STUDIES ON COST MINIMIZING CELLULOSIC BIOFUEL SUPPLY CHAIN DESIGN

A Dissertation

by

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ABSTRACT

This study addresses optimal design and configuration of a supply chain for a lignocellulosic biorefinery. To do this, a comprehensive two-stage stochastic Mixed Integer Programming (MIP) model was developed and implemented to represent a multi-feedstock ethanol supply chain under feedstock yield uncertainty. The model minimizes the expected cost of construction and operation of the chain, choosing the facilities, feedstock production locations, monthly harvest, feedstock movement and handling, storage and refining activity. Two regional Texas case studies are conducted to examine the consequences of alternative supply chain elements and yield uncertainty. Additionally, the impact of using data resolution is studied.

The study finds that incorporation of yield uncertainty is important and that its inclusion doubles feedstock contracting, resulting in substantial feedstock dumping costs when above average yields arise. In addition, using multiple (rather than single) feedstocks substantially lowers costs when there is inherent seasonality of feedstock harvest. The findings also indicate that remotely located storage depots with associated pellet plants allow exploitation of geographically stranded feedstocks. Our results in the Texas High Plains show the corn stover collection area moves from an 80 km radius to a 200 km radius when pellets can be exported at $150 per mg. Finally, the results show that use of higher resolution data improves the estimates of transportation costs and alters the supply chain design.

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Contributors

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INTRODUCTION

The US Congress renewable fuel production goals under the 2007 Energy Independence and Security Act (EISA) reflect a desire to increase energy security and reduce the environmental impact of fossil-based liquid fuels. The EISA Renewable Fuel Standard (RFS) provisions aspire to have renewable fuel blending at the level of 136 billion liters per year (BLPY) by 2022. Of that target, 60.5 BLPY and 19 BLPY must come from cellulosic biofuel and advanced biodiesel, respectively.

Such a goal implies that lignocellulosic feedstock refining is expected to be a major industry. However, widespread use of lignocellulosic feedstocks at high volumes would raise substantial logistical challenges. For example, a 30-million-liter plant at a conversion rate of 300 L of ethanol per milligram would require 100,000 mg of material, or the equivalent of 277,780 large square bales of feedstocks such as switchgrass to ensure year-round operation of the production process. Due to the low energy density and per hectare yields, large areas and volumes would be needed. In particular, with a 10 dry mg per ha yield, the production area would need to be 100,000 ha, which would be widely distributed across the landscape. In such a case, bio-refineries would experience significant costs of assembling and transporting the lignocellulosic feedstock needed.

Previous studies highlight the high logistics costs and assert that these would impede the growth of the renewable fuel industry (Osmani and Zhang 2013; Osmani and Zhang 2014; Wang 2013). Estimates indicate that logistics can account for as much as 40% of the final product cost.

Studies also suggest that improved supply chain design could reduce logistical costs cost by 50% (An and Searcy 2012).

Additionally, most lignocellulosic feedstocks – such as switchgrass or corn stover – are not available consistently throughout the year, exhibiting strong seasonality in potential harvest times and requiring storage facilities to smooth out feedstock supply. Proper storage schemes and potential densifying processes could reduce deterioration of stored feedstock and the total supply chain cost. Kim (2011) studied deterioration rates of corn stover under alternative storage methods. He points out that if the carbon dioxide equivalent price is higher than $200 per mg, the indoor storage method could effectively reduce the deterioration of corn stover and greenhouse gas (GHG) emissions below that of outdoor storage. Mani et al. (2006) also points out that the feedstock loss, storage costs, and transportation costs could be further lowered by employing methods such as pelleting for densifying and moisture removal.

The findings of previous studies indicate that cost-reducing designs may be a major factor in making the industry viable, and a careful design of a total farm to biofuel supply chain must accommodate uncertain supply, seasonality, feedstock energy density, and possible pretreatments, among other factors. However, while many studies consider individual components of the total biofuel supply chain, few cover the full chain while considering uncertain yields. Most previous studies have tackled yield uncertainty by estimating the cost impact of selecting yield outcomes, such as a low productivity year. While understanding the impact of yield uncertainty is important, this does not suggest how to design the supply chain for improved system reliability or how to deal with the issue of excess supply under higher yields. This study simultaneously addresses uncertainty and total system design.

Another important area of study is the impact of data scale on the design results for the supply chain. Many previous studies address the design of cellulosic ethanol supply chains (Osmani and Zhang 2013; Marvin et al. 2012; Gold and Seuring 2011; Chen and Fan 2012; Gebreslassie, Yao and You 2012; Cundiff, Dias and Sherali 1997). However, most only use regional- or county-scale resolution due to either data availability or computational capacity. This potentially omits crucial information on distribution, location, and spatial density of feedstock. Ignoring such information can reduce the effectiveness of supposed "optimal" designs.

Objectives

The overriding objective of this work is to lower the cost of lignocellulosic-based renewable fuel by developing cost-minimizing supply chain designs. To achieve this, several activities are pursued:

- First, a regionally independent modeling framework is developed, which can be adapted to local characteristics that will help with supply chain design under yield uncertainty.
- Second, the model is implemented in the context of two case studies, reflecting regional characteristics, possible feedstocks, and yield uncertainty.
- Third, the model is used to investigate questions regarding the total supply chain design, involving the following:
    - The optimal location of the biorefinery
    - The optimal strategy for using feedstocks, including chosen locations, seasonal supplies, transport routes, storage, pelleting and refining
    - Optimal location and operation of remote versus centralized storage
    - Optimal location and operation of remote pelleting
    - Impact of accessing out-of-region pellet sale possibilities

- Cost implications when remote storage and pelleting are employed or excluded
- Impact of uncertain supply on supply chain design and cost
- Impact of alternative conversion rates
- Consequences of increased spatial resolution

Methodology

A mixed integer, two-stage stochastic, mathematical programming model was developed for lignocellulosic biofuel biorefinery supply chain design. The model minimizes the annualized cost of constructing and operating the supply chain, less the revenue from pellet exports, while meeting a production goal of a given volume of bioethanol. In particular, given parameters such as availability of feedstock, yield variability, capital cost of facilities, cost of feedstock production, harvesting, storage, and transport, the model develops cost-minimizing decisions on the following: a) the location of biorefinery; b) whether to use central storage, remote storage depots and pelleting facilities, and if so their optimal location; c) the area of supply region contracted and where in the region to do the contracting; d) the monthly amount of feedstock harvested; e) the monthly movement of feedstocks through chain, including possible storage and pelleting; f) the monthly quantity of pellets produced; g) quantity to store, place of storage, and months to store feedstocks and pellets; h) handing of feedstock yield shortfalls and excesses; i) level of pellet exports; and j) monthly feedstock choice for refining.

Case studies

Two case study implementations of the model were completed. These were chosen to represent different feedstock compositions and spatial distribution. In an East Texas case, wood residues and switchgrass are considered the main feedstocks. In a Texas High Plains case, agricultural residues from corn and sorghum production, along with switchgrass and energy sorghum, are considered. Additionally, fee

CHAPTER II

LITERATURE ON THE ECONOMICS OF BIOFUEL SUPPLY CHAIN

In this chapter, previous studies relating to lignocellulosic biofuel supply chain systems are reviewed. We focus on the scope of the studies, the type of model used, and the basic findings.

There is substantial interest in expanding production of lignocellulosic biofuel. Total ethanol production rapidly increased from 6.04 billion liters in 2000 to 55.9 billion liters in 2015 (USEIA, 2018). However, the expansion has almost exclusively involved starch-based or first-generation ethanol and biodiesel, with the lignocellulosic industry component or second-generation quantity lagging expectations. The EISA of 2007 contemplated production levels of 11.35 BLPY in 2015, while actual 2015 production was just 540.55 million liters per year (MLPY). Given the actual cellulosic ethanol production level is significantly behind the goal, a study of the supply chain emerged to help fill the gap and boost the cellulosic biofuel industry.

Research scope

Gold and Seuring (2011) note that the main reasons for careful design of biofuel supply chain are a) to keep feedstock cost competitive; and b) to ensure continuous supply of feedstock. To achieve these goals, supply chain designs must determine the following: a) the locations and capacity of biorefineries, storage depots, and pellet plants; b) the amount of contracted feedstock supply area; c) whether to use single or multiple feedstocks; and d) the type of refining technology to use. On the other hand, the chain design must also incorporate tactical issues that may vary from year to year, such as a) the amount of feedstock harvested, stored/preprocessed, pelletized and shipped; b) the level of biofuel produced; and c) the manner in which 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 that the cellulosic biofuel supply chain requires large amounts of lignocellulosic feedstock, problems such as the seasonality and sourcing of feedstock make it even more challenging to operate the cellulosic biofuel supply. 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 chain

When evaluating bio-energy supply chain, a systems perspective must be taken, encompassing feedstock resources, harvest, movement, storage, and conversion. However, local characteristics and the large number of possible combinations of these components make direct comparisons between different bioenergy systems difficult (Mccormick and Kaberger, 2007). One commonplace way of analyzing and comparing different biofuel supply chain designs is Mixed Integer Programming (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 the optimal supply chain design in nine Midwestern US states. The major components considered in the study include feedstock supply region, storage, and biorefinery. Agricultural residues from five different grains are considered feedstock sources and the supply of each agricultural residue was constant over the analysis period. According to the results of the study, the high availability of agricultural residue allows the Midwestern region to produce 17.7 BLPY ethanol. In addition, the proposed model helps to determine the location and capacity of biorefineries across the study region. Note that this study does not consider possible supply variation due to weather and the possible use of prepossessing procedures to utilize the stranded feedstock.

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 contains two major components: choice of supply region and location of biorefinery. Multiple woody feedstocks are considered, and the yield of feedstocks is assumed constant. The results indicate that a distributed system generates higher profits and is more flexible when facing varying demand than is the centralized system. However, no prepossessing procedure is considered in this study to discuss the possibility of exporting pellet to external market. County-level spatial data are used in the analysis, and all feedstock distribution conditions and transportation activity within the county are ignored.

Ekşioğlu et al. (2010) developed a deterministic MIP model to identify the impact of adding an intermodal facility into the biofuel supply chain to estimate the total production cost of the corn-base ethanol supply chain. The yield of corn is assumed to be constant and the major components included in the supply chain are supply region, storage, and biorefinery. The results indicate 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 chain. This study does not consider possible supply variations due to weather or the possible use of prepossessing procedure to utilize the strand feedstock. In addition, the study does not consider any prepossessing procedure or the possibility of exporting pellet to external markets. Furthermore, rather than finer resolution spatial data, county-level data are used in this study.

Zhang et al. (2016) developed a multi-transport-mode MIP model to address the supply chain design problem in Michigan. Choice of supply region, amount/location of local storage, and biorefinery location are the major components of the proposed supply chain. Multiple woody feedstocks are used as the main feedstocks and the supply of each feedstock is assumed constant. The results of the study identify the optimal number, capacity, and location of biorefineries and storage depots. They also provide information on harvesting plans, transportation mode in each route, amount of feedstock shipped between different nodes in each period, and inventory level change over time. No prepossessing procedure is considered to discuss the possibility of exporting pellet to external markets. County-level spatial data are used in the analysis and all feedstock distribution conditions and transportation activity within the county are 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. The yield of the sole feedstock (switchgrass) is assumed to be constant. They state that the average delivered cost of switchgrass could be significantly lowered by using the multimodal transportation system: from 0.705($ L) to 0.505 ($ L) when moving from a truck-only system to a mixed rail and truck system. The study also demonstrates that 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. However, the study only considers a single source of feedstock and assumes no yield variation. County-level spatial data are used and all feedstock distribution conditions and transportation activity within the county are ignored.

In addition to the MIP model, Khanna et al. (2011) examined the economically viable supply of agricultural feedstock at different feedstock price and the regional production pattern for each feedstock in the US. The 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 into the model. They note that 617-923 million mg of feedstock could be produced in 2030 at a feedstock price of $140 per mg and that 18 million ha of idle cropland or cropland pasture would be required to supply this amount of feedstock. Additionally, the study also notes that the price of feedstock must be very high to achieve anything like the often studied BTS production goal. This study focuses on the availability of feedstock and does not provide information on biofuel supply chain design. County-level spatial data are used and all feedstock distribution conditions and transportation activity within the county were ignored.

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

Finer scale data arising from a Geographical Information System (GIS) can be used to characterize the cellulosic supply chain. Wang et al. (2017) used 36 km^2 (6 km by 6 km) 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 costs and required equipment. Panichelli and Gnansounou (2008) and Zhang et al. (2016) examined potential wood harvesting areas and further estimated the availability of woody material in the county level of the study region.

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

Although GIS provides an alternative means of determining the distribution of feedstock and facility locations, the method did not usually provide detailed information on tactical decisions, such as monthly inventory level, process level, and amount of feedstock transported for each feedstock type, since the focus of this type of approach is processing spatial data. Thus, GIS approaches usually require other methods, such as optimization, to determine the solutions to the tactical decisions to provide complete information to decision-makers.

Modeling of biofuel supply chain with uncertainty

Another key issue to be considered in the biofuel supply chain analysis is uncertainty. The works reviewed in the previous section assume that the supply of each feedstock is deterministic. However, the supply of feedstock is usually uncertain and subject to weather conditions. Therefore, although these studies identify key factors affecting the objectives, the results, if not interpreted correctly, may lead to problematic decisions when designing a supply chain. Thus, given that a large amount of feedstock is required to satisfy a commercialized level biorefinery, the incorporation of the uncertainty into the analysis framework is crucial for providing accurate information on supply chain setup and logistics decisions, as well as cost estimates. The literature examining the effects of uncertainties on configuration of the biorefinery supply chain are reviewed below.

Cundiff et al. (1997) conducted the earliest research that we found on the issue. This study takes an approach that minimizes the expected delivery and capacity expansion costs of switchgrass under yield uncertainty for a biorefinery location in Virginia. The researchers examined optimal logistic decisions under four different switchgrass yield conditions. Specifically, the model considers four different switchgrass availabilities, and the results show that the total cost of delivering switchgrass ranged from \$13 to \$15 per dry mg, with average costs of \$8-10 per dry mg for transportation, \$3 per dry mg for loading, and \$2 per dry mg for storage. The study does not consider land contracting, feedstock pre-processing, or ethanol conversion techniques. Although the results provide solutions to the questions of different feedstock supply, the approach inevitably suffers problems of dimensionality and certainty. The required computation ability increases exponentially when analyzing and organizing data in high-dimensional spaces. Thus, in addition to run model multiple time for each potential outcome, a multi-stage optimization model should be considered.

Chen and Fan (2012) developed a stochastic, two-stage MIP that utilizes multiple waste products for feedstocks. The entire supply chain from feedstock production to biofuel supply is considered. The study's main analyses address the comparative performance of the stochastic and deterministic model versions, ignoring or considering demand and supply uncertainties. The results show that the production cost of ethanol can be as low as $0.32 per L through optimal planning of the entire biofuel supply chain. The study was conducted at a county-/city-level centroid. For uncertainty, rather than using an empirical distribution from historical data, the probability used to reflect the feedstock supply fluctuation is assumed to be equal in 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 identify the optimal number, capacity, and location of the biorefinery and the selection of conversion technologies in the state of Illinois. Agricultural residue, woody materials, and energy crops are considered as inputs for the biorefinery in the study. The study considers feedstock supply region, storage, and biorefinery as essential components in the proposed supply chain. Although it provides information on selecting the biorefinery sites and managing the risk, the study assumes that the storage would be built on the same spot of biorefinery and does not consider remote depot or pellet plants for capturing stranded feedstock.

Azadeh et al. (2014) developed a stochastic MIP to simulate the supply and transportation of multiple types of feedstock to the biorefinery. The sources of uncertainty in the study are market price of biofuel and the yield fluctuation of feedstock supply. In addition, risk preference is included. The model considers only three components of biofuel supply chain: supply region, biorefinery, and ethanol demand points (e.g., biofuel blender). The major inputs in this study include agricultural residues, woody materials, and municipal wastes. The results identify the optimal locations of the biorefinery and storage, and they also provide solutions to the logistics questions on optimal inventory levels and transportation routes. However, the study does not consider uncertain supply in its analysis and thus does not account for a situation in which shortfall of feedstock occurs.

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 is introduced on crop yields and ethanol prices. The components included in the study are supply region, preprocessing station, and biorefinery, with storage included in the preprocessing station. The crop yield uncertainty is represented via a probability distribution based on historical data of energy crops. In the study, switchgrass is considered the primary feedstock, while corn stover and wheat straw are secondary feedstocks. When the switchgrass yield is high, less crop residue is used, and vice versa. The study highlights that the mean values of stochastic parameters have a significant impact on the second-stage decisions, while biorefinery location is insensitive to uncertainties. The study does not estimate the joint probability distribution of multiple feedstock supply, and again, the analysis was conducted at the county or city centroid level.

Marufuzzaman et al. (2014) developed an MIP model to address the biodiesel supply chain design, minimizing the delivery costs of biodiesel and carbon footprint under stochastic feedstock supply and technology improvement. Sludge was the major input for producing biodiesel, and this study considers the sludge supplier, biocrude plant, diesel plant, and customer to be the main components of the proposed supply chain. The results identify the number, capacity, and locations of biocrude plants, as well as the optimal transportation route for sludge and biodiesel. The study was conducted on a county-level scale, which should be sufficient, given that sludge production is usually point source. However, higher spatial resolution is needed when dealing with agricultural feedstock, since the missing link to the feedstock distribution information could lead to biased solutions in the logistics system.

Zhao (2017) studied design issues in the cellulosic biofuel supply chain. He developed a stochastic, two-stage mixed integer model to identify biorefinery, storage, and preprocessing facility locations across Texas. Specifically, he considers corn stover, switchgrass, and woody to be the feedstock when the model operates on a county-level scale. The results indicate that biorefineries are optimally located in dense feedstock production areas. The use of multiple feedstocks is seen to decrease the impact of seasonality and the need for storage. The study was conducted on a county-level scale, which again could lead to biased solutions in the logistics system due to the missing information on feedstock distribution. For uncertainty, rather than using an empirical distribution from historical data, the probability used to reflect the feedstock supply fluctuation is assumed to be equal for 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 consider pelleting to be a means of improving the use of stranded feedstock by reducing the size and moisture content of the feedstocks. Additionally, these studies were conducted at the county level, ignoring within-county heterogeneity in feedstock distribution and required transportation. Furthermore, most of the studies looked at single feedstock uncertainty in yield distributions with the distributions formed by regression over historical records or by simple assumptions, such as a uniform distribution. When multiple feedstocks are present, no study addresses the joint distributions, including correlations between crops.

To extend the existing work, this study developed an MIP model based on a sub-county, GIS-based feedstock supply and examined the impact of key factors of uncertainty, pelleting, storage, and conversion technology on the optimal supply chain design, logistics decisions, and system costs. Additionally, this study derived an empirical joint feedstock yield uncertainty distribution based on the historical data, reflecting the correlation of crops. Pelleting possibilities were added to the model to examine economic feasibility and its impact on the optimal supply chain design, logistics decisions, and total cost.

CHAPTER III

SUPPLY CHAIN DESIGN MODEL

This chapter concerns the conceptual model developed for supply chain design and the empirical method used to develop yield distributions that represent the joint uncertainty in the yields of the multiple feedstocks.

Estimating the land that could be employed and the available feedstock thereon, plus the associated feedstock movement and facility placements, can be challenging. At the end of this chapter, the concept of GIS-supported procedures used to process county-level feedstock supply into finer spatial scale supply is described.

Deterministic model development

An MIP model, which contains both continuous (material handling) and discrete (facility choice and location) variables, was developed to represent the supply chain and investments in facilities. The MIP model minimizes the total capital and operating costs across the whole biofuel supply chain less revenue from pellet exports, while delivering a given volume of feedstock to the biorefinery. The solutions produced by the MIP model identify the optimal location of the biofuel refinery, along with the locations and capacity of storage and pelleting facilities. The model considers a number of elements, including the following:

- Location of storage depots, biorefinery, and pelleting plants
- Capital and operating costs of facilities
- Rate of conversion of feedstock to ethanol
- Use of multiple versus single feedstocks

- GIS-based land parcels for feedstock harvest availability at the county or sub-county level
- A priori contracting for some feedstocks on a per hectare basis
- Ex-post payment for contracted feedstock removal on a per milligram basis by state of nature
- Whether to use each land parcel to supply feedstock by feedstock and land parcel
- Feedstock yield uncertain states of nature inclusion or non-inclusion
- Joint feedstock probability distribution of yields
- Monthly feedstock harvest by parcel and by state of nature that falls within feedstock-specific, allowable, harvest timing windows
- Cost incurring dumping of contracted excess feedstock by state of nature
- Optimal feedstock movement by month and state of nature
- Monthly feedstock movement by origin and destination, feedstock type, and state of nature
- Monthly storage additions/withdrawal, plus monthly deterioration by feedstock and state of nature
- Monthly pellet production by state of nature and feedstock used
- Monthly pellet exports at a sale price by state of nature
- Monthly choice of feedstock to refine by state of nature

In choosing between these items, the model minimizes total production plus annualized capital costs of the system less revenues from pellet exports. The model was built under deterministic conditions and then expanded into a two-stage stochastic model to consider how strategic operating decisions vary when uncertainty is considered.

Supply chain scope

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

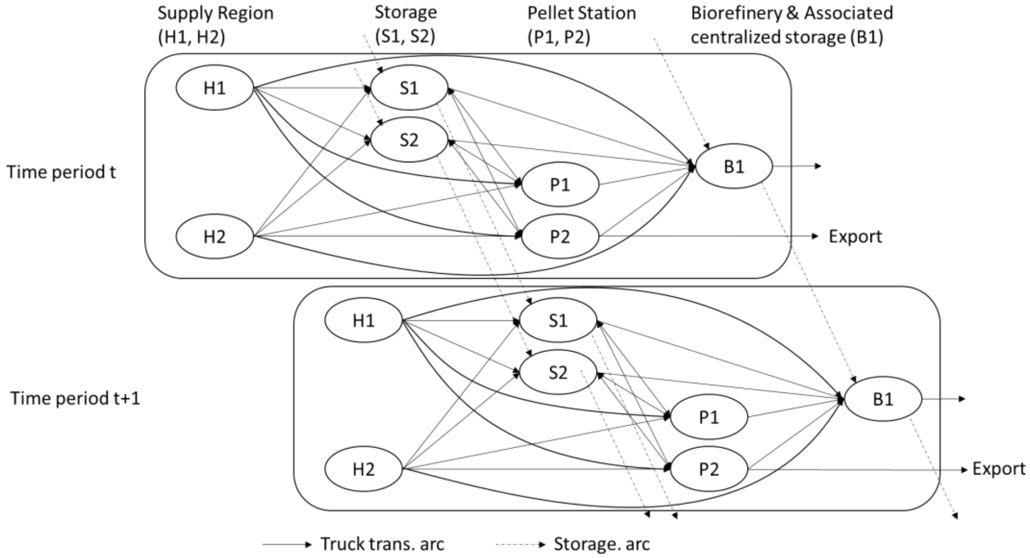

Figure 1 Conceptual framework of the supply chain. Adapted with permission from "Analyzing Impact of Intermodal Facilities on Design and Management of Biofuel Supply Chain" by Sandra D. EkşioğLu, Song Li, Shu Zhang, et al, 2010. Transportation Research Record, Volume 2191, pp. 144-151, Copyright [2010] by SAGE Publications.

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 movement defining components: feedstock supply locations; intermediate storage depots; pelleting stations; and biorefinery, possibly integrated with storage.

In terms of feedstock supply, the supply chain first involves the strategic decision of the lands to be contracted to produce feedstock. This involves payments to the farmer on a per hectare basis to gain participation (deferring the costs of planting) and per milligram of feedstock removed. The operational decisions are then made regarding where and when harvest is completed for each feedstock type, by month, when the month falls in the harvest window for that feedstock. Different harvesting and collection systems are used for different feedstock. Once harvested, it is moved to the edge of the fields and then transported to remote storage depots for later use, to pelleting stations to reduce size and moisture and improve storage capability, or directly to the biorefinery site for refining or storage.

