sorghum stover	0.44	0.86	0.63	0.44	0.86	0.63	0.44	0.86	0.63	1000Mg
Switchgrass	240.48	570.20	415.72	228.70	482.88	393.23	208.77	454.35	359.45	1000Mg
Total biomass dumpped	0.00	621.52	313.14	0.00	561.37	282.25	0.00	515.18	259.35	1000Mg
Corn stover	0.00	525.60	309.70	0.00	425.40	275.76	0.00	390.43	253.69	1000Mg
Energy sorghum	0.00	76.49	2.92	0.00	58.13	3.89	0.00	67.24	3.77	1000Mg
Sorghum stover	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	1000Mg
Switchgrass	0.00	19.42	0.51	0.00	77.84	2.60	0.00	57.51	1.88	1000Mg
Total biomass stored	2,589.60	1,786.13	2,107.42	2,186.09	1,572.73	1,766.88	2,010.97	1,427.40	1,626.30	1000Mg
Corn stover	1,337.47	0.00	301.55	1,001.82	0.00	197.45	916.56	0.00	179.05	1000Mg
Energy sorghum	246.58	0.00	294.30	221.06	32.32	196.80	218.61	0.00	190.30	1000Mg
Switchgrass	1,005.55	1,786.13	1,511.57	963.21	1,540.41	1,372.64	875.81	1,427.40	1,256.95	1000Mg
Total biomass processed	664.29	682.85	672.55	578.63	592.39	586.60	532.17	546.10	539.39	1000Mg
Corn stover	366.30	54.62	175.18	301.15	47.50	120.87	276.54	43.70	110.48	1000Mg
Energy sorghum	88.09	110.98	126.92	78.26	107.59	113.50	73.64	90.24	107.00	1000Mg
Sorghum stover	0.44	0.86	0.63	0.44	0.86	0.63	0.44	0.86	0.63	1000Mg
Switchgrass	209.46	516.39	369.82	198.78	436.45	351.60	181.56	411.30	321.29	1000Mg

Less biomass was harvested under the conversion rate improvement rate scenarios excepting for sorghum stover. Specifically, 31.1% to 37% less corn stover, 12% to 16.9% less energy sorghum, and, 5.4% to 13.5% less switchgrass. Given the yield of sorghum stover is low, the use of sorghum in both scenarios was small and unchanged. Note that switchgrass was still used as the main feedstock across the conversion rate scenarios. Again, this occurs since the switchgrass storage cost is relatively lower.

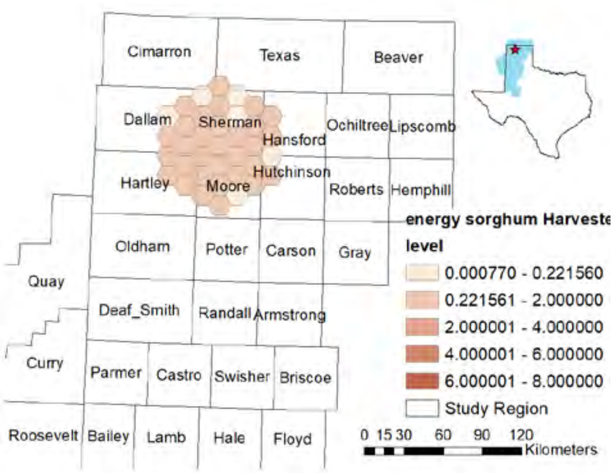
Meanwhile, the amount of biomass being dumped when the best yield of state of nature realized decreases as the conversion rate improves. The total amount of biomass dumped dropped by 9.8% and 17.1% under the medium and high improvement rate scenarios, respectively. This occurs since less land needs to be contracted to ensure sufficient supply, in turn decreasing dumping.



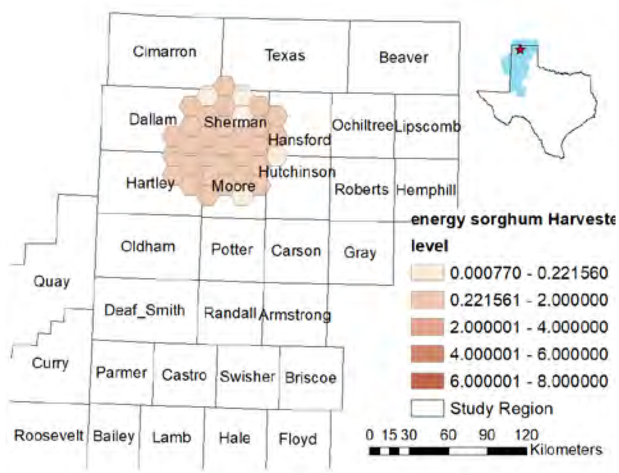
(a) Corn stover in medium improvement scenario



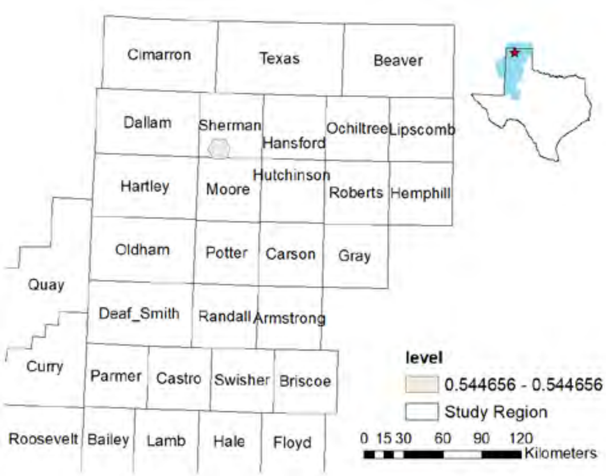
(b) Corn stover in high improvement scenario



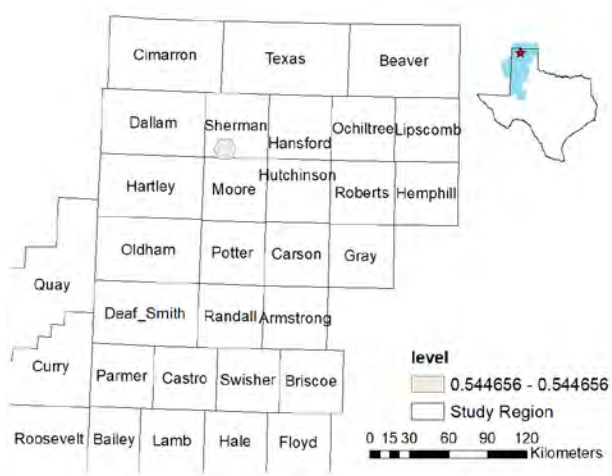
(c) Energy sorghum in medium improvement scenario



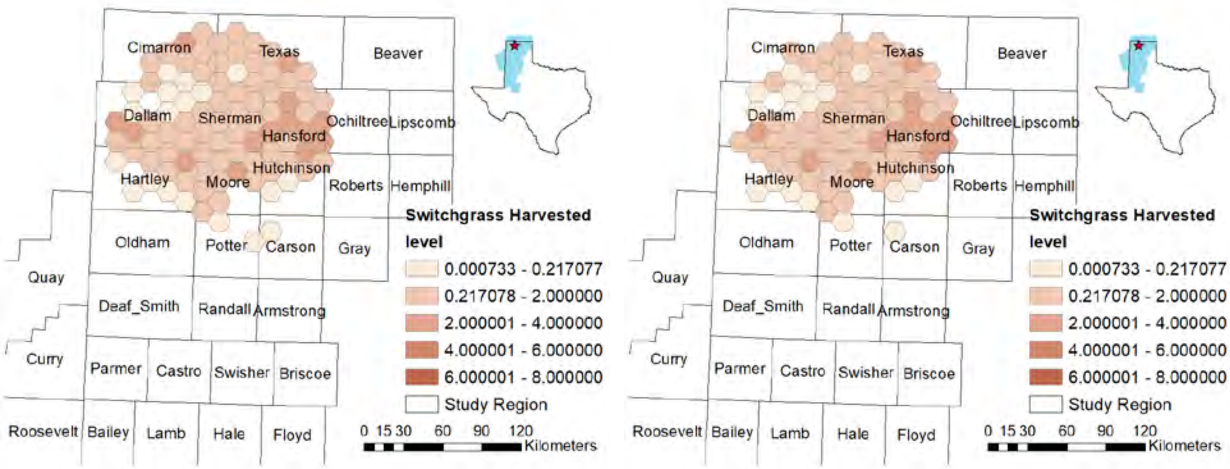
(d) Energy sorghum in high improvement scenario



(e) Sorghum stover in medium improvement scenario



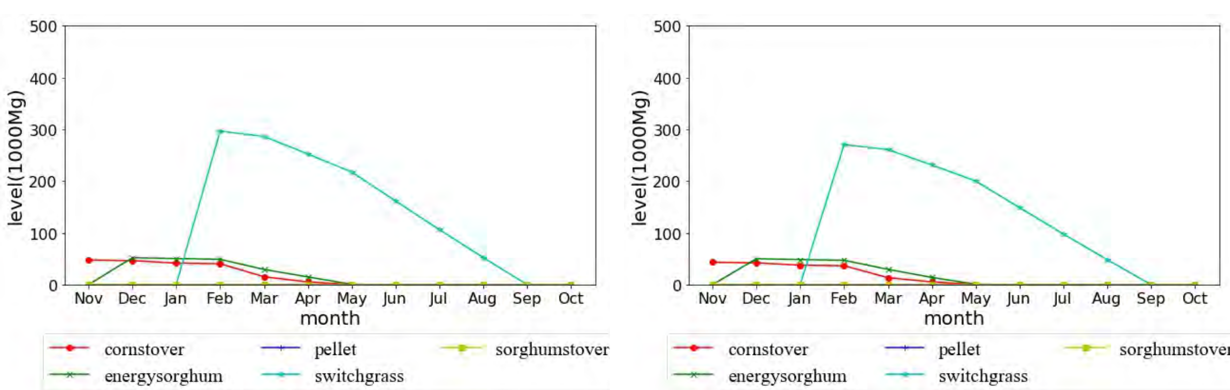
(f) Sorghum stover in high improvement scenario



(g) Switchgrass in medium improvement scenario (h) Switchgrass in high improvement scenario

Figure 16 Source of each biomass under different conversion rates scenarios

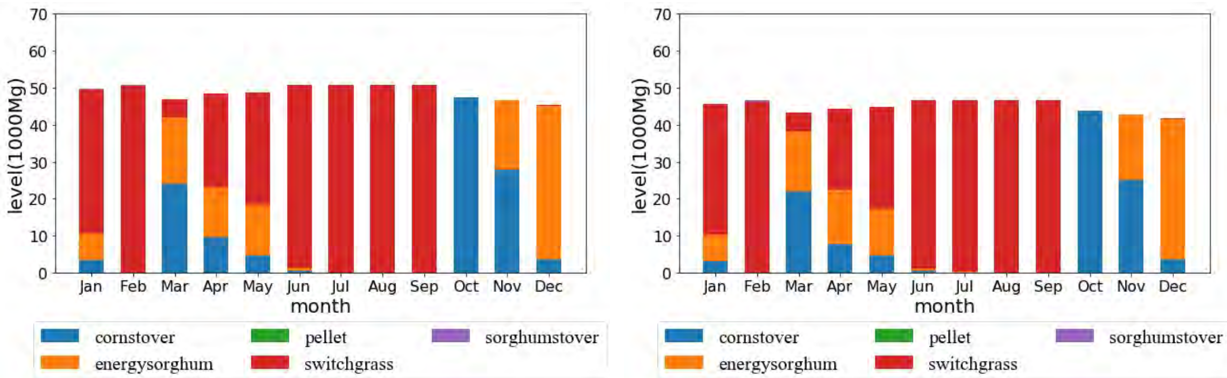
Figure 17 below illustrates the monthly storage inventory levels under the different conversion rates. Based on the figure, the monthly inventory level decreased due to less demand for biomass as conversion rate improved. In fact, around 300,000 Mg to 280,000 Mg of switchgrass were sent to storage and was then consumed from February to August. Additionally, 50,000 Mg of corn stover and energy sorghum were transported to storage in November and December correspondingly and used as inputs for following two to three months.



(a) Medium improvement scenario (b) High improvement scenario

Figure 17 Monthly inventory level in different conversion rate scenarios

The amount of each biomass processed throughout the analysis period is shown in Figure 18. According to that figure, the processing pattern is similar to the base case but with less being processed monthly as the conversion rate improves. Switchgrass was used as the main source of feedstock excepting in months when another biomass could be harvested. Specifically, 20% to 60% of the feedstock was switchgrass in March, April and May while more than 80% was switchgrass in January, February, and from June to September. Additionally, a combination of corn stover and energy sorghum provided the necessary feedstock in March, and April and from October to December. Since the storage cost of these two biomass feedstocks were higher they were mainly harvested and sent directly to the biorefinery. Only a small portion were stored and processed from March to May.



(a) Medium improvement scenario (b) High improvement scenario

Figure 18 Process level of conversion rate improvement scenarios

Impacts of Pellet Price on the Supply Chain Design under Stochastic Model

Now we examine the potential impact of possible pellet export sales. The above results show agricultural residues located on the outskirts of the region are the most likely feedstock to be converted into pellets and exported. If the biomass yield turned out to be well above average or if the conversion rate is improved, the biomass is simply dumped instead of making into pellet since the cost of dumping biomass is cheaper than pelletizing the biomass and storing them. But the introduction of an export sale possibility could change that.

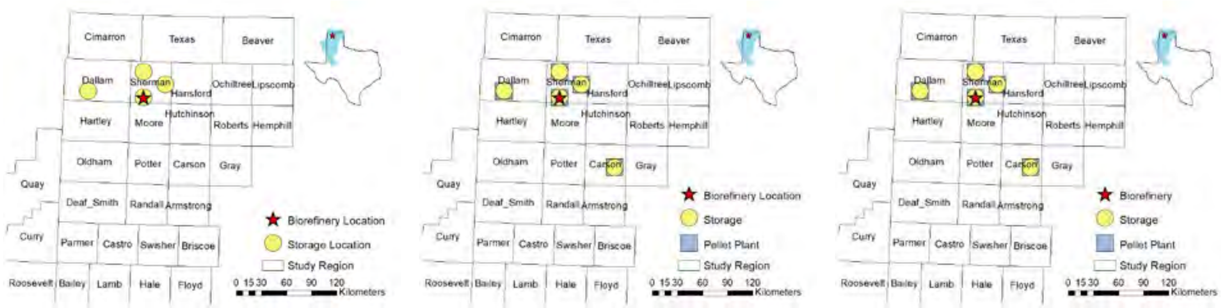
In setting up the scenarios we note that the herbaceous pellet market is relatively limited comparing to that for wood-based pellets and thus there is little information herbaceous pellet prices. We assume the price of herbaceous pellets is lower than that for woody pellets since the higher ash content9 reduces combustion efficiency and thus pellet value. Namely we assume the price for herbaceous pellets ranges from $98.56/Mg to $166.5/Mg if 12% ash content is assumed10. This led to the formation of two pellet price scenarios$100 and $150 per Mg that were used in the proposed model to simulate potential pellet price as compared to the price of zero in the base model.

Given that pellets are generally be transported by rail, this study insured each potential location of storage/ pellet plant has access to rail road. Figure 19 depicts the optimal locations of facilities under different pellet price scenarios. In both pellet price scenarios, five combined storage depots and pellet plants were selected and located near the biorefinery. The same facility setup was observed in both the low and high pellet price scenarios. In this study, a constraint on the total number of storage/pellet plant was applied to increase computation efficiency. Thus, given that all the available locations for pellet plant near the biorefinery have been selected for both case, the setup for both pellet price was identical.

---

[9] . Based on a study of Vermont grass energy partnership, the ash content in the herbaceous pellet is 12 to 15 times higher than woody pellet.

[10] Based on the report by Strauss and Walker (2017), the world market price for wood pellets ranged from $112 to $185 per Mg during the past four years. Thus, if 12% of ash content is assumed in the herbaceous pellet, then the price for herbaceous pellet ranges from $98.56/Mg to $$162.8/Mg



(a)Base case (b)$100/Mg (c)$150/Mg

Figure 19 Optimal locations for different price scenarios

Note that, at optimality, only one pellet plant was selected at each place due to the assumption that no stand-alone pellet plant is allowed. The assumption of no stand-alone pellet was made since the amount of pellets produced is relatively large, the raw biomass feedstock will need to be stored before converting into pellet. Given that we assumed that a pellet plant must be located in conjunction with a storage depot only one pellet plant was located at any place.

Table 18 below summarizes the expected cost of each component in the supply chain at different price scenarios. When the pellet sale option became available, the total cost dropped from base case by 6.2% and 26.5% for the $100/M and $150/Mg scenarios respectively. The improvement of the expected objectives in both scenarios resulted from pellet sale revenues which offset the increasing costs of an additional storage depot, pellet plant as well as the associated increased operating and transportation costs.

Table 18 Expected Cost of Each Component at Different Pellet Price

Item	Base case	$100/Mg	$150/Mg	Unit
Expected cost of supply chain	114,775.41	107,572.86	84,292.92	$1,000
Annualized cost of building biorefinery	24,504.40	24,504.40	24,504.40	$1,000
Annualized cost of building Storage	9,952.32	9,952.32	9,952.32	$1,000
Annualized cost of building Pellet Station		1,893.05	1,893.05	$1,000
Cost of contracting land	1,974.12	2,493.70	2,736.26	$1,000
Expected Cost of harvesting biomass	27,963.79	46,731.61	47,052.89	$1,000
Expected Cost of dumping biomass	17.61	35.97	32.66	$1,000
Expected Cost of storing biomass(offsite)	6,286.97	6,073.13	6,028.86	$1,000
Expected Cost of pelleting		12,115.33	12,386.33	$1,000
Expected Cost of producing ethanol	31,752.00	31,752.00	31,752.00	$1,000
Expected Cost of Transporting biomass	12,324.20	18,245.41	18,371.58	$1,000
Profit from export pellet		-46,224.06	-70,417.45	$1,000
Average cost of a gallon ethanol	0.60	0.56	0.44	$/L

Table 19 below lists the optimal solutions to the key decisions of different pellet price scenarios. Figure 20 depicts amount and area of each biomass being harvested under the different pellet price scenarios. Based on the figure and table, the land contracted for supply biomass first increased by 28.7% in the low-price scenario and 37.6% under the high-price scenarios. Note this reduced dumping with that biomass converted to pellets. Specifically, the land contracted increased by 20.9%, and by 39.8% for corn stover, 55.6% and by 50.3% for energy sorghum, and 32.2% and 33.2% for switchgrass respectively when the price of pellet increased from $100/Mg to $150/Mg compared with the based scenario. While more land was used for corn stover and energy sorghum, the land for sorghum stover remained the same across scenarios. Given more land was contracted, more biomass was harvested except for sorghum residue. Average amount harvest increased 147% and 152% times for corn stover, 54.9% and 49.8% for energy sorghum, and 32.3% and 33.2% for switchgrass.

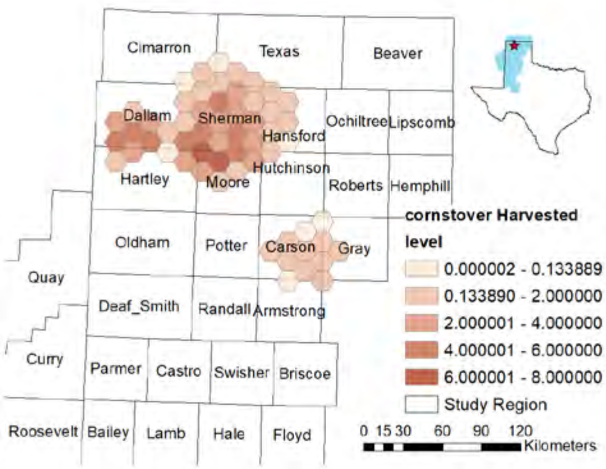
Table 19 Summary of the Key Decisions of Different Pellet Prices Scenarios

Item	Base scenario			$100/Mg			$150/Mg			Units
	Worst yield	Best yield	Average	Worst yield	Best yield	Average	Worst yield	Best yield	Average	
First-stage decision										
Total land contracted for biomass	252.36	252.36	252.36	325.00	325.00	325.00	347.36	347.36	347.36	1000Ha
Corn stover	124.17	124.17	124.17	150.16	150.16	150.16	172.71	172.71	172.71	1000Ha
Energy sorghum	23.64	23.64	23.64	36.81	36.81	36.81	35.54	35.54	35.54	1000Ha
Sorghum stover	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	1000Ha
Switchgrass	103.99	103.99	103.99	137.48	137.48	137.48	138.55	138.55	138.55	1000Ha
Second-stage decision										
Total biomass harvested	743.29	736.89	736.67	959.14	1,231.13	1,217.56	1,030.34	1,231.51	1,224.92	1000Mg
Corn stover	406.65	54.62	184.36	491.75	158.53	455.93	565.60	162.89	465.90	1000Mg
Energy sorghum	95.71	111.20	135.97	149.03	292.24	210.73	143.88	282.16	203.81	1000Mg
Sorghum stover	0.44	0.86	0.63	0.44	0.86	0.64	0.44	0.86	0.64	1000Mg
Switchgrass	240.48	570.20	415.72	317.93	779.51	550.26	320.41	785.61	554.57	1000Mg
Total biomass dumpped	0.00	621.52	313.14	0.00	543.13	147.04	0.00	644.14	226.25	1000Mg
Corn stover	0.00	525.60	309.70	0.00	543.13	141.52	0.00	644.14	221.27	1000Mg
Energy sorghum	0.00	76.49	2.92	0.00	0.00	5.52	0.00	0.00	4.98	1000Mg
Sorghum stover	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Switchgrass	0.00	19.42	0.51	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Total biomass stored	2,589.60	1,786.13	2,107.42	2,325.67	1,959.95	2,029.43	1,510.55	1,948.68	1,987.25	1000Mg
Corn stover	1,337.47	0.00	301.55	577.61	0.00	17.93	276.87	0.00	7.20	1000Mg
Energy sorghum	246.58	0.00	294.30	517.35	324.75	607.16	410.34	302.24	569.20	1000Mg
Switchgrass	1,005.55	1,786.13	1,511.57	1,230.71	1,635.20	1,404.34	823.33	1,646.44	1,410.85	1000Mg
Total biomass processed	664.29	682.85	672.55	666.44	671.88	669.61	582.31	672.60	667.36	1000Mg
Corn stover	366.30	54.62	175.18	252.30	54.62	102.55	204.82	54.62	100.18	1000Mg
Energy sorghum	88.09	110.98	126.92	133.28	198.04	189.92	131.35	192.36	184.25	1000Mg
Sorghum stover	0.44	0.86	0.63	0.44	0.00	0.61	0.44	0.00	0.61	1000Mg
Switchgrass	209.46	516.39	369.82	280.42	419.22	376.54	245.70	425.62	382.32	1000Mg
Total Pellet produced	0	0	0	210.7994394	475	462.241	381.94	475.00	472.58	1000Mg
Total pellelt stored	0	0	0	0	0	0	697.27	0.00	24.10	1000Mg
Total pellet Processed	0	0	0	0	0	0	87.59	0.00	3.13	1000Mg
Total pellet exported	0	0	0	210.7994394	475	462.241	294.35	475.00	469.45	1000Mg

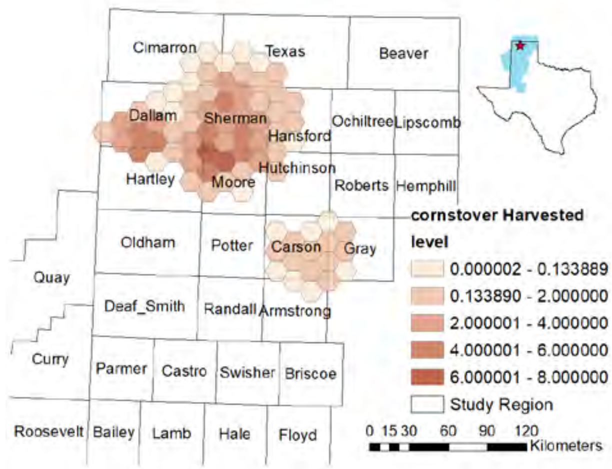
With the pellet sale option, the biomass that was disposed in the good states of nature in the base model was converted into pellets and sold. The biomass feedstocks used for producing pellet were switchgrass, corn stover and energy sorghum. Thus, the pellet plants were operated when these crops were harvested in January, February, October, November, and December.