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

In addition to storing biomass in a baled form, feedstock can be sent to pellet stations, where excess moisture is removed and the size is reduced, increasing energy density. Pellets are then stored, shipped, or exported by month. However, to assess the desirability of pelleting, it is important to weigh its lower transport costs per unit energy (due to lower moisture content and higher energy density), along with its export possibilities, against the capital and operating costs of the pelleting plant.

Finally, the transport of feedstock to the depots/pelleting stations/biorefinery is assumed to be carried out by truck, as 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.

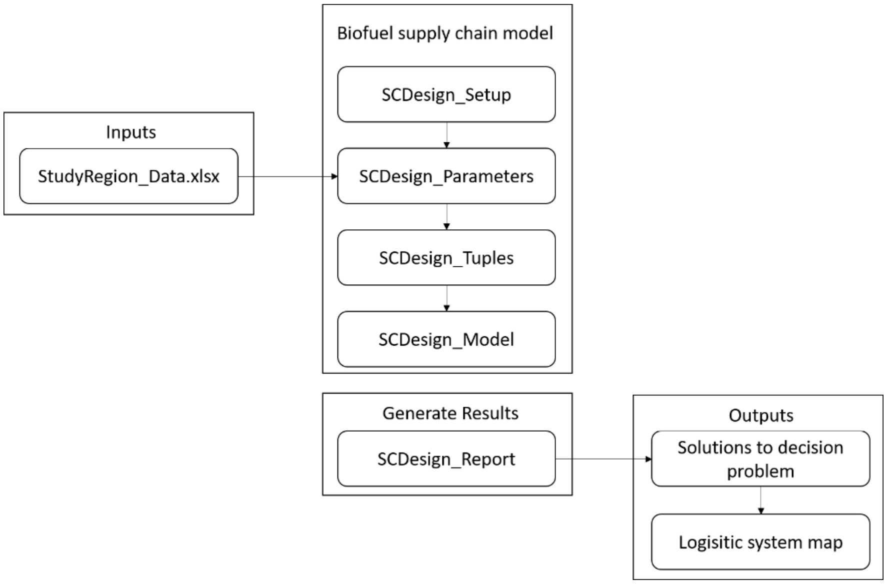

Figure 2 Basic framework of the model

The MIP biofuel supply chain model is programmed using the General Algebra Modeling System (GAMS) (GAMS Development Corp. 2019) and includes five components: sets, parameters, tuples, model, and report-writing. The components of the model are as follows:

- 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 reports script compiles the optimal solutions into a set of reports that inform an analyst on the aspects of the solution

The linear programming model component determines production on the contracted lands, the amount of each feedstock harvested, the amount of feedstock sent to intermediate storage depots, the amount of feedstock 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 produced, and the transportation movements of feedstocks by type in raw and pelleted form. The model minimizes total cost associated with construction of storage, pelleting, and the biorefinery, as well as feedstock contracting and the variable costs of production, storage, pelleting, feedstock conversion, and transportation, less the revenues from pelleting. In other words, the key parameters used in this study include the following: a) feedstock production/harvesting 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, pelleting plants, and biorefinery; e) costs of monthly storage by feedstock type and the associated cost of storage loading and unloading; f) cost of capacity for pellet manufacture; g) transport costs for both raw feedstocks and pelleted 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 integer aspect of the model resolves the location of the biorefinery, storage depots, and pelleting sites. The continuous aspect of the model determines the following: a) the area of energy crops, crop residues, and other locally available feedstocks in the supply region contracted; b) the amount of feedstock harvested; c) the amount of feedstocks and pellets transported between different supply chain components; d) the usage of feedstocks in refining; e) seasonal storage by type of feedstock and pellets in remote storage depots and in central storage; f) the quantity of pellets produced; and g) the volume of pellets exported.

Mathematical formulation

A list of model sets, parameters, and decision variables is given in Appendix A. As mentioned above, the first model version discussed assumes deterministic feedstock supply and a given level of ethanol production. The objective function minimizes the annual total capital and operating cost of the supply chain, involving a) contracting costs for the energy crops and crop residues, CLC; b) feedstock production costs, CBP; c) storage holding costs, CST; d) pelleting costs, CPL; e) transportation costs, CTP; f) capital cost of constructing facilities at the biorefinery, pelleting site, and storage depots, CAP; g) cost of dumping additional biomass feedstocks, $DUMP$; and h) revenue from exporting the pellet, $PLEX$. The total objective function including all these components is expressed in Equation (1).

$$Min\, CLC + CBP + CST + CPL + CTP + CAP + DUMP + EX \qquad (1)$$

Each component is mathematically described as follows:

$$CLC = \sum_{bi} c_{bi} M_{bi} \tag{2}$$

$$CBP = \sum_{bit} \alpha_b N_{bit} \tag{3}$$

$$CST = \sum_{bkt} \beta_b Q_{bkt} + \sum_{bjt} \beta_b Q_{bjt} \tag{4}$$

$$CPL = \sum_{blt} \gamma_b R_{blt} \tag{5}$$

$$\begin{aligned} CTP = & \sum_{bijt} \left(\delta_b + \epsilon_b \times D_{ij}\right) OBR_{bijt} \\ & + \sum_{bikt} (\delta_b + \epsilon_b \times D_{ik}) OST_{bikt} \\ & + \sum_{bilt} (\delta_b + \epsilon_b \times D_{il}) OPL_{bilt} \\ & + \sum_{bkjt} \left(\delta_b + \epsilon_b \times D_{kj}\right) PBR_{bkjt} \\ & + \sum_{bklt} (\delta_b + \epsilon_b \times D_{kl}) PPL_{bklt} \end{aligned} \tag{6}$$

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

$$DUMP = \sum_{bit} d_b W_{bit} \tag{8}$$

$$EX = \sum_{lt} ProfPLEX_{lt} \tag{9}$$

Equation (2) computes the total cost of contracting land, paid on a per hectare basis, where c_{bi} represents the per hectare cost of contracting land for feedstock type (b) at location (i). In this study, c_{bi} 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_{bi} is defined as the per hectare payment to the land owner that establishes the option of later collecting crop/woody residues. M_{bi} is the amount of land in hectares contracted for supply of feedstock (b) at location (i).

Equation (3) computes the cost of feedstock harvest. The cost of harvesting each milligram of feedstock type (b) is α_b , assumed to be invariant by location and time of year. The variable N_{bit} gives the milligram of feedstock type (b) harvested at location (i) in month (t).

Equation (4) computes the total cost of storing of feedstock, where β_b is the per milligram cost of storing feedstock type (b), assumed to be invariant by storage depot location and month. Q_{bkt} is the amount of feedstock (b) stored at storage depot (k) in month (t), and Q_{bjt} is the amount of feedstock (b) stored at biorefinery (j) in month (t).

Equation (5) computes the total cost of pelleting feedstock. Note that γ_b is the pelleting cost per milligram of raw feedstock (b) that is pelleted and assumed to be invariant, by pelleting location and month. R_{blt} is the mg of feedstock (b) that is pelleted at pelleting plant (l) in month (t).

Equation (6) computes the transportation costs within the supply chain, where OBR_{bijt} is the amount of feedstock (b) 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 per milligram feedstock (b) per kilometer traveled. OST_{bikt} is the amount of feedstock (b) 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) 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) 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). Finally, PPL_{bklt} is the amount of feedstock (b) 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) computes 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), 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, or a pellet station is built at location (j), location (k), and location (l), respectively.

Equation (8) computes the cost of dumping additional biomass. The cost dumping of each mg of feedstock type (b) is d_b , assumed to be invariant by location and time of year. The variable W_{bit} gives the amount of feedstock type (b) dumped at location (i) in month (t).

Equation (9) reflects the profit of exporting pellet. The unit profit of exporting each mg of pellet is $Prof$. The variable $PLEX_{lt}$ is the mg of pellet exported at location (l) in month.

The model is optimized subject to a set of constraints portrayed within Equations (10-20).

$$\sum_{t \in h(b)} N_{bit} = M_{bi} \; for \; all \; b, i \tag{10}$$

Algebraically, Equation (10) computes the area of feedstock (b) harvested in location (i), N_{bit}, across the appropriate possible harvest months (t) for the feedstock ($t \in h(b)$), requiring the sum of the hectares harvested across all relevant harvest months to be equal to the amount of contracted land in location (M_{bi}). Equality is required because we assume that all feedstock is harvested and then some dumped, thus all must be dealt with.

$$\sum\nolimits_{j} OBR_{bijt} + \sum\nolimits_{k} OST_{bikt} + \sum\nolimits_{l} OPL_{bilt} + W_{bit} = a_b N_{bit}\ for\ all\ b, i, t \tag{11}$$

Equation (11) ensures that for each feedstock (b) transported out of this supply region (i) in each month (t), the sum of the amounts sent to the refinery (OBR_{bijt}) at location (j), to storage (OST_{bikt}) at location (k), and to pelleting (OPL_{bilt}) at location (l), plus the amount dumped (W_{bit}) must equal the yield of the feedstock (a_b) multiplied by the area harvested N_{bit}. This means that the amount of feedstock of type (b) either shipped out or dumped is equal to that produced and harvested, requiring excess feedstock to be handled in the harvest months for this feedstock $t \in h(b)$. In this study, there is no on-site storage location. It is noted that, empirically, for some feedstocks, the dumping cost can be very low, and even zero, if the feedstock can be abandoned to decompose in the field (as is the case for some crop residues). Alternatively, we may assume that it simply waits on-site for pickup, as in the case of some woody materials. In the rest of the model, for notational simplicity, we do not use the $t \in h(b)$ restriction to signify that incoming shipment and dumping only occurs in the harvest months (this is implemented in the GAMS version).

$$\begin{aligned} &Q_{bkt} + (\sum\nolimits_{j} PBR_{bkjt} + \sum\nolimits_{l} PPL_{bklt})_{b \neq pellet} \\ &\qquad \leq (1 - \omega_b) Q_{bk,t-1} \\ &\qquad + \sum\nolimits_{i} OST_{bikt} + (\sum\nolimits_{l} PLST_{blkt})_{b=pellet}\ for\ all\ b, k, t \end{aligned} \tag{12}$$

Equation (12) balances storage by month. Specifically, the amounts of feedstock (b) stored at and shipped out from storage location (k) at (t) must not be greater than the amount of storage carried over from the previous month, adjusted for the storage loss (ω_b) and the new incoming supply. Outgoing shipments can go to either biorefinery location (j) or pelleting location (l). The variable PBR_{bkjt} gives the volume of feedstock (b) going from storage location (k) to biorefinery location (j) 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) held over from the previous month is represented by $Q_{bk,t-1}$, while $Q_{bk,t}$ is the material placed in storage that will be held over to the following month. Incoming shipments of feedstock (b) from supply location (i) to storage location (k) during month (t) is represented by OST_{bikt}. $PLST_{blkt}$ represents the shipment of pellet from pellet plant (l) to storage (k) during month (t). Additionally, there is a deterioration rate, ω_b, which reduces the amount of carryover storage.

$$Q_{bjt} + S_{bjt} \leq (1 - \omega_b)Q_{bj,t-1} + (\sum\nolimits_i OBR_{bijt})_{b \neq pellet} + (\sum\nolimits_k PBR_{bkjt} + \sum\nolimits_l PLBR_{pellet,ljt})_{b=pellet} \; for\ all\ b, j, t \tag{13}$$

Equation (13) is a similar supply-demand balance constraint for the feedstock at refinery location (j). There, the refinery usage of feedstock (b) during the month (t), plus the amount stored, must be less than 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 the pellet from pelleting site (l). Here, $Q_{bj,t-1}$ represents the storage of feedstock (b) at biorefinery location (j), carried over from month (t-1), and $Q_{bj,t}$ is the current amount stored into the following month. S_{bjt} is the volume of feedstock (b) used for processing at biorefinery location (j) during month (t), and the incoming transport is represented by OBR_{bikt}, PBR_{bkjt} and

$PLBR_{bljt}$[1] , which give the amount of feedstock (b) sent to biorefinery location (j) from supply region (i), from storage location (k), and from pelleting location (l), respectively, at month (t).

$$\left(\sum_{k} PLST_{lkt} + \sum_{j} PLBR_{ljt}\right) + PLEX_{lt} \leq \sum_{b}\left(\left(\sum_{i} OPL_{bilt} + \sum_{k} PPL_{bklt}\right) \times \kappa_b\right) \; for\ all\ l, t \tag{14}$$

Equation (14) is a supply-demand balance for pellets at pelleting location (l) during month (t). It limits usage to less than or equal to the incoming supply, multiplied by the pelleting yield. Here, the right-hand side of the equation gives the supply, which is equal to the pelleting yield for feedstock (b) (κ_b), multiplied by the volume of incoming feedstock. In particular, OPL_{bilt} is the volume of incoming feedstock type (b) from supply region (i), while PPL_{bklt} is the incoming amount from storage location (k). On the left-hand side of the equation, we have the disposition of the pellets, going to storage location (k), the biorefinery at (j), or export by month (t). There, $PLST_{lkt}$ is the volume of pellets sent out from pelleting location (l) to storage location (k). $PLBR_{ljt}$ represents the quantity of pellets shipped to biorefinery location (j). $PLEX_{lt}$ represents the quantity of pellets exported from pelleting location (l), if export is allowed. This assumes that items are immediately pelleted, when received from storage, allowing a delay between harvest and pelleting. Also, while we do not explicitly deal with storage at the plant, we only allow pelleting at storage locations; thus, (k=l) concerns storage at the pelleting location.

$$U_{jt} \leq \sum_{b} \lambda_b S_{bjt} \; for\ all\ j, t \tag{15}$$

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

Equation (15) is the supply-demand balance for ethanol produced at biorefinery location (j). It states that the variable giving the amount of ethanol produced at this location (U_{jt}) during (t) is less than or equal to the sum arising across the feedstock used.[2] Here, the amount of feedstock (b) in mg put through the refinery in this month is represented by S_{bjt}, and the conversion rate of feedstock to ethanol is given by λ_b.

$$G_t X_j \leq U_{jt} \; for \; all \; j,t \tag{16}$$

Equation (16) specifies the monthly (t) minimum volume of ethanol to be produced each month if the biorefinery is constructed. The parameter G_t gives the required amount in month (t) and is only a binding requirement if the biorefinery is constructed as signified by the binary variable (X_j) for refinery construction, equaling one. U_{jt} is the monthly (t) amount of ethanol produced at the biorefinery location.

$$\sum\nolimits_b Q_{bkt} \leq F_k Y_k \; for \; all \; k,t \tag{17}$$

$$\sum\nolimits_b Q_{bjt} \leq F_j X_j \; for \; all \; j,t \tag{18}$$

Equations (17) and (18) impose capacity constraints on the available storage: namely, the sum of feedstock (b) stored at a location, which in Equation (17) is storage location (k), and in Equation (18) is biorefinery location (j). The storage capacities in these locations are F_k and F_j, respectively, and these are multiplied by integer variables depending on whether storage location (k) and biorefinery location (j) are in fact constructed.

$$H_t \leq \sum\nolimits_b Q_{bjt} \; for \; all \; j,t \tag{19}$$

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

Equation (19) concerns the required amount of backup supply in storage at each biorefinery, where H_t is the minimum requirement in time (t).

$$\sum_j X_j \leq 1 \tag{20}$$

Equation (20) limits the number of bio refineries constructed to one.

Incorporating yield uncertainty – the stochastic model

Yield uncertainty is neglected in many existing studies. This is certainly striking, 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 to be contracted and would not respond to situations in which excess feedstock is produced. Simply put, the design of the biofuel supply chain must be accommodating of yield fluctuation and have planned procedures for responding to shortages and surpluses. Gebreslassie et al. (2012) argue that a deterministically based supply chain design may not work under conditions of shortage and is likely to generate a suboptimal, poorly performing model. Here, we extend the above deterministic model to account for yield uncertainty. Other uncertainties could also be built-in, but yield uncertainty is the only one to be addressed in this study.

Development of a probability distribution for feedstock yields

The first step in developing an uncertainty-accommodating model involves construction of a probability distribution for feedstock yield. This was achieved based on historical yields of associated crops that were de-trended using a regression. The yield data used in this study were retrieved from USDA NASS Quick Stats (USDA 2018). Due to a lack of data, wheat data are used as a proxy for switchgrass yields. Yields over time generally exhibit a trend reflecting technical progress, climate change, and other factors. Regression was used to estimate that trend.

The trend was then removed, with the variations above and below it forming the yield uncertainty probability distribution. Namely, the residuals from the regression equation estimated over historical yields were interpreted as equally likely crop yield variations in a yield expectation. The functional form of the estimated regression appears in Equation (21):

$$A_{bt} = \beta_{0\mathrm{b}} + \beta_{1\mathrm{b}} t + e_{\mathrm{bt}} \tag{21}$$

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 (e_{bt}) to the regression projection for each year is calculated to reflect the proportional deviation of crop yields from their predicted values. We then arrayed these proportional deviations from low to high and grouped them into intervals, each with a probability equaling the observations falling into that interval and divided by the number of historical observations. The mean of each interval was used as a representative value for the observations falling into that interval. This procedure forms a single feedstock distribution, with multiple feedstocks presented, so a joint distribution had to be formed.

The joint probability distribution was formed using historical observations. The yield distributions for each feedstock were divided into four yield intervals: bad, low, fine, and good. The ‘bad yield’ level for corn stover refers to any year with a yield deviation of 20.4% or more below its expected yield level, while the ‘low yield’ level includes those years with a deviation falling between 20.4% and 9% below the mean. Similarly, the ‘fine yield’ level refers to a deviation of between 9% below and 2.3% above the mean; and the ‘good yield’ level refers to the cases when the yield was above +2.3%. In turn, the joint distribution categorizes each historical year in terms of the combination of shocks for each of the feedstocks. In the case of Texas High Plains, to be studied in Chapter 4, there are three crops: when each has four possibilities, we have 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 estimated by dividing the number of observations in each bucket by the total number of observations. Table 1 below lists the probabilities for each state of nature used in the Texas High Plains case study.

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

Next, we formed 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 follows the classic Dantzig two-stage aircraft scheduling model. The first stage concerns state-of-nature-independent strategic decisions, such as 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 dispositions.

The objective function gives the first-stage capital and contracting costs, plus the probabilistically weighted tactical decision costs, as described in Equation (22):

$$Min\ CAPCON + \sum\nolimits_{s} Prob_s \times (CBP(s) + CST(s) + CPL(s) + CTP(s) + DUMP(s) + EX(s)) \tag{22}$$

Equation (22) includes terms for strategic decisions on capital and contracting ($CAPCON$), plus state of nature (s) dependent tactical decisions of feedstock harvest and removal, biorefinery processing (CBP), storage (CST), pelleting (CPL), transport (CTP), dumping ($DUMP$), and profit from exporting pellet (EX). The components of this are formed as follows:

$$CAPCON = \sum\nolimits_{j} \eta_j X_j + \sum\nolimits_{k} \rho_k Y_k + \sum\nolimits_{l} \phi_l Z_l + \sum\nolimits_{bi} c_{bi} M_{bi} \tag{23}$$

Equation (23) calculates the 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 $\sum_{bi} c_{bi} M_{bi}$ across the land area alternatives (i) and feedstock alternatives (b). It is noted that these are all chosen independent of the state of nature. In other words, these choices are made and their costs locked in before the yield state is known: they are irreversible and not modifiable under individual yield states. Thus, one cannot have a different amount or location of biorefinery, storage depot, pelleting plant, or contracted land under each state of nature; rather, the same is shared by all. Here, η_j is the annualized capital cost of constructing biorefinery facility (j), while ρ_k and ϕ_l are the annualized capital cost of constructing the storage depot at alternative (k) and at pelleting plant alternative (l). Additionally, c_{bi} 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 a hectare of feedstock type (b). X_j, Y_k, and Z_l are binary decision variables, which indicate whether a biorefinery, a depot, or a pelleting location is built. M_{bi} represents the amount of land contracted for production of feedstock (b) and location (i).

For the second stage variables, an additional subscript, (s), is introduced to represent the yield outcome within the stochastic model. They are weighted by the probability (Probs).

$$CBP(s) \quad = \sum\nolimits_{bit} \alpha_b N_{bit}(s) \ for\ all\ s \tag{24}$$

Equation (24) calculates the harvest cost of feedstock by state of nature. Therein, α_b is the cost of harvesting one mg of type (b) feedstock, while $N_{bit}(s)$ is the amount of feedstock (b) harvested from parcel (i) in month (t) under state of nature (s).

$$CST(s) \quad = \sum\nolimits_{bkt} \beta_b Q_{bkt}(s) + \sum\nolimits_{bjt} \beta_b Q_{bjt}(s) \ for\ all\ s \tag{25}$$

Equation (25) calculates the cost of storing feedstock under state of nature (s), where β_b is the cost of storing type (b) feedstock and $Q_{bkt}(s)$ and $Q_{bjt}(s)$ are the amount of feedstock (b) stored at depot (k) and biorefinery (j) in month (t) under state of nature (s), respectively.

$$CPL(s) \quad = \sum\nolimits_{blt} \gamma_b R_{blt}(s) \ for\ all\ s \tag{26}$$

Equation (26) calculates the total cost of pelletizing feedstocks with γ_b , giving the pelleting cost per milligram, and $R_{blt}(s)$ is the quantity of pellets derived from feedstock (b) at pelleting location (k) in month (t) under state of nature (s).

$$CTP(s) = \sum\nolimits_{bijt} \left(\delta_b + \epsilon_b \times D_{ij}\right) OBR_{bijt}(s) \tag{27}$$

$$+ \sum\nolimits_{bikt} (\delta_b + \epsilon_b \times D_{ik}) OST_{bikt}(s)$$

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

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

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

Equation (27) calculates the transportation costs in the supply chain, under state of nature (s), where $OBR_{bijt}(s)$ is the amount of feedstock (b) 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 per milligram feedstock (b) per kilometer traveled. $OST_{bikt}(s)$ is the amount of feedstock (b) 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) 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) 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). Finally, $PPL_{bklt}(s)$ is the amount of feedstock (b) 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).

$$DUMP(s) = \sum_{bit} d_b W_{bit}(s)\ \ for\ all\ s \tag{28}$$

Equation (28) calculates the cost of dumping additional biomass. The cost dumping of each milligram of feedstock type (b) is d_b and assumed to be invariant by location and time of year. The variable $W_{bit}(s)$ gives the amount of feedstock type (b) dumped at location (i) in month (t) under state of nature (s).

$$EX = \sum_{lt} Prof PLEX_{lt}(s) \ for\ all\ s \tag{29}$$

Equation (29) reflects the profit of exporting pellet. The unit profit of exporting each milligram of pellet is $Prof$. The variable $PLEX_{lt}(s)$ gives the milligram of pellet exported at location (l) in month (t) under state of nature (s).

The model is again optimized with respect to constraints expressed in Equations (30-40).

$$\sum_{t\in h(t)} N_{bit}(s) = M_{bi} \ for\ all\ b, i, s \tag{30}$$

Equation (30) requires the sum of land harvested of feedstock type (b) in supply region (i) across eligible harvest times (t) to be equal to the amount of contracted land for feedstock (b) (M_{bi}). This constraint is defined for each state of nature, allowing different harvest timing depending on yields, but requiring all contracted land to be harvested under each state of nature.

$$\sum_{j} OBR_{bijt}(s) + \sum_{k} OST_{bikt}(s) + \sum_{l} OPL_{bilt}(s) + W_{bit}(\mathrm{s}) \\ = a_{bs} N_{bit}(s) \ \forall b, i, t \in h(t), s \tag{31}$$

Equation (31) ensures that for each state of nature (s), the amount of feedstock (b) transported out from supply region (i), plus that dumped, equals the harvested area of feedstock (b) multiplied by the yield outcome for state of nature (s) (a_{bs}). The constraint is defined for each state of nature (s) during the relevant harvest periods for this feedstock ($t \in h(t)$). This again states that all the feedstock must be handled.

$$Q_{bkt}(s) + \sum_{j} PBR_{bkjt}(s) + (\sum_{l} PPL_{bklt}(s))_{b \neq pellet} \tag{32}$$

$$\leq (1 - \omega_b) Q_{bk,t-1}(s) + (\sum\nolimits_{i} OST_{bikt}(s))_{b \neq pellet}$$

$$+ (\sum\nolimits_{l} PLST_{blkt}(s))_{b = pellet} \; \forall b, k, t, s$$

Equation (32) calculates the stored feedstock of type (b) for each month and 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.

$$Q_{bjt}(s) + S_{bjt}(s) \tag{33}$$

$$\leq (1 - \omega_b) Q_{bj,t-1}(s)$$

$$+ (\sum\nolimits_{i} OBR_{bijt}(s))_{b \neq pellet} + (\sum\nolimits_{k} PBR_{bkjt}(s)$$

$$+ (\sum\nolimits_{l} PLBR_{bljt}(s)))_{b = pellet} \; \forall b, j, t, s$$

Equation (33) similarly calculates feedstock at the refinery. There, at biorefinery location (j), the sum of feedstock (b) converted into ethanol in month (t) and the feedstock stored into the following 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 from pelleting locations ($PLBR_{bljt}$) in month (t) and the feedstock carried in from storage location (k) in the previous month, adjusted for spoilage again for each state of nature.

$$\sum\nolimits_{k} PLST_{lkt}(s) + \sum\nolimits_{j} PLBR_{ljt}(s) + PLEX_{lt}(s) \leq (1-\kappa_a) \times \left(\sum\nolimits_{bi} OPL_{bilt}(s) + \sum\nolimits_{bk} PPL_{bklt}(s)\right) \ \forall\, l,t,s \tag{34}$$

Equation (34) balances pellets out and feedstocks in at pelleting location (l) in month (t), specifying that 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 loss.

$$U_{jt}(s) \leq \sum\nolimits_{b} \lambda_b S_{bjt}(s) \ \forall\, j,t,s \tag{35}$$

Equation (35) is the ethanol supply-demand balance constraint at biorefinery location (j) and it holds the variable for total ethanol manufactured ($U_{jt}(s)$) from all feedstocks to be less than the refining yield. The refining yield is the amount of processing activity for feedstock (b) under state of nature (s) ($S_{bjt}(s)$) , multiplied by the conversion rate (λ_b). The constraint is defined for each refinery location (j), month (t), and state of nature (s).

$$G_t X_j \leq U_{jt}(s) \ \forall\, \mathrm{j},t,s \tag{36}$$

Equation (36) requires production of a minimum amount of ethanol in each month that is equal for each state of nature at each potential biorefinery location and is only binding when the binary variable for construction of that refinery is one.

$$\sum\nolimits_{b} Q_{bkt}(s) \leq F_k Y_k \ \forall k,t,s \tag{37}$$

$$\sum\nolimits_{b} Q_{bjt}(s) \leq F_j X_j \ \forall j,t,s \tag{38}$$

Equations (37) and (38) limit the sum of feedstock (b) stored at storage location (k) or biorefinery location (j) to less than its capacity, F_k and F_j , multiplied by an integer variable identifying whether 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. The volume stored can vary by state of nature, but the capacity cannot.

$$H_t \leq \sum_b Q_{bjt}(s) \ \forall j, t, s \tag{39}$$

Equation (39) imposes a minimum safety requirement, H_t, for a given volume of storage required for biorefinery, to prepare for emergency use at all times and under all states of nature.

$$\sum_j X_j \leq 1 \tag{40}$$

Equation (40) is a configuration constraint which limits the number of biorefineries built to one.

Spatial representation of the availability of feedstock

The design of the biofuel supply chain is geographically dependent on the potential locations for facilities, transport routes, and so on. A supply chain study with finer spatial data would better reflect the logistics and fuel production costs. Most existing studies use relatively coarse county-level geographic representation to reduce the demand for high computational ability. However, a coarser representation of the region and the possible incidence of large-modeled regions could inaccurately represent the possibilities and bias the solutions. A finer scale representation using GIS data to consider the supply chain for a biorefinery is used in this study to address the above issue. For this purpose, we break the region into finer grid cells. Two-hundred square kilometer hexagons were used, as these can effectively reflect the feedstock distribution in the study region and contain the model structure at a manageable size. This yields 10-20 cells within the study region counties.

GIS data site selection and resolution scheme

With respect to GIS use, this study proceeds in two stages. First, we looked at county level herbaceous and woody crop feedstock availability in a large area in the general study region and located a multi-county service region that could support a biorefinery. We then disaggregated the county-level data into a finer spatial grid.

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

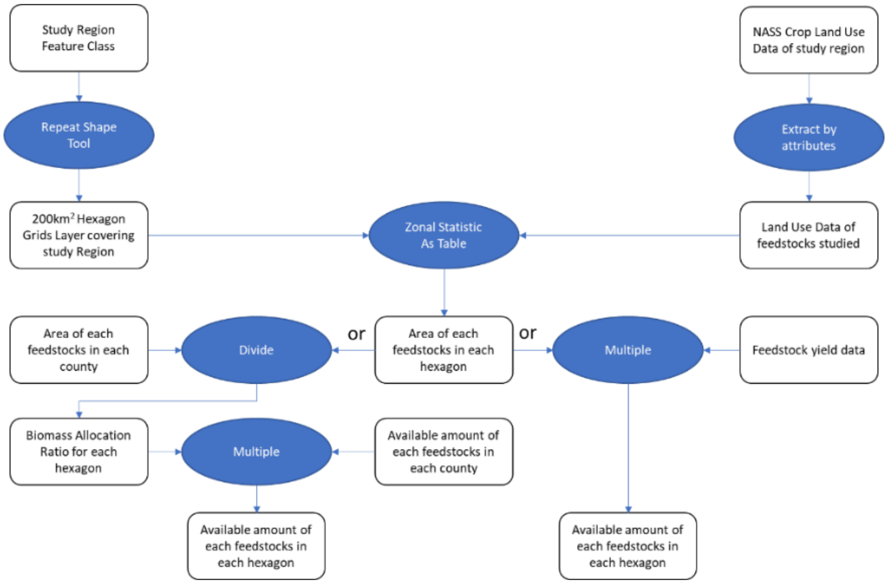

Figure 3 **Conceptual framework of processing spatial data**

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

For the exact locations, a 200 km^2 hexagon layer was first developed across a multi-county region, using the repeated shaping tool in ArcMap. Hexagons are used, as they efficiently cover the study region without significant sampling bias from edge effects and curvature and they can cover the study region without overlap.

For the data, land use layers from the NASS Cropland Data Layer (CDL) are used (USDA 2018). The available feedstock regions from other land uses were developed using the “extracted by attributes” tool in ArcMap. In the East Texas case study, the tool was used to identify flat pasture land areas for feedstock production, along with forested lands potentially available for harvest. In the Texas High Plains case study, we use the 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 used in a zonal statistics tool as input to calculate the area in pixels of each land use in each hexagon. Here, the pixels are 30 m by 30 m (900 m^2). The available area of land use per pixel was then calculated by multiplying the pixels count and pixel size. For example, in a hexagon, if there were 20 pixels where land use was classified as land growing dryland sorghum, the sorghum area in the hexagon was set as equal to 20 m multiplied by 900 m (18,000 m^2 or 1.8 ha).

CHAPTER IV

REGIONAL SUPPLY CHAIN MANAGEMENT CASE STUDY: TEXAS HIGH PLAINS

Introduction

There is growing interest in the production of second-generation biofuels from agricultural residues, forest residues, energy crops, and industrial waste feedstocks. Relative to first-generation biofuel processes, second-generation feedstocks reduce energy-food competition through use of residues, higher yielding energy crops, and/or utilization of marginal land. Furthermore, the energy and GHG balances for second-generation feedstocks are more favorable (Wang et al. 2012; Wang et al. 2011; Humbird et al. 2011; Qin et al. 2006).

The RFS, as laid out in the 2007 EISA, indicates a required blending of 136,000 MLPY by 2020. Furthermore, no more than 57,000 MLPY can come from first-generation biofuels and at least 61,000 MLPY must come from cellulosic based biofuels. However, those anticipated blending levels have not been met. For example, in 2015, only 540.55 MLPY of cellulosic biofuel was produced, despite a target of 11,350 MLPY (EPA 2016). Additionally, much of this came from sources not originally contemplated – with biogas from landfills, municipal wastewater treatment facility digesters, and agricultural manure digesters amounting to 93% of the cellulosic biofuel in 2018 (Hansen 2017). Agricultural and forest-based production is therefore quite small.

Commercial production has not grown quickly due to issues of cost and large-scale conversion technology. Several studies argue that technological challenges must be resolved before lignocellulosic feedstock-based production can become cost competitive (Krishnakumar and Ileleji 2010; Hess, Wright and Kenney 2007).

One big challenge hindering cellulosic ethanol expansion is the logistics component of the production costs. Many studies (Hess et al. 2007; An and Searcy 2012; Park et al. 2017) argue that the logistics costs associated with cellulosic biofuel are substantial, comprising 30-50% of total production costs. This arises due to widely spatially dispersed distribution of feedstock, low energy density, and high-water content. Moreover, logistics costs are increased by short harvesting windows for some feedstocks that require additional labor, alternative harvest equipment, and substantial storage investment, plus storage operations.

Beyond those cost issues, logistics system design is further complicated by the inherently uncertain nature of lignocellulosic feedstock yields, as the source crops are strongly influenced by weather conditions and thus yields vary from year to year.

All these factors considered, supply chain system design can be complex, obliged to deliver feedstocks at low costs throughout the year while accommodating yield uncertainties. In this chapter, a case study was conducted in the High Plains of Texas concerning supply chain design and the factors described above.

The chapter is presented as follows. First, the background to 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 supply chain implications of considering and ignoring uncertainty. We also study the consequences of allowing or eliminating remote storage and pelleting and then conduct a sensitivity analyses of the impact of conversion rate improvement and alternative pellet prices. Finally, an analysis is conducted to examine the effect of using high-resolution, sub-county level spatial data versus county-level data.

Problem statement

Conceptually, a cellulosic biofuel supply chain consists of the following: a) a set of feedstock production locations (e.g. H_1, H_2, …, H_i); b) multiple feedstocks that can be produced, F_1, F_2, …, F_b, with alternative harvest seasons; c) a biorefinery located potentially at sites B_1, B_2, …, B_j; d) possible locations for storage at sites S_1, S_2, …, S_k ; and e) potential locations, P_1, P_2, …, P_l, for densifying the bulky feedstock via pelleting into small, dry, and more energy-dense pellets. Designing the supply chain involves determining 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 feedstocks and pellets to the refinery on a year-round basis. Additionally, provisions are needed to handle variation in feedstock yields.

A MIP model was developed to model the choice variables associated with the items above and minimize the costs of investment and operations, less revenue from pellet exports. The model minimizes the cost of making a given amount of cellulosic ethanol, and in doing that, manipulates the following variables:

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

- The location of pelleting plant(s) and the quantity of pellets produced
- The amount of each feedstock transported, stored, and pelletized between the units of the supply chain, at each time of year and 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 feedstock availability in proximity to transport routes in a 45-county region in the Texas High Plains. Based on studies by the National Renewable Energy Laboratory (NREL) (Aden et al. 2002; Humbird et al. 2011), a biorefinery which can process at least 2,000 dry mg of feedstock per day is assumed to yield 187 MLPY of cellulosic ethanol, with 264 liters per mg of feedstock. It is also assumed that the biorefinery operates at full capacity for 8,500 hours per year (around 97% of the time). Given those assumptions, the minimum annual feedstock requirement to be collected from the current study region is approximately 708,100 mg. For the study, a set of potential biorefinery locations were preselected, ensuring that each had access to a major road or railroad, while being a sufficient distance from nearby cities to avoid environmental and traffic issues.

In line with 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 feedstock estimates from the Bioenergy Knowledge Discovery Framework (KDF) (Langholtz, Stokes and Eaton 2016), the candidate biorefinery locations were narrowed down to those where sufficient feedstock was available. Table 2 below lists the ten counties with the most available feedstock.

Table 2 Top ten counties in the study region with the most available feedstock

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

Of the counties in the study region, Castro, Lamb, and Sherman contain the most feedstock and are considered potential locations for a biorefinery. A total of 45 counties in Texas, New Mexico, and Oklahoma fell within an 80 km radius of Castro, Lamb, and Sherman, and these were selected as potential feedstock-supplying regions. Texas contains 39 of those counties, located in USDA crop reporting districts one and two. Six counties are included from adjacent areas in the bordering states of New Mexico and Oklahoma.

Once the study region boundary had been determined, a more detailed spatial analysis was conducted to identify suitable locations for the biorefinery within each candidate county. This was achieved by breaking the whole study region into 200 square km hexagons – a geographic area that we judge to reflect the heterogeneity of feedstock distribution without significantly degrading the model solution time. The potential biorefinery locations are considered to be candidates of one or more storage depots and pellet plants. Additionally, hexagons in the outlying counties which fall within the 80 km radius periphery of the potential biorefinery, have access to both rail and road transportation, and are located away from the towns and cities are considered potential locations for distributed storage and pelleting plants.

Figure 4 below depicts the boundary and potential locations of storage and pelleting plants in the study region.

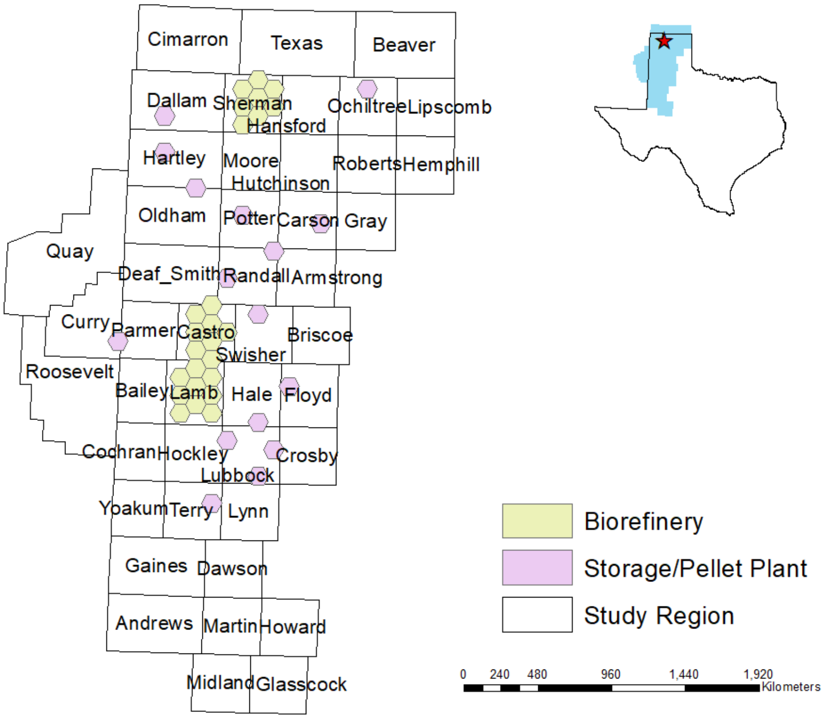

Figure 4 Potential locations for biorefinery, storage, and pellet plants

Feedstock considered in the study

Four types of lignocellulosic feedstock are considered sources of cellulosic feedstock: corn stover, sorghum stover, switchgrass, and energy sorghum. The DOE 2016 Billion-Ton study (BTS) (Langholtz et al. 2016) estimates that corn stover is the most abundant feedstock in the region, with a potential supply of 75-112 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 that the harvest window for corn stover coincided with that of harvesting corn grain and was thus October to November. Moreover, the yield of corn stover used in the study is assumed to be proportional to the yield of corn grain. Based on 2016 BTS (Langholtz et al. 2016), a bushel of corn (or 25.4 kg) is associated with 0.0237 tons corn (or 0.0215 mg) stover. Following Wilhelm et al. (2007), we assume that stover retained on the land to prevent wind and water erosion amounts to 4.84 mg per ha. Given an assumed regional typical corn grain yield of 12.8 mg per ha[3] (USDA NASS, 2017), the corn stover yield used in the study is assumed to be an average of 6.01 mg per ha.

Sorghum is also a candidate feedstock in the region. A productive, drought-resistant species, its different types can be used to produce ethanol depending on the conversion technology applied. In the present study, two types of sorghum are considered: a) sorghum residues from conventional sorghum grain production and b) high feedstock sorghum varieties grown as an energy crop and referred to here as ‘energy sorghum’. The harvest window for energy sorghum is assumed to be identical to that of sorghum grain, beginning in November and ending in December, and the harvesting windows for sorghum stover is assumed to be from December to February. The yield of sorghum stover is also assumed to be proportional to the grain yield. Based on the 2016 BTS, a bushel (25.4 kg) of sorghum grain can provide 0.0241-ton (or 0.0219 mg) sorghum stover, and the resultant yield of sorghum stover is 5.41 mg per ha, considering the yield of sorghum in the High Plains region is 247.5 bushels per ha, based on the FASOM model developed by Beach and McCarl et al. (Beach et al. 2010). Following the assumption made above and assuming 4.84 mg per ha of the sorghum stover is left for erosion control, 0.57 mg per ha is used as the yield of sorghum stover in this study.

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[3] Given the yield of corn grain in the NHP is 203.9 Bu/acre, 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

Switchgrass is also a possible feedstock in this study. Qin et al. (2006) conducted a feasibility analysis for replacing coal with switchgrass in power generation, examining the associated environmental, energy, and economic aspects. They highlight that a high yield switchgrass can be price competitive with other feedstock sources and reduce GHG emissions. Due to its ability to adapt to various environments, switchgrass is recommended by the U.S. Department of Energy (USDOE) as a 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 is 10.02 mg per ha (McCarl et al., 2018).

Land use constraint and contract scheme

To ensure sufficient year-round feedstock supply, the biofuel supply chain must contract land with the owners before receiving feedstock. Several types of land are considered by the model: 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 choices of land here were made with the intention of not expanding agricultural water consumption. Thus, the crop residues can be collected from both irrigated and non-irrigated land, while energy crops can only be grown and harvested on dryland.

The contracting schemes used for agricultural residues and energy crops are assumed to be developed as follows: the biorefinery would pay a fixed fee per hectare and a per-milligram-removed fee. The per hectare fee consists of the annualized establishment cost for energy crops, the cost of replacing nutrients when the crop residue is removed, and the land opportunity cost. Later, we will also discuss a per-milligram-removed payment. The per hectare cost of energy crops, following the switchgrass maintenance for feedstock production budget in Griffith et al.

(2012), is composed of the establishing cost prorated over 10 years, annual maintenance, and switchgrass operation cost. (Specifically, a total annual cash cost of $718 per ha is used to establish and maintain switchgrass.) The establishment and maintenance cost of energy sorghum is $ 491.1 per ha.

The nutrient replacement cost for agricultural residue follows the estimate from Sawyer (2018). Specifically, the cost of removing the nutrients provided by a milligram corn stover can be estimated from the cost of replacing the nutrients by adding additional fertilizer. Given that prices for P_2O_5 and K_2O are $ 0.84 and $ 0.53 per kg, respectively, the complete removal of 9.79 mg corn stover from a hectare of land requires 34.8 kg of P_2O_5 and 149.3 kg of K_2O. Thus, the cost of removing all corn stover from a hectare of land is $37.29 and the cost of compensating the loss per milligram of corn stover used in this study is $3.8. For simplicity, this study assumes the per milligram cost of collecting sorghum stover is identical to that of corn stover.[4] In addition to the establishment cost/nutrient replacement cost, land rent in the study region is used to reflect the opportunity cost of the land. As energy crops can only be planted on dry land, a $24 per acre or $59.4 per ha rental rate (USDA NASS Quick Stats 2017) is used for the study region.

Harvest cost

The estimated harvesting and collection method and associated costs (i.e., the per milligram cost) are based on the DOE uniform-format feedstock supply system (Hess et al. 2009). For the corn stover, the harvesting and collection process begins immediately after grain harvesting. A tractor and flail shredder with windrower are used to windrow the standing stubble, cobs, husks, leaves, and tops (i.e., stover) left on the ground. Once the moisture content of the

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[4] 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 P_2O_5, 20.2 kg K_2O, and 1.35 kg S

windrowed stover is sufficiently low,[5] a large square baler pulled by a tractor creates 1.2 m wide by 1.2 m high by 2.4 m long large square bales (3’ by 3’ by 8’). The square bales are then picked up and moved to edge of the field by a self-propelled stacker. For simplicity, we assume that the harvesting and collection processes for corn stover and sorghum stover are identical.

Switchgrass, unlike crop residues, does not need to be harvested after extracting the grain and requires different equipment to stover. To harvest switchgrass, the use of a self-propelled windrower with a disc header is assumed. The cut and conditioned switchgrass is first deposited on the field, forming a windrow. A square baler and self-propelled stacker are then used to bale and move switchgrass. The conditioning process which crushes the stem of switchgrass is used to increase the speed of the drying and to reduce dry matter loss.

Table 3 lists the equipment and estimated costs of harvest and collection operations. The numbers were taken from 2009 but have been inflation-adjusted to 2018 in Table 8.

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)

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

Storage cost

When placed in storage, the feedstock must be protected and preserved to avoid deterioration and reduce the fire risk, presumably by covered storage in a hoop barn. Figure 5 shows the setup of the storage facility assumed for the present study. Given the weight of each large bale is approximately 0.52 mg, each hoop barn can hold 1,000 mg of feedstock.[6] Stacks within a hoop barn are separated with 2 m between them, and hoop barns are assumed to be placed 15 m away to help prevent fire loss and ensure access for fire-fighting equipment (PSU 2016). Feedstock loss per year is assumed to be 3% when using a hoop barn for storage (Darr and Shah 2012).

Each depot is assumed to have a capacity of 100,000 mg, which means it is composed of 100 hoop barns. This study further assumes that the hoop barns are placed in a 10 by 10 configuration, with a setback distance of 18 m between barns (Darr and Shah 2012; ISU 2017). Thus, a land area of with dimensions of 392 m by 532 m, or 20.85 ha, is needed. In terms of cost, we follow Darr and Shah (2012) and assume the one-time construction cost of a hoop barn of \$120 per m^2 and the consequent fixed cost of building the depot with 100 hoop barns is \$27,377,280. Assuming these barns last for 20 years, the resultant annualized cost of building storage depots is \$2,584,000. In addition, if the storage facility were located on pasture land and the land rent for pasture land was \$18.1 per ha, the cost would amount to \$318 per year for the entire depot.

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[6] 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 mass contained in a hoop barn is around 1000mg

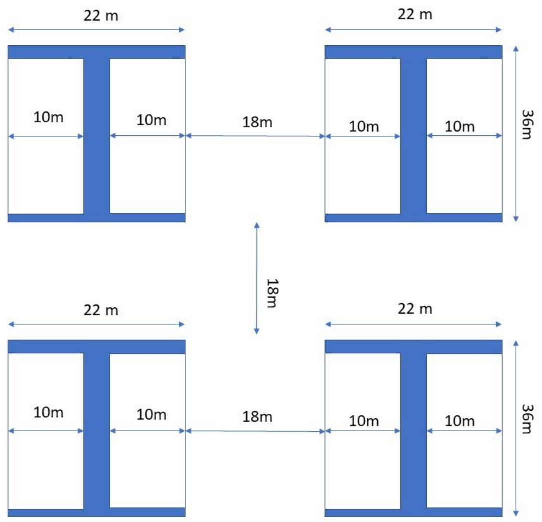

Figure 5 **Formation of the indoor storage**

There is also a variable cost for 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 the same per milligram.

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 at a rate of 80 bales per hour. Table 4 below lists 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 considers pelleting to be a means of densifying the feedstock to reduce volume, transportation costs, and deterioration, as well as potentially allowing 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, with feedstock used to produce pellets. Pelleting usually consists of three main stages: size reduction, drying, and densification. The pellet process begins with size reduction. Specifically, a telehandler removes a square bale from a stack and loads it onto a conveyer, which feeds the bale into the grinder. The ground feedstock is then sent to a rotating drum dryer to reduce moisture content. After drying, the feedstock passes through a hammer mill which further reduces the feedstock to finer particles and the resultant feedstock is then sent to the pressing mill to form pellets. Finally, the cooled and screened pellets are moved by conveyer to a truck and transported to biorefinery or nearby storage depot and placed in a storage bin for later use or exported to another location.