In addition to helping reduce the amount of biomass being dumped, the remote pelleting option along with external market also allowed use of stranded biomass. Argo et al. (2013) argued that the remoted prepossessing depots provide additional options for geographically stranded feedstocks that are not within an 80-km biorefinery radius. If each depot can participate external market, more of stranded biomass which was not economically feasible for collection can be captured and pelleted for sale and use. Our results support Argo et al. (2013) since corn stover was collected from a larger supply area and used in producing pellets for export as the pellet price rose. Specifically, compared to the base case, the supply region for the corn stover increased from 60 to 90 km in both the pellet price scenarios. The additional corn stover collected was sent to the closest remote pellet plant and converted into pellets. Meanwhile, in both low and high pellet price scenarios, around 26% of the pellets were made from switchgrass and the rest from corn stover. Almost all the pellets were exported to external markets.

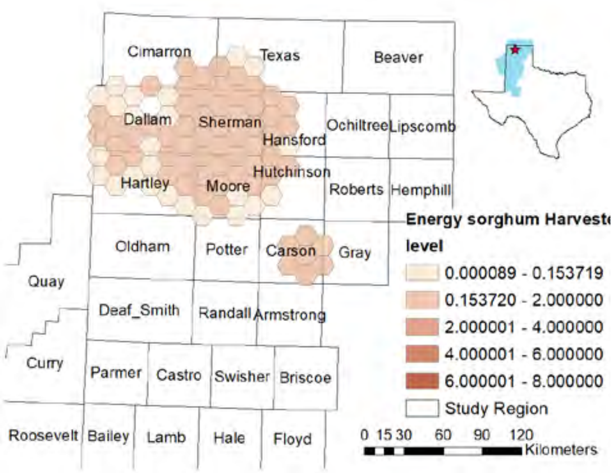
The amount of biomass being dumped when the best yield of state of nature was realized decreased by 53% and 27.7% when the pellet price was \$100/Mg and \$150/Mg respectively. Here more biomass was dumped at the high pellet price scenario relative to low pellet price scenario is due to the limitations on number of pellet plant allowed in the study region. As mentioned earlier, a constraint on the total number of storage/pellet plant was applied to increase computation efficiency. Thus, given that all the available locations for pellet plant near the biorefinery have been selected at high pellet price scenario, part of biomass had to be dumped once the pellet production capacity was reached. In other words, less biomass will be dumped in the high pellet price scenario if the limitation on the overall pellet plant capacity can be further increased. Therefore, even more biomass was used to produce pellet, there was still 221,270 Mg of biomass being dumped at high pellet price scenario.



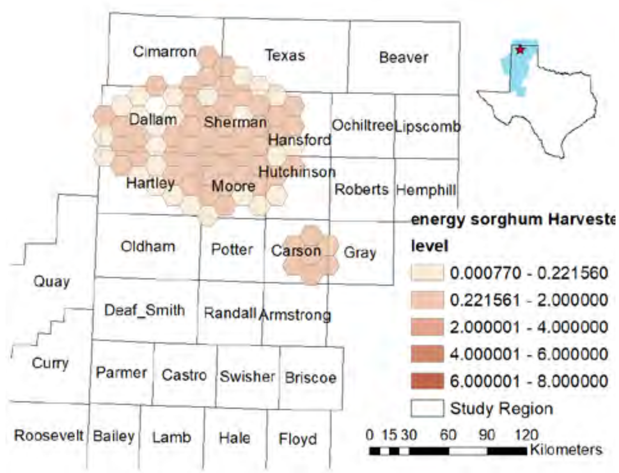
(a) Corn stover $100/Mg scenario



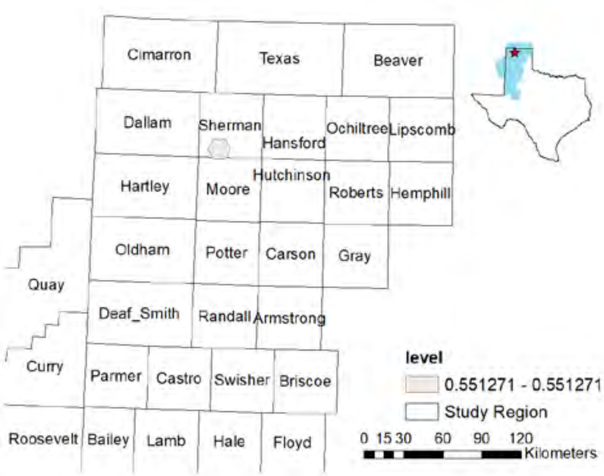
(b) Corn stover $150/Mg scenario



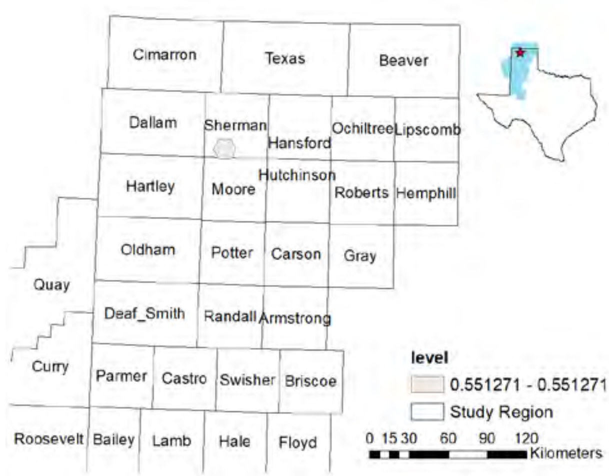
(c) Energy sorghum $100/Mg scenario



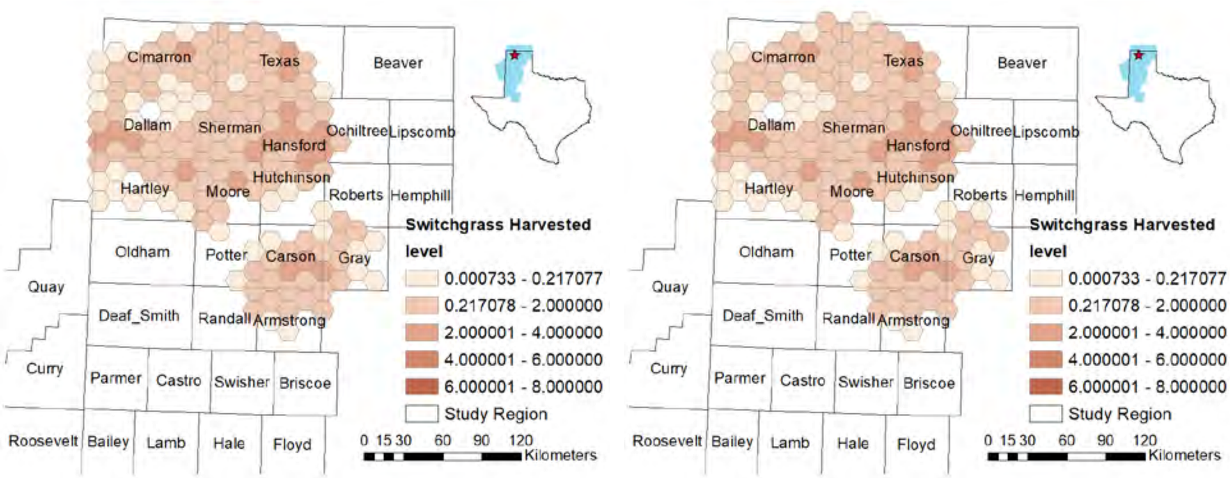
(d) Energy sorghum $150/Mg scenario



(e) Sorghum stover $100/Mg scenario



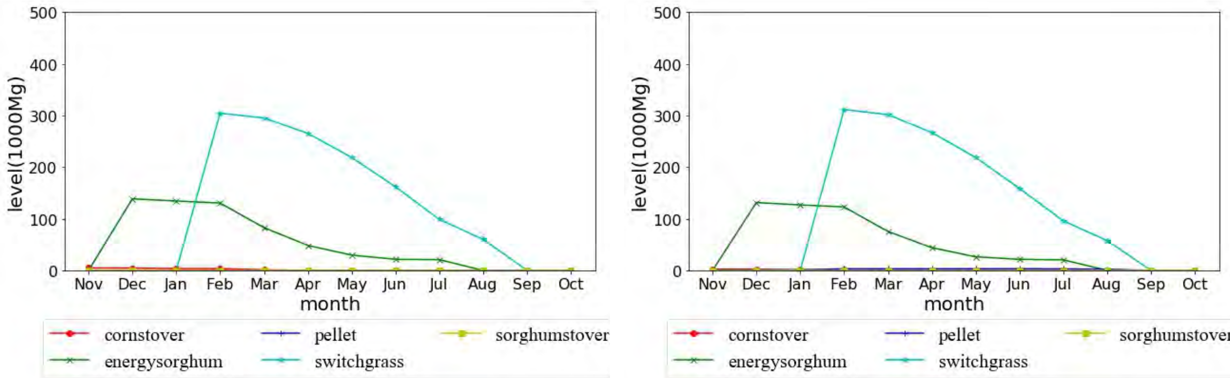
(f) Sorghum stover $150/Mg scenario



(g) Switchgrass $100/Mg scenario (h) Switchgrass $150/Mg scenario

Figure 20 Source of each biomass at different pellet prices

Figure 21 shows the storage levels for each biomass. Here we see the storage pattern for low and high pellet price scenarios are similar and storage is confined to energy sorghum and switchgrass. Specifically, in both scenarios, around 125,000 Mg of energy sorghum was stored in December and another 310,000 Mg of energy sorghum was added to storage in February. Note that since there is no restriction on the amount of pellets being exported, all the pellet was exported once produced to save storage costs. Again, given the switchgrass has the lowest storage cost, it is used as the major input for the biorefinery in both scenarios.

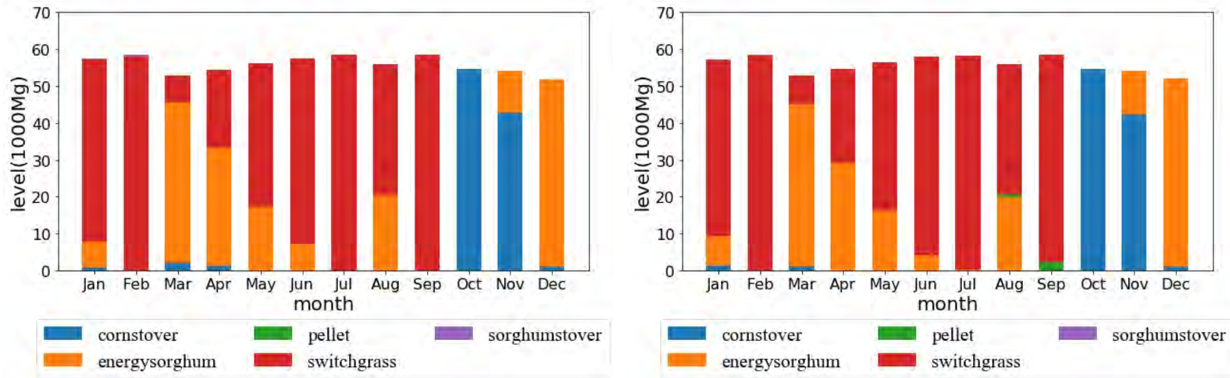


(a) $100/Mg scenario (b) $150/Mg scenario

Figure 21 Monthly inventory level at different pellet prices

The amount of each biomass processed throughout the analysis period is depicted in Figure 22. As mentioned above, switchgrass and energy sorghum were the main inputs throughout the year under both pellet price scenarios and all pellets were exported. Note that as pellet price rose, in addition to contracting for more corn stover, a portion of corn stover which was used for producing ethanol in the base case now is input to the pellet plants. More corn stover was used to produce pellets due to both low collecting cost and low yield fluctuation. Additionally, more energy sorghum was used in low and high price scenario to produce ethanol.

At discussed above, the cheapest biomass will be the first used as feedstock to the biorefinery and the cost of utilizing such biomass will gradually increase with the distance of available biomass. When the cost of using such biomass is equal to whichever the second cheapest alternative, the model will switch feedstocks. Given that pellets can be sold, a new pattern arose, namely, the crop cheap storage cost and nearby the biorefinery was used as the main input for the biorefinery. As for the feedstock in more remote locations, rather than transport them to biorefinery, they were converted to pellets and exported to the external market.



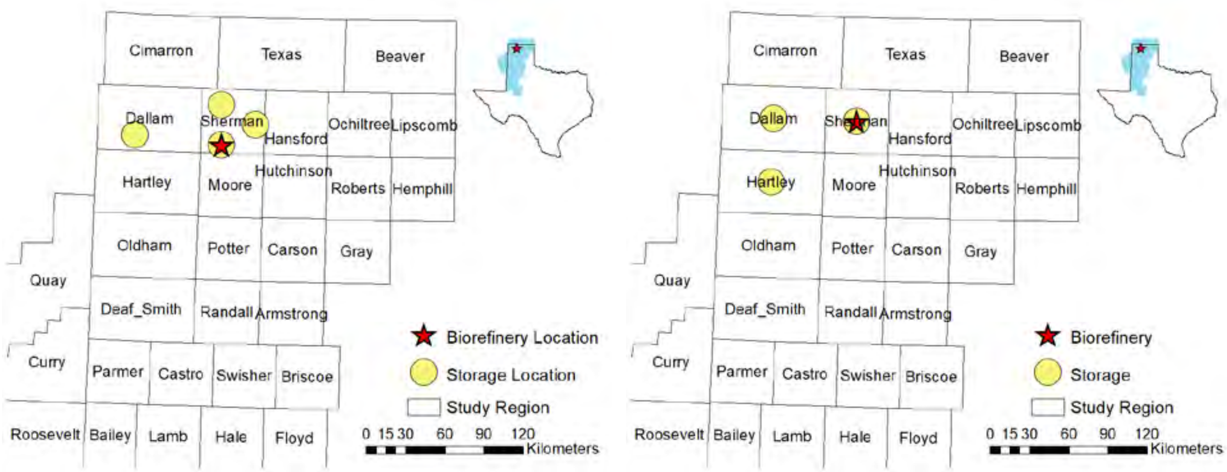
(a) $100/Mg scenario (b) $150/Mg scenario

Figure 22 Monthly biomass processed level of different pellet price scenarios

Experiments with Geographic Scale

Another experiment was done on the effects of incorporating high resolution spatial data into the model. Although the potential of supply chain analysis at a fine spatial scale has been increasingly recognized, studies at finer scales have been limited. In fact, one of the challenges in a study is the amount of spatial detail used to depict the transportation cost of the widely distributed biomass feedstock. With the current capabilities of spatial analysis, substantial high resolution geographical data and techniques can be employed to better depict biomass movement which may well affect the optimal facility placement and the logistic decisions. Thus, an experiment was conducted with alternative scales to help us understand the impact of spatial data scale on supply chain design. This involved using finer scale hexagon-based information as opposed to just using county information for this study. In this case we ran a version of the model specified only at a county level and a model specified with the hexagons as above then examine the differences between the optimal placement and configuration of the cellulosic biofuel supply chain along with the implications for cost and other decisions.

Figure 23 depicts the optimal locations of facilities under the two scale alternatives. In both scenarios, five storage depots were selected and located near the biorefinery. Yet, with the county level scale data, one storage was chosen at Hartley county whereas with finer resolution data that was located in Sherman county.



(a)Hexagon level scale (b)County level scale

Figure 23 Optimal facilities in different geographic scales

The results show the higher resolution spatial data also leads to different estimates of transportation cost. Table 20 below shows the comparisons of cost for each of the supply chain components between county level and hexagon level geographic scale.

Table 20 Expected Cost of Each Component at Different Geographic Scale

Item	Base case	County scale	Unit
Expected cost of supply chain	114,775.41	113,672.82	$1,000
Annualized cost of building biorefinery	24,504.40	24,504.40	$1,000
Annualized cost of building Storage	9,952.32	9,952.32	$1,000
Annualized cost of building Pellet Station			$1,000
Cost of contracting land	1,974.12	1,997.34	$1,000
Expected Cost of harvesting biomass	27,963.79	27,708.47	$1,000
Expected Cost of dumping biomass	17.61	80.09	$1,000
Expected Cost of storing biomass(offsite)	6,286.97	6,087.79	$1,000
Expected Cost of pelleting			$1,000
Expected Cost of producing ethanol	31,752.00	31,752.00	$1,000
Expected Cost of Transporting biomass	12,324.20	11,590.41	$1,000
Average cost of a gallon ethanol	0.60	0.60	$/L

Based on Table 20, the expected cost estimated with county-level spatial data case is 1% less than the objectives with hexagon scale data. The different in objectives is because the county level model depicts movements to and from county centroids as opposed to the hexagon centroids. The results also indicate differences in land contracted and greater amounts of feedstock dumping under the county level scale case.

Summary and Discussion

This chapter reports on a case study that addresses the optimal design of a multi-feedstock biofuel supply chain system in the context of the Texas High Plains. A two-stage stochastic mixed integer model was used to minimize the expected total supply chain cost while determining facility locations (i.e. biorefinery, storage and pellet plants), feedstock land contracting, feedstock movement, storage use, pelleting volume, land allocation for feedstock, remote versus centralized storage, pellet sale and feedstock choice in refining. The model was used to see the effects of uncertainty incorporation, centralized versus decentralized storage, use of pelleting, alternative conversion rates, pellet export prices and the effects of spatial detail. Several observations arise from model use.

First, we find that incorporation of yield uncertainty is an important factor affecting the need for feedstock contracting, the amount of excess feedstock dumping costs and supply chain operation when different yield outcomes are realized. 46.5% more land for biomass feedstocks was contracted under uncertainty as a safety margin to keep the refinery running when yields are low. On the other hand, when high yields were present the model needed to deal with excess feedstock and about 736,000 Mg of total biomass was used in refining while 621,000 Mg of excess feedstock was dumped at a cost. Also, as discussed below possibilities for pellet export helps in managing the excess. Additionally, we find that due to the high level of fixed cost and the constant requirement for feedstock across sates of nature that total cost was not very sensitive to the variations in contracting and dumping with the cost of ethanol produced only varying by one cent per liter ($0.590/L versus $0.602/L) between the deterministic and the stochastic models. However, given the estimates of the empirical states of nature distribution and parameters in this study factors are relatively conservative, the impact of uncertain yield could be greater than the prediction here. Besides, the "optimal" plan from the stochastic model is generally robust across the yield outcomes and not the best possible position for all (or maybe even any) of the possible yield events. Thus, the stochastic model solution provides the decision maker with the flexibility to adjust the logistic decisions based on the varying yields.

Second the impact of different supply chain designs was examined. Unrestricted design, central storage only and no pelleting scenarios were examined to see the impact on the supply chain design, operation and cost. The results indicate that total costs were essentially stable across these configurations. Yet, with remote facilities, storage and pelleting can be placed near places with high biomass density and allow more efficient use of biomass plus lower transport costs, spoilage and possible exports.

In terms of allowing pelleting the base scenario did not consider export of pellets to external markets. However, when pelleting and exports are allowed then one can exploit otherwise stranded biomass. Thus, although the total cost does not vary much across these three scenarios, a supply chain with remote storage/pelleting and export possibilities seems better manage uncertain yield and can lower total cost of ethanol as seen in the pelleting price results.

When pelleting is not allowed, the average cost of cellulosic biofuel ranges from $0.59L to $0.602/L when pellet exports were not allowed. However, allowing exports lowers cost to as little as $0.44/L. Nevertheless, these costs estimated from all the scenarios are still higher than the current average first generation ethanol production cost, $0.33/L. Judging from these figures, building a cellulosic biofuel supply chain in the present study region seems not a privately economically competitive option and some form of subsidy or blending mandate would be needed. For example, EPA provides an opportunity for obligated parties facing blending restrictions to purchase Cellulosic Waiver Credit (CWC) which has to be greater than $0.066/L or $0.79 minus the wholesale price of gasoline per Liter. Currently, the CWC price for 2018 is $0.51/L. Table 21 lists the average cost of each scenario with and without CWC incentives and shows the net cost in almost all the scenarios is lower than the current market price.

Third, analyses were conducted to examine the impact of conversion rate improvements. The improved conversion rate also reduced feedstock demand to generate the model fixed amount of ethanol and reduced costs across the elements of the supply chain. We also found conversion rate improvements altered supply chain design. Specifically, facilities were placed closer to the biorefinery as the greater ethanol yield shrunk the supply region. This caused the average cost to drop from $0.602/L to $0.56/L and $0.54/L as the conversion rates improved and this may make it attractive under subsidies for the plant to increase ethanol volume.

Fourth, analyses of pellet export possibilities of $100 and $150/Mg were carried out. There the results showed that the high export price possibility changed both the optimal locations of facilities and the feedstock usage pattern plus increased the optimal number of storage and pellet plants. Additionally, under the higher pellet price the impact of uncertain yield of herbaceous biomass was mitigated by less dumping and added profit from exporting the pellets. The supply chain can involve added contracting to insure supply when yields are low and then can pellet the excess when high yields are realized.

Table 21 Average Cost of Each Scenario with and without the CWC Incentive

Scenarios	Average cost without incentives	Average cost with incentives (CWC)	Unit
Base case (deterministic)	0.59	0.08	$/L
Base case (stochastic)	0.602	0.092	$/L
No-pellet	0.602	0.092	$/L
Central storage	0.603	0.093	$/L
Medium improvement	0.56	0.05	$/L
High improvement	0.54	0.03	$/L
Low pellet price	0.56	0.05	$/L
High pellet price	0.44	-0.07	$/L

Finally, we experiment with the granularity of regional representation and found it beneficial to use a more disaggregated representation as opposed to a County level one. The finer scale, in our opinion, gave a more complete idea of appropriate supply chain design, contracting localities and commodity movement plus altered facility locations.

Conclusions

Determining the optimal supply chain/logistics system design is an important component in achieving low cost biofuel production. Previous studies of supply chain design have chosen biorefinery and feedstock production locations using ad hoc procedures, or they have employed an optimization model but used a coarse regional representation. The studies have also largely ignored crop yield variability. This study developed and applied a modeling framework at a relatively fine geographic scale for the choice of production locations, storage depot locations, pelleting plant locations and biorefinery location plus the production levels for multiple feedstocks and the manner they are stored, pelleted and moved through the system monthly. To do this a mixed-integer programming model linked based on regional high resolution spatial data and stochastic yields was developed. In turn the model was used in a case study to evaluate how a number of factors affect the optimal placement and configuration of a lignocellulosic biofuel supply chain. We feel this modeling framework can also be extended to evaluate feedstock production in other regions for the emerging advanced biofuel or biomass power electrical generation industries as we have used it in East Texas and are using it in Oklahoma.

In addition to developing a new analytical supply chain design and operation optimization framework, this study also developed case study-based findings which may help others in supply chain design. For the Texas High Plains case study which is the subject of this essay we considered use of agriculture residues along with energy crops. The results indicated that a supply chain with remote storage sites and pellet plants can use biomass more efficiently based on their distribution leading to a modest reduction in the costs of total supply chain production. Besides, with the government incentives such as cellulosic wavier credits, the cost of cellulosic ethanol using the optimized supply chain systems appears price competitive with current ethanol supplied in the market. Furthermore, if pellets can be exported, this can mitigate the cost of handling additional biomass under good yield outcomes and would create an additional source of income for the biorefinery. Moreover, as the ethanol production technology breakthroughs may occur in the future, the amount of biomass required, and the associated logistics costs is expected to be lowered due to the improved conversion rate.