A pellet plant is assumed to produce 13.4 mg of pellets per hour with an annual production capability of 100,000 mg of pellets. During pelleting, 5% of the feedstock 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 to be $3,278,954 (Hoque et al. 2006), as detailed in Table 5, with the plant lasting 20 years and having an annual cost of $309,486. The variable costs include raw feedstock, operation and maintenance for each processing stage, personnel, and land opportunity in the form of land rental rates. The feedstock cost is deducted from the operating costs in this study because it is covered elsewhere in the model. The adjusted estimated operating cost is, as detailed in Table 6, $21.42 per mg of pellets produced.

Pellet storage cost is also considered in Table 6. The resultant variable operating cost and operating cost is $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)

Feedstock transportation and handling

The transportation and handling operations involve in loading/unloading feedstock and moving it from supply regions to intermediate storage locations for pelleting or the biorefinery. As the transportation distance in this study is relatively short, truck transport is assumed.

To compute cost, we assume the use of a 2.4 m-wide by 16 m-long, 3-axle flatbed trailer to move the large square bales (1.2 m by 1.2 m by 2.4 m). Thus, 26 large square bales can be moved in a single load. A telehandler is 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 per truckload. As the weight of each bale is approximately 0.52 mg or 13.52 mg per truckload, the loading and unloading cost is $5.41 per mg, with an assumed 25% moisture content (Hess et al. 2009).

The variable cost, on the other hand, in line with that of Mahmudi and Flynn (2006), is assumed to be proportional to distance traveled. Based on their study, we assume the feedstock moisture content is 25%, and therefore, the estimated variable cost of truck transportation is $0.148 per mg per 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 per mg per km.

To calculate the per milligram cost of movement, a distance matrix was developed. ArcMap was first applied to identify the longitude and latitude of the centroid within each hexagon in the supply region. As that the road system in the study region is largely rectangular in Texas High Plains, once the coordinates of centroid were specified, the Euclidean distance of any two points was multiplied by a winding factor 1.4 to approximate the actual travel distance, in line with the study by Segebaden (1964).

Feedstock preprocessing and handling at the biorefinery

Figure 6, adapted from Mu et al. (2010), depicts the flow diagram of two biorefinery processes. The top diagram shows a biochemical process and the bottom shows a thermochemical process. Mu et al. (2010) indicate that the biochemical method has a slight edge over the thermochemical method if the conversion efficiency of the biochemical process is improved as anticipated, noting that this method has a smaller environment impact. Thus, in this study, biochemical conversion technology is assumed to be the primary technology used to produce ethanol.

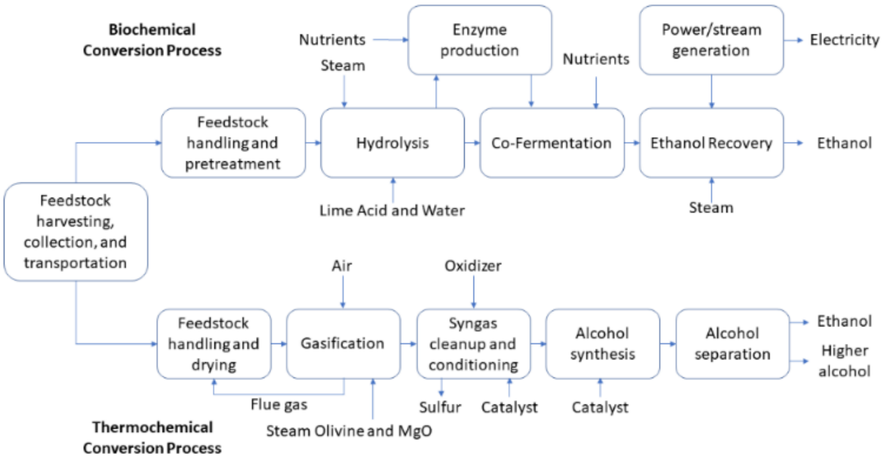

Figure 6 Biochemical and thermochemical conversion processes. Adapted with permission from "Comparative Life Cycle Assessment of Lignocellulosic Ethanol Production: Biochemical Versus Thermochemical Conversion" by Dongyan Mu, Thomas Seager, P. Suresh Rao, et al, 2010. Environmental Management, Volume 46, pp. 565-578, Copyright [2010] by Springer Science Business Media, LLC.

Based on Figure 6, the biochemical process can be described as follows: lignocellulosic feedstock is pretreated, hydrolyzed, fermented, and distilled, as it is transformed into ethanol (Mu et al. 2010; Foust et al. 2009; Wright and Brown 2007). 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 feedstock is then washed and loaded into a pretreatment stage, where the hemicellulose part of the ground feedstock is broken into simple sugars by adding diluted sulfuric acid. Other chemicals are added to facilitate enzymatic cellulose hydrolysis. The mixed solids and liquids are then fermented and further converted into a liquid containing ethanol and byproducts. The ethanol is then separated through distillation. The lignin that is not decomposed is collected and used to generate heat and electricity for the process.

The capacity of the biorefinery is assumed to be 261.9 MLPY, operating 24 hours a day for 310 days a year. The construction cost is detailed in Table 7 and estimated to be $220.1 million, with the plant lasting 20 years at 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 L with an enzyme cost of $0.068 per L.

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)

Other Assumptions

The current study assumes the equipment capital costs to be amortized as a constant payment. Equation (41) 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 lifespan and a 7% discount rate.

$$\text{Amortized } Annual\ cost = \frac{(initial\ investiment)}{(1-(1+r)^{-n})} \tag{41}$$

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

Table 8 summarizes the parameters used in the model, with all costs adjusted to 2017 USD.

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	718(2012)	768.00	$/ha	(Griffith et al. 2012)
Energy Sorghum	491(2017)	491(2017)	$/ha	(AgriLife, 2017)
Corn stover	108.54	108.54	$/ha	Assumed
Sorghum stover	73.84	73.84	$/ha	Assumed
Harvesting Cost				
Switchgrass	16.44(2009)	18.82	$/DM Mg	(Hess et al. 2009)
Energy Sorghum	23.89(2009)	27.35	$/DM Mg	Assumed
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	14.50		DM Mg/ha	(AgriLife, 2017)
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	

The planning horizon for a single year was divided into 12 periods. In this way, we are able to identify the availability of equipment and labor by considering the probable working days. Based on the work of Soloranzo-Campos (1990), Table 9 lists the number of good working days in each month in the study region. The resultant estimate is 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	0.57	0.5	0.44	0.4	0.37	0.37	0.41	0.46	0.53	0.59	0.62	0.6
actual days available	13.1	10	10.12	8.8	8.5	8.14	9.43	10.58	11.6	13.5	13.64	13.8

Source: Soloranzo-Campos (1990)

Although the actual available days differ across the month, this study uses the month with fewest available days (June) to plan the labor and equipment required for harvest. As the supply of labor and equipment is difficult to change monthly, it is preferable to determine the required labor and machinery based on the worst case to ensure sufficient supply throughout the analysis period.

Modeling uncertainty in feedstock 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[7] from 1950 to 2016. Ten states of nature reflecting the yield fluctuation were constructed and implemented into stochastic model.

To derive the states of nature, this study first removed yield trends assumed to arise due to technological progress. This was achieved by regressing historical data (USDA NASS 2017) on yields of hay (used as a proxy for switchgrass), sorghum, and corn on time to identify the trend. The unexplained error (residuals) from that trend was then used to form the yield deviations. Once the residuals had been obtained, yield deviation proportions were formed as a ratio of the yearly residuals after trend removal to the regression projected yields for that year.

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[7] 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

The residuals were then applied to current High Plains yields to develop a distribution for the feedstock.

Since multiple feedstocks were available, joint states of nature represent the multi-feedstock distribution of feedstock yield deviations. The probability of these states of nature were derived from the historical data. To keep the model size tractable, the deviations for each feedstock are grouped into four yield levels: bad, low, fine, and good. The bad yield level for corn stover refers to any year with a shock equal to or less than 20.4% below the expected yield level; low yield level refers to the years with a deviation of between 20.4% and 9% below the projected yield level. ‘Fine’ is recorded when the yield deviation is between 9% below and 2.3% above the projected yield; and ‘good’ occurs when the yield is better than 2.3% above the mean. To develop each state of nature, we developed a joint distribution by categorizing each historical year by combining the ratios of all three feedstocks, resulting in 64 potential combinations. However, many of those combinations never occurred and were thus eliminated. The probability of each state of nature was then estimated by dividing the number of observations falling into each joint state of nature by the total number of observations. The yield deviations exhibited strong correlations across crops, which shows that certain key factors (such as precipitation) play an important role in influencing crop yields. For example, during the 2011 drought, all 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

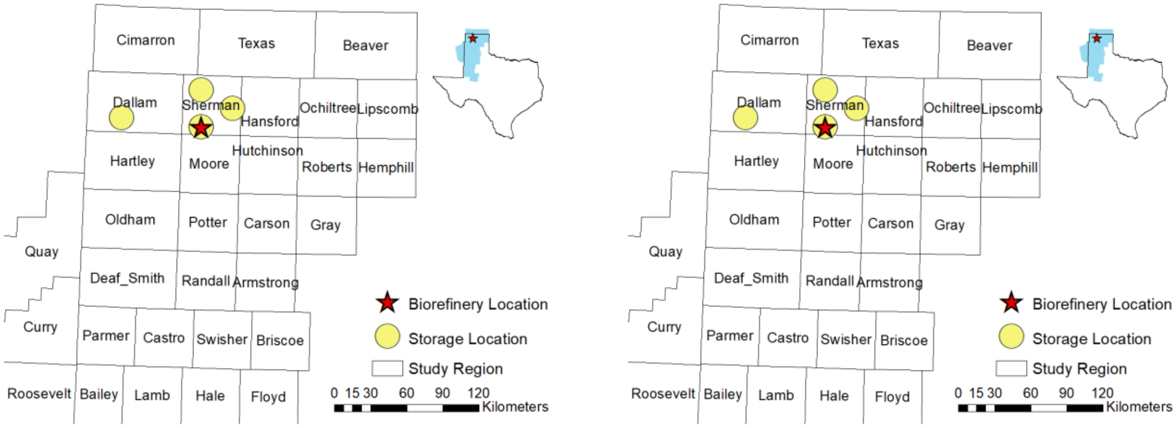
Model analyses and results

This section presents the results of the analyses conducted in this study. The findings associated with including and excluding yield uncertainty are considered first, followed by the results on the impact of including and excluding different supply chain designs, conversion rates, and pellet prices. A set of results is then included on the effect of using higher resolution spatial data.

The model was executed using GAMS software, with CLPLEX as the solver and a tolerance gap that terminates when the gap between the best possible integer solution and the realized objective falls at or below 0.1%.

Effects of including and excluding yield uncertainty

The first experiment involved running the model with and without yield uncertainty. In the model without yield uncertainty, the projected yields were used, whereas in the stochastic model, the above probability distribution was used. Figure 7 depicts the resultant optimal facilities for the deterministic and stochastic models.



(a) Deterministic model (b) Stochastic model

Figure 7 Optimal locations in the deterministic and stochastic models

As shown in Figure 7, the optimal locations of the biorefinery, storage depots, and pellet plants are identical across the models. The biorefinery is 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.

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 of the stochastic model. The stochastic model exhibits higher costs of contracting land and operating storage, with lower costs for transporting feedstock.

Table 11 Expected costs in the deterministic and stochastic models

Item	Determinisitc	Stochastic	Unit
Expected cost of supply chain	113,026.9	114,775.4	$1,000
Annualized cost of building biorefinery	24,504.4	24,504.4	$1,000
Annualized cost of building Storage	9,952.3	9,952.3	$1,000
Annualized cost of building Pellet Station			$1,000
Cost of contracting land	985.2	1,974.1	$1,000
Expected Cost of harvesting biomass	26,985.8	27,963.8	$1,000
Expected Cost of dumping biomass		17.6	$1,000
Expected Cost of storing biomass(offsite)	5,763.9	6,287.0	$1,000
Expected Cost of pelleting			$1,000
Expected Cost of producing ethanol	31,752.0	31,752.0	$1,000
Expected Cost of Transporting biomass	13,083.4	12,324.2	$1,000
Average cost of producing ethanol	0.59	0.60	$/L

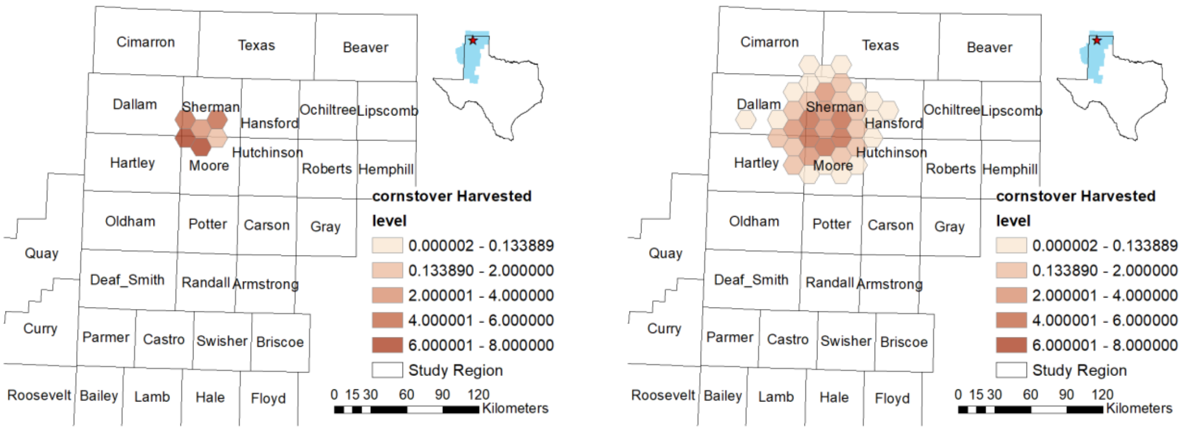
Table 12 summarizes the key decisions of the deterministic and stochastic models.

In the stochastic model, the investments in capital and contracted land are determined before uncertainty is resolved, thus the transport, pelleting storage, dumping, and feedstock processing decisions are made with knowledge of the realized yield state. To reveal some of the resultant variation, the first column in the stochastic model represents the decisions made when the worst yield state of nature is realized, while the second column depicts the decisions in the best state of nature and the third column shows the computed average level of decisions.

Table 12 Summary of the decisions from the deterministic and stochastic models

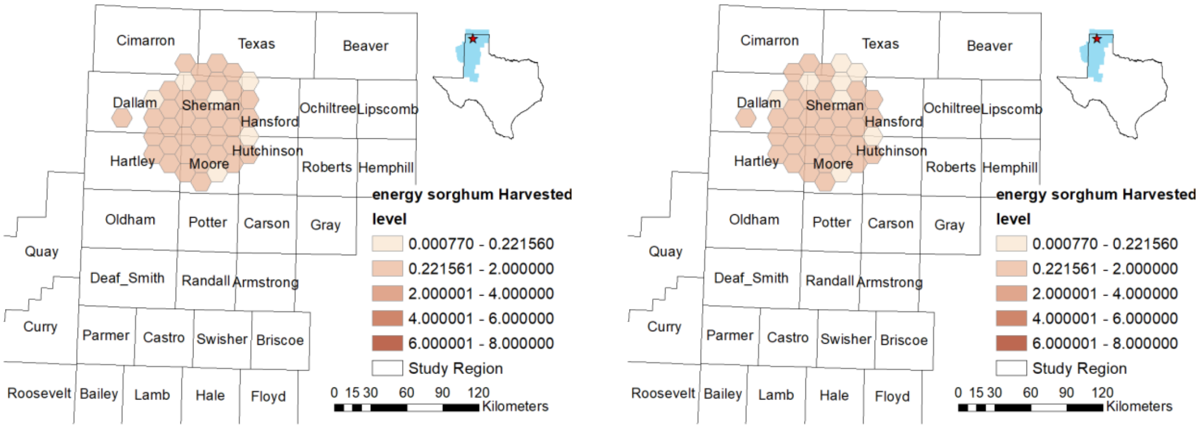
Item	Deterministic	Stochastic			Units
		Worst yield	Best yield	Average	
First-stage decision					
Total land contracted for biomass	172.2	252.4	252.4	252.4	1000Ha
Corn stover	27.6	124.2	124.2	124.2	1000Ha
Energy sorghum	23.2	23.6	23.6	23.6	1000Ha
Sorghum stover	0.6	0.6	0.6	0.6	1000Ha
Switchgrass	120.8	104.0	104.0	104.0	1000Ha
Second-stage decision					
Total biomass harvested	735.1	743.3	736.9	736.7	1000Mg
Corn stover	109.2	406.7	54.6	184.4	1000Mg
Energy sorghum	135.9	95.7	111.2	136.0	1000Mg
Sorghum stover	0.6	0.4	0.9	0.6	1000Mg
Switchgrass	489.3	240.5	570.2	415.7	1000Mg
Total biomass dumpped		0.0	621.5	313.1	1000Mg
Corn stover		0.0	525.6	309.7	1000Mg
Energy sorghum		0.0	76.5	2.9	1000Mg
Sorghum stover		0.0	0.0	0.0	1000Mg
Switchgrass		0.0	19.4	0.5	1000Mg
Total biomass stored	1,918.0	2,589.6	1,786.1	2,107.4	1000Mg
Corn stover		1,337.5	0.0	301.6	1000Mg
Energy sorghum	243.1	246.6	0.0	294.3	1000Mg
Sorghum stover					1000Mg
Switchgrass	1,675.0	1,005.5	1,786.1	1,511.6	1000Mg
Total biomass processed	676.9	664.3	682.9	672.5	1000Mg
Corn stover	109.2	366.3	54.6	175.2	1000Mg
Energy sorghum	128.4	88.1	111.0	126.9	1000Mg
Sorghum stover	0.6	0.4	0.9	0.6	1000Mg
Switchgrass	438.6	209.5	516.4	369.8	1000Mg

Figure 8 depicts sources of each feedstock and its associated distribution in deterministic and stochastic model.



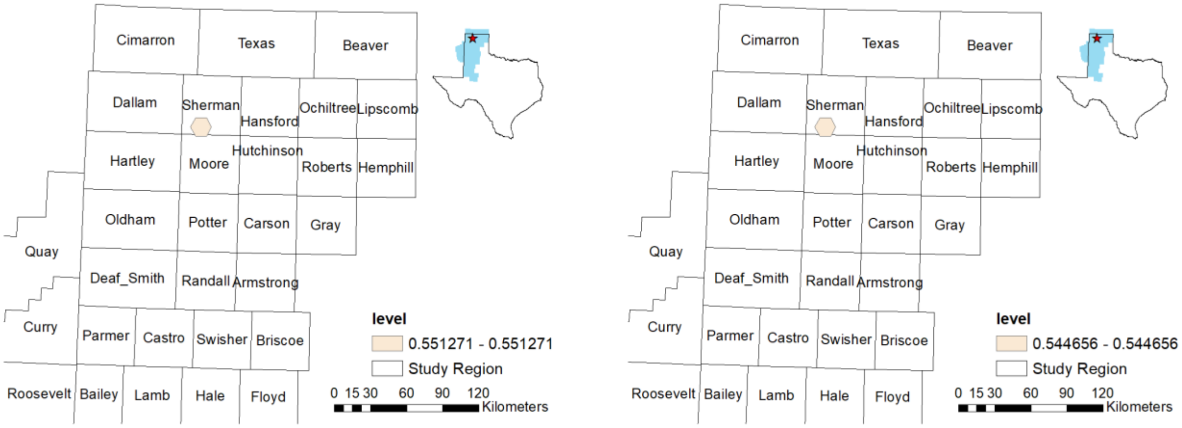
(a) Corn stover in deterministic model

(b) Corn stover in stochastic scenario



(c) Energy sorghum in deterministic model

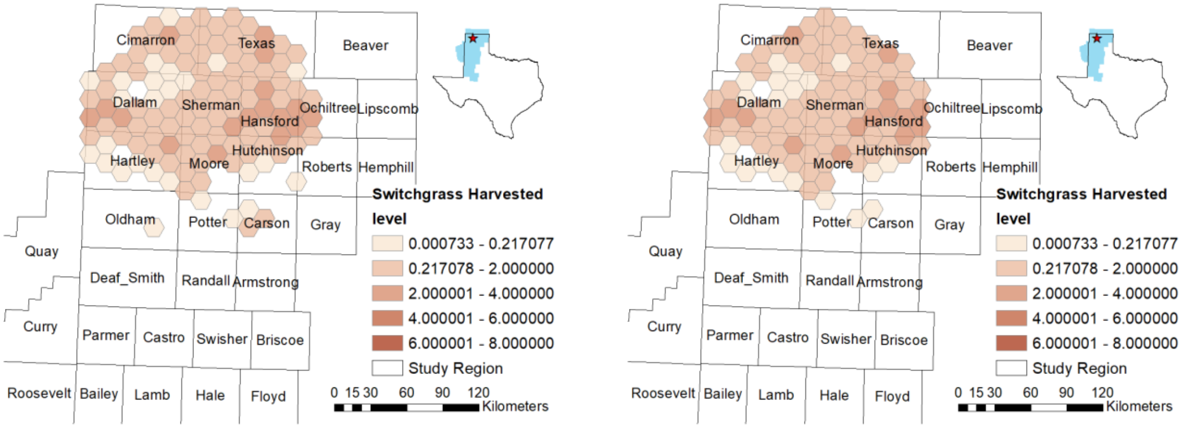
(d) Energy sorghum in stochastic scenario



(e) Sorghum stover in deterministic model

(f) Sorghum stover in stochastic scenario

Figure 8 **Feedstock land contracted in the deterministic and stochastic models**



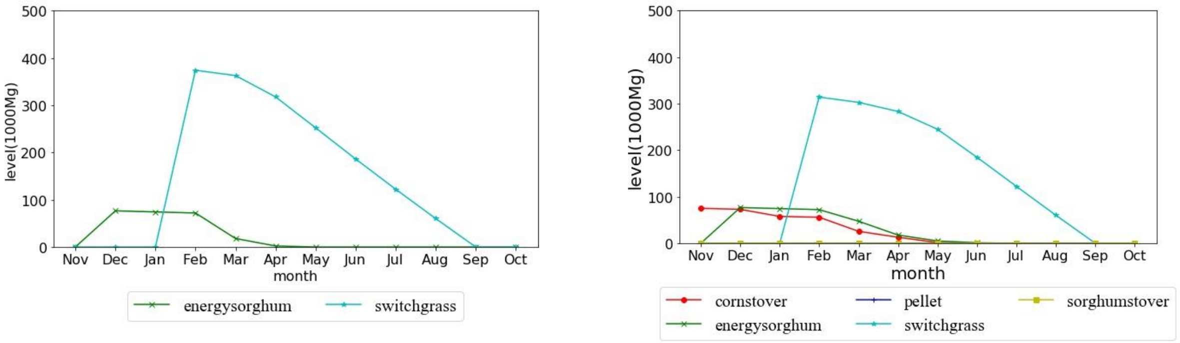
(g) Switchgrass in deterministic model

(h) Switchgrass in stochastic scenario

Figure 8 Continued

Here, we see the amount of land contracted differs substantially when considering yield uncertainty. Nearly 46.5% more land is contracted in the stochastic model than in the deterministic model. Consequently, the supply region increases from 15 km in the deterministic model to 60 km in the stochastic model for corn stover, remains at 60 km for energy sorghum and 15 km for sorghum stover, and slightly decreases from 90 to 80 km for switchgrass. The drastic increase in the land contracted for corn stover ensures the biorefinery has sufficient feedstock when the low yields are realized. The amount of switchgrass harvested in the stochastic model is 15% lower, likely due to the higher yield fluctuation relative to the other feedstocks, while the amount of corn stover increases by 68.7%. Additionally, in the stochastic model, all the feedstock harvested when the worst yield state of nature occurs is sent to storage or biorefinery with no feedstock dumped. On the other hand, around 30% of the total feedstock is dumped when the best yield state of nature is realized. As the dumping cost for agricultural residues are low, almost all feedstock dumped is corn stover.

The monthly storage inventory levels are shown in Figure 9.

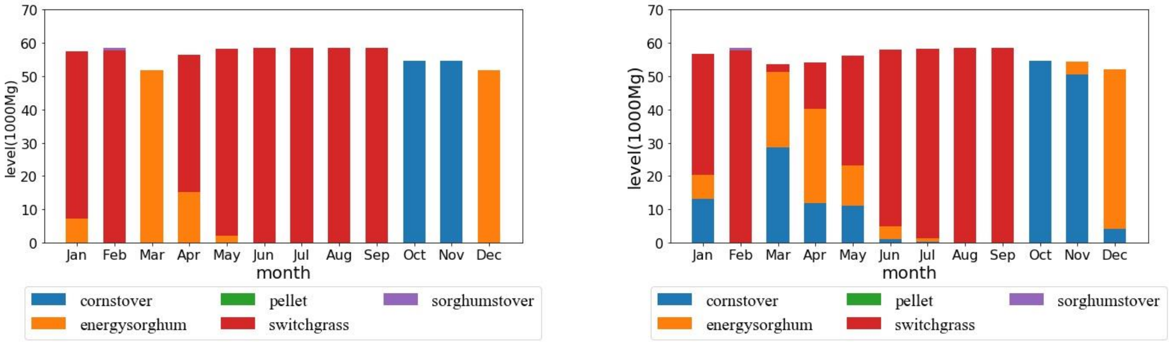


(a) Deterministic model (b) Stochastic model

Figure 9 **Inventory level in the deterministic and stochastic models**

Under deterministic yields, approximately 90,000 mg of energy sorghum is placed in storage in February, with another 380,000 mg of switchgrass in March. In the stochastic model, an average of 90,000 mg of corn stover is placed in storage in January, with another 90,000 mg of energy sorghum added in February. Additionally, 310,000 mg switchgrass is placed in storage and becomes the main input for the biorefinery later in the year. Thus, when the yield is known in the deterministic model, more switchgrass is used, due its low storage cost. Less is used in the stochastic model due to higher yield variability. Meanwhile, in both models, switchgrass is stored longer than other feedstock, given its relatively low storage cost.

Figure 10 depicts the monthly amounts of feedstock processed in the two models.



(a) Deterministic model (b) Stochastic model

Figure 10 Monthly processing by feedstock type

In both cases, switchgrass is the dominant feedstock throughout most of the year. Specifically, under deterministic yields, switchgrass is the dominant feedstock in January and 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 feedstock processing under yield uncertainty generally follows the same pattern, except with greater use of corn stover. Switchgrass again dominates in January and 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 increases in January, and from March to May replacing switchgrass, which has relatively high yield fluctuation.

Effects of eliminating decentralized storage and pellet plants

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

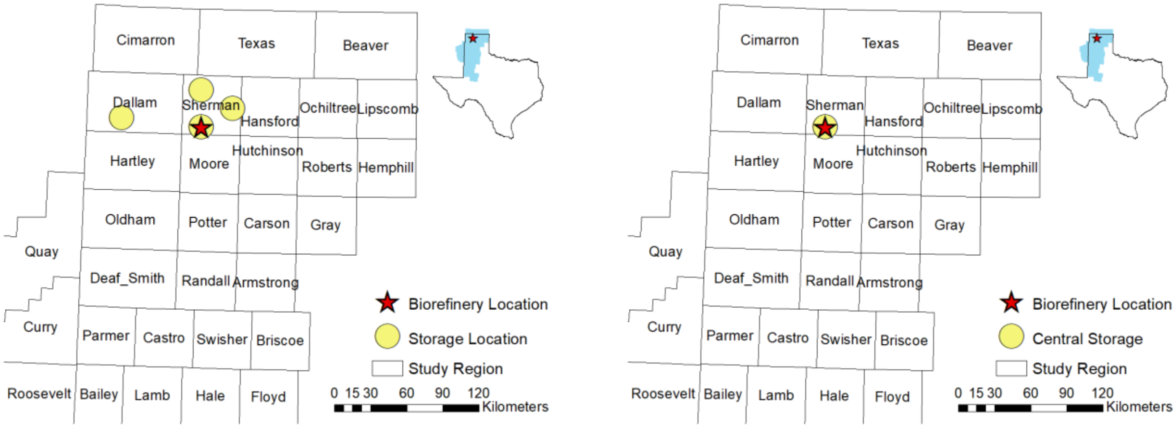
13. It is noted that when remote depots are not allowed, the centralized storage is five times larger than in the other cases.

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

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

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



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

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

Table 14 summarizes the cost components for these cases. The total cost under the no-pellet and central storage scenario is not meaningfully different from that of the base case. The no-pellet and base case costs are identical, and the central storage scenario expected cost is only 0.1% higher than in the base scenario. The higher cost in the central scenarios is primarily caused by the increased costs of contracting land and harvesting feedstock, 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	114775.4	114775.4	114940.3	$1,000
Annualized cost of building biorefinery	24504.4	24504.4	24504.4	$1,000
Annualized cost of building Storage	9952.3	9952.3	9952.3	$1,000
Annualized cost of building Pellet Station				$1,000
Cost of contracting land	1974.1	1974.1	1998.6	$1,000
Expected Cost of harvesting biomass	27963.8	27963.8	28028.7	$1,000
Expected Cost of dumping biomass	17.6	17.6	15.7	$1,000
Expected Cost of storing biomass(offsite)	6287.0	6287.0	6299.7	$1,000
Expected Cost of pelleting				$1,000
Expected Cost of producing ethanol	31752.0	31752.0	31752.0	$1,000
Expected Cost of Transporting biomass	12324.2	12324.2	12389.0	$1,000
Average cost of a gallon ethanol	0.602	0.602	0.603	$/L

Table 15 lists the key decisions in these three cases.

The no-pellet scenario results are identical to those of the base case, since there is no pelleting at optimality. There are only minor differences between the central storage and base cases. Specifically, 0.1% more land is contracted in the central storage scenarios, with contracting increasing for all feedstock except switchgrass. Specifically, the land used for corn stover and energy sorghum increases by 0.4% and 5%, respectively. Simultaneously, the land contracted for switchgrass drops by 3%. The smaller amount of land contracted for sorghum stover increases by more than four times in the central storage scenario.

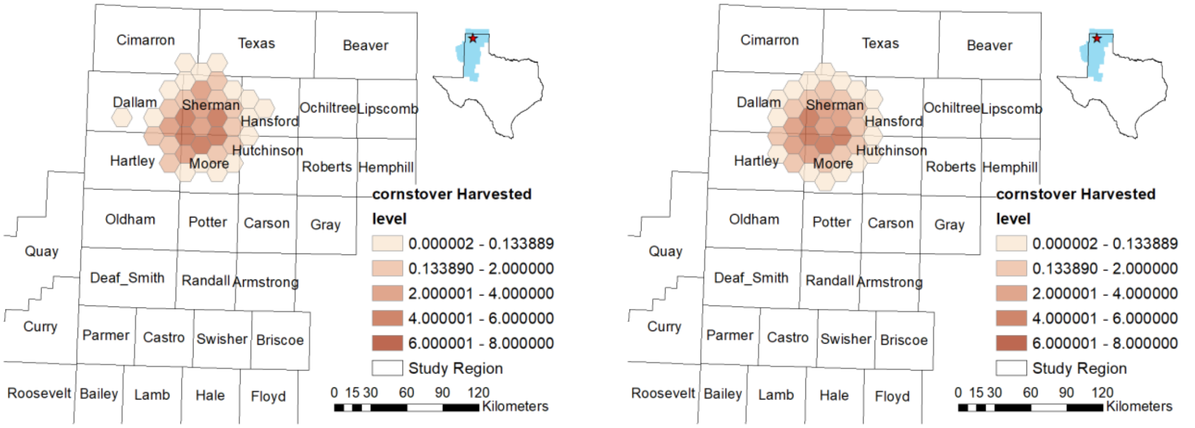
Table 15 Summary of the key decisions: no-pellet and centralized storage scenarios

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	102.0	102.0	102.0	102.0	102.0	102.0	102.1	102.1	102.1	1000Ha
Corn stover	50.2	50.2	50.2	50.2	50.2	50.2	50.4	50.4	50.4	1000Ha
Energy sorghum	9.6	9.6	9.6	9.6	9.6	9.6	10.1	10.1	10.1	1000Ha
Sorghum stover	0.2	0.2	0.2	0.2	0.2	0.2	1.2	1.2	1.2	1000Ha
Switchgrass	42.0	42.0	42.0	42.0	42.0	42.0	40.4	40.4	40.4	1000Ha
Second-stage decision										
Total biomass harvested	743.3	736.9	736.7	743.3	736.9	736.7	743.0	736.9	736.0	1000Mg
Corn stover	406.7	54.6	184.4	406.7	54.6	184.4	408.6	54.6	189.1	1000Mg
Energy sorghum	95.7	111.2	136.0	95.7	111.2	136.0	100.7	111.2	143.0	1000Mg
Sorghum stover	0.4	0.9	0.6	0.4	0.9	0.6	2.3	4.6	3.4	1000Mg
Switchgrass	240.5	570.2	415.7	240.5	570.2	415.7	231.4	566.5	400.5	1000Mg
Total biomass dumpped	0.0	621.5	313.1	0.0	621.5	313.1	0.0	615.5	310.4	1000Mg
Corn stover	0.0	525.6	309.7	0.0	525.6	309.7	0.0	528.4	307.3	1000Mg
Energy sorghum	0.0	76.5	2.9	0.0	76.5	2.9	0.0	86.3	3.1	1000Mg
Sorghum stover	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Switchgrass	0.0	19.4	0.5	0.0	19.4	0.5	0.0	0.9	0.0	1000Mg
Total biomass stored	2589.6	1786.1	2107.4	2589.6	1786.1	2107.4	2594.6	1786.1	2122.8	1000Mg
Corn stover	1337.5	0.0	301.6	1337.5	0.0	301.6	1325.6	0.0	277.5	1000Mg
Energy sorghum	246.6	0.0	294.3	246.6	0.0	294.3	296.3	0.0	330.8	1000Mg
Switchgrass	1005.5	1786.1	1511.6	1005.5	1786.1	1511.6	972.8	1786.1	1514.6	1000Mg
Total biomass processed	664.3	682.9	672.5	664.3	682.9	672.5	663.7	682.9	671.4	1000Mg
Corn stover	366.3	54.6	175.2	366.3	54.6	175.2	368.6	54.6	180.7	1000Mg
Energy sorghum	88.1	111.0	126.9	88.1	111.0	126.9	91.6	111.0	132.9	1000Mg
Sorghum stover	0.4	0.9	0.6	0.4	0.9	0.6	2.3	4.6	3.4	1000Mg
Switchgrass	209.5	516.4	369.8	209.5	516.4	369.8	201.2	512.7	354.5	1000Mg

Figure 12 depicts the optimal amount and area of each feedstock collected.

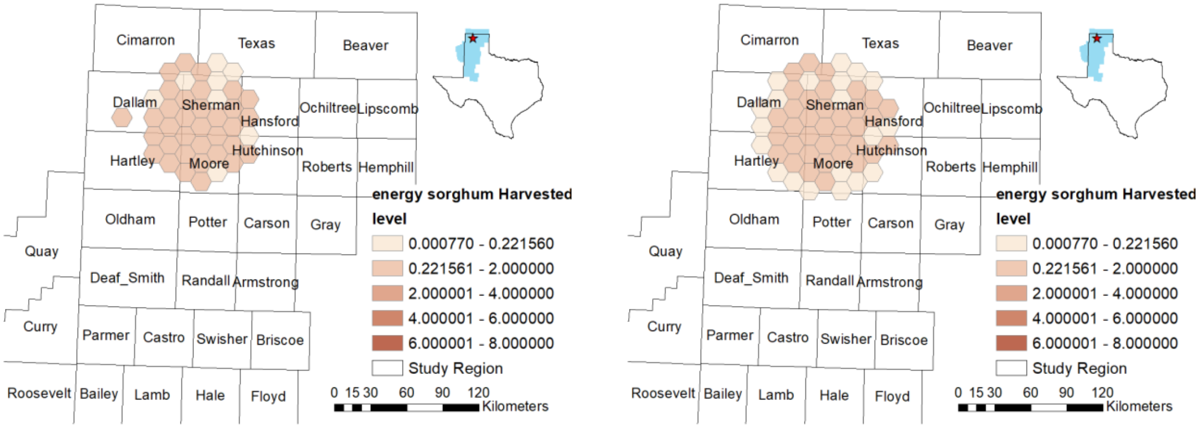
Compared to the base case, the central storage supply region is unchanged, at a 60 km radius for corn stover. The supply region increases from 50 to 60 km for energy sorghum and drops from 90 to 80 km for switchgrass, while the supply region for sorghum stover expands to 15 km. The amount of feedstock harvested generally follows the land contracted results. In the centralized storage-only scenario, the amount of feedstock harvested increases by 2.5% for corn stover, 5.1% for energy sorghum, and 436% for sorghum stover. The amount of switchgrass harvested drops by 3%.

Meanwhile, the amount of feedstock dumped in the best yield state of nature slightly decreases (0.8%) under central-only storage. The smaller amount of feedstock dumped under central storage is due to the decreasing use of the more variable switchgrass, with more corn stover and energy sorghum contracted and harvested.



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

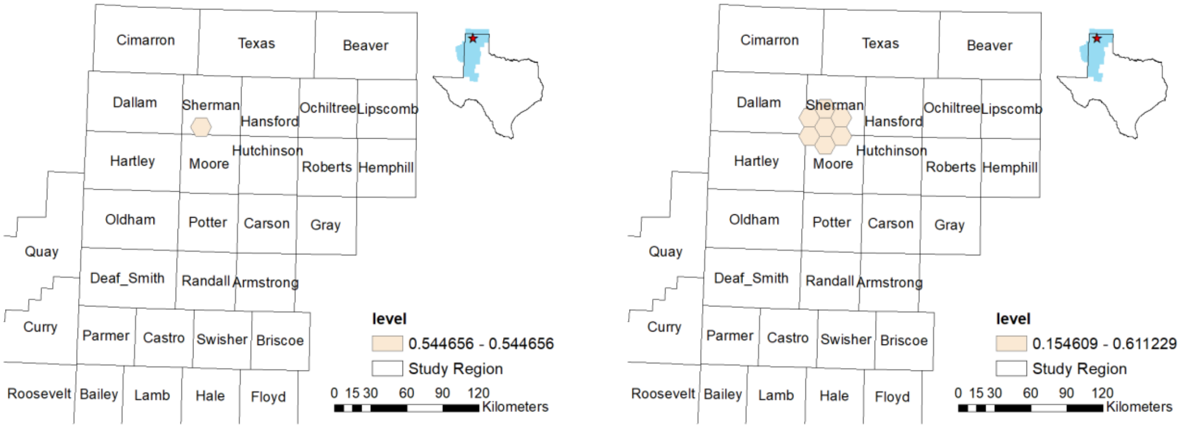
(b) Corn stover in central storage scenario



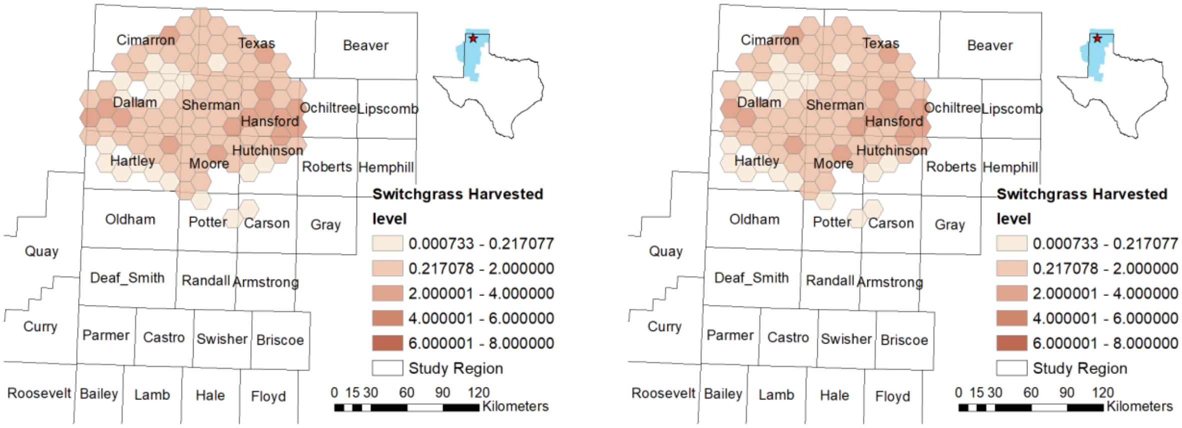
(c) Energy sorghum in base/no-pellet scenario

(d) Energy sorghum in central storage scenario

Figure 12 **Source of feedstock in no-pellet and centralized-only storage scenarios**



(h) Sorghum stover in base/central storage scenario (h) Sorghum stover in central storage scenario

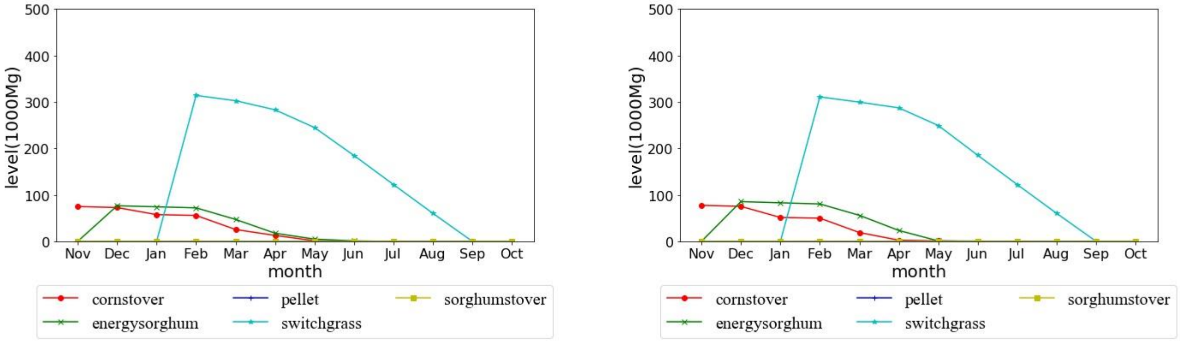


(h) Switchgrass in base/central storage scenario (h) Switchgrass in central storage scenario

Figure 12 Continued

Figure 13 depicts the storage inventory levels in the base case/no-pellet and central storage cases. It is noted here that the inventory levels are similar. Switchgrass is used as the major source of feedstock throughout the analysis periods, reflecting its lower storage costs. Specifically, more than 300,000 mg of switchgrass is placed in storage in February and then supplied to the biorefinery between February and September. The storage placement for corn stover is around 80,000 mg in November, with the corn stover used from November to April.

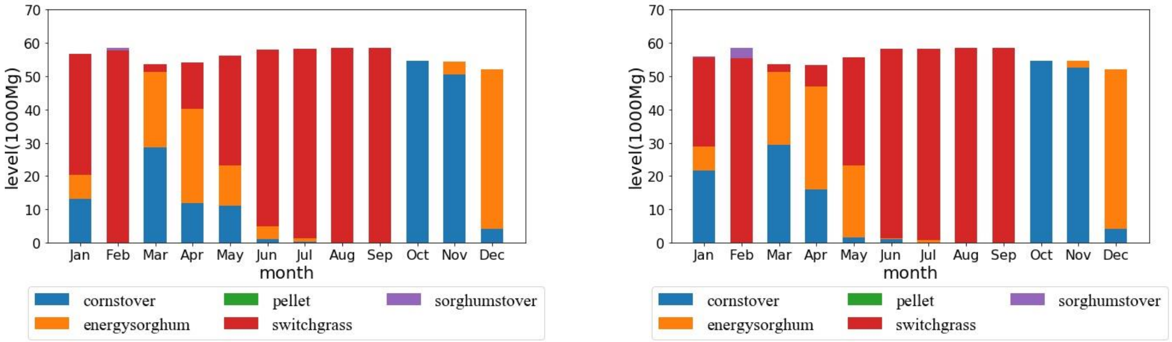
The inventory level for energy sorghum is similar to that of corn stover. Around 85,000 mg of energy sorghum is placed in storage and held from December to April in all scenarios.



(a) Base/no-pellet scenario (b) Central storage scenario

Figure 13 Monthly inventory levels: no-pellet and central facility scenarios

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



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

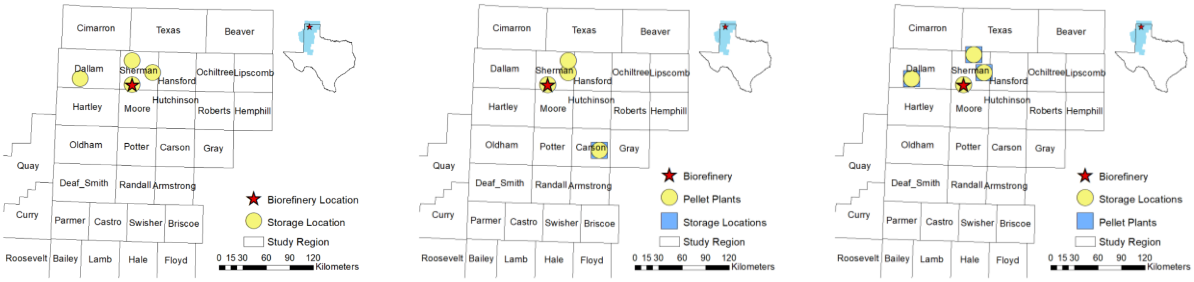
Figure 14 Comparison of process levels: no-pellet and central scenarios

This analysis has so far focused on comparison of different supply chain designs with the base case. In the following sections, the results of sensitivity analyses are presented, using the stochastic model to examine the impact of altering biofuel conversion rates and the export price of pellets.

Comparison of multiple- and single-source feedstock scenario results

The following analysis discusses the impact of available feedstock on the supply chain. Due to its relatively low energy density, large volumes of feedstock are required to produce usable quantities of energy. Thus, storage is commonly required in a supply chain system when feedstock exhibits seasonality. As shown in previous sections, storage plays a critical role to ensuring a sufficient supply of feedstock to the biorefinery when there are multiple sources of feedstock with different harvesting windows. The current study considers the impact of utilizing a single feedstock, rather than multiple sources. As corn stover and switchgrass are the major feedstocks used in the current study region, two single source scenarios (only corn stover and only switchgrass) are considered. We begin by presenting the results of the optimal locations and then discuss the cost components and optimal logistical decisions.

The optimal locations of the biorefinery, storage depots, and pellet plants for multiple and two single source scenarios are depicted in Figure 15.



(a) All feedstock scenario (b) Switchgrass only (c) Corn stover only

Figure 15 The optimal locations of facilities for single and multiple feedstock cases

The optimal biorefinery location, in the southwest of Sherman county, is the same for the three scenarios. Five storages are selected for the scenario in which multiple feedstocks are available, while six selected in the switchgrass-only and corn stover-only scenarios. In both switchgrass-only and corn stover-only scenarios, three storages are selected at the same biorefinery location, while the remaining storages are placed away from the biorefinery depending on the distribution of feedstock. Unlike in the switchgrass-only and corn stover-only scenarios, when multiple feedstocks are available, less feedstock is stored as the biorefinery can consume more feedstock directly from the supply region, due to the overall longer harvesting window.

Meanwhile, given the storage costs for both switchgrass and corn stover are higher than the cost of their pellet, the results from both single source scenarios indicate that part of the feedstock is converted to pellet and stored over the planning horizon. At optimal, one- and three-pellet plants are selected in the switchgrass-only and corn stover-only scenarios. The locations of pellet plants are placed relatively far from the biorefinery, as they are primarily used to reduce transportation costs and avoid deterioration and storage.

Table 16 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 is 20.9% higher than the case in which multiple feedstocks are available, while the corn stover-only scenario has costs 24.5% higher than those of the multiple feedstock case. The higher cost of both single-source feedstock scenarios is due to more land being contracted for switchgrass and corn stover, the need to construct and operate new storage depots and pellet plants, and the increased costs of transportation between facilities.