The current model presented in the dissertation, however, involves a few simplifying assumptions, which can be relaxed in future research. For example, although we focused on existing crop lands for energy crop production the use of marginal lands may be superior lowering competition with current food and fiber products. Second, we might better model different rental rates in depicting the supply of the land and consider what to do as a supply chain benefits from technological advances in conversion rates. Third we did not consider, the risk preference of the biorefinery planner and the land owners and further analysis on risk preference may be in order. Fourth, this study assumed farm level feedstock production costs are fixed, while they are likely to be uncertain due to the weather, pest and other production conditions. Further study could better represent risk and risk reactions. Along the same line a uniform regional distribution of yields was creased using 4 states for each crop and 64 in total. However, the region may exhibit less than perfect correlation across production locations and yields may be more variable than state statistics reveal as those add over many farms. Thus, work could be done on better representation of yield uncertainty. Finally, this study assumes a fixed ethanol production level and additional work might consider the possibilities of expanded biorefinery production if for example pellet export opportunities arose, conversion rates improved, or fuel sale prices rose.

CHAPTER V

REGIONAL SUPPLY CHAIN MANAGEMENT CASE STUDY: EAST TEXAS

Introduction

A growing interest in the production of the second-generation biofuels has been observed in the past two decades. Although today first-generation, corn-based ethanol is commonly blended with gasoline, the expansion of its production has raised food security and environmental concerns reference. Second-generation biofuel made from lignocellulosic biomass which includes woody and crop residues has been advanced as an alternative and in fact was assigned a mandate level in the Renewable Fuel standard formulated in the Energy Independence and Security act of 2007.

However, the production of lignocellulosic biofuel is substantially smaller than many anticipated. In the Renewable Fuel Standard (RFS), a minimum mandated amount of 61,000 Million Liters Per Year (MLPY) of cellulosic biofuel is supposed to be required by 2020. Yet, only 540.55 MLPY of cellulosic biofuel was produced by 2015 which falls far short of the 11,350 Million Liter Per Year (MLPY) RFS proposed mandate for 2015 and there has been no substantial expansion in production since then. In fact, of the three commercial sized plants constructed only one remains operating and that operates at levels well below its nameplate capacity.

Several studies pointed out that one of the big challenges facing cellulosic ethanol production is the logistics of moving a large volume of material to a biorefinery facility. A main reason for high logistic cost is that the lignocellulosic biomass feedstocks such as switchgrass, corn residue and logging residues are bulky, containing high moisture, plus are widely distributed across the landscape with some possibilities only available in a short harvesting window which in turn requires substantial storage for year-round refinery operation. There is also substantial year to year variation in yields of some feedstocks which complicates total supply chain design. Another probable cause for the high logistics cost could be inefficient supply chain design. This thesis addresses optimal supply chain design for a lignocellulosic biorefinery.

To address cellulosic biofuel supply chain design, a supply chain optimization model incorporating the feedstock yield uncertainty will be conceptualized, implemented and used to study optimal design along with the costs and benefits of including or excluding select elements in that chain. We will look at the value of including or excluding storage, pelletizing, and multiple feedstocks. In addition, this study used spatial techniques to allow us to conduct the study at a relatively fine resolution of analysis in contrast to most earlier studies that operated at the county level. The problems using county level data are that it neglects the heterogeneous distribution of biomass feedstock within the county and that counties are not uniform in size. As a result, the logistics designs in these studies are coarse and do not fully reflect the true costs in each county.

Yield uncertainty when included encompasses years with both shortfalls and excesses. Assuming the firm contacts for a lower probability distribution safety margin then it would be common to have more production generated than needed. The size of the safety margin and the handling of excess feedstock are other issues addressed in this study. To our best knowledge, few studies have considered how to deal yield variability, safety margins and extra feedstock. Thus, allow excess to be dealt with we add options such as dumping excess or pelleting then storing or exporting the pellets.

In this chapter, results from a case study that examined biofuel supply chain design in an East Texas region are presented. For feedstocks woody biomass (i.e. logging residue and thinning residue) and switchgrass are considered. The model used determines the cost minimizing logistic design including the optimal locations of biorefinery, storage and pelleting plants plus the optimal seasonal feedstock mix. The results of the proposed model were then used to provide insights on including or excluding decentralized storage, pelleting, yield uncertainty and use of single versus multiple feedstocks.

Case Study

Study Region and Potential Sites for Facilities

The study region was determined based on a spatial analysis of biomass availability in proximity to transport routes in a 22 county East Texas region. Based on National Renewable Energy Laboratory (BREL) studies (Aden et al. 2002; Humbird et al. 2011), a biorefinery which can process at least 2000 dry Mg of biomass per day was assumed in turn yielding 189 million liters of cellulosic ethanol per year. Furthermore, we assumed the biorefinery operated 8500 hours per year (around 95% of the time) and under an assumed yield of 264 liters per metric ton the minimum annual feedstock requirement that needs to be collected from the current study region is about 730,000 Mg. Furthermore, the current study selected potential biorefinery locations as those in the region which have access to a major road or railroad to transport biomass and each potential site would be away from cities to avoid environmental and traffic issues.

In this East Texas case study dedicated energy crops (switchgrass) and substantial amounts of woody biomass can be drawn upon. To ensure woody biomass, an additional constraint was imposed on most of the analyses that requires at least half of the annual feedstocks coming from woody biomass. Also, since it comes from a perennial and can be measured the woody biomass was modeled without any yield uncertainty. In addition, although Sabine County in Louisiana is located within 80-km radius of collecting region, it was ruled out from the study region due to the limited crossings over the Sabine river[11]. Furthermore, according to Aden et al.(2002), the maximum collection radius was set at 80-km as within that radius sufficient actual plus potential feedstock is available to meet the 2,000 Mg per day design we assume. Based on these criteria and the available biomass estimates from the Bioenergy Knowledge Discovery Framework (KDF)(Langholtz et al. 2016) and Texas Forest Service (TFS) (Staples et al. 2008), Angelina county and Trinity county chosen as the potential counties where the biorefinery could be located. Additionally, the surrounding 20 counties which fall within 80-km radius of Trinity and Angelina counties and Trinity and Angelina counties were selected as the potential feedstock supply region. Figure 24 below shows the study region in East Texas

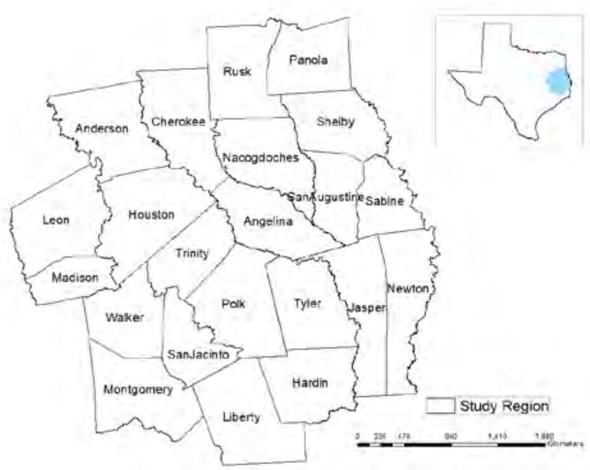


Figure 24 East Texas study region

Once the study region boundary was determined, a more detailed spatial analysis was conducted to identify the suitable locations for the biorefinery, remote storage and pelleting

[11]Sabine County in Louisiana is separated from the study region by the Sabine river and only a single state highway passes through into the Texas part of the East Texas case study region.

within the 20 counties. The whole study region broken into 200 square km hexagons which were deemed large enough to adequately reflect the heterogeneity of the potential feedstock distribution but were not so fine so as to greatly increase the computation time. For biorefinery sites 13 hexagons within the central Trinity and Angelina counties were selected, as they had ready access to both rail and road transportation and were away from the cities. Similarly, hexagons in the outlying counties which fell within the 50-mile radius periphery of the potential biorefineries plus had access to both rail and road transportation and were located away from the cities were considered as the potential locations for distributed storage and pelleting plants. Figure 25 below depicts the potential locations of storage and pelleting plant in the present study region.

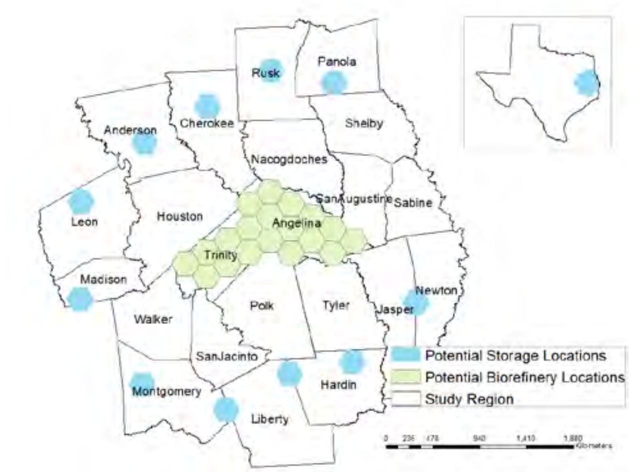


Figure 25 Potential storage/pellet locations

Biomass Considered in the Study Region and its Availability

Land cover in the 22-county study region involved 25% evergreen forest, 5% each for deciduous forest and mixed forest, 23% pasture land, 16% woody wetland, 12% shrubland and 14% cropland based on USDA Cropland Data Layer(CDL) (USDA 2018). Based this composition, multiple lignocellulosic biomass feedstocks are considered. These are forest logging residues, forest thinning residues and switchgrass. The data and methods used to estimate feedstock potential availability depended on feedstock. For the woody biomass, the biomass available on the ground arise from existing forest sites with the Texas Forest Service (TFS) estimating the volume available at 2.94 million Mg based on a survey (Staples et al. 2008). This potential biomass is made up of 1.08 million Mg from logging residues and 1.86 million Mg came from thinning residues12. Note that the estimates of woody biomass from TFS data was used in the current study instead of those from Billion-Ton Study 2016 (BTS). This is done since the BTS focus on the national-level biomass supply results in some assumptions that so not fit very well in the current study region. For example, the estimates from BTS only considers only timberland which can grow 0.6 cubic meters per acre per year and are relatively conservative relative to the actual yield in east Texas. Therefore, it is more appropriate to apply the survey data from TFS in this study.

Table 22 below listed all the woody residue in the study region.

Note that not all the biomass on the ground is assumed to be useful as feedstock for a biorefinery. Gan et al.(2013) indicated that only the forest residues close to a road should be considered accessible when conducting analysis. Additionally, part of the residue needs to be left on the ground to reduce erosion. Moreover, some of the woody biomass could be used for other purposes. Based on Gan et al.(2013), the available woody biomass supply for the biorefinery can be expressed as in Equation below.

$$S = \theta\lambda(A - M)$$

[12] Including softwood and hardwood

where θ is the accessibility rate, λ is biomass recovery rate, A is the total available biomass and M is the biomass consumed from other use. The current study assumed only the forest within a half kilometer distance was accessible and that made 75% of the forest area within the study region available. Within the accessible forest, we assume 85% of the woody biomass is recoverable, and the rest left to prevent erosion(Gan et al. 2013). We also assume that there is no other demand for the woody biomass was assumed with all the woody biomass recovered becoming feedstock for the biorefinery.

Table 22 Estimated Woody Residues in The Study Region

County	Logging Residues		Thinning Residues		Total
(1000 Mg)	Softwood	Hardwood	Softwood	Hardwood	
Anderson	18.4	11.5	32.4	62.9	125
Angelina	45.3	19.4	25.7	51.5	142
Cherokee	32.2	26.5	30	59.7	148
Hardin	29.4	24.8	35.9	69.2	159
Houston	28.2	9.3	29.1	56.4	123
Jasper	48.1	19.8	39.4	77.8	185
Leon	3.6	2.2	20	38.3	64.1
Liberty	21.2	32.4	35.8	64.8	154
Madison	0	0.3	9.7	18.7	28.7
Montgomery	18.2	8.3	34.7	68	129
Nacogdoches	48.5	22.1	33.4	66.6	171
Newton	61.4	17.4	40.6	77.7	197
Panola	30	17.1	30.1	58.8	136
Polk	91.4	17.4	42.3	83.6	235
Rusk	23	14.7	27.1	52.6	117
Sabine	33.3	13.8	16.4	31.3	94.8
San Augustine	43.9	22.1	15.3	30.7	112
San Jacinto	24.1	7.7	24.7	48.6	105
Shelby	31.3	11	21.3	41	105
Trinity	36.1	4.7	19.3	36.8	96.9
Tyler	64.4	28.9	41	77.9	212
Walker	17.5	3.7	28.4	53.7	103
Total	749.5	335.1	632.6	1226.6	2944

Source: (Staples et al. 2008)

The woody biomass data that have been discussed so far are those at the county level scale. To expand our analysis to a finer scale, a method was developed to allocate the county level woody biomass to each hexagon was applied. The basic idea behind this allocation is considers the relative ratios of forest land at the county level to that at the within county hexagon level. Specifically, NASS CDL for the study region (USDA 2018) which cover cropland use, fallow/idle cropland, forest, shrubland and barren. The forest classification was overlapped with the hexagon grid and the county boundary to calculate the number of forest pixels falling within each hexagon and each county. Given the grid size of CDL is 30 m by 30 m or 900 square meters, we can obtain the area of forest in each hexagon/county by multiplying the number of forest pixels by the 900 square meter pixel size. For example, if a hexagon contained three forest pixels then the forest area falling within this hexagon is 2,700 square meters. Once the forest area of each hexagon/county was calculated, the available woody biomass in each hexagon was derived by multiplying figuring the ratio of forest biomass yield to the number of forest pixels in the hexagon relative to the forest pixels in the county then allocating that share of the county yield to that pixel. For example, suppose a hexagon had 2,700 square meters of forest and the county 27,000, then that pixel would be assigned 10% of the county level yield.

For the switchgrass, we can assume the eligible land in the hexagon is the area of pixels in pasture. Switchgrass was assumed to be potentially grown on pasture land and the yield of switchgrass used in the study was 4.05 Mg per acre or 10 Mg per ha based on the assumed yields in FASOM (McCarl et al. 2018) that ultimately arose in the EPA RFS Analysis (Beach and McCarl, 2010).

Procurement Cost of Biomass

Given that woody biomass can be left on site and picked up year-round, no harvesting window was imposed. Additionally, due to the perennial nature of trees and the fact you can measure them before harvest the yield uncertainty was set to zero. In this study, the procurement cost of logging residue, $30/ Mg, was used based on Gan et al.(2006) and Gan and Smith(2012). According to their studies, a system the logging residue procurement system consisted of a feller-buncher/grapple to skid whole trees to a landing, flail processing at the landing, and a tub-grinder for residue comminution was applied. For removal cost, this study applied a $50/Mg cost thinning residue removal cost as estimated by Drews et al.(2001) which involves use of a harvester, forwarder, and chipper.

Unlike woody biomass that can be picked up at any time, collecting switchgrass involves contracting the land priori, harvesting it during a limited window and agreeing to buy all that is produced. Particularly, supply chain planner has to determine the amount of land contracted growing switchgrass before the knowing its yield information. Specifically, we assumed a fixed, volume independent per acre cost and then a per ton removed cost would be used in the contracting arrangements for switchgrass. The per hectare cost of energy switchgrass, following Griffith et al. (2010), is composed of the amortized cost of establishing and maintaining switchgrass. Specifically, $576 /ha cost was used to establish and maintain switchgrass, and, thus, $58.25/Mg cost was applied in the study considering the yield for switchgrass was 9.9 Mg/ha.

The harvesting and collection method and associated costs (i.e. the per Mg cost) used were based on DOE uniform-format feedstock supply system (Hess et al. 2009). To harvest switchgrass, a self-propelled windrower with a disc header is assumed to be used to cut the switchgrass. The cut and conditioned switchgrass is then deposited on the field forming a windrow. Then later, a square baler and self-propelled stacker are used to bale and move switchgrass. Note that the conditioning process which crushes the stem of switchgrass is used to speed up drying and reduce dry matter loss.

Table 23 lists the equipment and estimated costs of harvest and collection operations

Table 23 Equipment and Cost Estimates for Switchgrass

Logistics processes	Grain Harvest Condition & Windrow	Baling	Collect& moving biomass	Dry Matter Loss	Total Costs
Equipment	Self-propelled windrower with disc header	275 hp tractor and large square baler	Self-propelled stacker		
Bulk DM Density	1.14 Mg/300 windrow-meter	0.58Mg/bale			
Cost($/DM Mg)	3.31±0.78	10.77±1.06	1.87±0.308	0.48±0.231	16.44±1.59

Source: Hess et al.(2009)

Storage Cost

Most harvested biomass need be preserved to avoid deterioration and fire danger. Suppose the large square bales are stacked and stored in a hoop barn structure, each barn hoop is 22m wide by 10m high and 36m long (ISU 2017). Figure 5 shows the setup of an indoor storage facility assumed in the present study. Based on the study by ISU (2017), each hoop barn contains two stacks, and each stack is assumed to be placed in a 10m×10m×36m formation (i.e. 65'×30'×115') with 4 bales wide with long-side of the bale, 8 bales height with the short side of the bale and 30 bales long with the short side of the bale. Given the weight of each large bale is around 0.52 Mg, each hoop barn can hold around 1000Mg of biomass[13]. Stacks within a hoop barn are separated with 2 meters distance and hoop barns are assumed to be placed 15 meters away to keep the fire from spreading to other stack and to ensure the access for fire-fighting equipment (PSU 2016). According to Darr and Shah (2012), the consequent deterioration rate of applying hoop barn for storing biomass is around 3%.

In this study, each facility is assumed with 100,000 Mg capacity which is equivalent to hold 100 hoop barns of feedstock at any one time. This study further assumed that the hoop barns

[13] Given the mess of each bale is 0.52/ Mg, the total mess of each stack can be calculated as 4*8*30*0.52= 499.2 Mg. therefore the mess contained in a hoop barn is around 1000Mg

of biomasses are placed with a 10 by 10 formation in the storage facility with a setback distance 18 meters between each barn (Darr and Shah 2012). Thus, a land is with dimensions of 392 by 532 meter would be needed. Based on a study by Darr and Shah(2012), the building cost of a hoop barn was $120 per square meter and the consequent fixed cost of building the hoop barn of this size is $27,377,280. In addition, suppose the storage facility is located on the pasture land and the land rent for pasture land is $18.1/ha, the cost for rent per year is $318.

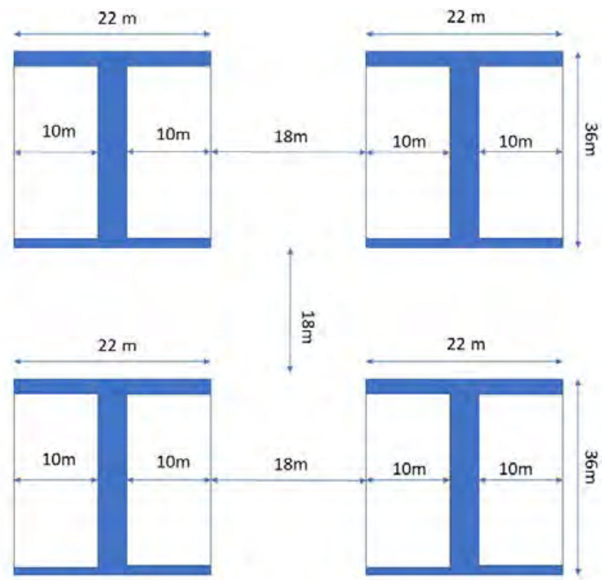


Figure 26 formation of the indoor storage

There is also a variable cost of moving bales in and out. This includes the costs of stacking, and storage. The storage equipment for stacking both all the non-pelleted feedstocks is identical. A Telehandler is used to pick up large square bales from the truck and stack them in the formation mentioned above at a rate of 80 bales per hour. Table 4 below listed the variable bale storage cost.

Table 24 Storage Cost of Switchgrass

Logistics processes	Stacking	Storage	Dry matter loss	Total variable costs
Equipment	Loader (Telehandler)	Land rent & stack maintenance		
Cost(Switchgrass)($/DM Mg)	0.904±0.132	0.11±0.01	1.17±0.35	2.184

Source: Hess et al.(2009)

Size Reduction Option(Pelleting)

The current study also considered the option to densify the biomass to reduce the transportation cost and deterioration. Following Hoque et al.(2006) and Mani et al.(2006), this study assumed that a pellet plant could be built at the same location of storage and use the stored biomass to produce pellets. Pelleting usually consists of three stages: drying, size reduction and densification. Depending on the type of biomass pelleted, additional processes and chemical materials may be needed to ensure the quality of pellet. The pellet process begins with size reduction. Specifically, a telehandler removes the square bales from the stack and loads them on a conveyer which feeds the bale into the grinder. The ground biomass is then sent to a rotating drum dryer by conveyer to reduce moisture content. After drying, the biomass passes through a hammer mill which further reduces the biomass to finer particles and the resultant biomass is then sent to the pressing mill to form the pellets. Finally, the cooled and screened pellets are moved by conveyer to either trailer and transported to biorefinery or to a storage bin for later use.

In this study, a pellet plant was assumed to be capable of producing pellets at the rate of 13.4 Mg/hr. with the annual production being 100,000 Mg. The capital cost of the plant was estimated at $3,278,954 (Hoque et al. 2006) and each plant will operate 24 hours a day for 310 days a year. During the process 5% of the biomass was assumed to be lost. The variable costs of pellet production as estimated in previous studies included the raw biomass cost, operation and maintenance costs for each processing stage, personnel cost and land rent. The biomass cost was dropped from the operating cost in this study as it is covered elsewhere in the model and the adjusted estimated operating cost of producing pellets was $21.42/Mg.

Pellet storage was also considered. The assumed pellet storage processes are moving the pellet to storage bin along with labor cost. The resultant variable cost and the operating cost was $2.51 per Mg. Table 5 and Table 6 list the capital cost of the equipment for the pellet production plant and the operating cost of the pellet production.

Table 25 Capital Cost of a Pellet Plant

Item	Purchase cost ($)	Installation cost ($)	Annuity
Solid fuel burner	184,545	92,272	37,611
Rotary drum dryer	566,813	340,088	93,377
Drying fan	49,766	19,906	9,466
Multiclone	49,766	19,906	9,466
Hammer mill	95,881	38,352	18,238
Pellet cooler	51,050	38,288	9,198
Screen shaker	38,352	23,011	8,337
Packaging unit	138,380	30,863	22,994
Storage bin	38,352	23,011	5,350
Misc. equipment	170,112	68,045	32,358
Front end loader	200,000		27,174
Fork lift	164,000		22,282
building	72,051		6,282
Total	2,329,829	949,125	

Source: Hoque et al. 2006

Table 26 Variable Cost of Producing Pellet

Description	Annual cost($/year)	Unit cost($/Mg)
Producing pellet		
Drying	657,090	6.54
Hammer mill	27,531	0.27
Pellet mill	63,135	0.63
Pellet cooler	9,841	0.1
Screening	2,531	0.03
Miscellaneous equipment	16,475	0.16
Personnel cost	617,000	6.17
Maintenance and land rent	2,401	0.02
Operating cost of pelleting		21.42
Storing pellet		
Packaging	64,210	0.64
Storing	1,000	0.01
Personnel cost	186,880	1.86
Total cost of storing		2.51

Source: Hoque et al. 2006

Biomass Transportation and Handling

The transportation and handling operations involved a fixed cost for loading and unloading plus a variable cost per unit of distance. Given the transportation distances in this study were relatively short, usage of truck was assumed for the base case. Namely we assume a 2.4-meter-wide by 16-meter-long 3-axle flatbed trailer would be used to move the large square bales which means a truck load is 26 large square bales that needed to be loaded and moved. Per unit loading cost were assumed to be $5.41 per Mg under a 25% moisture content assumption (Hess et al. 2009). The variable cost was a linear multiple of distance following Mahmudi and Flynn (2006). Based on their study, the estimated variable cost of truck transportation for bale was $0.148/Mg per kilometer moved.