Table 16 Expected costs of each component multiple- and single-source scenarios

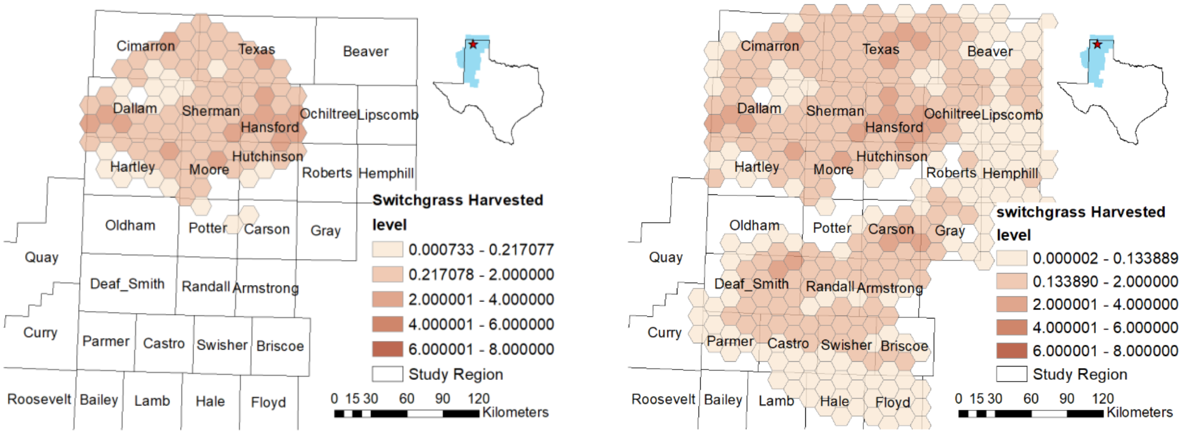
Item	Base case	Only switchgtass	Only cornstover	Unit
Expected cost of supply chain	114775.4	138848.7	142970.1	$1,000
Annualized cost of building biorefinery	24504.4	24504.4	24504.4	$1,000
Annualized cost of building Storage	9952.3	21868.8	21868.8	$1,000
Annualized cost of building Pellet Station		378.6	1135.8	$1,000
Cost of contracting land	1974.1	1406.5	3987.1	$1,000
Expected Cost of harvesting biomass	27963.8	27786.4	29499.0	$1,000
Expected Cost of dumping biomass	17.6	1969.4		$1,000
Expected Cost of storing biomass(offsite)	6287.0	8483.9	9286.1	$1,000
Expected Cost of pelleting		1361.2	5513.2	$1,000
Expected Cost of producing ethanol	31752.0	31752.0	31752.0	$1,000
Expected Cost of Transporting biomass	12324.2	19337.5	17170.0	$1,000
Average cost of a gallon ethanol	0.60	0.73	0.75	$/L

To ensure a consistent supply of feedstock over the planning horizon, approximately four times and three times as much land is contracted for switchgrass and corn stover production, respectively, in the single-source scenarios. In the switchgrass-only scenario, the cost of storage increases by 34% with respect to multi-feedstock. A 57% higher transportation cost is also observed, as additional transportation occurs between the supply region and the storage and between the storage and the biorefinery. For corn stover-only scenario, the cost of storage increases by 47% with respective to multi-feedstock. A 39% higher transportation cost is also observed due to the additional transportation between the supply region and the storage and between the storage and the biorefinery.

Table 17 Summary of the decisions: multiple- and single-source feedstock scenarios

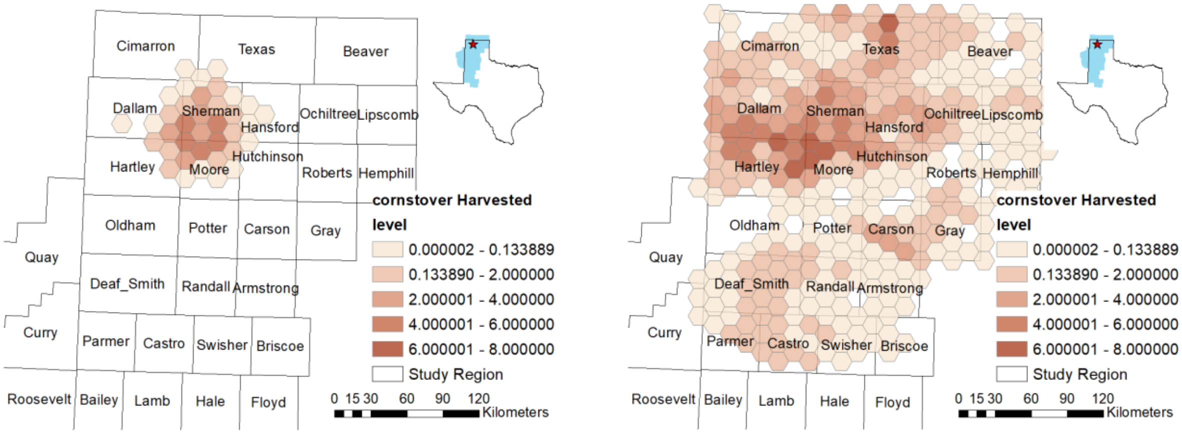
Item	all feedstocks			only switchgrass			only cornstover			Units
	Worst yield	Best yield	Average	Worst yield	Best yield	Average	Worst yield	Best yield	Average	
First-stage decision										
Total land contracted for biomass	102.0	102.0	102.0	168.9	168.9	168.9	147.1	147.1	147.1	1000Ha
Corn stover	50.2	50.2	50.2	0.0	0.0	0.0	147.1	147.1	147.1	1000Ha
Energy sorghum	9.6	9.6	9.6	0.0	0.0	0.0	0.0	0.0	0.0	1000Ha
Sorghum stover	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	1000Ha
Switchgrass	42.0	42.0	42.0	168.9	168.9	168.9	0.0	0.0	0.0	1000Ha
Second-stage decision	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Total biomass harvested	743.3	736.9	736.7	765.3	777.4	777.2	728.7	728.7	728.7	1000Mg
Corn stover	406.7	54.6	184.4	0.0	0.0	0.0	728.7	728.7	728.7	1000Mg
Energy sorghum	95.7	111.2	136.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Sorghum stover	0.4	0.9	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Switchgrass	240.5	570.2	415.7	765.3	777.4	777.2	0.0	0.0	0.0	1000Mg
Total biomass dumpped	0.0	621.5	313.1	0.0	1540.5	883.4	0.0	0.0	0.0	1000Mg
Corn stover	0.0	525.6	309.7	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Energy sorghum	0.0	76.5	2.9	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Sorghum stover	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Switchgrass	0.0	19.4	0.5	0.0	1540.5	883.4	0.0	0.0	0.0	1000Mg
Total biomass stored	2589.6	1786.1	2107.4	1326.2	2529.8	2518.0	3259.5	3259.5	3259.5	1000Mg
Corn stover	1337.5	0.0	301.6	0.0	0.0	0.0	1436.9	1436.9	1436.9	1000Mg
Energy sorghum	246.6	0.0	294.3	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Sorghum stover	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Switchgrass	1005.5	1786.1	1511.6	1231.2	2486.2	2473.7	0.0	0.0	0.0	1000Mg
Pellet	0.0	0.0	0.0	95.0	43.6	44.4	1822.5	1822.5	1822.5	
Total biomass processed	664.3	682.9	672.5	760.3	775.1	774.9	668.9	668.9	668.9	1000Mg
Corn stover	366.3	54.6	175.2	0.0	0.0	0.0	458.6	458.6	458.6	1000Mg
Energy sorghum	88.1	111.0	126.9	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Sorghum stover	0.4	0.9	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Switchgrass	209.5	516.4	369.8	665.3	731.6	730.5	0.0	0.0	0.0	
Pellet	0.0	0.0	0.0	95.0	43.6	44.4	210.3	210.3	210.3	1000Mg

Table 17 lists the optimal decisions when multiple and single sources of feedstock are available; and Figure 16 illustrates the supply region of switchgrass for the multi-feedstock and switchgrass-only scenarios. When all sources of feedstock are available, only switchgrass and corn stover within 60 km and 40 km radius of the biorefinery are harvested, and the amount of switchgrass and corn stover collected varies from 240,000 mg to 570,000 mg and from 406,000 mg to 54,000 mg, depending on the yield states of nature.



(a) Switchgrass: multi-feedstock scenario

(b) Switchgrass: single source scenario



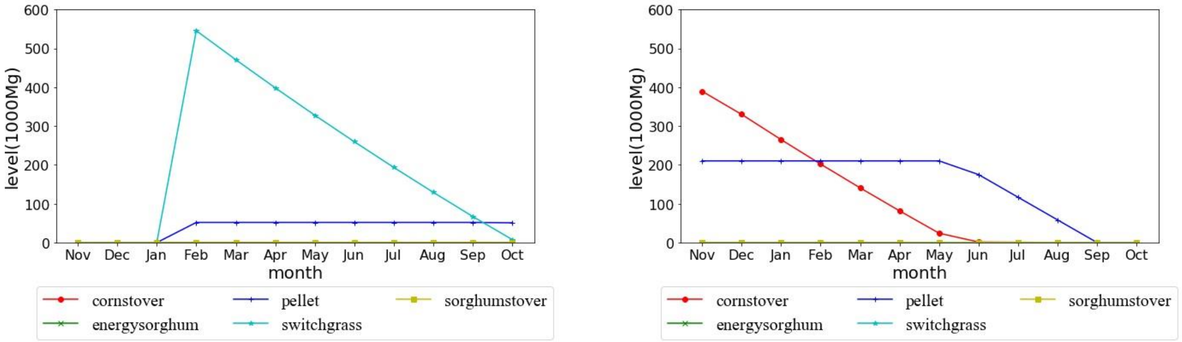
(c) Corn stover: multi-feedstock scenario

(d) Corn stover: corn stover only scenario

Figure 16 Amount of feedstock harvested in multiple- and single-source scenarios

When only switchgrass is available, the area and amount of switchgrass harvested in the single-feedstock scenarios are greater than in the multi-feedstock case. Switchgrass within a 60 km radius is sent to the biorefinery and consumed during the harvesting season in both switchgrass-only and multi-feedstocks scenarios. However, switchgrass outside this range is harvested and sent to the closest storage or pellet plant to be used later in the non-harvesting season. Of the switchgrass, 770,000 mg is stored and used from March to September, with an average of 44,600 mg of the pellets stored from March to November. When only corn stover is available, an average of 720,000 mg of corn stover is stored and used between March and September, with an average of 210,000 mg of corn stover pellets stored from March to November.

Figure 17 depicts the storage inventory levels in the switchgrass-only and corn stover-only cases. We see that for both single source scenarios, a large portion of the feedstock is harvested and used as the major source of feedstock throughout the analysis periods, while the remainder of the feedstock is converted into pellet, stored across the analysis period, and consumed immediately before the following harvesting window. In the switchgrass-only scenario, more than 500,000 mg of switchgrass is placed in storage in February and used as the non-harvesting season supply to the biorefinery from February to September. Additionally, 44,600 mg of switchgrass pellet is stored from February to October and used as the major feedstock in November. In the corn stover-only scenario, the storage placement for corn stover is approximately 400,000 mg in November, with the stored corn stover used during the non-harvesting season from November to May. Approximately 200,000 mg of corn stover pellets is kept in storage from November to May in the following year and used as the major source for ethanol production from June to September.

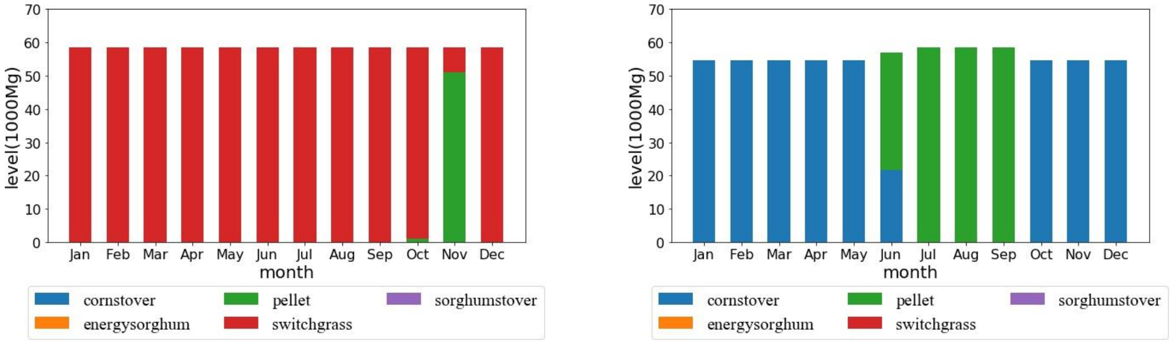


(a) Only switchgrass scenario

(b) Only corn stover scenario

Figure 17 Monthly inventory levels: switchgrass and corn stover scenarios

Figure 18 illustrates the feedstock processes over the plan horizon for both single-source scenarios. When only switchgrass is available, baled switchgrass is processed into ethanol from November to the following October, while switchgrass pellets are consumed in October and November. The choice of pellets and baled switchgrass reflects assumptions around deterioration, storage, transport, and the cost of making pellets. These assumptions are manifest in a number of ways. First, the switchover after October is due to the marginal cost of keeping baled switchgrass exceeding that of pellets, thus the plant switches to pellets. Second, the deterioration rate increases when feedstock is stored in baled form. Furthermore, the cost of moving the pellet is cheaper than that of moving baled feedstock. Therefore, part of the switchgrass is converted into pellets in February, stored from February to September, and then consumed before the beginning of the following harvesting season. Similar results are observed in corn stover-only scenarios. Baled corn stover is processed into ethanol from October to June, while corn stover pellets are consumed from June to September.



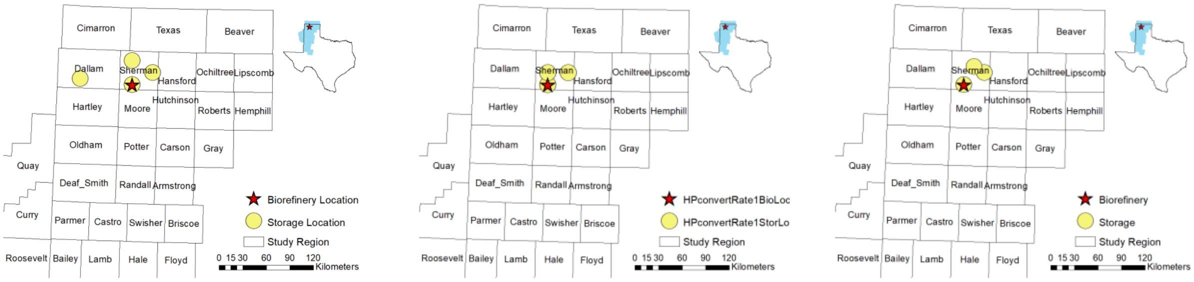
(a) Only switchgrass scenario (b) Only woody material scenario

Figure 18 Monthly feedstock process levels: switchgrass and corn stover scenarios

Impact of conversion rate improvement on supply chain design

The conversion rate is assumed to range from 70 to 80 gal per mg. The current performance is limited as most of the lignin content of the feedstock 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 more than 90 gal per mg. To examine the impact of conversion rate improvements, a sensitivity analysis is conducted, studying 15% and 25% increases in conversion rates.

Figure 19 depicts the facility types and locations for different conversion rates. It is noted that higher biofuel conversion rates affect the storage locations. With higher conversion rates, the facilities move closer to the biorefinery, as a smaller supply region is needed. Additionally, no pellet plant is used to reduce the size of feedstock in either conversion rate scenario, as feedstock need only be transported within a smaller supply region. The closer location and lower volume of feedstock eliminates the need for transport cost reductions in the pelleting process. Fewer storage facilities are selected for both the medium- and high-improvement scenarios, with four rather than five. Two storage facilities are placed at the biorefinery location, with the other two placed near the biorefinery and no pellet plant is used.



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

Figure 19 Optimal locations for improved conversion rate scenarios

Table 18 summarizes the expected cost of each component under the alternative conversion rates. Expected cost of medium and high improved scenarios decreases by 7.5% and 10.5%, respectively.

Table 18 Expected cost of each component in different conversion rate scenarios

Item	Base case	Medium improvement	High improvement	Unit
Expected cost of supply chain	114,775.4	106,155.7	102,626.1	$1,000
Annualized cost of building biorefinery	24,504.4	24,504.4	24,504.4	$1,000
Annualized cost of building Storage	9,952.3	7,961.9	7,961.9	$1,000
Annualized cost of building Pellet Station				$1,000
Cost of contracting land	1,974.1	1,682.5	1,546.9	$1,000
Expected Cost of harvesting biomass	27,963.8	24,147.5	22,225.5	$1,000
Expected Cost of dumping biomass	17.6	38.8	33.1	$1,000
Expected Cost of storing biomass(offsite)	6,287.0	5,384.3	5,002.9	$1,000
Expected Cost of pelleting				$1,000
Expected Cost of producing ethanol	31,752.0	31,752.0	31,752.0	$1,000
Expected Cost of Transporting biomass	12,324.2	10,684.3	9,599.5	$1,000
Average cost of a gallon ethanol	0.60	0.56	0.54	$/L

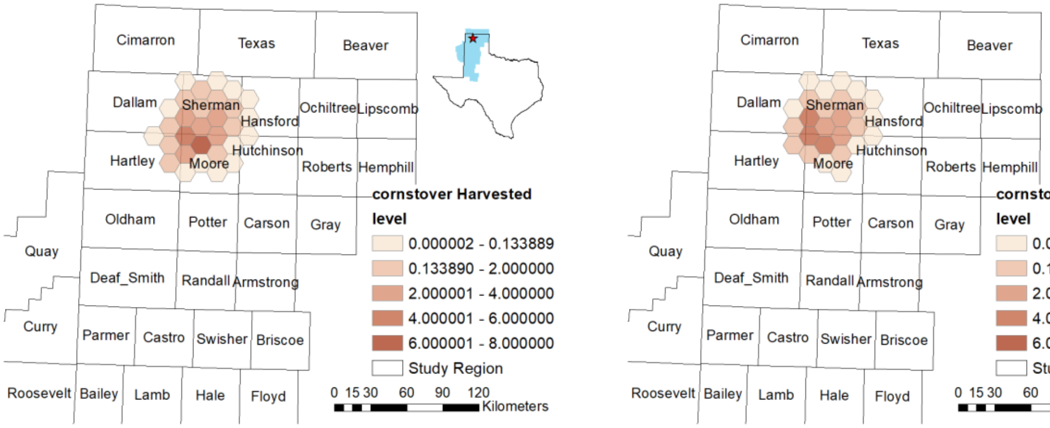
Table 19 summarizes the key decisions under the alternative conversion rates.

For these results, the study assumes an identical amount of cellulosic biofuel is produced in all cases, even when the conversion rates improve and less feedstock is thus needed. The biorefinery could collect the same amount of feedstock as in the base case, producing more ethanol, but this is not considered here.

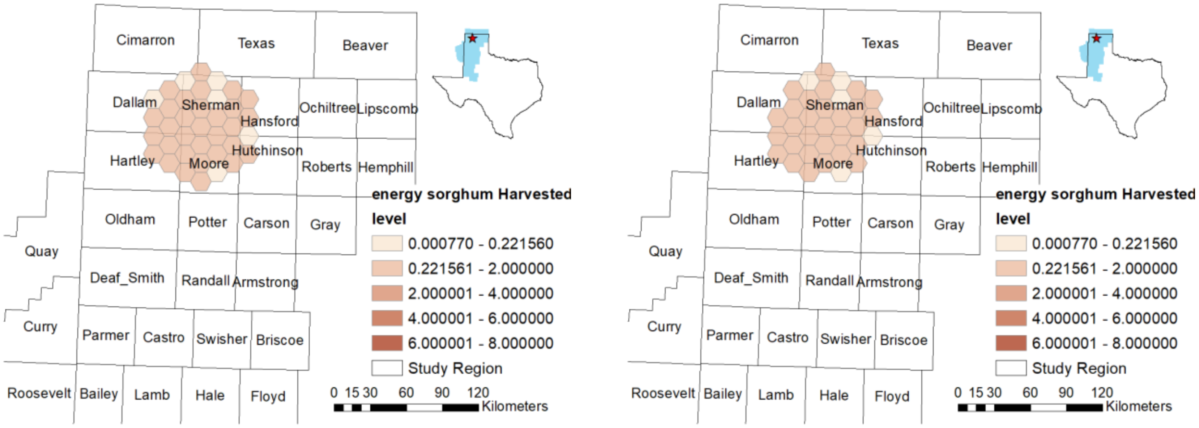
Table 19 Summary of the key decisions of different conversion rates scenarios

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	252.4	252.4	252.4	221.7	221.7	221.7	203.6	203.6	203.6	1000Ha
Corn stover	124.2	124.2	124.2	101.2	101.2	101.2	92.9	92.9	92.9	1000Ha
Energy sorghum	23.6	23.6	23.6	21.0	21.0	21.0	19.9	19.9	19.9	1000Ha
Sorghum stover	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1000Ha
Switchgrass	104.0	104.0	104.0	98.9	98.9	98.9	90.3	90.3	90.3	1000Ha
Second-stage decision										
Total biomass harvested	743.3	736.9	736.7	645.7	640.0	640.4	593.9	589.4	589.0	1000Mg
Corn stover	406.7	54.6	184.4	331.4	47.5	126.9	304.3	43.7	116.0	1000Mg
Energy sorghum	95.7	111.2	136.0	85.1	108.8	119.6	80.4	90.5	112.9	1000Mg
Sorghum stover	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	1000Mg
Switchgrass	240.5	570.2	415.7	228.7	482.9	393.2	208.8	454.4	359.4	1000Mg
Total biomass dumpped	0.0	621.5	313.1	0.0	561.4	282.2	0.0	515.2	259.4	1000Mg
Corn stover	0.0	525.6	309.7	0.0	425.4	275.8	0.0	390.4	253.7	1000Mg
Energy sorghum	0.0	76.5	2.9	0.0	58.1	3.9	0.0	67.2	3.8	1000Mg
Sorghum stover	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Switchgrass	0.0	19.4	0.5	0.0	77.8	2.6	0.0	57.5	1.9	1000Mg
Total biomass stored	2,589.6	1,786.1	2,107.4	2,186.1	1,572.7	1,766.9	2,011.0	1,427.4	1,626.3	1000Mg
Corn stover	1,337.5	0.0	301.6	1,001.8	0.0	197.4	916.6	0.0	179.1	1000Mg
Energy sorghum	246.6	0.0	294.3	221.1	32.3	196.8	218.6	0.0	190.3	1000Mg
Switchgrass	1,005.5	1,786.1	1,511.6	963.2	1,540.4	1,372.6	875.8	1,427.4	1,256.9	1000Mg
Total biomass processed	664.3	682.9	672.5	578.6	592.4	586.6	532.2	546.1	539.4	1000Mg
Corn stover	366.3	54.6	175.2	301.1	47.5	120.9	276.5	43.7	110.5	1000Mg
Energy sorghum	88.1	111.0	126.9	78.3	107.6	113.5	73.6	90.2	107.0	1000Mg
Sorghum stover	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	1000Mg
Switchgrass	209.5	516.4	369.8	198.8	436.4	351.6	181.6	411.3	321.3	1000Mg

Figure 20 details the supply regions by feedstock, when different conversion rate scenarios are applied. The contracted land of medium and high improved scenarios is reduced by 12.1% and 19.3%, respectively. Land used for collecting corn stover is reduced by the largest amount, from 18.5% and 25.2%, while that of energy sorghum decreases by 11% and 15.9%, switchgrass area drops by 4.9% and 13.1%, and sorghum stover land remains unchanged. The results indicate that the corn stover supply region slightly decreases from 60 to 50 km and 45 km in the medium- and high-improvement scenarios. The areas for energy sorghum and sorghum stover collected maintain 50 km and 15 km radiuses across the scenarios. The supply region for switchgrass reduces from 90 km to 70 km and 60 km in the medium- and high-improvement scenarios.

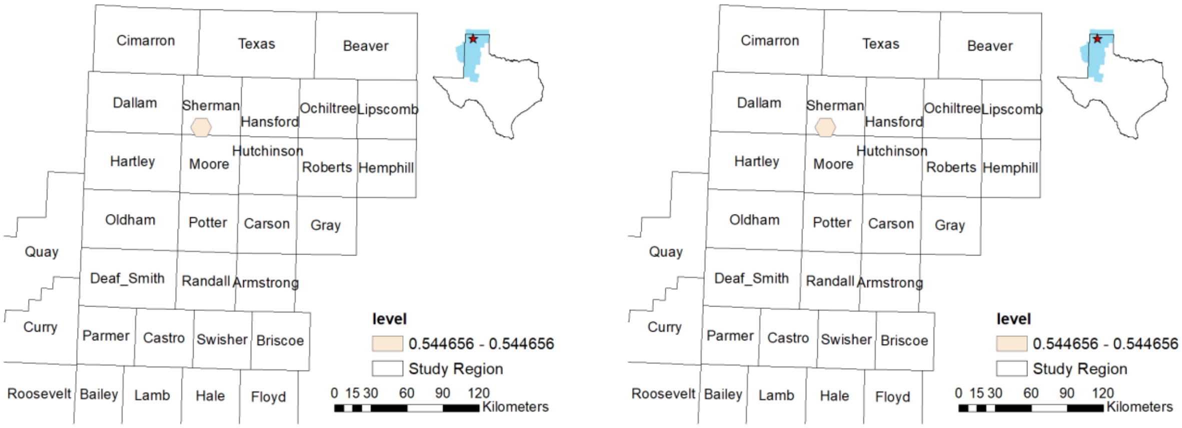


(a) Corn stover in medium improvement scenario (b) Corn stover in high improvement scenario

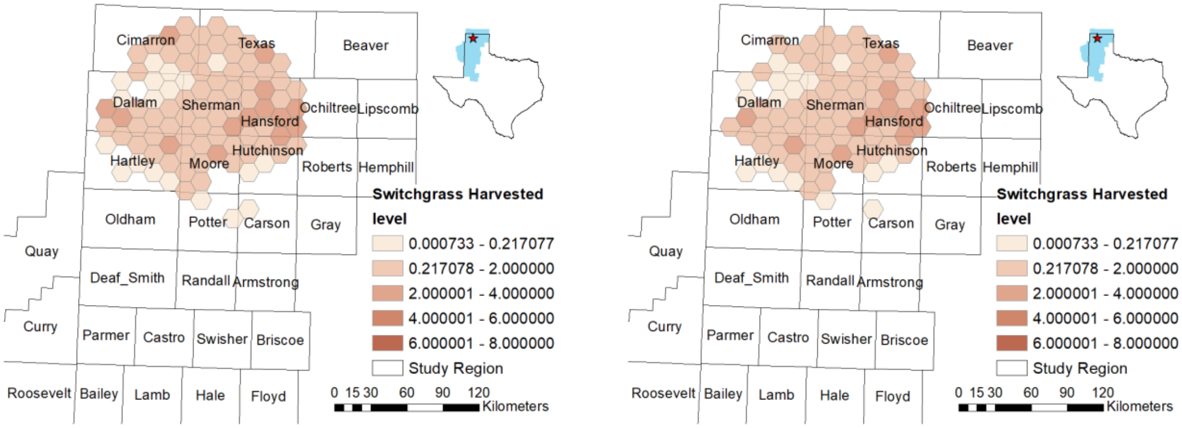


(c) Energy sorghum in medium improvement scenario (d) Energy sorghum in high improvement scenario

Figure 20 Source of each feedstock in different conversion rate scenarios



(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

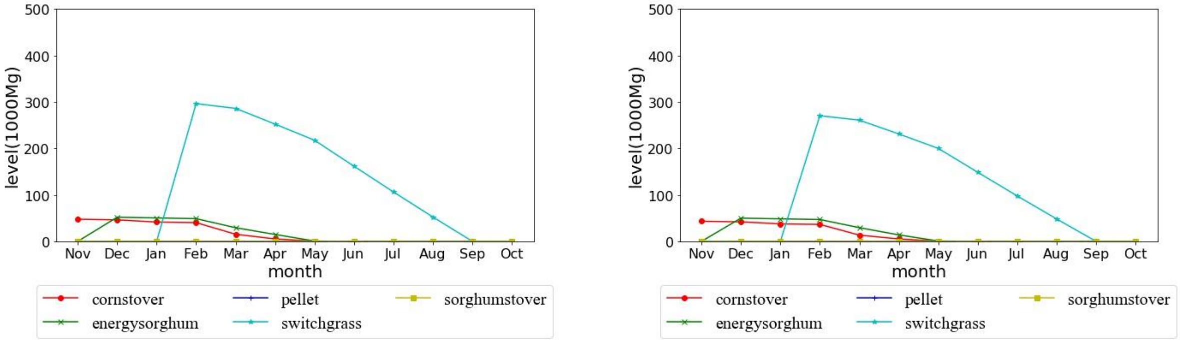
Figure 20 Continued

Less feedstock is harvested in the conversion rate improvement rate scenarios, with the exception of sorghum stover. Specifically, the harvested corn stover falls from 31.1% to 37%, energy sorghum from 12% to 16.9%, and switchgrass from 5.4% to 13.5%. As the yield of sorghum stover is low, the use of sorghum in both scenarios is small and unchanged. Switchgrass is still used as the main feedstock across the conversion rate scenarios. Again, this is due to the relatively low switchgrass storage costs.

The amount of feedstock dumped when the best yield of state of nature is realized decreases as the conversion rate improves. The total amount of feedstock dumped falls by 9.8%

and 17.1% in the medium- and high-improvement rate scenarios, respectively. This occurs as less land is required for a sufficient supply, in turn decreasing dumping.

Figure 21 below illustrates the monthly storage inventory levels for the different conversion rates.

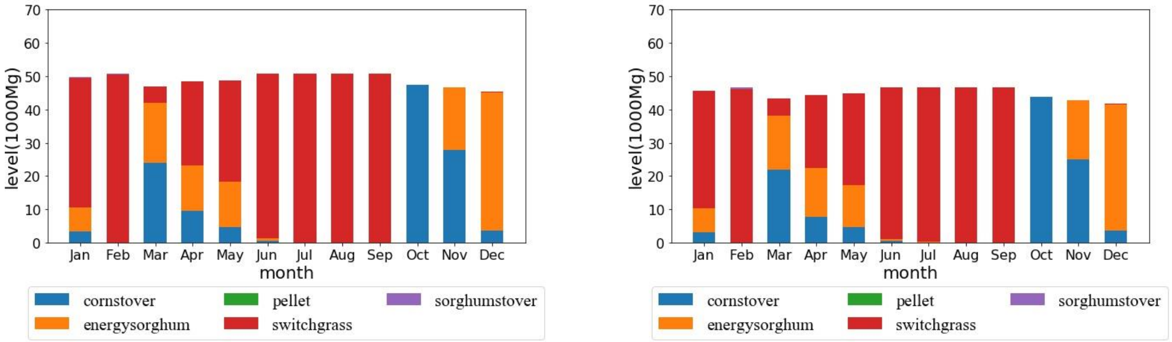


(a) Medium improvement scenario

(b) High improvement scenario

Figure 21 Monthly inventory levels in different conversion rate scenarios

The monthly inventory level decreases due to lower demand for feedstock, as conversion rate improves. In fact, approximately 280,000 mg to 300,000 mg of switchgrass is sent to storage and then consumed between February and August. Additionally, 50,000 mg of corn stover and energy sorghum are transported to storage in November and December and used as inputs for the following two to three months.



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

Figure 22 Process level of conversion rate improvement scenarios

The amount of each feedstock processed throughout the analysis period is shown in Figure 22. 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 is used as the main source of feedstock excepting in months when another feedstock could be harvested. Specifically, 20% to 60% of the feedstock is switchgrass in March, April and May while more than 80% is switchgrass in January, February, and from June to September. Additionally, a combination of corn stover and energy sorghum provides the necessary feedstock in March, and April and from October to December. Since the storage costs of these two feedstocks are higher, they are mainly harvested and sent directly to the biorefinery. Only a small portion are stored and processed from March to May.

Impact of pellet price on the supply chain design in the stochastic model

Reflecting the potential impact of possible pellet export sales, the above results show that agricultural residues located on the outskirts of the region are the most likely feedstock to be converted into pellets and exported. If the feedstock yield is well above average or the conversion rate improves, the feedstock is simply dumped, rather than being made into pellet, since the cost of the dumping feedstock is lower than that of pelletizing and storing it. However, the introduction of an export sale possibility could affect this.

In the development of the scenarios, we noted that the herbaceous pellet market was relatively limited, compared to that of wood-based pellets, and thus there was little information on herbaceous pellet prices. We assume that the price of herbaceous pellets was lower than that of woody pellets, since the higher ash content[8] reduces combustion efficiency and thus pellet value. Specifically, the price for herbaceous pellets is thought to range from $98.56 per mg to $166.5 per mg if 12% ash content is assumed.[9] This led to the formation of two pellet price scenarios of $100 and $150 per mg, which were used in the proposed model to simulate potential pellet price, as opposed to the price of zero in the base model.

As pellets are generally transported by rail, this study ensures that each potential location for a storage/pellet plant has railroad access. Figure 23 depicts the optimal locations of facilities in the different pellet price scenarios. In both scenarios, five combined storage depots and pellet plants are selected and located near the biorefinery. The same facility setup is observed in both the low- and high-price scenarios. In this study, a constraint on the total number of storage/pellet plants is applied to increase computation efficiency. Thus, given that all available locations for pellet plants near the biorefinery have been selected for both cases, the basis for both pellet prices is identical.

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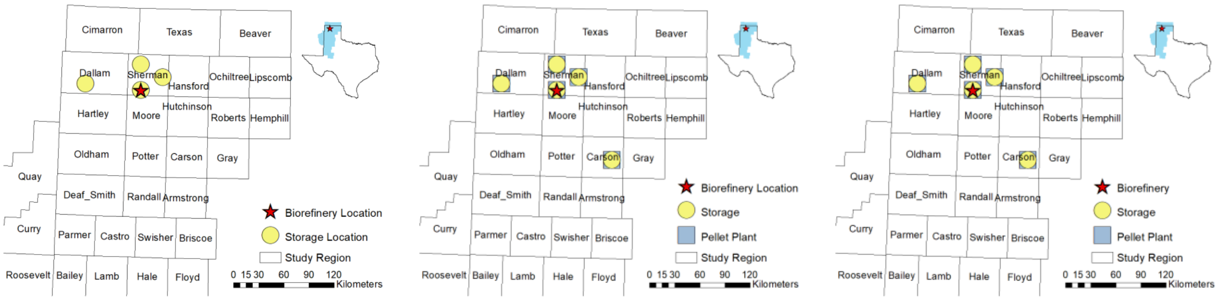
[8]. Based on a study of Vermont grass energy partnership, the ash content in the herbaceous pellet is 12 to 15 times higher than woody pellet.

[9] 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 per mg to $$162.8 per mg



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

Figure 23 Optimal locations for different price scenarios

At optimality, one pellet plant is selected at each location due to the assumption that no stand-alone pellet plant is allowed. This assumption is made because the quantity of pellets produced is relatively large, thus the raw feedstock will be stored before conversion into pellet. As we assume that a pellet plant must be located in conjunction with a storage depot, one pellet plant is located at each location.

Table 20 below summarizes the expected cost of each component in the supply chain at different price scenarios. When the pellet sale option is available, the total cost falls from the base case by 6.2% and 26.5% for the $100 and $150 per mg scenarios, respectively. The improvement of the expected objectives in both scenarios results from pellet sale revenues offsetting the increasing costs of an additional storage depot and pellet plant, as well as the associated increased operating and transportation costs.

Table 20 Expected cost of each component at different pellet prices

Item	Base case	$100/Mg	$150/Mg	Unit
Expected cost of supply chain	114,775.4	107,572.9	84,292.9	$1,000
Annualized cost of building biorefinery	24,504.4	24,504.4	24,504.4	$1,000
Annualized cost of building Storage	9,952.3	9,952.3	9,952.3	$1,000
Annualized cost of building Pellet Station		1,893.1	1,893.1	$1,000
Cost of contracting land	1,974.1	2,493.7	2,736.3	$1,000
Expected Cost of harvesting biomass	27,963.8	46,731.6	47,052.9	$1,000
Expected Cost of dumping biomass	17.6	36.0	32.7	$1,000
Expected Cost of storing biomass(offsite)	6,287.0	6,073.1	6,028.9	$1,000
Expected Cost of pelleting		12,115.3	12,386.3	$1,000
Expected Cost of producing ethanol	31,752.0	31,752.0	31,752.0	$1,000
Expected Cost of Transporting biomass	12,324.2	18,245.4	18,371.6	$1,000
Profit from export pellet		-46,224.1	-70,417.4	$1,000
Average cost of a gallon ethanol	0.60	0.56	0.44	$/L

Table 21 below lists the optimal solutions to the key decisions. Based on the table, the land contracted for supply feedstock increases by 28.7% in the low-price scenario and 37.6% in the high-price scenario. This reduces dumping, with feedstock converted to pellets. Specifically, the contracted land increases by 20.9% and 39.8% for corn stover, 55.6% and 50.3% for energy sorghum, and 32.2% and 33.2% for switchgrass when the price of pellet increases from $100 per mg to $150 per mg, respectively, compared with the base scenario. While more land is used for corn stover and energy sorghum, the land for sorghum stover remains the same in all scenarios. As more land is contracted, more feedstock is harvested, with the exception of sorghum residue. The average harvest increases by 147% and 152% for corn stover, 54.9% and 49.8% for energy sorghum, and 32.3% and 33.2% for switchgrass.

Table 21 Summary of the key decisions of different pellet prices scenarios

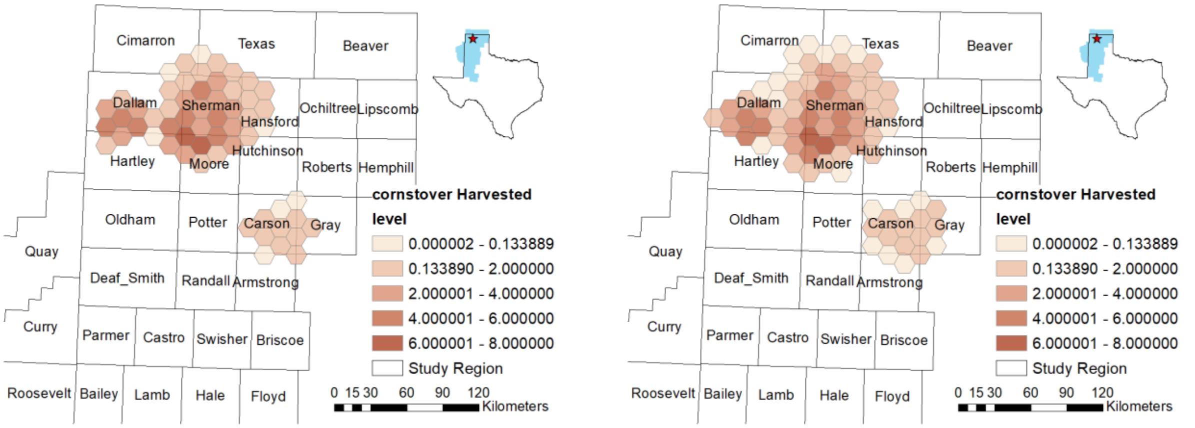
Item	Base scenario			$100/Mg			$150/Mg			Units
	Worst yield	Best yield	Average	Worst yield	Best yield	Average	Worst yield	Best yield	Average	
First-stage decision										
Total land contracted for biomass	252.4	252.4	252.4	325.0	325.0	325.0	347.4	347.4	347.4	1000Ha
Corn stover	124.2	124.2	124.2	150.2	150.2	150.2	172.7	172.7	172.7	1000Ha
Energy sorghum	23.6	23.6	23.6	36.8	36.8	36.8	35.5	35.5	35.5	1000Ha
Sorghum stover	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1000Ha
Switchgrass	104.0	104.0	104.0	137.5	137.5	137.5	138.6	138.6	138.6	1000Ha
Second-stage decision										
Total biomass harvested	743.3	736.9	736.7	959.1	1231.1	1217.6	1030.3	1231.5	1224.9	1000Mg
Corn stover	406.7	54.6	184.4	491.8	158.5	455.9	565.6	162.9	465.9	1000Mg
Energy sorghum	95.7	111.2	136.0	149.0	292.2	210.7	143.9	282.2	203.8	1000Mg
Sorghum stover	0.4	0.9	0.6	0.4	0.9	0.6	0.4	0.9	0.6	1000Mg
Switchgrass	240.5	570.2	415.7	317.9	779.5	550.3	320.4	785.6	554.6	1000Mg
Total biomass dumpped	0.0	621.5	313.1	0.0	543.1	147.0	0.0	644.1	226.3	1000Mg
Corn stover	0.0	525.6	309.7	0.0	543.1	141.5	0.0	644.1	221.3	1000Mg
Energy sorghum	0.0	76.5	2.9	0.0	0.0	5.5	0.0	0.0	5.0	1000Mg
Sorghum stover	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Switchgrass	0.0	19.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Total biomass stored	2589.6	1786.1	2107.4	2325.7	1960.0	2029.4	1510.5	1948.7	1987.2	1000Mg
Corn stover	1337.5	0.0	301.6	577.6	0.0	17.9	276.9	0.0	7.2	1000Mg
Energy sorghum	246.6	0.0	294.3	517.3	324.8	607.2	410.3	302.2	569.2	1000Mg
Switchgrass	1005.5	1786.1	1511.6	1230.7	1635.2	1404.3	823.3	1646.4	1410.8	1000Mg
Total biomass processed	664.3	682.9	672.5	666.4	671.9	669.6	582.3	672.6	667.4	1000Mg
Corn stover	366.3	54.6	175.2	252.3	54.6	102.5	204.8	54.6	100.2	1000Mg
Energy sorghum	88.1	111.0	126.9	133.3	198.0	189.9	131.3	192.4	184.2	1000Mg
Sorghum stover	0.4	0.9	0.6	0.4	0.0	0.6	0.4	0.0	0.6	1000Mg
Switchgrass	209.5	516.4	369.8	280.4	419.2	376.5	245.7	425.6	382.3	1000Mg
Total Pellet produced	0.0	0.0	0.0	210.8	475.0	462.2	381.9	475.0	472.6	1000Mg
Total pellelt stored	0.0	0.0	0.0	0.0	0.0	0.0	697.3	0.0	24.1	1000Mg
Total pellet Processed	0.0	0.0	0.0	0.0	0.0	0.0	87.6	0.0	3.1	1000Mg
Total pellet exported	0.0	0.0	0.0	210.8	475.0	462.2	294.3	475.0	469.4	1000Mg

With the pellet sale option, the feedstock disposed in good states of nature in the base model is converted into pellets and sold. The feedstock used to produce pellet is switchgrass, corn stover, and energy sorghum; thus, the pellet plants are operated when these crops are harvested in January, February, October, November, and December.

In addition to helping to reduce the amount of feedstock dumped, the remote pelleting option and external market allow the use of stranded feedstock. Argo et al. (2013) argue that the remote prepossessing depots provide additional options for geographically stranded feedstocks that are not within an 80 km biorefinery radius. If each depot can participate in the external market, more of the stranded feedstock which is not economically feasible for collection can be captured and pelleted for sale and use. Our results support those of Argo et al. (2013), as corn stover is collected from a larger supply area and used in production of pellets for export as the pellet price rises. Specifically, compared to the base case, the supply region for corn stover increases from 60 to 90 km in both pellet price scenarios. The additional corn stover collected is sent to the closest remote pellet plant and converted into pellets and then exported to external markets. The amount of pellet exported is relatively small and has little impact on market price; thus, exogeneous prices are used throughout this study.

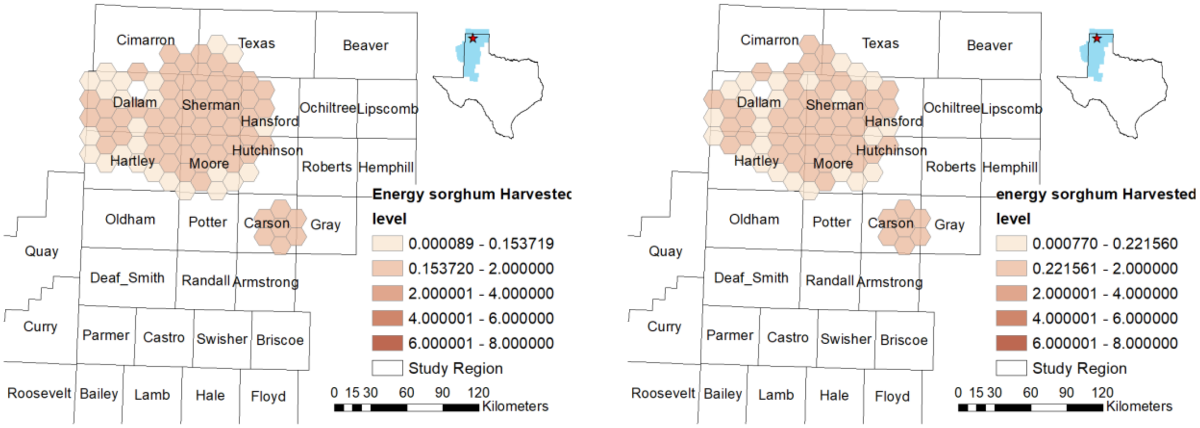
The amount of feedstock dumped when the best yield of state of nature is realized decreases by 53% and 27.7% when pellet price is $100 per mg and $150 per mg, respectively. More feedstock is dumped in the high price scenario than in the low price scenario due to the limitation on the number of pellet plants allowed in the study region. As mentioned earlier, a constraint on the total number of storage/pellet plants is applied to increase computation efficiency. Thus, given that all available locations for plants near the biorefinery are selected in the high-price scenario, part of the feedstock must be dumped once the pellet production capacity is reached. In other words, less feedstock will be dumped in the high-price scenario if the limitation on overall pellet plant capacity can be further increased. Therefore, even with more feedstock used to produce pellets, 221,270 mg of feedstock is dumped in the high pellet price scenario.

Figure 24 depicts the amount and area of each feedstock harvested in the different pellet price scenarios.