As for transporting and handling wood, this study assumed the wood was shipped and that the transportation and handling cost was similar to the cost of moving grain. Based on the study by Ortiz et al.(2011), the total cost for chipping, loading using an auger and unloading by opening gates and dumping was $2.74 per Mg. For the variable cost of transporting wood chips by truck, we used the cost of, $0.07/Mg-Km as estimated by Ortiz et al.(2011).

Preprocessing and Handling at Biorefinery

Two conversion methods are commonly used to process lignocellulosic biomass into biofuel: biochemical and thermochemical processes. Based on the study of Mu et al.(2010), the ethanol yield and cost of biochemical conversion is expected to be lower than that of thermochemical conversion in the near term. Thus, this study assumed that all the feedstocks were converted into ethanol through a biochemical process. In turn the capacity of the biorefinery was assumed to be 261.95 million liters per year based on 24 hours a day operation for 310 days a year. The assumed capital cost of that type of plant was $220.1 million (Aden et al. 2002). The variable cost used in the study contained two parts: operating cost and the cost of purchasing enzymes. Based on the estimates of Huang et al. (2010), the operating cost was set at $0.3 per gallon and the cost of enzymes at $0.26 per gallon. Table 27 lists the assumed capital cost components for a biochemical biorefinery.

Table 27 Capital Cost Components for Building a Biorefinery

Item	Cost($)
Pretreatment	22,700,000
Conditioning	9,400,000
Fermentation	11,200,000
Distillation and solid recovery	26,100,000
Wastewater treatment	3,700,000
Storage	2,400,000
Boiler	46,000,000
Utilities	5,500,000
Total installed cost	127,000,000
Misc. costs	93,100,000
Total cost	220,100,000

Source: Aden and Foust 2009

The conversion rates for logging residue, thinning residue and switchgrass through bioconversion process were assumed to be 59.8 gal/Mg, 74.76 gal/Mg, and 71.94 gal/Mg, correspondingly(Foust et al. 2009). The logging residue yields were lower since we assume they would contain limbs, branches and bark and that content would reduce the ethanol yield by 20% due to their lower enzymatic hydrolyzability (Frankó, Galbe and Wallberg 2015 and BT16).

Yield Uncertainty Considerations

Incorporation of yield uncertainty requires formation of an empirical probability distribution for the feedstock yields. This was only done for switchgrass since the woody biomass in the study region could be estimated before removal plus more could be removed if supplies were short. The Switchgrass yield probability distribution was developed by using Texas level historical records on hay[14] yield from 1950 to 2016. These historical data were first detrended to obtain the residual deviation of the crop yield in each year. Then the residuals for

[14] Given that there is no record of switchgrass production during this period, hay yield is used as approximation in this study

each year were divided by the associated expected yield created by evaluating the regression used in the detrending. This created a set of proportional yield deviations relative to mean yield centered on one. In turn these were arranged from low to high and then clustered into ten different groups. The number of records falling into the group divided by the total number of records was used as the estimate of the probability of each state of nature and the median proportion in that interval was used as the relative amount of yield for the states of nature. The deviation results are in Table 28.

Table 28 Switchgrass Yield Level's State of Nature

	deviation	probability
state of nature1	-0.55	0.01
state of nature2	-0.45	0.02
state of nature3	-0.34	0.05
state of nature4	-0.24	0.10
state of nature5	-0.14	0.17
state of nature6	-0.04	0.20
state of nature7	0.06	0.20
state of nature8	0.17	0.14
state of nature9	0.27	0.08
state of nature10	0.37	0.03

Other Assumptions

The cost estimates include total purchase and ownership costs for all needed equipment. To incorporate those into our annual model we needed an estimate of the amortized cost of holding the items for one year. This was done by amortizing the cost and in doing so a 20-year life and a 7% discount rate were used and plugged into equation below:

$$\text{Amortized } Annual\ cost = \frac{(initial\ investiment)}{(1-(1+r)^{-n})}$$

We also needed an assumption on the number of days biomass can be collected. Based on the study of Soloranzo-Campos (1990) the number of good working days in each month in the study region15 is listed in Table 29.

Table 29 Probability of Working Days

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Probability of working day	0.74	0.68	0.71	0.63	0.65	0.6	0.61	0.65	0.67	0.71	0.73	0.74
Actual days available	22.94	19.04	22.01	18.9	20.15	18	18.91	20.15	20.1	22.01	21.9	22.94

[15] According to Soloranzo-Campos, east Texas was located in the Area 8 in his study. Thus, the probability of working days in Area 8 was applied to reflect the impacts of weather on operation days

Table 30 Key Parameters Used in The East Texas Case Study

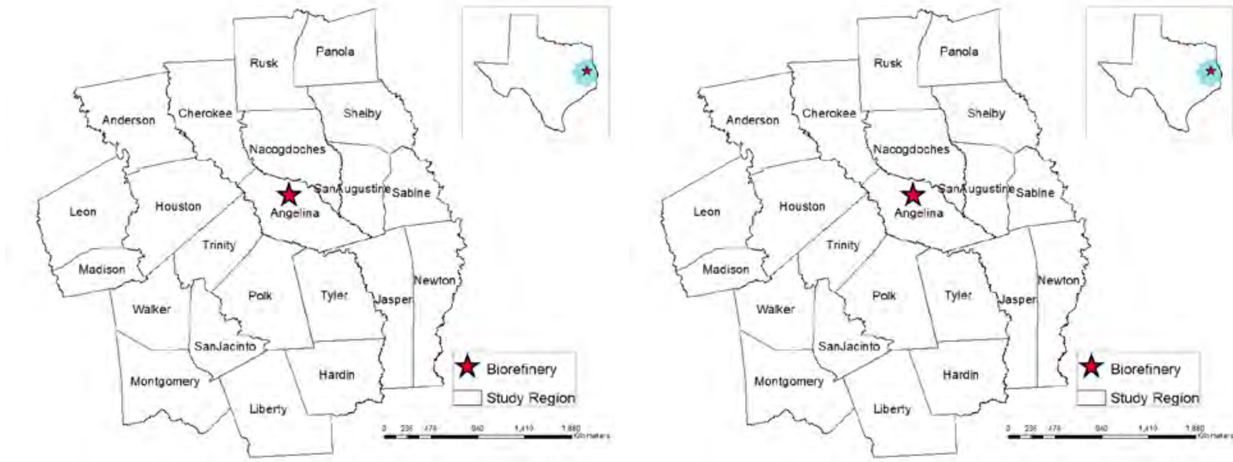
Input parameter	Original Value	Adjusted Value	Unit	Source
Biorefinery Capacity	21735		1000 L/ mo.	Assumed
Storage Capacity	100		1000 Mg/mo.	Assumed
Pelleting Plant Capacity	100		1000 Mg /yr.	(Hoque et al. 2006)
Fixed Costs of Biorefinery	190,800(2005)	239,061	1000$	(Aden and Foust 2009)
Fixed Costs of Storage	27,377	27,377	1000$	(ISU 2017, Duffy 2007)
Fixed Costs of Pelleting Plant	3,278(2006)	4,011	1000$	(Hoque et al. 2006)
Operating Cost of biorefinery	0.13(2005)	0.165	$/L	(Huang et al. 2010)
Operating Cost of Storage				
Switchgrass	2.184(2009)	2.75	$/DM Mg	(Hess et al. 2009)
Pellet	2.51(2006)	3.07	$/DM Mg	(Hoque et al. 2006)
Operating Cost of pelleting	21.42(2006)	26.21	$/DM Mg	(Hoque et al. 2006)
Minimum ethanol production	15876		1000 L/ mo.	Assumed
Loading/unloading Cost				
Large squared Bale	5.41(2009)	6.19	$/DM Mg	(Hess et al. 2009)
Pellet	2.74(2011)	2.99	$/DM Mg	(Ortiz et al. 2011)
Variable transportation cost				
Large squared Bale	0.148(2006)	0.18	$/DM Mg-Km	(Mahmudi and Flynn 2006)
Pellet	0.07(2010)	0.078	$/DM Mg-Km	(Ortiz et al. 2011)
Cost of purchasing woody biomass				
Logging residue	30(2012)	32.09	$/DM Mg	
Thinning Residue	50(2012)	53.49	$/DM Mg	(Gan and Smith 2012)
Contract & establishment cost				
Switchgrass	323.21(2014)	358.66	$/Ha	(Wang et al. 2014)
Harvesting Cost				
Switchgrass	16.44(2009)	18.82	$/DM Mg	(Hess et al. 2009)
Yield				
Switchgrass	10.02		DM Mg/Ha	FASOM
Interest Rate	0.07			
Deterioration rate	0.03			
Water content	0.25			
Project life span	20		year	

Analysis Results

This section presented the results of the analyses conducted in this study. The first analysis involves comparison of the results from the deterministic and the stochastic models in an effort to examine the impact of uncertainty on the supply chain design. Sensitivity analysis will also be carried out on the value of using multiple versus types of biomass, the effect of different conversion rates, the effect of alternative pellet prices and the effect of increases in the accessible forest areas. Moreover, this study also contribution to supply chain analysis by incorporating high resolution spatial data into the proposed model. Although the potential of supply chain analysis at a fine spatial scale has been increasingly recognized, studies has remained very limited and has not fully exploited this potential. Further improving the capacity to draw spatial implications of supply chain analysis at high spatial resolution is essential. In fact, one of the challenge in the previous study is to precisely reflect the transportation cost of biomass feedstock since cellulosic biomass usually distributes widely. With breakthrough in spatial analysis, substantial high resolution geographical data and techniques can be employed in the analysis and help us better understand how biomass feedstocks distribution affect the optimal facility placement and the logistic decisions. Thus, an experiment of geographic scale was conducted to help us understand the impact of spatial data scale on the cellulosic biofuel supply chain design. The resultant model was executed on General Algebra Modeling System (GAMS) software using CPLEX as solver with a tolerance gap between the best theoretical integer solution and the best objective value found is set at 0.1%.

Comparison of Deterministic Model versus Stochastic Model Results

Figure 27 depicts the optimal locations of facilities in the solutions for the deterministic and stochastic model. As shown in the figure, the biorefinery was optimally placed at the center of Angelina county in both models. No intermediate storage or pelleting plants were selected in either case, only a small amount of switchgrass was stored at the biorefinery for emergency use and the rest of them was consumed within the harvest window. Outside the harvest window, woody materials were sent directly from supply region to biorefinery. In other words, the presence of woody materials year-round makes using stored switchgrass unattractive.



(a)Deterministic model (b)Stochastic model

Figure 27 optimal locations in deterministic and stochastic model

The main difference between the objective function values of the two models involved the cost of contracting land, purchasing thinning residue and the cost of dumping additional switchgrass. All these costs were higher under yield uncertainty. Table 31 below summarizes the costs of stochastic model vs. the deterministic model. For the deterministic model, fixed cost of biorefinery, cost of collecting biomass, producing ethanol and transportation accounted for 23.1%, 31.1%, 32.2% and 12.8% of the objective function value, respectively. Besides, 0.6% of total cost came from emergency storage and land contracted for switchgrass. In the stochastic model, 22.8%, 31.1%, 31.9% and 12.7 shares of the objective arise from fixed biorefinery cost, the cost of collecting biomass, conversion cost, and transportation cost. The cost of contracting land, dumping biomass, and emergency storage accounted for the rest of 1.2% of total cost. The expected cost of the stochastic model was 2.76% higher than the total cost of the deterministic model.

Table 31 Expected Costs of Each Component in Deterministic and Stochastic Model

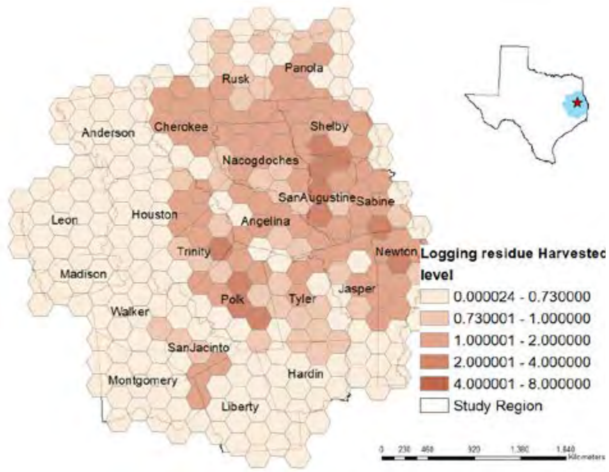
Item	Determinisitc	Stochastic	Unit
Expected cost of supply chain	97,650.56	98,656.54	$1,000
Annualized cost of biorefinery	22,565.67	22,565.67	$1,000
Annualized cost of storage	0.00	0.00	$1,000
Annualized cost of pellet plant	0.00	0.00	$1,000
Cost of contracting land	183.79	331.58	$1,000
Expected harvesting cost	30,407.66	30,767.73	$1,000
Expected dumping cost	0.00	481.81	$1,000
Expected storage cost	453.75	453.75	$1,000
Expected pelleting cost	0	0.00	$1,000
Expected conversion cost	31,500.00	31,500.00	$1,000
Expected transporting cost	12,539.69	12,556.00	$1,000
Profit form exporting pellet	0.00	0.00	$1,000
Average cost of ethanol	0.51	0.52	$/L

Table 32 below summarizes the key decisions in deterministic and stochastic models. Note that in deterministic model, all the decisions were made as if the switchgrass yield was always its average value. In the stochastic model, the contracted land was determined in advance before the uncertainty was resolved while different harvest, transport and usage decisions were made depending on the realized yield state of nature. Consequently, there were 10 sets of these decisions. Thus, we had to summarize the decisions and we chose to present the two extremes and the average. In the following tables, the first column under the stochastic model represents the decisions that resulted when the worst yield state of nature was realized the second column depicts those under the best yield state of nature and the third column shows the probability weighted average level of decisions across the states of nature.

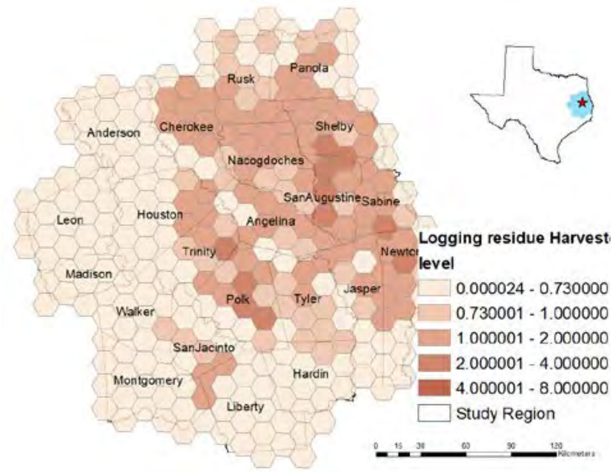
Table 32 Summary of the Key Decisions from Deterministic and Stochastic Model

Item	Determinisitc	Stochastic			Units
First Stage decision		Worst Yield	Best Yield	Average	
Total land contracted for biomass	17.47	31.52	31.52	31.52	1000Ha
Switchgrass	17.47	31.52	31.52	31.52	1000Ha
Second stage decision					
Total biomass harvested	722.69	721.51	722.51	722.50	1000Mg
Switchgrass	175.14	142.84	175.15	174.82	1000Mg
Logging residue	209.56	209.71	208.60	208.61	1000Mg
Thinning residue	337.98	368.96	338.76	339.07	1000Mg
Total biomass stored	0.00	0.00	0.00	0.00	1000Mg
Switchgrass	0.00	0.00	0.00	0.00	1000Mg
Logging residue	0.00	0.00	0.00	0.00	1000Mg
Thinning residue	0.00	0.00	0.00	0.00	1000Mg
Total biomass dumped	0.00	0.00	257.47	135.12	1000Mg
Switchgrass	0.00	0.00	257.47	135.12	1000Mg
Average biomass traveled distance	62.26	69.00	61.46	63.23	Km
Switchgrass	17.43	23.67	14.13	18.34	Km
Logging residue	74.63	74.71	74.62	74.66	Km
Thinning residue	77.82	83.31	77.81	77.86	Km
Total biomass processed	722.69	721.51	722.51	722.50	1000Mg
Switchgrass	175.14	142.84	175.15	174.82	1000Mg
Logging residue	209.56	209.71	208.60	208.61	1000Mg
Thinning residue	337.98	368.96	338.76	339.07	1000Mg

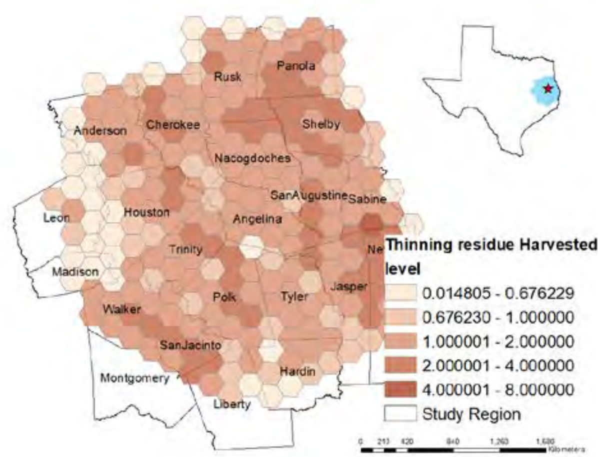
Figure 28 depicts the land harvested for each biomass at optimal for deterministic and stochastic models.



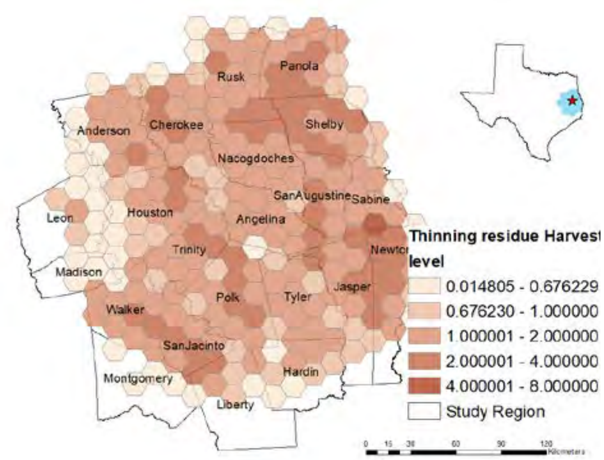
(a) Source for logging residue in deterministic model



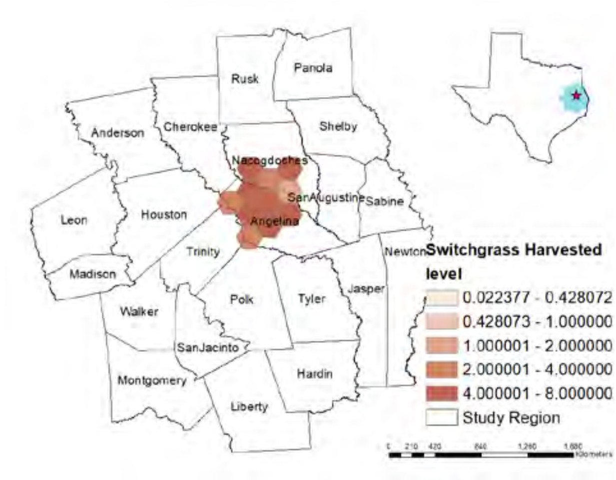
(b) Source for logging residue in stochastic model



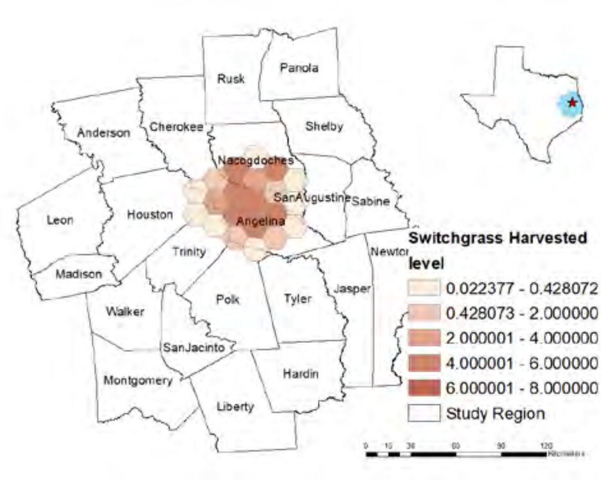
(c) Source for thinning residue in deterministic model



(d) Source for thinning residue in stochastic model



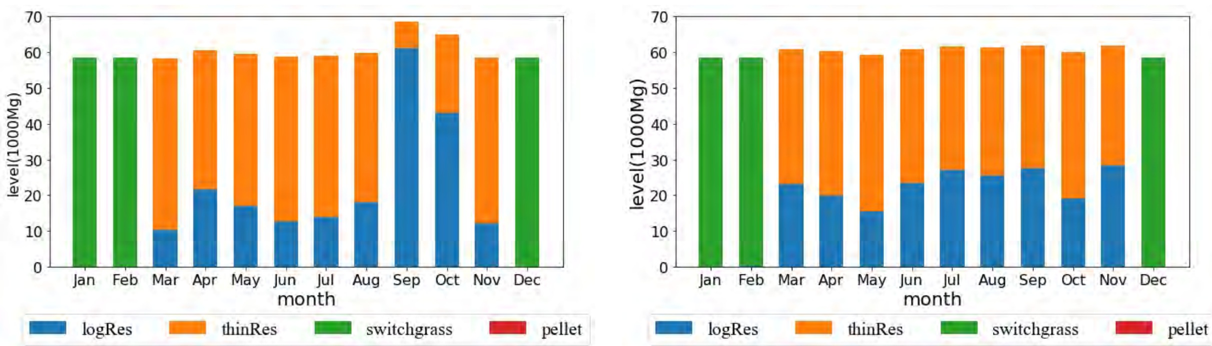
(e) Source for switchgrass in deterministic model



(f) Source for switchgrass in stochastic model

Figure 28 Source of each biomass in deterministic and stochastic models

Based on Table 32 and Figure 28, the amount and supply region of logging residue were basically identical in both the deterministic and stochastic models and the supply area used covered most of the study region. The harvesting level of logging residue near the biorefinery was the highest and decreased as the hexagons became further away from the biorefinery due to the increasing shipping cost. Moreover, we see only a 0.3% increase in the use of thinning residue when the yield of switchgrass was uncertain. The supply region of thinning residue in the stochastic model was basically the same as its counterpart in the deterministic model except for slight enlargement in the southwest corner. As for the switchgrass, the area of switchgrass harvested almost doubled although the expected harvesting level decreased slightly in the stochastic model. Namely under uncertain yields, 80% more land was contracted in the stochastic model than in the deterministic model to ensure sufficient available supply when the worst state of nature realized. The different harvest level across states of nature also affected the average distance per Mg biomass traveled. When the worst scenario resolved, the average distance a Mg feedstock traveled was 69 km. When the best yield condition of switchgrass occurred, the distance biomass traveled dropped to 61.5 Km since closer switchgrass could be relied on under the good states of nature. However, the more distant switchgrass needed to be removed and the model chose to dump it rather than store or pelletize.



(a)Deterministic model (b)Stochastic model

Figure 29 Monthly biomass process level of deterministic and stochastic model

Figure 29 depicts the monthly biomass processed level under the deterministic and yield uncertainty cases. In both cases, switchgrass was used as the major source of feedstock during its harvest window (in January, February and December) while ae mix of logging and thinning residue were used as the feedstock in other months. The exact source of the woody biomass in both cases depended on their spatial distribution and the relative ethanol yields. On the one hand, biomass next to the biorefinery was first used up to the extent which the cost of obtaining this biomass plus the shipping cost divided by the conversion rate was equal to that for the second cheapest biomass source. By the same token, once the delivery cost of the second cheapest biomass divided by the conversion rate became higher than that for its next cheapest biomass, model then switched to use that biomass, and kept mixing until the demand of biorefinery was satisfied. For example, in the deterministic case above, thinning residue nearby the biorefinery which has the higher conversion rate was first used to satisfy the demand of biorefinery when switchgrass was not available. As the cost of using thinning residue increased with the distance between supply region and the biorefinery, some logging residue near the biorefinery was used. However, the logging residue was used up to the point where its price plus the moving cost divided by its lower conversion rate was equal to the delivery cost divided by the conversion rate of the farther away thinning residue. Based on this idea, the model select different mix of logging and thinning residue until the minimum requirement was satisfied. Also, note that the service area for thinning was larger than that for logging residue which reflects the difference in conversion rates.

Comparison of Multiple and Single Source of Feedstock Scenarios for the Results

This study following discussed the impacts of storage on the biofuel supply chain. Due to the relatively low energy density of biomass, it takes a large volume to produce usable quantities of energy. Thus, storage is commonly required in a supply chain system. A properly developed storage plan can help balance issues of feedstock harvest timing, random supply shortages, and feedstocks deterioration and loss. As shown in the high plains chapter, storage played a critical role to ensure sufficient supply of feedstock to the biorefinery when multiple sources of biomass with different harvesting windows were presented. Yet, unlike the high plains region where energy crops and their residues were the major source of feedstock, readily available woody biomass throughout the plan horizon makes east Texas an ideal place to have a logistic system in which biomass was delivered to the biorefinery just in time for use16. The current study examined the impacts if only one feedstock is allowed comparing the logistic decisions of multiple sources and single source scenarios. In the multi-feedstock scenario, biorefinery obtained its feedstock from multiple sources including woody biomass and switchgrass and thus no storage was needed. While when only switchgrass was available, storage played a key role

[16] So called “Just-in-time” delivery system

due to the seasonality of switchgrass harvest. We first present results on the optimal locations and then discuss the cost components and the optimal logistic decisions.

The storage and the optimal locations of biorefinery, storage depots and pellet plants for multiple and single source scenario were depicted in Figure 30.

(a)All biomass scenario (b)Only woody materials available (c)Only switchgrass available

Figure 30 The optimal locations of facilities for single and multiple feedstock cases

Compared to the single source, switchgrass only scenario, when multiple feedstock or woody material by itself are available, it makes using switchgrass storage unnecessary. Thus, the multi feedstock scenario exhibits a significant saving in fixed cost, and storage costs as well as in transportation cost. When woody biomass was available (with or without switchgrass), the supply chain setup was basically the same except for the location of the biorefinery. with no storage or pellet plants employed.

In terms of the biorefinery location, the optimal location when no switchgrass could be used moved 10 km to the southeast of the location in the multi feedstock case. This occurred because more thinning residue was distributed to the southeast, so the plant was moved to a closer location.

The optimal biorefinery location in the switchgrass only scenario was located at the northeast of Angelina county closer to more pasture land. additionally, six storage depots were selected to store the switchgrass for later use in the non-harvesting periods. Three of the six selected depots were placed in Cherokee county and the rest of the depots along with a pellet plant were placed in Panola county. The pellet plant in the Panola county was mainly used to reduce the water and volume of harvested switchgrass and avoid the costs from both deterioration and storage cost. Noted that in the base scenario, the pelletizing option does not help reduce the amount of biomass being dumped. Given that pelletizing is not allowed to be exported and pellet manufacture cost is relatively high, the additional biomass will be dumped rather than turned into pellets. However, if pellets can be exported, the storage/pellet depots could provide additional options for handling excess production and geographically stranded feedstocks that are not within an 80-km biorefinery radius.

Table 33 below summarizes the cost of each component across these scenarios. Based on the results, the expected cost of the proposed supply chain when only switchgrass is available was 38% higher than the case when multiple feedstocks were available while the woody biomass only scenario had a cost that was 3% higher than the multiple feedstock case. The higher cost when only switchgrass available was resulted from the more lands contracted for switchgrass, the cost of constructing and operating new storage depots and pellet plants. On the other hand, the higher expected cost under the woody biomass only scenario was because of the increasing service area for woody biomass and its associated transportation cost. Specifically, the cost of obtaining woody biomass and transporting them to the biorefinery increased by 7.7% for thinning residue and 12.6% for logging reside compared to the multi feedstock case.

Table 33 Expected costs of each component multiple and single source models

Item	all feedstocks	Only switchgrass	Only woody	Units
Expected cost of supply chain	98,656.54	134,746.81	101,633.98	$1,000
Annualized cost of biorefinery	22,565.67	22,565.67	22,565.67	$1,000
Annualized cost of storage		21,868.76		$1,000
Annualized cost of pellet plant		378.61		$1,000
Cost of contracting land	331.58	1,776.62		$1,000
Expected harvesting cost	30,767.73	26,454.35	33,150.32	$1,000
Expected dumping cost	481.81	3,204.12		$1,000
Expected storage cost	453.75	8,493.48	280.50	$1,000
Expected pelleting cost		1,162.84		$1,000
Expected conversion cost	31,500.00	31,500.00	31,500.00	$1,000
Expected transporting cost	12,556.00	17,334.23	14,137.49	$1,000
Profit form exporting pellet				$1,000
Average cost of ethanol	0.52	0.71	0.53	$/L

To ensure consistent supply of feedstock over the planning horizon, around nine times as much pasture land was contracted for switchgrass production in the switchgrass only scenario. a main source of this was the almost doubled fixed facility cost due to the need to construct storage depots and pellet plants. Additionally, under switchgrass only the cost of storing increased by 5.6 times with respective to the multi feedstock case while dumping cost increased by to 17.7 times that in the multi feedstock case. A 36.5% higher transportation cost was also observed since additional transportation occurred between supply region and storage as well as the storage and biorefinery. Moreover, comparing the base scenario, the averaged travel distance for switchgrass to the biorefinery increased by two to three times depending on state of nature. Given the cost of transporting baled biomass was higher than that for woody chips due to the high moisture content, the increasing use of switchgrass also contributed to a higher realized transportation cost in the single source scenario.

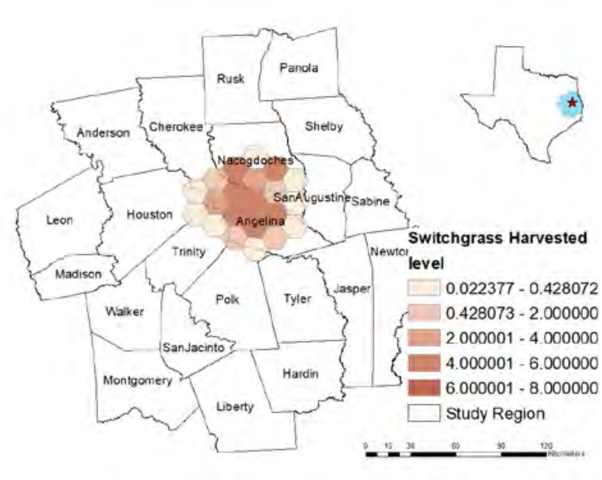
Table 34 Summary of the key decisions from multiple and single source feedstocks models

Item	all feedstocks			only switchgrass			only woody	Units
	Worst Yield	Best Yield	Average	Worst Yield	Best Yield	Average		
First-stage decision								
Total land contracted for biomas	31.52	31.52	31.52	168.88	168.88	168.88	0.00	1000Ha
Switchgrass	31.52	31.52	31.52	168.88	168.88	168.88	0.00	1000Ha
Second-stage decision								
Total biomass harvested	721.51	722.51	722.50	765.33	777.44	777.23	746.03	1000Mg
Switchgrass	142.84	175.15	174.82	765.33	777.44	777.23	0.00	1000Mg
Logging residue	209.71	208.60	208.61	0.00	0.00	0.00	315.99	1000Mg
Thinning residue	368.96	338.76	339.07	0.00	0.00	0.00	430.04	1000Mg
Total biomass stored	0.00	0.00	0.00	1,231.15	2,486.21	2,473.66	0.00	1000Mg
Switchgrass	0.00	0.00	0.00	1,231.15	2,486.21	2,473.66	0.00	1000Mg
Logging residue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Thinning residue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Total biomass dumped	0.00	257.47	135.12	0.00	1,540.52	883.44	0.00	1000Mg
Switchgrass	0.00	257.47	135.12	0.00	1,540.52	883.44	0.00	1000Mg
Average biomass traveled distan	69.00	61.46	0.00	47.33	38.98	0.00	0.00	Km
Switchgrass	23.67	14.13	0.00	47.33	38.98	0.00	0.00	Km
Logging residue	74.71	74.62	0.00	0.00	0	0.00	0.00	Km
Thinning residue	83.31	77.81	0.00	0.00	0	0.00	0.00	Km
Total biomass processed	721.51	722.51	722.50	0.00	0.00	0.00	735.23	1000Mg
Switchgrass	142.84	175.15	174.82	0.00	0.00	0.00	0.00	1000Mg
Logging residue	209.71	208.60	208.61	0.00	0.00	0.00	305.19	1000Mg
Thinning residue	368.96	338.76	339.07	0.00	0.00	0.00	430.04	1000Mg
Pellet Produced	0.00	0.00	0.00	95.00	43.55	44.36	0.00	1000Mg
Pellet Processed	0.00	0.00	0.00	95.00	43.55	44.36	0.00	1000Mg

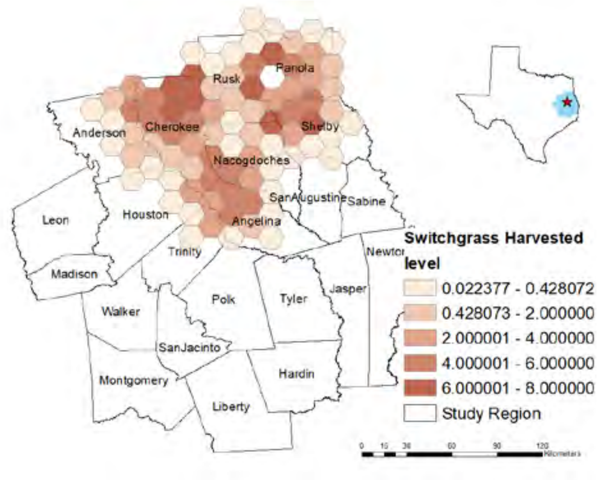
Table 34 lists the optimal decisions when multiple and single sources of feedstock are available and Figure 31 illustrates supply region of switchgrass for the multi feedstock and switchgrass only scenarios. Based on the figure and Table 34, when all sources of feedstock are available, only switchgrass within 40-km radius of the biorefinery was harvested, and the amount of switchgrass collected varied from 0.14 million Mg to 0.17 million Mg depending on the yield states of nature. Also, the amount of woody biomass increased by 0.5% and 8.8% for logging and thinning residues respectively when the worst switchgrass yield happened comparing to the case where best yield was realized. Given that thinning residue can produce more ethanol than logging residue, more thinning residue was used to fill the minimum requirement when the bad yield occurred.

When only switchgrass was available, the area and the amount of switchgrass harvested in the single feedstock scenarios was greater than under the multi feedstock case. Switchgrass within 40-km radius of biorefinery was sent to biorefinery and consumed during the harvesting season for both scenarios. However, switchgrass outside this range was harvested and sent to the closest storage or pellet plant to be used later in the non-harvesting season. 2.47 million Mg of switchgrass was stored and used from March to September and 45,000 Mg of switchgrass pellets were stored from March to November.

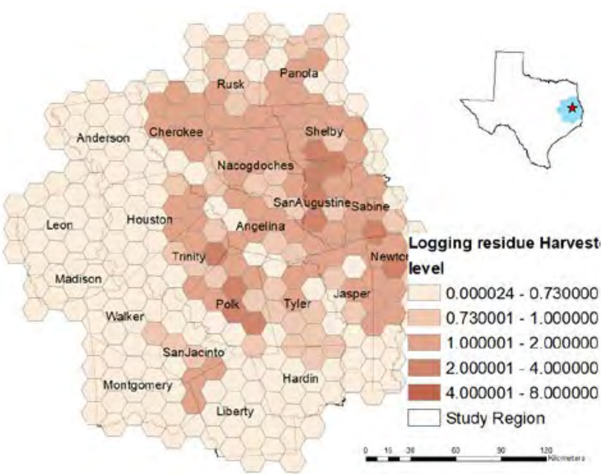
When only woody biomass was available, the use of both woody materials increased although the increase was larger for thinning residue due to its higher ethanol conversion rate. Meanwhile, the collecting region of woody materials collected reduced, and the associated collecting level was higher than in the multi feedstock case. For example, Figure 31(e) to (f) shows the source of thinning residue in the multi feedstock case and woody residue only scenario and the source of thinning residue reduced from 100-km in former to around an 85-km radius in the later. Additionally, the same figures also depict that the collecting level in each hexagon was more intensive in the woody biomass only scenario given that the color was darker and evenly distribution than those in the multi feedstock case. The change of collecting region and level was due to the distribution of woody materials. Since the density of woody biomass in each spatial unit was higher, more woody biomass can be collected from a smaller area incurring lower transportation costs. Therefore, as demand for woody material increased, more intensive collecting activities were observed in the region within 85-km radius of the biorefinery in the woody biomass only scenario comparing to those in the multi feedstock case.



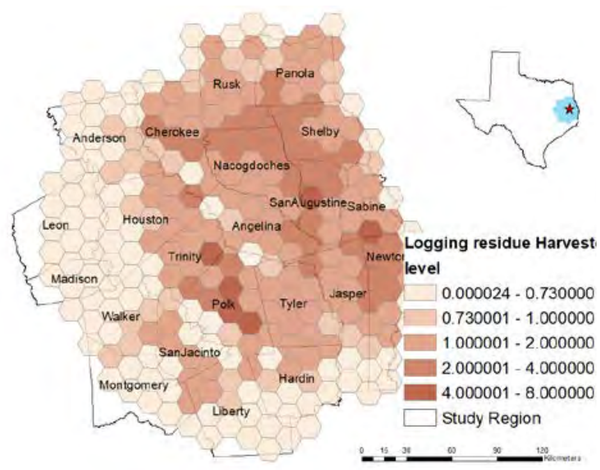
(a) switchgrass harvested in multi-feedstock scenario



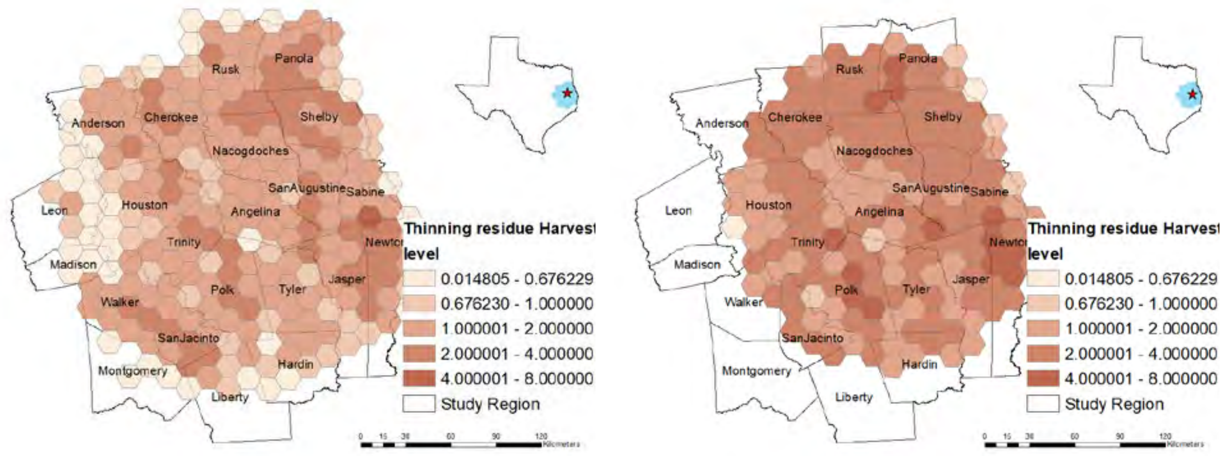
(b) switchgrass harvested in single source scenario



(c)Source for logging residue in the multi-feedstock scenario



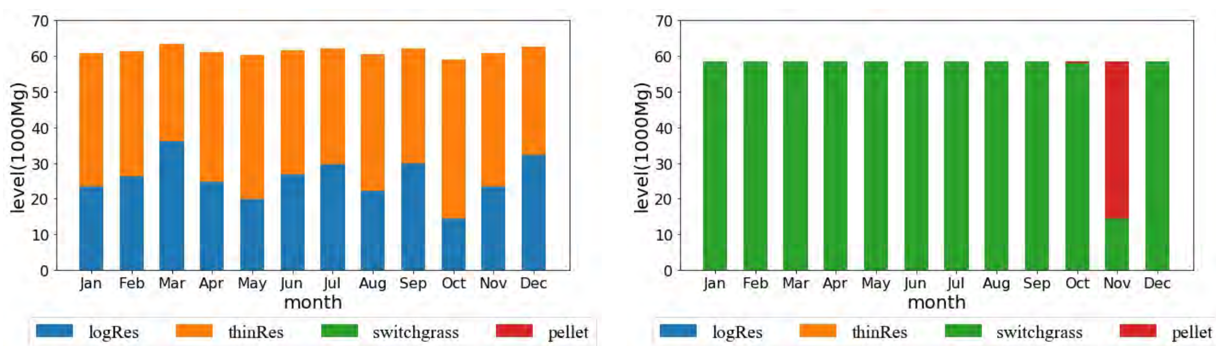
(d)Source for logging residue in the woody biomass only scenario



(e)Source for thinning residue in the multi-feedstock scenario

(f)Source for thinning residue in the woody biomass only scenario

Figure 31 Amount of each biomass harvested in no storage and storage scenario



(a)Only woody material scenario

(b)Only switchgrass scenario

Figure 32 Monthly biomass process level of multiple and single source scenarios

Figure 32 above showed the amount of each biomass process throughout the plan horizon. In the multi feedstock scenario and switchgrass only scenario, switchgrass was converted to ethanol during the December to February harvest season. Outside that harvesting window, if available a mix of logging residue and thinning residue was used. When only switchgrass was available, baled switchgrass was processed into ethanol from April to September while switchgrass pellets were consumed in October and November. Choice between pellets and stored switchgrass reflected assumptions on deterioration, storage, transport and cost of making pellets. This manifested itself in a couple of ways. First the switchover after October was because the marginal cost of keeping baled switchgrass exceeded that of pellets so the plant switched over to pellets. Second, there is an increasing deterioration rate when biomass is stored in the baled form. Furthermore, the cost of moving the pellet is cheaper than baled biomass. Therefore, part of switchgrass was converted into pellets in February, stored from February to September, and then consumed before the beginning of harvesting season. The results show that in both scenarios, the pellet option does not help reduce the amount of biomass being dumped. Given that pellets are not allowed to be exported in this scenario and the pelletizing cost is relatively high, the additional biomass was dumped rather than turned into pellets.

Impacts of Ethanol Conversion Rate Improvements

Sensitivity analyses were conducted to examine the impacts of key parameters on the structure and cost of the supply chain using only the stochastic model. As discussed in the High Plains chapter, a foreseeable improvement on the conversion rate is expected due to the efforts from R&D. Based on the study of Mu et al.(2010), the improvement in conversion with biochemical process is expected to range from 15 to 25% . To simulate the impact of conversion rate improvement, a sensitivity analysis was conducted which examined medium and high improvement (i.e. 15% and 25 % improvement in conversion rate) scenarios.

The optimal locations for facilities and types built under the different conversion rate scenarios was unaffected by the improvement in the biofuel conversion rate. Only one biorefinery is picked which is at the center of Angelina county and no storage or pelleting facilities were constructed. Table 35 summarizes total cost and its components as well as the key logistic decisions under different conversion rate scenarios. For the medium improvement scenario, the fixed cost of building the biorefinery was 24.5% of total cost while the operating costs of obtaining biomass, producing ethanol and transportation accounted respectively for 28.8%, 34.2% and 11.5% of the average cost across the states of nature. As for the high improvement scenario, 25.4%, 27.3%, 35.5% and 10.78% of the expected objective were fixed facility construction cost, the cost of obtaining biomass, conversion cost, and transportation cost. The costs of contracting land, dumping biomass, and emergency storage accounted for the rest of (0.8%) total cost and fell under the increased conversion rate.

Table 35 Expected Costs of Each Component in Different Conversion Rates Scenarios

Item	Base scenario	Medium improvement	High improvement	Units
Expected cost of supply chain	98,656.54	91,854.18	88,527.35	$1,000
Annualized cost of biorefinery	22,565.67	22,565.67	22,565.67	$1,000
Annualized cost of storage	0.00	0.00	0.00	$1,000
Annualized cost of pellet plant	0.00	0.00	0.00	$1,000
Cost of contracting land	331.58	185.91	171.04	$1,000
Expected harvesting cost	30,767.73	26,479.29	24,206.50	$1,000
Expected dumping cost	481.81	87.36	81.10	$1,000
Expected storage cost	453.75	453.75	453.75	$1,000
Expected pelleting cost	0.00	0.00	0.00	$1,000
Expected conversion cost	31,500.00	31,500.00	31,500.00	$1,000
Expected transporting cost	12,556.00	10,582.20	9,549.29	$1,000
Profit form exporting pellet	0.00	0.00	0.00	$1,000
Average cost of ethanol	0.52	0.48	0.46	$/L

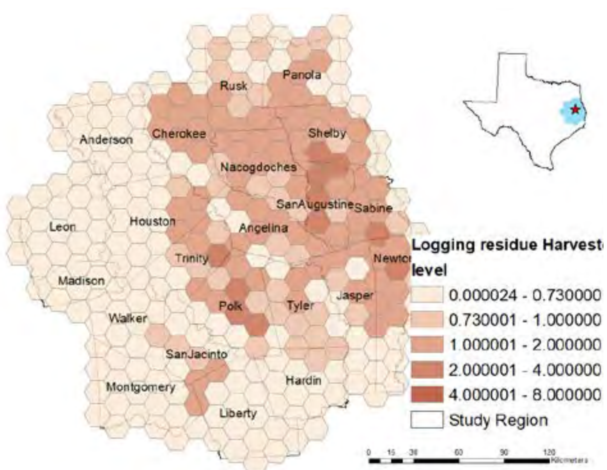
While the optimal biorefinery locations for all three scenarios were identical, the expected total cost was reduced by 6.8% to 10.2% in the medium and high conversion rate improvement scenarios. The reduction came from lower costs of contracting, harvesting, transporting and dumping excess biomass since now less feedstock and growing acreage is needed.

Table 36 below summarizes key decision variables from the solution under the ethanol conversion improvement scenarios. Note that the scenarios all produce a constant amount of ethanol. It is possible that the biorefinery might chose to collect the same level of feedstock as in the base case and produce more ethanol but that is not the scenario run here.

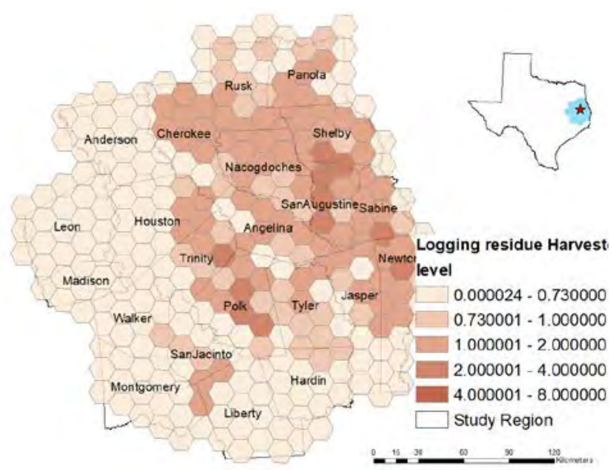
Figure 33 illustrates the supply regions for each biomass under the different conversion rate scenarios. The results indicate that both the amount of biomass harvested, and land area used generally decreased as the conversion rate increased (Table 36). Compared to the base- no improvement scenario, the overall biomass harvested decreased by 12.3% and 18.9% when the conversion rate increased by 15% and 25%. In terms of feedstocks the amount of logging residue utilized reduced by 0.4% and 1.6%, while switchgrass use was reduced by 15.9% and 22.7 % and thinning residue by 17.8 % and 27.7%. The harvested area for logging residue does not change under the conversion rate scenarios. However, both the harvesting region and amount of thinning residue and switchgrass decreased as the conversion rate improved. For the thinning residue, the harvesting region reduced from a 90-km radius to 85- km radius and then 70- km radius of the biorefinery as the conversion rate improved. As for the switchgrass, the harvesting area of switchgrass shrink from a 30-km radius to a 10-km radius when the conversion rate became higher. For each biomass, that closest to the biorefinery was used first.

Table 36 Summary of the Key Decisions of Different Conversion Rates Scenarios

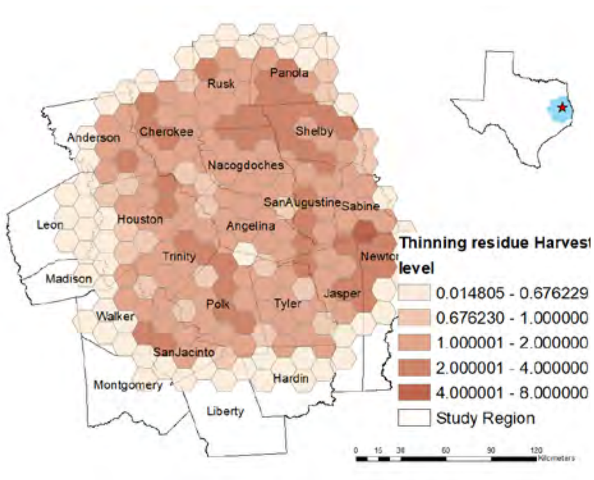
Item	Base scenario			Medium improvement			High improvement			Unit
	Worst yield	Best yield	Average	Worst yield	Best yield	Average	Worst yield	Best yield	Average	
First-stage decision										
Total land contracted for biomass	31.52	31.52	31.52	17.67	17.67	17.67	16.26	16.26	16.26	1000Ha
Switchgrass	31.52	31.52	31.52	17.67	17.67	17.67	16.26	16.26	16.26	1000Ha
Second-stage decision										
Total biomass harvested	721.51	722.51	722.50	631.20	633.69	633.50	583.67	585.77	585.67	1000Mg
Switchgrass	142.84	175.15	174.82	80.08	152.30	146.88	64.78	140.12	135.04	1000Mg
Logging residue	209.71	208.60	208.61	209.27	205.02	208.53	209.39	205.71	206.18	1000Mg
Thinning residue	368.96	338.76	339.07	349.93	275.67	278.03	309.49	239.94	244.45	1000Mg
Total biomass stored	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Switchgrass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Logging residue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Thinning residue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Total biomass dumped	0.00	257.47	135.12	0.00	90.26	26.89	8.89	83.04	12.47	1000Mg
Switchgrass	0.00	257.47	135.12	0.00	90.26	26.89	8.89	83.04	12.47	1000Mg
Average biomass traveled distance	69.00	61.46	0.00	69.43	57.10	0.00	67.53	55.17	0.00	Km
Switchgrass	23.67	14.13	0.00	17.54	12.76	0.00	15.44	12.54	0.00	Km
Logging residue	74.71	74.62	0.00	74.70	74.20	0.00	74.56	73.21	0.00	Km
Thinning residue	83.31	77.81	0.00	78.37	68.77	0.00	73.69	64.29	0.00	Km
Total biomass processed	721.51	722.51	722.50	631.20	633.69	633.50	583.67	585.77	585.67	1000Mg
Switchgrass	142.84	175.15	174.82	80.08	152.30	146.88	64.78	140.12	135.04	1000Mg
Logging residue	209.71	208.60	208.61	209.27	205.02	208.53	209.39	205.71	206.18	1000Mg
Thinning residue	368.96	338.76	339.07	349.93	275.67	278.03	309.49	239.94	244.45	1000Mg



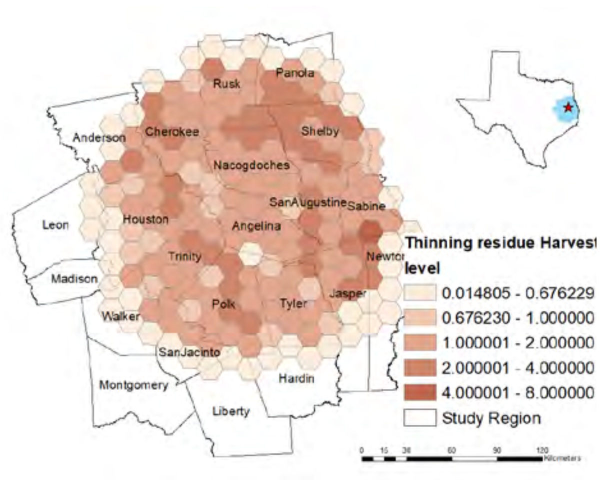
(a) Logging residue medium improvement scenario



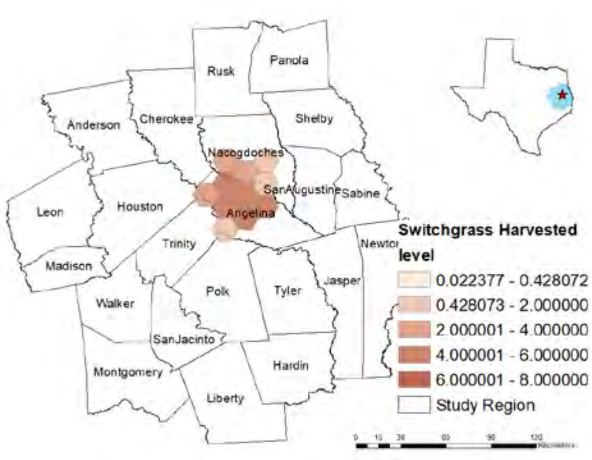
(b) Logging residue high improvement scenario



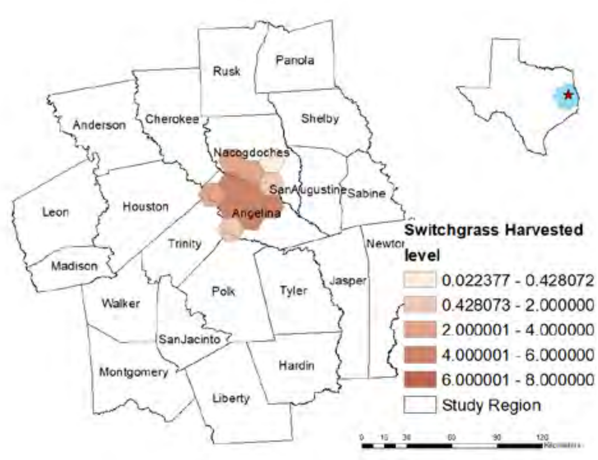
(c) Thinning residue medium improvement scenario



(d) Thinning residue high improvement scenario



e) Switchgrass medium improvement scenario

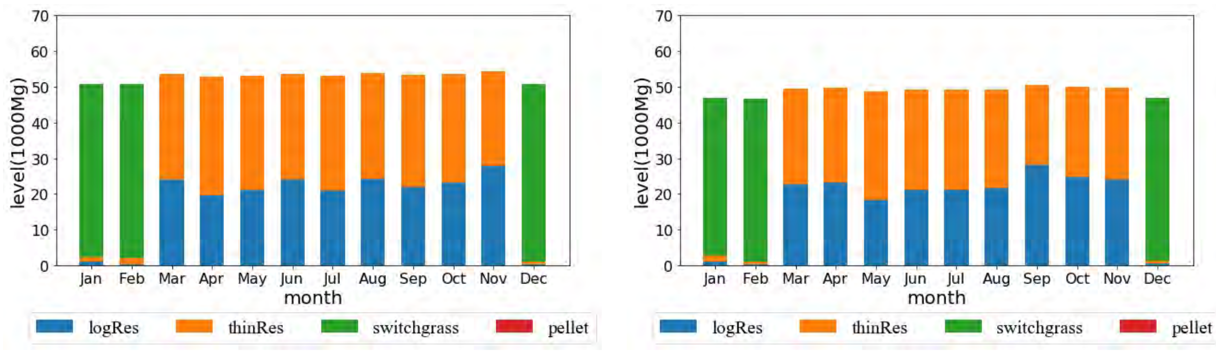


(f) Switchgrass high improvement scenario

Figure 33 Source of each biomass in different conversion rate scenario

Figure 34 below shows biomass use by month under the different conversion rates. Switchgrass was used as the major biomass source during its harvesting window. Since the optimal solution did not include storage for all three conversion rate scenarios, switchgrass was not used outside of its harvest months. A mix of logging and thinning residue was used in the other months.

As ethanol can be made with less feedstock when the conversion rate improved, the feedstock volumes are smaller.



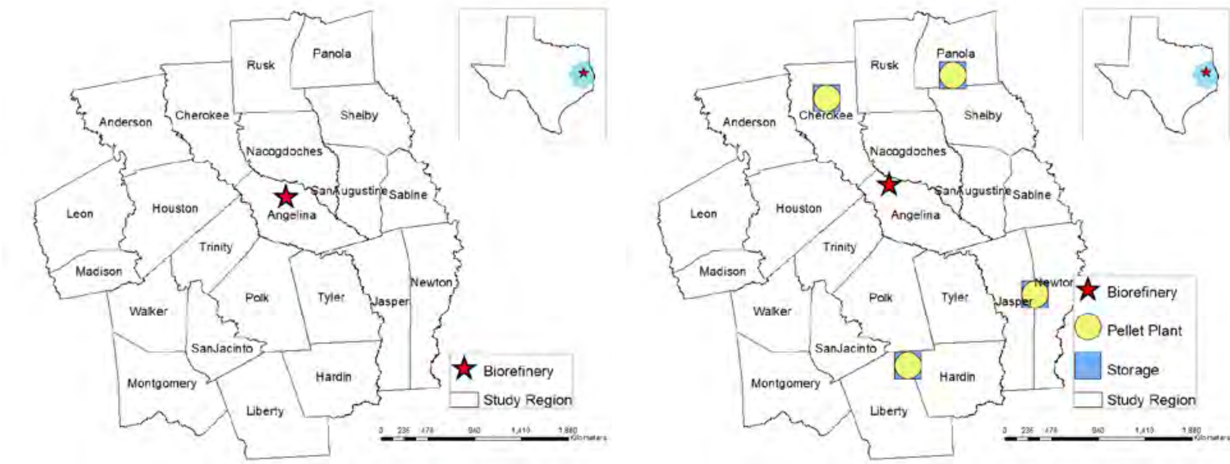
(a)Medium improvement scenario (b)High improvement scenario

Figure 34 Monthly biomass process level of different conversion rates scenarios

Impacts of Alternative Pellet Prices

The potential impact of higher pellet prices was examined to see when pelleting was better than dumping. As shown above, pellets were not produced under the base case and were produced only when switchgrass was the only feedstock available. However, a higher pellet price might change that result.

According to Puall (2018), switchgrass pellets can be produced and marketed as a fuel for a price of $150 per Mg. The world market price for wood pellets ranged from $112 to $185 per metric ton during the past four years. Based on this, two different price scenarios, a low and high price scenario was formed (i.e. $ 100 and $150 per Mg) to simulate potential pellet export possibilities as compared to a zero price in the base model.



(a)Base case/$100 per Mg Scenario (b)$150 per Mg Scenario

Figure 35 Optimal locations for different price scenarios

Figure 35 illustrates the optimal locations of biorefinery, storage and pelleting plants under the two pellet price scenarios. When the pellet price was both zero and $100/Mg, pelleting was not done, with the solutions being the same as we saw for the base. When the pellet price increased to $150/Mg pelleting was done. This caused the model to choose to build ten storage depots with associated pelleting plants and, move the biorefinery location to the northwest corner of Angelina county closer to the switchgrass supplies. of the storage depot pelleting plants were in Cherokee, Jasper, Liberty and Shelby counties with one plat in Jasper county and three in each of the other counties. By assumption each pelleting plant also had an associated storage depot.

Table 37 summarizes the expected cost components and the key logistic decisions under the pellet price scenarios. This shows identical solutions for the zero and $100 prices but under the $150/Mg price scenario, pellets were produced. In turn, the profit from exporting the pellet helped reduce the expected objective function value by 30.3% compared to the base scenario even though cost increased within every cost category.

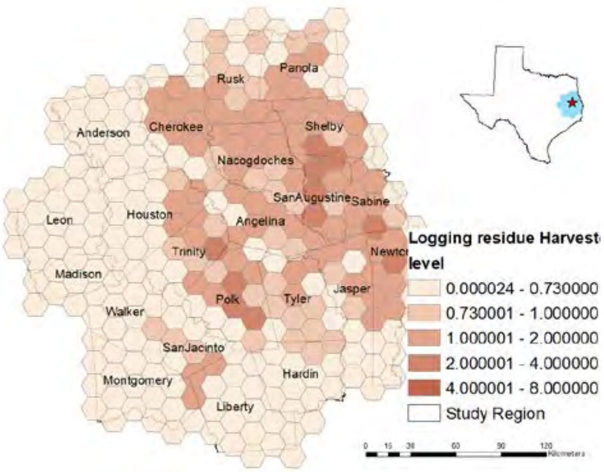
Table 37 Expected Costs of Each Component in Different Pellet Prices Scenarios

Item	Base sceanrio	$100/Mg scenario	$150/Mg scenario	Units
Expected cost of supply chain	98,656.54	98,656.54	68,739.44	$1,000
Annualized cost of biorefinery	22,565.67	22,565.67	22,565.67	$1,000
Annualized cost of storage			36,447.94	$1,000
Annualized cost of pellet plant			3,786.10	$1,000
Cost of contracting land	331.58	331.58	1,495.53	$1,000
Expected harvesting cost	30,767.73	30,778.02	60,721.14	$1,000
Expected dumping cost	481.81	1,209.03	844.92	$1,000
Expected storage cost	453.75	453.75	1,415.11	$1,000
Expected pelleting cost			24,257.93	$1,000
Expected conversion cost	31,500.00	31,500.00	31,500.00	$1,000
Expected transporting cost	12,556.00	12,556.00	24,533.38	$1,000
Profit form exporting pellet			-138,828.28	$1,000
Average cost of ethanol	0.51	0.51	0.36	$/L

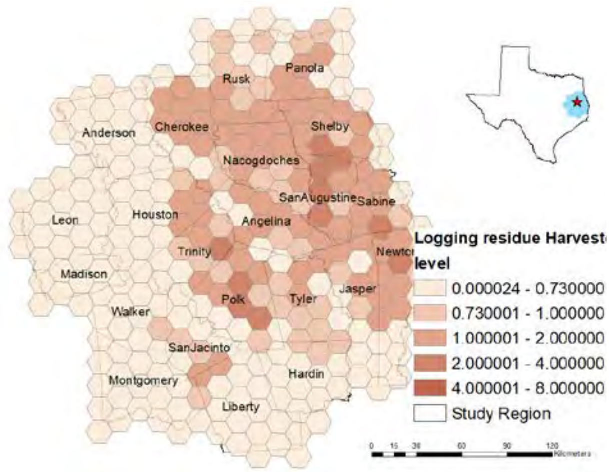
Table 38 below lists the optimal solutions to the key decisions of different pellet price scenarios. Figure 36 depicts amount and area of each biomass being harvested under different price scenarios. Based on the figure and the figure, use of logging and thinning residue decreased when the price was $150/Mg with switchgrass becoming the major source of feedstock. The average amount of land harvested for switchgrass increased by three times compared to the base scenario. All the switchgrass harvested was within a 35 km radius of the biorefinery or pelleting plants. The switchgrass took on a different pattern hers with it clustered around the pelleting operations and not all in proximity to the biorefinery. The supply region for the logging residue was unchanged across the scenarios but the thinning residue area was reduced. The amount of biomass being dumped increased with the higher prices, but the percentage dumped dropped. In the base case, around 9% of switchgrass was dumped while only 5.5% to 6% of switchgrass was dumped when the pellets can be exported at a high price. In other words, with the option of exporting pellets became available, over supplies of switchgrass in the uncertain scenarios can be used more efficiently by converting them into pellets and exported. Here more biomass was dumped in the high pellet price scenario relative to low pellet price scenario is due to the limitations on number of pellet plants allowed in the study region. In this study, a constraint on the total number of storage/pellet plant was applied to increase computation efficiency. Thus, given that all the available locations for pellet plant near the biorefinery have been selected at high pellet price scenario, part of biomass had to be dumped once the pellet production capacity was reached. In other words, less biomass will be dumped in the high pellet price scenario if the limitation on the overall pellet plant capacity can be further increased.

Table 38 Summary of the Key Decisions of Different Pellet Prices Scenarios

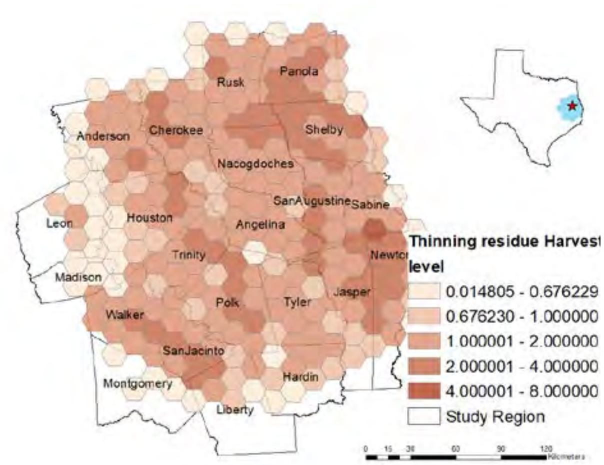
Item	Base scenario($0/Mg)			$100/Mg scenario			$150/Mg scenario			Units
	Worst yield	Best yield	Average	Worst yield	Best yield	Average	Worst yield	Best yield	Average	
First-stage decision										
Total land contracted for biomass	31.52	31.52	31.52	31.52	31.52	31.52	142.16	142.16	142.16	1000Ha
Switchgrass	31.52	31.52	31.52	31.52	31.52	31.52	142.16	142.16	142.16	1000Ha
Second-stage decision										
Total biomass harvested	721.51	722.51	722.50	721.51	722.51	722.50	1,222.91	1,750.58	1,704.01	1000Mg
Switchgrass	142.84	175.15	174.82	142.84	175.15	174.82	644.24	1,486.38	1,290.59	1000Mg
Logging residue	209.71	208.60	208.61	209.71	208.60	208.61	209.71	160.53	188.95	1000Mg
Thinning residue	368.96	338.76	339.07	368.96	338.76	339.07	368.96	103.67	224.47	1000Mg
Total biomass stored	0.00	0.00	0.00	0.00	0.00	0.00	898.97	349.59	290.40	1000Mg
Switchgrass	0.00	0.00	0.00	0.00	0.00	0.00	898.97	349.59	290.40	1000Mg
Logging residue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Thinning residue	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Total biomass dumped	0.00	257.47	135.12	0.00	257.47	135.12	0.00	464.84	107.34	1000Mg
Switchgrass	0.00	257.47	135.12	0.00	257.47	135.12	0.00	464.84	107.34	1000Mg
Average biomass traveled distance	69.00	61.46	0.00	69.00	61.46	0.00	46.44	32.21	0.00	Km
Switchgrass	23.67	14.13	0.00	23.67	14.13	0.00	28.29	26.10	0.00	Km
Logging residue	74.71	74.62	0.00	74.71	74.62	0.00	43.18	71.18	0.00	Km
Thinning residue	83.31	77.81	0.00	83.31	77.81	0.00	84.37	50.20	0.00	Km
Total biomass processed	721.51	722.51	722.50	721.51	722.51	722.50	703.10	723.61	719.29	1000Mg
Switchgrass	142.84	175.15	174.82	142.84	175.15	174.82	233.53	459.41	331.81	1000Mg
Logging residue	209.71	208.60	208.61	209.71	208.60	208.61	100.61	160.53	163.00	1000Mg
Thinning residue	368.96	338.76	339.07	368.96	338.76	339.07	368.96	103.67	224.47	1000Mg
Pellet Produced	0.00	0.00	0.00	0.00	0.00	0.00	492.11	950.00	925.52	1000Mg
Pellet Processed	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1000Mg
Pellet Exported	0.00	0.00	0.00	0.00	0.00	0.00	492.11	950.00	925.52	1000Mg



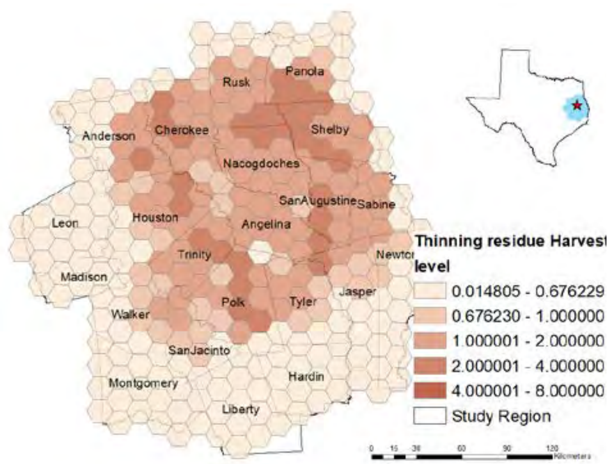
(a) Logging residue $100/Mg scenario



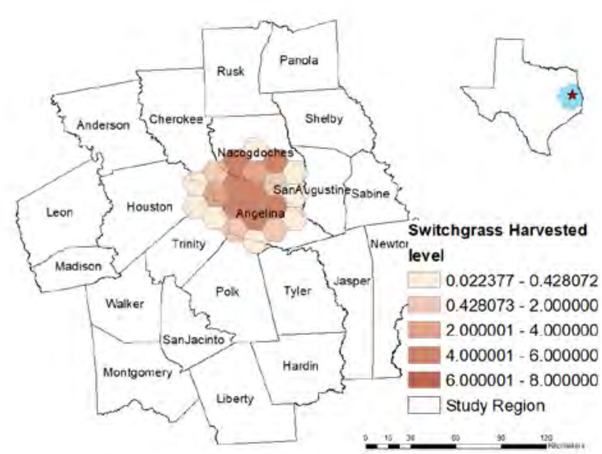
(b) Logging residue $150/Mg scenario



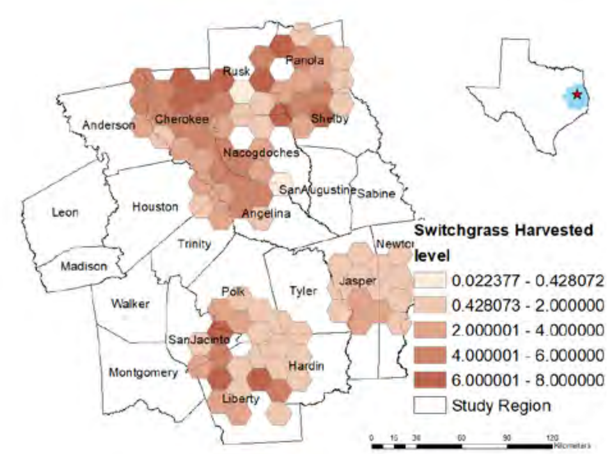
(c) Thinning residue $100/Mg scenario



(d) Thinning residue $150/Mg scenario



(e) Switchgrass $100/Mg scenario

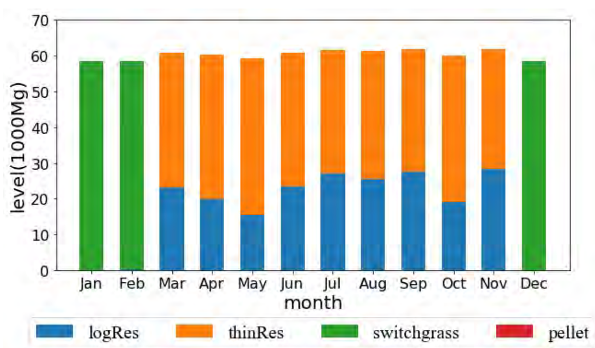


(f) Switchgrass $150/Mg scenario

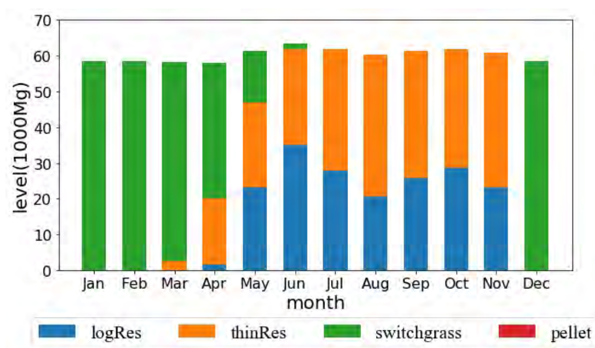
Figure 36 Source of each feedstock under different pellet price scenarios

The amount of each biomass used by the biorefinery throughout the analysis period is depicted in Figure 37.

Here we see the pellet price was \$150/Mg, switchgrass was used outside of the harvest window both as a feedstock and as a source of material for making pellets. Additional switchgrass was stored in baled form and used in March, April, and May. The mix of logging and thinning residue was now used as the major biomass source from May to November due to the increasing supply of switchgrass and the construction of storage.



(a) \$100/Mg scenario



(b)\$150/Mg scenario

Figure 37 Monthly biomass processed level of different pellet price scenarios

Impacts of Increases in Accessible Forest Area

The potential impact of increasing accessible forest area on the supply chain was examined. Up until now we assumed that only the forest area within half km of the forest road system could be used, resulting in feedstock being available from about 75% of the overall forest area. Here we examine cases where the accessible forest increased from that within a half km of a road to that within one km and 1.6 km (i.e. one mile).

At optimality, the biorefinery location was insensitive to the accessible forest rate alternatives. Table 39 below summarizes the cost breakdown and key logistic elements for the accessible area scenarios. The expected supply chain costs drop as the accessible area increases. Under the alternatives the accessible forest increased from the base level of 75% to 90% and 98%. In turn, the expected cost dropped by 2% and 2.9%. The reduction in cost came from replacing switchgrass with more thinning and logging residue that was now close to the biorefinery.

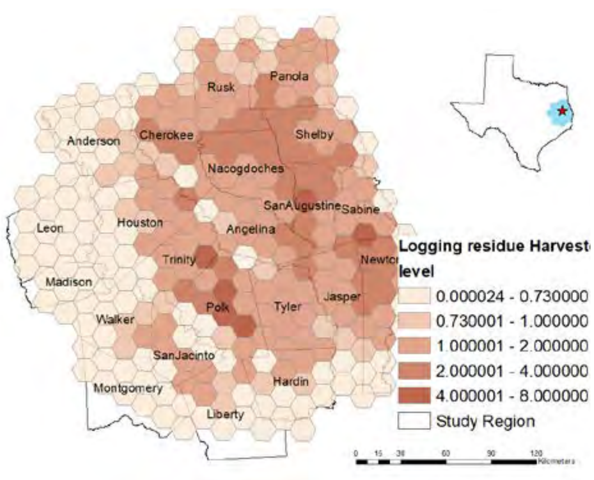
Table 39 Expected Costs of Each Component in Different Forest Accessible Rate Scenarios

Item	Base scenario	90% accessible scenario	98% accessible scenario	Units
Expected cost of supply chain	98,656.54	96,279.11	95,772.00	$1,000
Annualized cost of biorefinery	22,565.67	22,565.67	22,565.67	$1,000
Annualized cost of storage	0.00	0.00	0.00	$1,000
Annualized cost of pellet plant	0.00	0.00	0.00	$1,000
Cost of contracting land	331.58	213.80	213.80	$1,000
Expected harvesting cost	30,767.73	29,691.69	29,215.61	$1,000
Expected dumping cost	481.81	106.32	107.34	$1,000
Expected storage cost	453.75	453.75	453.75	$1,000
Expected pelleting cost	0.00	0.00	0.00	$1,000
Expected conversion cost	31,500.00	31,500.00	31,500.00	$1,000
Expected transporting cost	12,556.00	11,747.88	11,715.97	$1,000
Profit form exporting pellet	0.00	0.00	0.00	$1,000
Average cost of ethanol	0.52	0.51	0.50	$/L

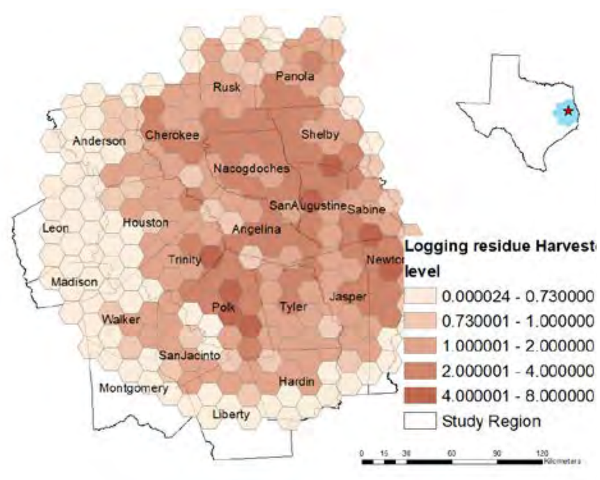
Table 40 summarizes the key decisions and Figure 38 depicts the feedstock supply locations.

Table 40 Summary of the Key Decisions of Different Forest Access Rates Scenarios

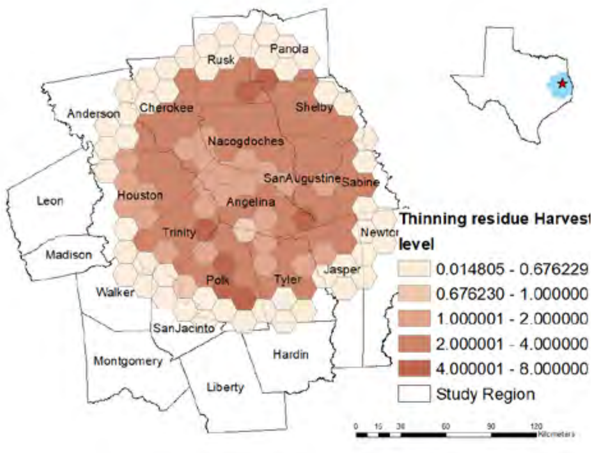
Item	Base scenario			90% accessible scenario			98% accessible scenario			Units
	Wrost yield	Best yield	Average	Wrost yield	Best yield	Average	Wrost yield	Best yield	Average	
First-stage decision										
Total land contracted for biomass	31.52	31.52	31.52	20.32	20.32	20.32	20.32	20.32	20.32	1000Ha
Switchgrass	31.52	31.52	31.52	20.32	20.32	20.32	20.32	20.32	20.32	1000Ha
Second-stage decision										
Expected biomass harvested	721.51	722.51	722.50	739.06	742.66	742.46	748.56	751.49	751.32	1000Mg
Switchgrass	142.84	175.15	174.82	20.73	175.15	168.20	8.22	175.15	168.08	1000Mg
Logging residue	209.71	208.60	208.61	320.44	309.31	309.61	370.28	353.42	353.90	1000Mg
Thinning residue	368.96	338.76	339.07	397.89	258.20	264.65	370.06	222.92	229.34	1000Mg
Expected biomass dumped	0.00	257.47	135.12	0.00	103.80	31.65	0.00	103.80	31.77	1000Mg
Switchgrass	0.00	257.47	135.12	0.00	103.80	31.65	0.00	103.80	31.77	1000Mg
Average biomass traveled distance	69.00	61.46	0.00	68.67	52.36	0.00	66.57	51.18	0.00	Km
Switchgrass	23.67	14.13	0.00	9.21	14.12	0.00	1.88	14.12	0.00	Km
Logging residue	74.71	74.62	0.00	74.48	72.15	0.00	74.25	71.51	0.00	Km
Thinning residue	83.31	77.81	0.00	67.09	54.60	0.00	60.35	48.06	0.00	Km
Expected biomass processed	721.51	722.51	722.50	739.06	742.66	742.46	748.56	751.49	751.32	1000Mg
Switchgrass	142.84	175.15	174.82	20.73	175.15	168.20	8.22	175.15	168.08	1000Mg
Logging residue	209.71	208.60	208.61	320.44	309.31	309.61	370.28	353.42	353.90	1000Mg
Thinning residue	368.96	338.76	339.07	397.89	258.20	264.65	370.06	222.92	229.34	1000Mg



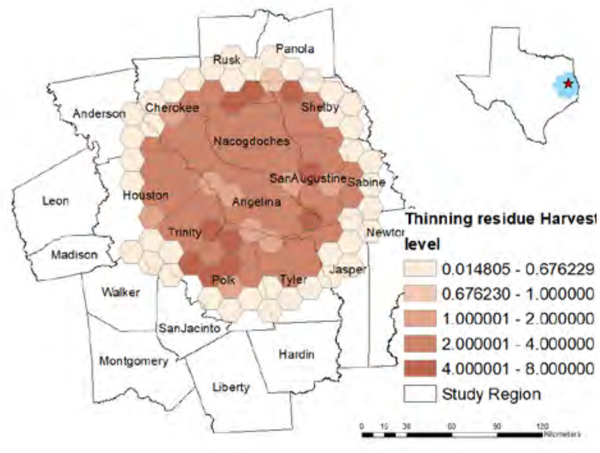
(a) Source of logging residue 90% access rate scenario



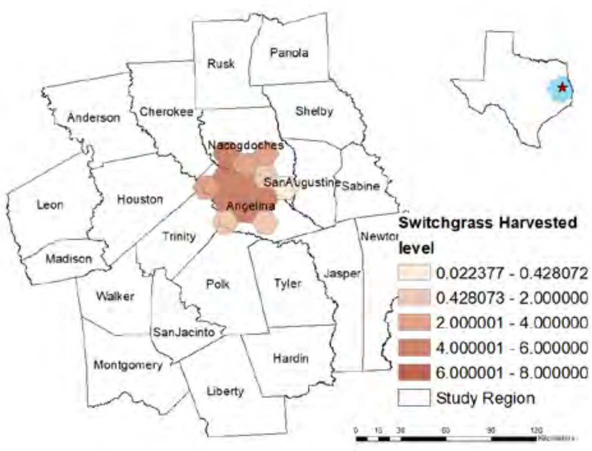
(b) Source of logging residue 98% access rate scenario



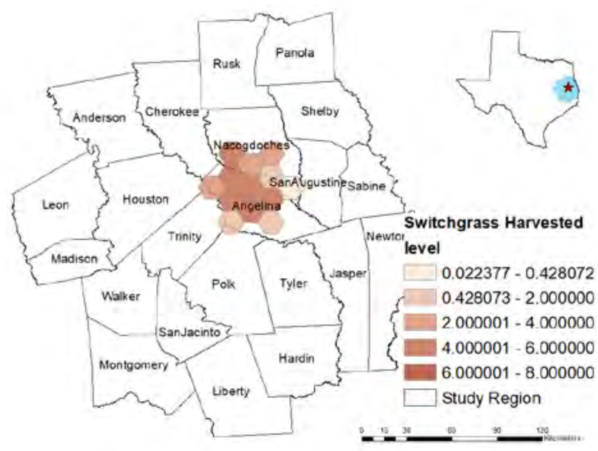
(c) Source of thinning residue 90% access rate scenario



(d) Source of thinning residue 98% access rate scenario



(e) Source of switchgrass 90% access rate scenario

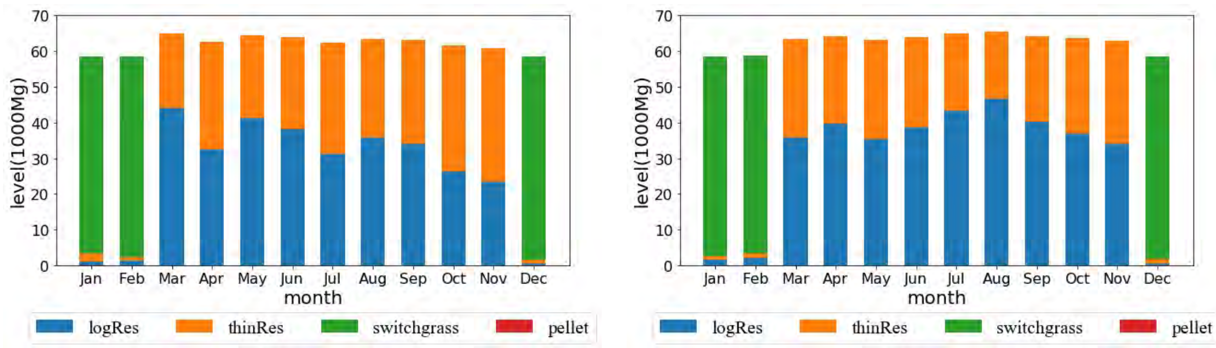


(f) Source of switchgrass 98% access rate scenario

Figure 38 Source of each feedstock under different forest access rates scenarios

Based on Table 40 and Figure 38, the sourcing areas for each feedstock became smaller with the usage of logging and thinning increasing.

For logging residue usage increased by 48% and 68% under the one km and one-mile scenarios. This lowered the amount and cost of contracting land for switchgrass with less switchgrass being harvested, dumped and transported. The logging residue which used to be collected within a 100-km radius now dropped to an 80-km radius under the 1-mile scenario. The harvesting region for thinning residue decreased from 80-km radius to 60-km radius while the harvesting region for switchgrass remained within the area 15-km to 20-km radius.



(a)90% access rate scenario (b)98% access rate scenario

Figure 39 Monthly biomass processed level of different forest access rates scenarios

The amount of each biomass processed by month is depicted in Figure 39 under the accessibility scenarios. Again, switchgrass was used in its harvesting season: January, February and December. In the rest of the months, a mix of logging residue and thinning residue was used. Noted that the increasing in the accessible forest region provided more thinning and logging residue closer to the biorefinery replacing more distant switchgrass. Similarly, when the accessible forest increased, the thinning residue farthest away was replaced by additional logging residue near the biorefinery. Therefore, a significant decrease in switchgrass and thinning residue was observed as more forest became accessible.

Experiments with Geographic Scale

Another analysis was done to examine the consequences of using the finer scale hexagon-based information as opposed to just using county information for this study. In this case we ran a version of the model specified only at a county level and a model specified with the hexagons as above then examine the differences between the optimal placement and configuration of the cellulosic biofuel supply chain along with the implications for cost and other decisions. The results show when applying the higher resolution spatial data naturally give more detailed information on the regions selected for biomass production and the more precise identification of transportation routes, but also lead to different estimates of transportation cost. Table 41 below shows the comparisons of cost for each of the supply chain components. This shows essentially identical costs for each supply chain element excepting for the transportation cost. This is because the movements are generally set up in the county level model from the centroids of the counties but using the more detailed model gives a more accurate representation of county heterogeneity and the locations of feedstock production which in turn raises the cost. With the high resolution spatial data, the transportation cost is 4% higher than when using county level data.

Table 41 Costs Comparison between County Level and Hexagon Level Data in East Texas

	County-level spatial data	Hexagon spatial data
Fixed cost	22,565.67	22,565.67
Collecting/harvesting cost	32,025.76	32,025.76
Storage cost	453.75	453.75
Pelleting cost	0.00	0.00
Transportation cost	12,060.29	12,556.35
Ethanol production cost	31,500.00	31,500.00

Summary and Discussion

In this chapter, explorations of supply chain design were done using a cost minimizing two-stage stochastic mixed integer model. The model was subjected to scenarios on a) whether to include uncertainty in crop yield, b) improved biomass to ethanol conversion rate, c) alternative pellet export prices, d) whether the biorefinery handled on a single or multiple feedstock, and e) forest accessibility. Important observations from the results above are summarized below.

First, the results comparison of deterministic and stochastic model showed that uncertainty was an important factor affecting the contracting of feedstock and handling of excess supplies - dumping costs. Under uncertainty 80% more land for switchgrass needed to be contracted so that demand of the biorefinery could be met under the worst yield outcome. Additionally, when the best yield state of nature was realized, around 175 Mg of switchgrass was used as feedstock while 135 Mg or 15.7% of available biomass was dumped. A takeaway message from this is when designing a supply chain, one must not only consider the bad yield, but also the handling of excess feedstock when higher yields occur.

Analyses were also conducted to examine the impact of different levels of feedstock to ethanol conversion rates. Here we found the feedstock facilities were invariant to increases but that the supply region became smaller as conversion rates increased. The improving conversion rate directly lead to less need for biomass and in turn reduced biomass contacting, transport and processing costs across the supply chain. In turn the average cost of fuel production dropped from \$0.51/L to \$0.36/L as the conversion rates improved. Note that this study assumes the biorefinery will produce identical amounts of cellulosic biofuel as the conversion rate improve whereas expanding production might also be an alternative.

Analyses over alternative pellet export prices was carried out and there we found no effect of a price under \$100 but a strong reaction when the price was \$150 a high price changed both the optimal locations of facilities and the feedstock usage pattern. We also ran a number of alternative prices and found the critical cost is between \$110 and \$120 per Mg. In that case the biorefinery location moved to the northwestern corner of Angelina county which is nearer to available pasture land for growing switchgrass. Additionally, we found when the pellet price become high enough, the dumping of excess yield of switchgrass is reduced by pelletizing and exporting.

Finally, different accessibility of forests residues was considered. The results showed that the change in accessible forest area did not alter biorefinery location or cause storage depot and pelleting plants to be constructed. However, this did affect the area and harvesting volumes of the biomass types. The harvested area became smaller for each feedstock as the accessible forest area became larger and the harvesting level of logging and thinning residue was larger from a smaller supply region. Concurrently, the harvesting results for switchgrass were unchanged.

Based on the totality of the results, the average cost of cellulosic biofuel ranged from \$0.51/L to \$0.71/L in the absence of pellet export revenues. When pellet price was \$150 the average cost drops to \$0.36/L, but this remains above than the current average ethanol production cost, \$0.33/L largely from corn. Judging from these figures, building a cellulosic biofuel supply chain in the present study region is not an economically feasible option today. However, if government mandates rise then the proposed supply chain system would be more competitive. For example, given that todays and the anticipation for future volumes of cellulosic biofuel production are much less than the anticipated mandated volume of cellulosic biofuel in the proposed RFS under EISA, then there is room to raise the required mandate which would stimulate production. Furthermore, todays cellulosic waiver credit on cellulosic ethanol is set by EPA at the greater of \$0.25 or \$3.00 per gallon minus the wholesale price of gasoline (EPA2018). This means given today's gasoline price as reported by EIA is \$1.91) meaning that the CWC would be \$1.09 per gallon and adding this to today's wholesale ethanol of \$1.26 a price for selling cellulosic ethanol at the wholesale level 0f \$2.35 per gallon which is \$0.62 per liter. In turn if such conditions persist and the assumptions used in our modeling are accurate then the cellulosic ethanol is unprofitable under base conditions but becomes profitable under some of the alternative scenarios

In addition to the impacts from different key parameters, different supply chain designs were also discussed in this study. Multiple feedstock, woody materials only and switchgrass only scenarios were run and compared to see the impact of overall costs on the supply chain. Based on the results of these three scenarios, this study found out that the total costs can be reduced significantly if wood is allowed because we assumed it does not require covered storage. Given that it could be picked up from accessible piles year-round, a just in time system was employed and this avoids the fixed cost of building storage depots and pelleting plants, plus avoids the substantial variable storage costs. On the other hand a switchgrass only system requires this storage and relative to the multi feedstock case raises cost by 36% and 24% relative to a wood only case. Therefore, the ability of providing seasonal switchgrass and year-round woody materials in east Texas is a beneficial outcome when designing a low cost cellulosic supply chain.

Conclusions

Determining the optimal configuration is an important topic in the development of low cost biofuel production. Previous studies of supply chain design have used either a GIS model for choosing biorefinery and feedstock production locations using ad hoc procedures without including any optimization in the process, or they have employed a mathematical programming model for system optimization but using a coarse representation of the region. The studies have also largely ignored stochastic variation in crop yields. This study attempted to develop a modeling framework at a relatively fine geographic scale for the choice of production locations, storage depot locations, pelleting plant locations and biorefinery location plus the associated volumes of multiple feedstock harvested and moved through the system monthly. To do this a mixed-integer programming model linked with high resolution spatial data and stochastic yields was developed to evaluate how a number of factors affect the optimal placement and configuration of a lignocellulosic biofuel supply chain. The framework can also be extended to evaluate feedstock production in other regions for the emerging advanced biofuel or biomass power electrical generation industries.

In addition to developing new analytical framework four supply chain design and operation, this study also has developed several findings which can help make a more efficient cellulosic biofuel industry. For an Eastern Texas case study, we found use of multiple feedstocks, in this case, woody biomass and switchgrass, allow the firm to operate without expensive storage depots and pelleting facilities with a Just in time feedstock delivery system employed. The model supply chain your switchgrass during its harvest window and woody residues during the rest of the year. Avoiding the need for storage significantly reduces the construction, storage costs of the feedstock. We also found that the optimal supply chain under current conditions generated a cost of ethanol production that was slightly higher than the wholesale ethanol price plus the revenue obtained under government incentives like the current cellulosic wavier credits However we found that with either a) advances in the conversion rates of biomass into ethanol; b) increased forest accessibility and/or density or c) the possibility of earning revenues by exporting excess production in the form of pellets could lower the cost so they were quite competitive.

We also found it beneficial to use the more aggregate representation of the region as opposed to a County level risk presentation because it gave a more complete idea of appropriate supply chain design.

Finally, this study like others has limitations and the issue merits further research. This study assumed that there was no alternative use for the woody materials in east Texas. However, there may be demands that should be considered. Second, although different ethanol conversion rates were assumed for the two basic sources of woody biomass feedstocks (thinning and logging residues), this study does not distinguish the impact on the conversion rate from different tree species. A detailed study on the supply and characteristics of woody materials could be a key for more accurate estimates in the future.

Third, better land market modeling could also be pursued. The study assumed all the targeted land in study region could be contracted while, in real world, the contracting decision will be affected by the heterogeneous characteristics of the land and its current uses. Fourth, the risk preference of the supply chain owners is not considered in this study. In fact, risk neutrality is assumed while it is more likely that decision makers are risk averse. Thus, a further analysis on risk preference could be conducted. Fifth, this study assumed the production costs are fixed, while they are likely to be uncertain due to the weather and soil condition and the impacts of these factors could be examined. Sixth, this study assumes a fixed demand for the ethanol. Future work could conduct a sensitivity analysis on different ethanol production levels or to develop demand functions to better simulate market responses.

CHAPTER VI

CONCLUSION

This dissertation analyzes supply chain design involved with supplying lignocellulosic biomass to an ethanol plant. A two-stage stochastic MIP model is developed and implemented that represents a multi-feedstock ethanol supply chain under feedstock yield uncertainty. The model minimizes expected cost by determining the optimal values of the design decisions. First stage yield uncertainty independence decision includes both facility locations and capacity alternatives and amount of land contracted for each feedstock. Second stage, yield outcome dependent decisions include monthly feedstock harvest, storage, palletization, refining and transport. In the analysis we study the consequences of alternative supply chain design and the incorporation or omission of yield uncertainty along with the impact of using a high-resolution sub county regional resolution versus a lower resolution county level portrayal.

Chapter 2 of this dissertation contains a literature review on the supply chain design issue and the lignocellulosic context. Chapter 3 develops a conceptual, mathematical programming model plus discusses an approach to developing an empirical distribution of uncertain yields and approaches to development of a spatial representation of the region. The model is then applied in two case studies in Texas where it is used to address a variety of supply chain design issues. Chapter 4 addresses a case study in the Texas High Plains and reports on analyses considering the inclusion of uncertainty, use of centralized storage only, possibility of pelleting, the effect of conversion rate improvements, the effect of pelleting export possibilities and the effect of alternative degrees of spatial representation. Chapter 5 is similar but reports on a case study in East Texas where the same issues are considered along with the issue of using only a single versus multiple feedstocks and different accessibilities of feedstocks from regional forests. Then lastly this chapter presents conclusions based on findings from the case studies and later presents conclusions regarding the methodology.

Several comparisons in terms of supply chain design were made to help us understand the impact different component on the optimal supply chain setup. First, this study compared the results of only using a single feedstock as opposed to multiple feedstocks scenario. There we find that use of multiple feedstocks is superior particularly when there is inherent seasonality of the biomass feedstocks. If there is a year-round availability of freshly harvested feedstocks, as was true with logging and thinning residues in East Texas, then the model chooses not to add any storage and operates a "Just in time" supply chain system which in turn reduces the ethanol production cost significantly. In contrast, when only using switchgrass which has strong seasonality then we see increasing storage and transportation costs were observed since biomass need to be stored throughout the year to ensure sufficient supply of biomass for biorefinery. Moreover, even if multiple sources of feedstock are available, but when each feedstock exhibited distinct harvest seasons, increasing storage cost, biomass deterioration and transportation cost were observed. Comparing the results across the two case studies we find the cost per liter ethanol is $0.520/L in East Texas when storage is not required and is $0.602/L in the High Plains.

Second this study compared the results of unrestricted design, central storage only and no pelleting scenarios to see the impact of different supply chain designs on the supply chain setup, logistics decisions and the associated costs. The results indicate that pelleting is not chosen and thus the total costs and logistic decisions of the no pelleting scenario were the same as the unrestricted case. While the supply setup and total cost were different from the base case, the land contracted before uncertainty resolved and logistics decisions in centralized storage scenario were essentially the same as base case as well.

Although the results here exhibit no significant difference across unrestricted, no-pellet and central storage only scenarios, with remote facilities, storage and pellet plant can be placed near locations with high biomass density and allow more efficient use of biomass plus lower transport costs. Thus, in the presence of pellet export possibilities that remotely located storage depots with associated pellet plants provide options that allow the exploitation of geographically stranded feedstocks that are not near enough to biorefinery locations to be moved directly. Our results in the Texas High Plains case study show the corn Stover collection area goes from an 80 km radius to a 200 km one when pellets can be exported at a $150/mg price. Within the larger radius the remote stover collected was sent to a remote combined storage depot and pellet plant and was then converted into pellets and mostly exported. Similarly, more switchgrass was harvested and exported in the pellet form at $150/Mg export price. This study also find that pellet exports can substantially reduce the price of producing fuel.

Analyses were also conducted to examine the impact of different levels of feedstock to ethanol conversion rates. Here we found the feedstock facilities were invariant to increases but that the supply region became smaller as conversion rates increased. The improving conversion rate directly lead to less need for biomass and in turn reduced biomass contacting, transport and processing costs across the supply chain. In turn the average cost of fuel production dropped from $0.602/L to $0.54/L in Texas High Plains and from $0.51/L to $0.36/L in East Texas as the conversion rates improved. Note that this study assumes the biorefinery will produce identical amounts of cellulosic biofuel as the conversion rate improve whereas expanding production might also be an alternative.

Furthermore, we find that incorporation of yield uncertainty is an important factor. In particular such uncertainty affects the need for feedstock contracting, the amount of excess feedstock dumping costs and tactical supply chain operation. In both case studies, more land for biomass feedstocks was contracted under uncertainty as a safety margin to keep the refinery running when yields are low. On the other hand, when high yields were present the model needed to deal with excess feedstock and about 736,000 Mg and 722,510 Mg of total biomass were used in refining while 621,000 Mg and 135,120 Mg of excess feedstock were dumped at a cost in Texas High Plains and East Texas correspondingly. In the latter case, amount of biomass being dumped was much less than the former because the presence of year-round biomass such as logging and thinning residues.

Additionally we find that due to the high level of fixed cost and the constant requirement for feedstock across sates of nature that total cost was not very sensitive to the variations in contracting and dumping with the cost of ethanol produced only varying by one cent per liter ($0.59/L versus $0.602/L in Texas High Plains and $0.51/L versus $0.52/L in East Texas) between the deterministic and the stochastic models. However, given the estimates of the empirical states of nature distribution and parameters in this study factors are relatively conservative, the impact of uncertain yield could be greater than the prediction here. Besides, the "optimal" plan from the stochastic model is generally robust across the yield outcomes and not the best possible position for all (or maybe even any) of the possible yield events. Thus, the stochastic model solution provides the decision maker with the flexibility to adjust the logistic decisions based on the varying yields.

In terms of methodology, few previous supply chain studies have examined supply chain design in a framework using high resolution spatial data within an optimization setting while also considering yield uncertainty. A number of these studies have applied mathematical programming approaches for system optimization but have used a relatively coarse representation of the region (for example on a county basis) or it is also quite common to see the studies ignore crop yield uncertainty. In this dissertation, a two-stage stochastic mixed integer models are formulated to provide an analysis framework at a relatively fine geographic scale for the choice of production locations, storage depot locations, pelleting plant locations and biorefinery location plus land allocation to specific feedstocks, amounts harvested, amounts stored, amounts pelleted amounts of excess supply dumped and the movement of feedstock through the system on a monthly basis. The results of the experiment showed that transportation cost, in both cases, was affected as the geographic scale changed. Specifically, when high resolution spatial data was applied, the transportation cost was reduced by 6.3% in the Texas High Plains while it was increased by 4.1% in East Texas compared to the county level cases. Additionally, the higher resolution data stimulated a change in the storage locations in Texas High Plains due to the altered precision of feedstock density portrayal. Thus, we conclude that the biofuel supply chain design and logistic decisions are sensitive to geographic scale and that more precise data will improve the supply chain design.

Finally, while not discussed here, the proposed framework is not limited to the state of Texas and can also be extended to cases elsewhere plus it can be used to consider supply chains for biomass feedstock powered electricity generation.

The current model presented in the dissertation, however, has several limitations, which point us the future research directions. For example, in Texas High Plains, in addition to collect agriculture residue, we also consider growing energy crops on dryland cotton, sorghum and wheat land. However, it may be possible to grow these crops on some marginal pasture/range land which would introduce less food – energy competition. Such an issue could be addressed in further research.

Additionally, this study assumed all the woody materials in east Texas are available for biorefinery inputs. However, demand for woody materials in the real world are ignored in this study. Besides, although different ethanol conversion rates were assumed for woody biomass feedstocks from multiple process, this study does not distinguish the impact on the conversion rate from different tree species. A detailed study on the supply and characteristics of the species mix and associated woody materials supply could be a subject of additional research.

Beyond this the model assumes that the firm could readily use multiple feedstocks and did not introduce any fixed costs of for example maintaining different handling and chemical treatment processes that were needed for utilization of say would versus switchgrass versus corn Stover. This again provides a possible direction for further research.

In terms of assumptions about the decision-maker, the risk preference of the biorefinery planner and the farmers are not treated in this study. In fact, the biorefinery planner is assumed to be risk neutral in the study but that they consider the full probability distribution of outcomes. However, they may well be risk averse. Thus, a further analysis on risk preference should be conducted to prevent provide biased information for decision maker.

Yield uncertainty is another area where the work could be extended. Here we assume perfectly correlation across the entire region in terms of yield uncertainty, but this may not be the case. Also, we used state level data to set up the yield distribution, but more local data may be more variable (as in the paper by Kim and McCarl). Furthermore, a four-step probability distribution was introduced for each crop and a more detailed one might be desirable. Again, these are fodder for future research.

In terms of feedstock production, this study assumed the production costs are fixed and the same across the region, while they are likely to vary from year to year in place to place due to the weather, pests and other conditions. It is important for the future study to manage risk by analyzing the impacts of these factors. In this study biofuel producers are assumed to own the whole supply chain. However, it is common that different segment of the proposed supply chain is owned and operated by other stakeholders. Therefore, the impacts of different ownerships on supply chain design are of interest to explore.

Finally, this study assumes that the biorefinery produces a constant level of ethanol. Uncertainty in yields, alterations in subsidy programs and varying factor/product prices may make it desirable for the biorefinery to vary this volume and this could be studied in future research.

REFERENCES

Aden, A., and T. Foust. 2009. "Technoeconomic analysis of the dilute sulfuric acid and enzymatic hydrolysis process for the conversion of corn stover to ethanol." *Cellulose* 16(4):535–545.

Aden, A., M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas. 2002. "Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover." NATIONAL RENEWABLE ENERGY LAB GOLDEN CO.

Alex Marvin, W., L.D. Schmidt, S. Benjaafar, D.G. Tiffany, and P. Daoutidis. 2012. "Economic Optimization of a Lignocellulosic Biomass-to-Ethanol Supply Chain." *Chemical Engineering Science* 67(1):68–79.

An, H., and S.W. Searcy. 2012. "Economic and energy evaluation of a logistics system based on biomass modules." *Biomass and Bioenergy* 46:190–202.

Argo, A.M., E.C. Tan, D. Inman, M.H. Langholtz, L.M. Eaton, J.J. Jacobson, C.T. Wright, D.J. Muth, M.M. Wu, Y.-W. Chiu, and R.L. Graham. 2013. "Investigation of biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system and advanced uniform biomass logistics designs." *Biofuels, Bioproducts and Biorefining* 7(3):282–302.

Azadeh, A., H. Vafa Arani, and H. Dashti. 2014. "A stochastic programming approach towards optimization of biofuel supply chain." *Energy* 76:513–525.

Chen, C.-W., and Y. Fan. 2012. "Bioethanol supply chain system planning under supply and demand uncertainties." *Transportation Research Part E: Logistics and Transportation Review* 48(1):150–164.

Cundiff, J.S., N. Dias, and H.D. Sherali. 1997. "A linear programming approach for designing a herbaceous biomass delivery system." *Bioresource Technology* 59(1):47–55.

Dal-Mas, M., S. Giarola, A. Zamboni, and F. Bezzo. 2011. "Strategic design and investment capacity planning of the ethanol supply chain under price uncertainty." *Biomass and Bioenergy* 35(5):2059–2071.

Darr, M.J., and A. Shah. 2012. "Biomass storage: an update on industrial solutions for baled biomass feedstocks." *Biofuels* 3(3):321–332.

De Meyer, A., D. Cattrysse, and J. Van Orshoven. 2015. "A generic mathematical model to optimise strategic and tactical decisions in biomass-based supply chains (OPTIMASS)." *European Journal of Operational Research* 245(1):247–264.

Drews, E.S., B.R. Hartsough, J.A. Doyal, and L.D. Kellogg. 2001. "Harvester-Forwarder and Harvester-Yarder Systems for Fuel Reduction Treatments." *Journal of Forest Engineering* 12(1):81–91.

Ekşioğlu, S., S. Li, S. Zhang, S. Sokhansanj, and D. Petrolia. 2010. "Analyzing Impact of Intermodal Facilities on Design and Management of Biofuel Supply Chain." *Transportation Research Record: Journal of the Transportation Research Board* 2191:144–151.

Foust, T.D., A. Aden, A. Dutta, and S. Phillips. 2009. "An economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion processes." *Cellulose* 16(4):547–565.

Frankó, B., M. Galbe, and O. Wallberg. 2015. "Influence of bark on fuel ethanol production from steam-pretreated spruce." *Biotechnology for Biofuels* 8(1):15.

Gan, J., A. Jarrett, and C.J. Gaither. 2013. "Forest Fuel Reduction and Biomass Supply: Perspectives from Southern Private Landowners." *Journal of Sustainable Forestry* 32(1–2):28–40.

Gan, J., and C.T. Smith. 2006. "Availability of logging residues and potential for electricity production and carbon displacement in the USA." *Biomass and Bioenergy* 30(12):1011–1020.

Gan, J., and C.T. Smith. 2012. "Biomass Utilization Allocation in Biofuel Production: Model and Application." *International journal of forest engineering* 23(1):38–47.

Gebreslassie, B.H., Y. Yao, and F. You. 2012. "Design under uncertainty of hydrocarbon biorefinery supply chains: Multiobjective stochastic programming models, decomposition algorithm, and a Comparison between CVaR and downside risk." *AIChE Journal* 58(7):2155–2179.

Gold, S., and S. Seuring. 2011. "Supply chain and logistics issues of bio-energy production." *Journal of Cleaner Production* 19(1):32–42.

Hess, J.R., C.T. Wright, and K.L. Kenney. 2007. "Cellulosic biomass feedstocks and logistics for ethanol production." *Biofuels, Bioproducts and Biorefining* 1(3):181–190.

Hess, J.R., C.T. Wright, K.L. Kenney, and E.M. Searcy. 2009. "Uniform-Format Solid Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Bulk Solid from Lignocellulosic Biomass–Executive Summary." Idaho National Laboratory (INL).

Hoque, M., S. Sokhansanj, T. Bi, S. Mani, L. Jafari, J. Lim, P. Zaini, S. Melin, T. Sowlati, and M. Afzal. 2006. "Economics of pellet production for export market." In *2006 ASAE Annual Meeting*. American Society of Agricultural and Biological Engineers, p. 1.

Huang, Y., C.-W. Chen, and Y. Fan. 2010. "Multistage optimization of the supply chains of biofuels." *Transportation Research Part E: Logistics and Transportation Review* 46(6):820–830.

Humbird, D., R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen, J. Lukas, B. Olthof, and M. Worley. 2011. “Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis of corn stover.” National Renewable Energy Laboratory (NREL), Golden, CO.

Iowa State University. 2017."BioCentury Research Farm." Available at: http://www.biocenturyresearchfarm.iastate.edu/facilities/biomass_storage.html

Khanna, M., X. Chen, H. Huang, and H. Onal. 2011. “Supply of Cellulosic Biofuel Feedstocks and Regional Production Pattern.” *American Journal of Agricultural Economics* 93(2):473–480.

Kim, J., M.J. Realff, J.H. Lee, C. Whittaker, and L. Furtner. 2011. “Design of biomass processing network for biofuel production using an MILP model.” *Biomass and Bioenergy* 35(2):853–871.

Kim, S.W. 2011. *The Effect of Transaction Costs on Greenhouse Gas Emission Mitigation for Agriculture and Forestry*. Texas A & M University. Available at: http://oaktrust.library.tamu.edu/bitstream/handle/1969.1/ETD-TAMU-2011-05-9546/KIM-DISSERTATION.pdf.

Krishnakumar, P., and K.E. Ileleji. 2010. “A comparative analysis of the economics and logistical requirements of different biomass feedstock types and forms for ethanol production.” *Applied engineering in agriculture* 26(5):899–907.

Langholtz, M.H., B.J. Stokes, and L.M. Eaton. 2016. “2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy.” 1. Available at: https://www.osti.gov/scitech/biblio/1271651-billion-ton-report-advancing-domestic-resources-thriving-bioeconomy.

Mahmudi, H., and P.C. Flynn. 2006. “Rail vs truck transport of biomass.” In *Twenty-Seventh Symposium on Biotechnology for Fuels and Chemicals*. Springer, pp. 88–103.

Mani, S., S. Sokhansanj, X. Bi, and A. Turhollow. 2006. “ECONOMICS OF PRODUCING FUEL PELLETS FROM BIOMASS.” *Applied Engineering in Agriculture* 22(3):421.

Marufuzzaman, M., S.D. Eksioglu, and Y.E. Huang. 2014. “Two-stage stochastic programming supply chain model for biodiesel production via wastewater treatment.” *Computers & Operations Research* 49:1–17.

Mccormick, K., and T. Kaberger. 2007. “Key barriers for bioenergy in Europe: Economic conditions, know-how and institutional capacity, and supply chain co-ordination.” *Biomass and Bioenergy* 31(7):443–452.

Mu, D., T. Seager, P.S. Rao, and F. Zhao. 2010. “Comparative Life Cycle Assessment of Lignocellulosic Ethanol Production: Biochemical Versus Thermochemical Conversion.” *Environmental Management* 46(4):565–578.

O’Brien, D.M., T.J. Dumler, and R.D. Jones. 2010. “The economics of selling crop residue biomass for cellulosic ethanol production at the farm level.” *Selected Paper prepared for presentation at the Agricultural & Applied Economics Association*:25–27.

Ortiz, D.S., A.E. Curtright, C. Samaras, A. Litovitz, and N. Burger. 2011. *Near-Term Opportunities for Integrating Biomass into the U.S. Electricity Supply: Technical Considerations*. Rand Corporation.

Osmani, A., and J. Zhang. 2014. “Economic and environmental optimization of a large scale sustainable dual feedstock lignocellulosic-based bioethanol supply chain in a stochastic environment.” *Applied Energy* 114:572–587.

Osmani, A., and J. Zhang. 2013. “Stochastic optimization of a multi-feedstock lignocellulosic-based bioethanol supply chain under multiple uncertainties.” *Energy* 59:157–172.

Park, Y.S., J. Szmerekovsky, A. Osmani, and N.M. Aslaam. 2017. “Integrated Multimodal Transportation Model for a Switchgrass-Based Bioethanol Supply Chain.” *Transportation Research Record: Journal of the Transportation Research Board* 2628:32–41.

Qin, X., T. Mohan, M. El-Halwagi, G. Cornforth, and B.A. McCarl. 2006. “Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment.” *Clean Technologies and Environmental Policy* 8(4):233–249.

Sawyer, J. 2018. “Nutrient removal when harvesting corn stover | Integrated Crop Management.” Available at: https://crops.extension.iastate.edu/nutrient-removal-when-harvesting-corn-stover-0 [Accessed January 26, 2018].

Segebaden, G. von. 1964. “Studies of cross-country transport distances and road net extension.”

Staples, T., W. Xu, Y. Li, and B. Carraway. 2008. “ESTIMATION OF WOODY BIOMASS AVAILABILITY FOR ENERGY IN TEXAS.”

USDA. 2018. “CropScape - NASS CDL Program.” Available at: https://nassgeodata.gmu.edu/CropScape/ [Accessed January 21, 2018].

USDA. 2018. “USDA NASS Quick Stats.” Available at: https://quickstats.nass.usda.gov/.

USDA-Natural Resources Conservation. 2011. “Release Brochure for Blackwell switchgrass (Panicum virgatum).” Available at: https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/kspmcrb10372.pdf [Accessed January 26, 2018].

USEPA. 2018.“Cellulosic Waiver Credit Price Calculation for 2018 Available at: www.epa.gov/renewable-fuel-standard-program/cellulosic-waiver-credit-price-calculation-2018-0.

Wang, M., J. Han, J.B. Dunn, H. Cai, and A. Elgowainy. 2012. "Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use." *Environmental Research Letters* 7(4):045905.

Wang, M.Q., J. Han, Z. Haq, W.E. Tyner, M. Wu, and A. Elgowainy. 2011. "Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes." *Biomass and Bioenergy* 35(5):1885–1896.

Wang, Z. 2013. "A GIS-based Multi-objective Optimization of a Lignocellulosic Biomass Supply Chain: A Case Study in Tennessee." *Masters Theses*. Available at: http://trace.tennessee.edu/utk_gradthes/2472.

Wilhelm, W.W., J.M.F. Johnson, D.L. Karlen, and D.T. Lightle. 2007. "Corn Stover to Sustain Soil Organic Carbon Further Constrains Biomass Supply." *Agronomy Journal* 99(6):1665.

Wright, M.M., and R.C. Brown. 2007. "Comparative economics of biorefineries based on the biochemical and thermochemical platforms." *Biofuels, Bioproducts and Biorefining* 1(1):49–56.

Zhang, F., D.M. Johnson, and J. Wang. 2016. "Integrating multimodal transport into forest-delivered biofuel supply chain design." *Renewable Energy* 93:58–67.

APPEENDIX A

LIST OF SYMBOLS

Sets	
i	Biomass supply region
j	Potential biorefinery location
k	Potential storage location
l	Potential Pellet station locations
b	Feedstock type
t	Time periods
Parameters	
α_b	Cost of establishing feedstock b
a_b/a_{bs}	Yield of feedstock b/ Yield of feedstock b under state of nature s
c_{ib}	Cost of contract a hectare land at location i for feedstock b
γ	Cost of pelleting biomass
δ_b	Cost of loading/unloading feedstock b
ϵ_b	Cost of transporting feedstock b per Mg Per Km
η_j	Annualized fixed cost of biorefinery
ρ_k	Annualized fixed cost of storage
ϕ_l	Annualized fixed cost of pellet station
κ_a	Pelleting loss (%)
λ_b	Conversion rate of feedstock b (Liter/Mg)
ω_b	Deteriorate rate (%)
D_{zd}	Transport distance from starting point z to destination d
F_k	Inventory capacity of at storage location k
F_j	Inventory capacity of at biorefinery location j (Mg)
G_t	Demand for the ethanol at time t (Liter)
H_t	Minimum biorefinery storage at time t (Mg)

$Prob_s$	Probability of state of nature s realized

First stage decision variables

X_j	Binary variable. Weather to build a biorefinery at j. (1=yes; 0=no)
Y_k	Binary variable. Weather to build a storage at j. (1=yes; 0=no)
Z_l	Binary variable. Weather to build a pellet station at l. (1=yes; 0=no)
M_i	Amount of land contracted at supply region i (1000 hectare)

Second stage decision variables

N_{bit}	Amount of feedstock b harvested at supply region i in month t (1000Mg)
$OBR_{bijt}/OBR_{bijt}(s)$	Amount of feedstock b sent from production region i to biorefinery j in month t (under states of nature s) (Mg)
$OST_{bikt}/OST_{bikt}(s)$	Amount of feedstock b sent from supply region i to storage location k in month t (under states of nature s) (Mg)
$OPL_{bilt}/OPL_{bilt}(s)$	Amount of feedstock b sent from supply region i to pellet station l in month t (under states of nature s) (Mg)
$PBR_{bkjt}/PBR_{bkjt}(s)$	Amount of feedstock b sent from storage location k to biorefinery location j in month t (under states of nature s) (Mg)
$PPL_{bklt}/PPL_{bklt}(s)$	Amount of feedstock b sent from storage location k to pellet station l in month t (under states of nature s) (Mg)
$PLST_{blkt}/PLST_{blkt}(s)$	Amount of pellet b sent from pellet location l to storage location k in month t (under states of nature s) (Mg)
$PLEX_{lt}/PLEX_{lt}(s)$	Amount of pellet exported in month t (under states of nature s) (Mg)
$Q_{bkt}/Q_{bkt}(s)$	Amount of feedstock b being stored at Depot k in month t (under states of nature s) (Mg)
$Q_{bjt}/Q_{bjt}(s)$	Amount of feedstock b being stored at biorefinery location j in month t (under states of nature s) (Mg)
$R_{blkt}/R_{blkt}(s)$	Amount of feedstock b sent from pellet station l to storage location k in month t (under states of nature s) (Mg)
$R_{bljt}/R_{bljt}(s)$	Amount of feedstock b sent from pellet station l to biorefinery location j in month t (under states of nature s) (Mg)

$S_{bjt}/S_{bjt}(s)$	Amount of feedstock b being convert to ethanol at biorefinery location j in month t (under states of nature s) (Mg)
U_{bjt}	Amount of ethanol being produced from biomass b at biorefinery location j in month t (Liter)

Acronyms

CLC,	Contracting cost for biomass
CBP	Biomass production cost
CST	Biomass storage holding cost
CPL	Pelleting cost
CTP	Transportation cost
CAP	Capital cost of biorefinery, storage and pellet plant