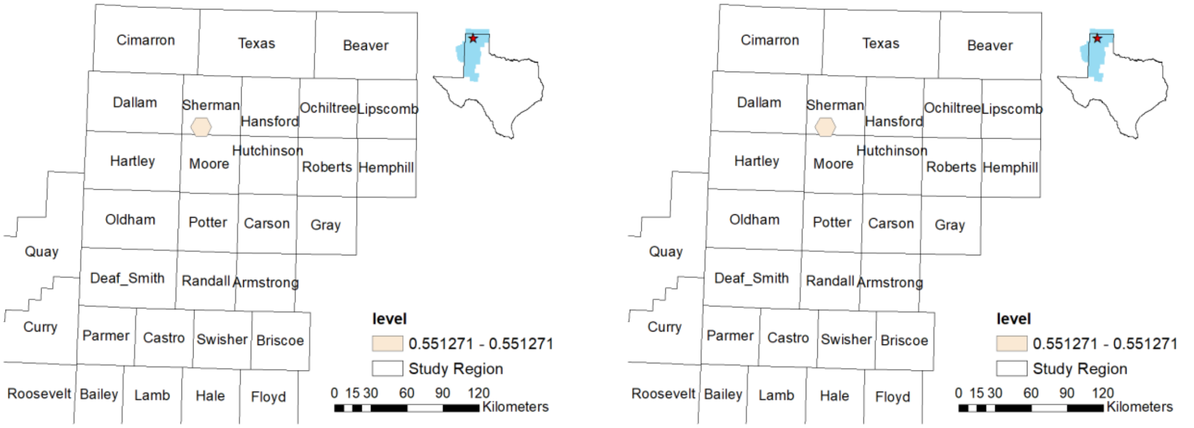
(a) Corn stover $100/Mg scenario

(b) Corn stover $150/Mg scenario



(c) Energy sorghum $100/Mg scenario

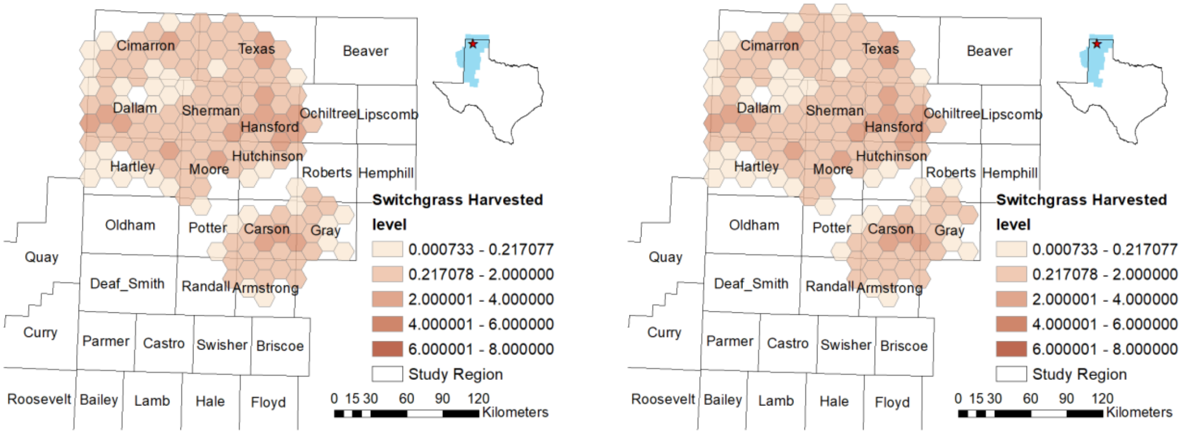
(d) Energy sorghum $150/Mg scenario



(e) Sorghum stover $100/Mg scenario

(f) Sorghum stover $150/Mg scenario

Figure 24 Source of each feedstock at different pellet prices

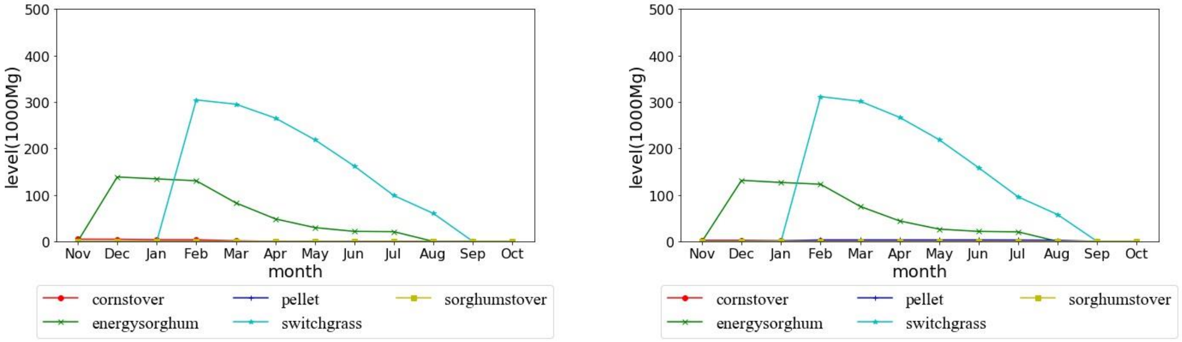


(g) Switchgrass $100/Mg scenario

(h) Switchgrass $150/Mg scenario

Figure 24 Continued

Figure 25 shows the storage levels for each feedstock on a monthly basis for different pellet price scenarios.



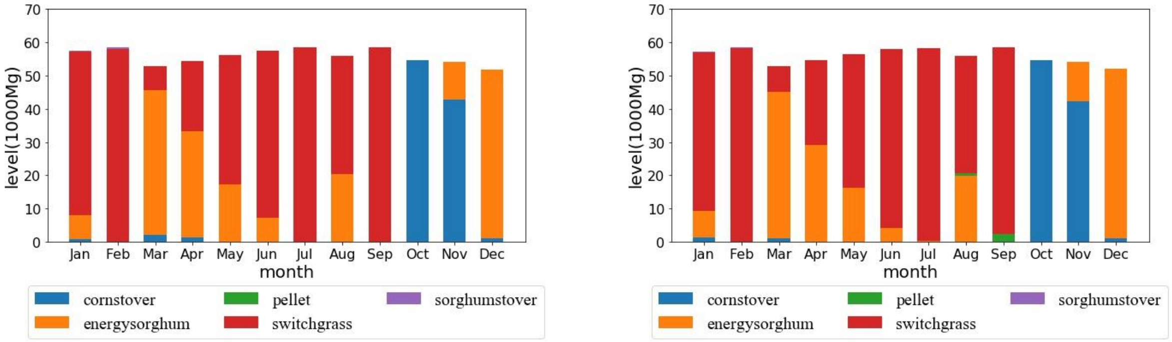
(a) $100/Mg scenario

(b) $150/Mg scenario

Figure 25 **Monthly inventory level for different pellet prices**

The storage patterns for low- and high-price scenarios are similar as the storage for both scenarios is confined to energy sorghum and switchgrass. Specifically, in both scenarios, approximately 125,000 mg of energy sorghum is stored in December and another 310,000 mg of energy sorghum added to storage in February. As there is no restriction on the quantity exported, all pellet is exported once produced to reduce storage costs. Again, given the switchgrass has the lowest storage cost, it is used as the major input for the biorefinery in both scenarios.

The amount of each feedstock processed throughout the analysis period is detailed in Figure 26.



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

Figure 26 Monthly feedstock processed in different pellet price scenarios

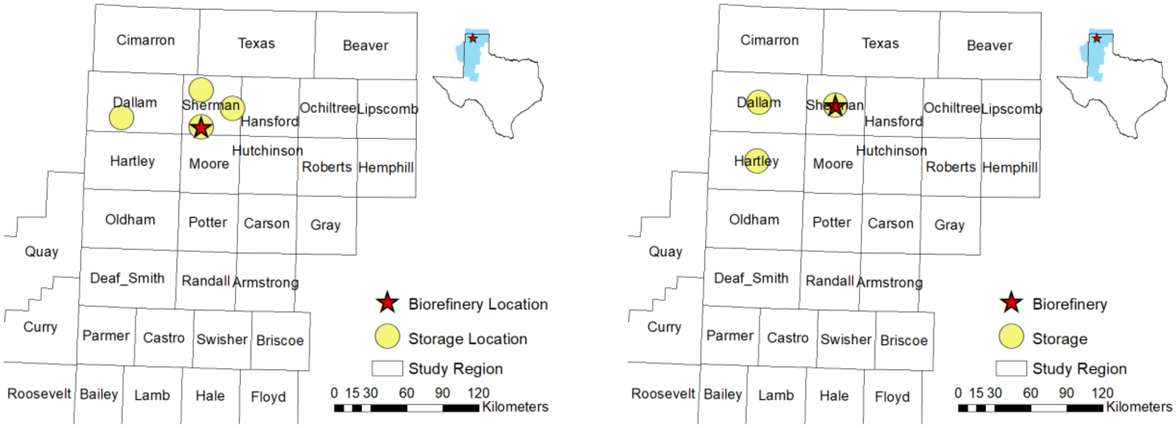
As mentioned above, switchgrass and energy sorghum are the main inputs throughout the year in both pellet price scenarios, with all pellets exported. As pellet price rises, more corn stover is contracted and the portion used for producing ethanol in the base case is input into the pellet plants. More corn stover is used to produce pellets due to both low collection cost and low yield fluctuation. Additionally, more energy sorghum is used in low- and high-price scenarios to produce ethanol.

As discussed above, the cheapest feedstock is used first as feedstock to the biorefinery, with the cost of this gradually increasing as distance increases. When the cost of using such feedstock is equal to the second cheapest alternative, the model will switch feedstocks. As that pellets can be sold, a new pattern arises; namely, the crop with the lowest storage costs and closest to the biorefinery will be used as the main input for the biorefinery. As for the feedstock in more remote locations, rather than transport it to the biorefinery, it is converted to pellets and exported to the external market.

Experiments with geographic scale

Another experiment is 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 Another experiment considers the effects of incorporating high resolution spatial data into the model. Although the potential for supply chain analysis at a fine spatial scale is increasingly recognized, studies of finer scales have been limited. In fact, one of the study challenges is the amount of spatial detail used to depict the transportation costs of the widely distributed feedstock. With the current capability of spatial analysis, substantial high-resolution geographical data and techniques can be employed to better depict feedstock movement, which may well affect the optimal facility placement and logistical decisions. Thus, an experiment was conducted using alternative scales to aid understanding of the impact of spatial data scale on supply chain design. This involved using finer scale hexagon-based information, as opposed to relying on county information. We ran a version of the model specifying the county level and another using the hexagons, as above. We then examined the differences between the optimal placement and configuration of the cellulosic biofuel supply chain, along with the implications for cost and other decisions.

Figure 27 illustrates the optimal locations of facilities in the two scale alternatives. In both scenarios, five storage depots are selected close to the biorefinery. With the county-level scale data, one depot is chosen in Hartley county, whereas with finer resolution data, one is located in Sherman county.



(a)Hexagon level scale

(b)County level scale

Figure 27 Optimal facilities on different geographic scales

The results indicate that the higher resolution spatial data leads to different estimates of transportation costs. Table 22 below illustrates the cost comparisons for each of the supply chain components, between county-level and hexagon-level geographic scale. The costs estimated using county-level spatial data are 1% less than the objectives using hexagon-scale data. The difference is due to the county-level model depicting movement to and from county centroids, as opposed to hexagon centroids. The results also indicate differences in land contracted and larger amounts of feedstock dumping in the county-level scale case. The results in Table 22 do not reflect a significant difference in the overall cost of managing biofuel supply chain when spatial units are applied. However, agricultural feedstock is usually distributed unevenly across the study region. When managing a biofuel supply chain, this could lead to inefficient decisions if the results of the analysis are used, without accounting for the heterogeneity of feedstock distribution.

Table 22 Expected cost of each component at different geographic scale

Item	County-level spatial data	Hexagon spatial data	Unit
Expected cost of supply chain	113,672.8	114,775.4	$1,000
Annualized cost of building biorefinery	24,504.4	24,504.4	$1,000
Annualized cost of building Storage	9,952.3	9,952.3	$1,000
Annualized cost of building Pellet Station			$1,000
Cost of contracting land	1,997.3	1,974.1	$1,000
Expected Cost of harvesting biomass	27,708.5	27,963.8	$1,000
Expected Cost of dumping biomass	80.1	17.6	$1,000
Expected Cost of storing biomass(offsite)	6,087.8	6,287.0	$1,000
Expected Cost of pelleting			$1,000
Expected Cost of producing ethanol	31,500.0	31,500.0	$1,000
Expected Cost of Transporting biomass	11,590.4	12,324.2	$1,000
Average cost of a gallon ethanol	0.60	0.60	$/L

Concluding comments

This chapter reports a case study that addresses the optimal design for 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 when determining facility locations (biorefinery, storage, and pellet plants), contracted feedstock land, feedstock movement, storage use, pelleting volume, land allocation for feedstock, remote versus centralized storage, pellet sale, feedstock choice in refining, and the effects of spatial detail. Several observations arise from model use.

First, we find that the incorporation of yield uncertainty significantly affects the need for feedstock contracting, the excess feedstock dumping costs, and supply chain operations when different yield outcomes are realized. There is 46.5% more land for feedstock contracted under circumstances of uncertainty, as a safety margin to ensure that the refinery is able to continue running when yields are low. On the other hand, when high yields arise, the model must deal with excess feedstock, with approximately 736,000 mg of total feedstock used in refining and 621,000 mg of excess feedstock dumped at a cost. As discussed below, the possibility for pellet export helps to manage the excess. Additionally, we find that due to the high fixed costs and consistent requirement for feedstock across states of nature, costs are not sensitive to 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 that the estimates of the empirical states of nature distribution and parameters in this study are relatively conservative, the impact of uncertain yield could be greater than the prediction. In addition, the “optimal” plan from the stochastic model is generally robust across the yield outcomes. Thus, the stochastic model solutions provide the decision maker with the flexibility to adjust the logistic decisions based on the varying yields.

Second, the impact of different supply chain designs is examined. The results indicate that total costs are essentially stable across these configurations. Yet, with remote facilities, storage and pelleting can be placed near places with high feedstock density and allow more efficient use of feedstock plus lower transport costs, spoilage and possible exports. Noted that different setup supply chain scenarios do not consider export of pellets to external markets. However, when pelleting and exports are allowed then one can exploit otherwise stranded feedstock. 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 able to manage uncertain yield and can lower total cost of ethanol as seen in the pelleting price results.

When pellet sale is not allowed, the average cost of cellulosic biofuel ranges from $0.59L to $0.602/L. 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 Based on these figures, a cellulosic biofuel supply chain in the present study region is not an economically competitive option for a private enterprise 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 must 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 23 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.

Furthermore, analyses are conducted to examine the impact of conversion rate improvements. The improved conversion rate reduces feedstock demand to generate the amount of ethanol is fixed by the model and costs across the elements of the supply chain. We also find that conversion rate improvements alter the supply chain design. Specifically, facilities are placed closer to the biorefinery as the greater ethanol yield shrinks the supply region. This causes the average cost to fall from $0.602 L to $0.56 L and $0.54 L as the conversion rates improves and subsidies make increasing ethanol volume attractive to the plant.

Moreover, analyses of pellet export possibilities of $100 and $150 per mg are carried out. The results show that the possibility of high export price changes both the optimal locations of the facilities and the feedstock usage pattern, as well as increasing the optimal number of storage and pellet plants. Additionally, with the higher pellet price, the impact of uncertain yield of herbaceous feedstock is mitigated by reduced dumping and increased profit from exporting the pellets. The supply chain can involve added contracting to ensure supply when yields are low, and then the excess can be pelleted when high yields are realized.

Table 23 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)	0.60	0.09	$/L
No-pellet	0.60	0.09	$/L
Central storage	0.60	0.09	$/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, experimentation with the granularity of regional representation reveals that it is beneficial to use a more disaggregated representation than a county-level form. The finer scale, in our opinion, gives a more complete view of appropriate supply chain design, contracting localities, and commodity movement, plus the altered facility locations.

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 over the past two decades. Today, first-generation, corn-based ethanol is commonly blended with gasoline, but its expansion has raised food security and environmental concerns. Second-generation biofuel made from lignocellulosic feedstock, which includes woody and crop residues, has been advanced as an alternative and was, in fact, assigned a mandate level in the RFS formulated in the EISA of 2007.

However, the production of lignocellulosic biofuel has been substantially lower than many anticipated. In the RFS legislation, 61 BLPY of cellulosic biofuel was expected to be required by 2020. However, only 0.54 BLPY was produced in 2015, with most of this from captured methane, which is far short of the 11.35 RFS proposed by the 2015 mandate, and there has been no substantial expansion in agricultural feedstock-based production since then. In fact, of the three commercial-sized plants constructed, only one remains in operation and this is operating at levels well below its nameplate capacity.

Several studies point out that one of the largest challenges facing cellulosic ethanol production is the logistics of moving a large volume of material. The primary reason for the high logistics cost is that the lignocellulosic feedstocks are bulky, containing high levels of moisture, and are widely distributed across the landscape. Some feedstock types are only available in a short harvesting window, requiring substantial storage for year-round refinery operation. There is also substantial year-to-year variation in yields, which complicates supply chain design. Another probable cause of the high logistics cost could be inefficient supply chain design. This thesis addresses optimal supply chain design for a lignocellulosic biorefinery.

To achieve this, a supply chain optimization model incorporating feedstock yield uncertainty was conceptualized and implemented, and used to study the costs and benefits of including or excluding the following in the chain: remote storage, pelletizing, multiple feedstocks, and yield uncertainty. In addition, we consider the implications of higher resolution spatial data on changes in conversions cost.

Yield uncertainty, when included, encompasses years with both shortfalls and excesses. Assuming the biorefinery contracts for a lower probability distribution safety margin, higher production levels than necessary would be expected. The size of the safety margin and the handling of excess feedstock are other issues addressed in this study. To our knowledge, few existing studies consider how to deal with yield variability, safety margins, and extra feedstock. To explore the issue of excess, we include the options of (1) dumping and (2) pelleting, then storing or exporting the pellets.

This chapter presents the results of a case study that examines biofuel supply chain design in an East Texas region. For feedstocks, woody feedstock (i.e., logging residue and thinning residue) and switchgrass are considered. The model identifies a cost-minimizing logistical design, including the optimal locations for biorefinery, storage, and pelleting plants and the optimal seasonal feedstock mix. The results of the proposed model are then used to provide insights on including or excluding decentralized storage, pelleting, yield uncertainty, and the use of single or multiple feedstocks.

Case study

Study region and potential sites for facilities

The study region was determined based on a spatial analysis of feedstock availability in proximity to transport routes in a 22-county East Texas region. Based on NREL studies (Aden et al. 2002; Humbird et al. 2011), the assumed biorefinery can process upwards of 2,000 dry mg of feedstock per day, in turn yielding 187 million liters of cellulosic ethanol per year, with an assumed yield of 264 liters per mg. Furthermore, we assume the biorefinery operates 8,500 hours per year (approximately 97% of the time). Given those assumptions, the minimum annual feedstock requirement to be collected from the current study region is approximately 708,100 mg. Furthermore, the potential biorefinery locations are those in the region with access to a major road or railroad on which to transport feedstock, and each potential site is some distance from the city to avoid environmental and traffic issues.

In this case study, dedicated energy crops (switchgrass) and substantial amounts of woody feedstock can be drawn upon. To ensure woody feedstock, an additional constraint was imposed on the analyses, which requires at least half of the annual feedstock to come from woody feedstock. Also, as it comes from a forestry operations continue year-round, the woody feedstock was modeled without any yield uncertainty. Although Sabine county in Louisiana is located within an 80 km radius of the collecting region, it was ruled out of the study region due to the limited crossings over the Sabine River.[10] In line with Aden et al. (2002), the maximum collection radius was set at 80 km, as sufficient actual plus potential feedstock is available to meet the 2,000 mg per day design. Based on these criteria and the available feedstock estimates

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[10] 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.

from the KDF (Langholtz et al. 2016) and the Texas Forest Service (TFS) (Staples et al. 2008), Angelina county and Trinity county were chosen as potential locations for the biorefinery. Additionally, the surrounding 20 counties falling within an 80 km radius of Angelina and Trinity were selected for the potential feedstock supply region.

Once the study region boundary had been determined, a more detailed spatial analysis of the 20 counties was conducted to identify the suitable locations for the biorefinery, remote storage, and pelleting. The whole study region was broken into 200 square km hexagons deemed large enough to adequately reflect the heterogeneity of the potential feedstock distribution, while not so fine as to greatly increase the computation time. For potential biorefinery sites within the central Trinity and Angelina counties, 13 hexagons with ready access to both rail and road transportation and located some distance from the cities were selected. Similarly, hexagons in the outlying counties which fall within the 80 km radius periphery of the potential biorefineries, have access to both rail and road transportation, and are located some distance from the cities are considered potential locations for distributed storage and pelleting plants.

Figure 28 below depicts the boundary and the potential locations for storage and pelleting plants in the present study region.

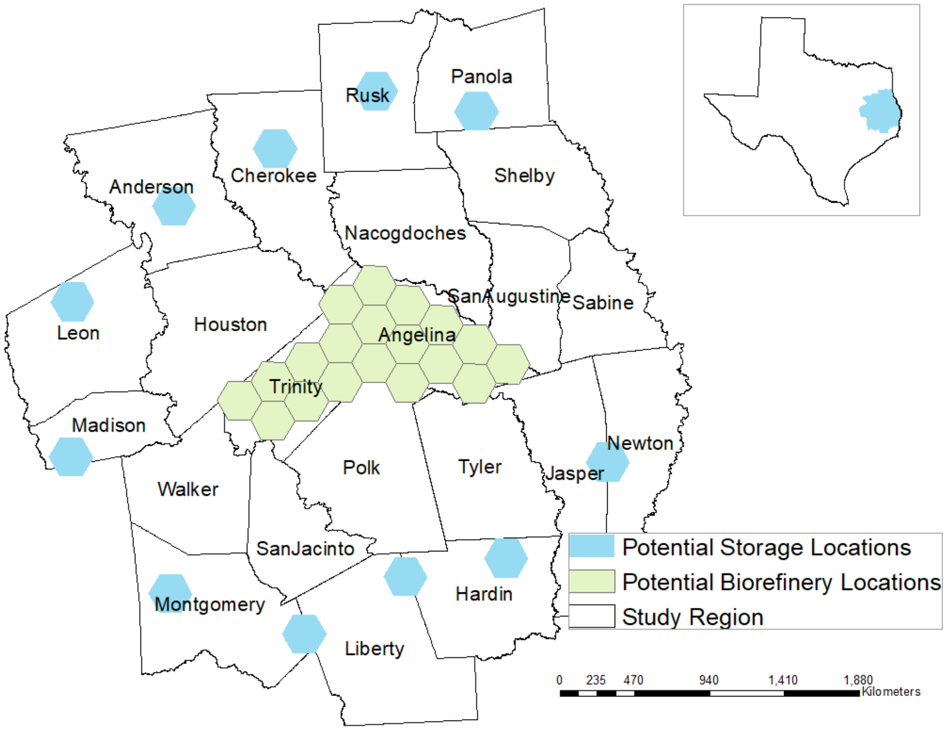

Figure 28 **Potential storage/pellet locations**

Feedstock considered in the study region and its availability

Land cover in the 22-county study region comprises 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 CDL (USDA 2018). Multiple lignocellulosic feedstocks are thus considered, including forest logging residues, forest thinning residues, and switchgrass. The data and methods used to estimate feedstock potential availability depend on the feedstock. For the woody feedstock, the feedstock available on the ground arose from existing forest sites, with the TFS estimating the available annual volume at 2.94 million mg, based on a survey (Staples et al.

2008). This potential feedstock comprises 1.08 million mg from logging residues and 1.86 million mg annually from thinning residues.[11]

It is noted that the estimates of woody feedstock from TFS data are used in the current study, rather than those of BTS 2016. The local assessment is considered more accurate due to the BTS focus on the national-level feedstock supply, which relies on assumptions less appropriate to the current study region. For example, the BTS estimates only consider timberland which can grow 0.6 m^3 per acre per year, which is conservative relative to the actual yield in East Texas. Therefore, the survey data from TFS is considered more appropriate for this study.

Not all the feedstock on the ground is assumed to be useful as feedstock for a biorefinery. Gan et al. (2013) indicate that only the forest residues close to a road should be considered accessible when conducting analysis. Additionally, part of the residue must be left on the ground to reduce erosion. Moreover, some of the woody feedstock could be used for other purposes. Based on the findings of Gan et al. (2013), the available woody feedstock supply for the biorefinery is expressed as in Eq (42):

$$S = \theta\lambda(A - M) \tag{42}$$

where θ is the accessibility rate, λ is feedstock recovery rate, A is the total available feedstock, and M is the feedstock consumed from other use. The current study assumes that only the forest within a half-kilometer distance is accessible, which makes 75% of the forest area within the study region available. Within the accessible forest, we assume 85% of the woody feedstock is recoverable, with the rest left to prevent erosion (Gan et al. 2013). We also assume

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[11] Including softwood and hardwood

that there is no other demand for the woody feedstock, with all that recovered becoming feedstock for the biorefinery.

The woody feedstock data that has been discussed thus far are those from the county-level scale. To expand our analysis to a finer scale, a method has been developed to allocate the county-level woody feedstock to each hexagon. The basis of this allocation considers the relative ratios of forest land at the county level to that within the county hexagon level. This is specifically the NASS CDL for the study region (USDA 2018), comprising cropland use, fallow/idle cropland, forest, shrubland, and barren. The forest classification overlaps with the hexagon grid and the county boundary to calculate the number of forest pixels falling within each hexagon and each county. As the grid size of CDL is 30 m by 30 m (900 m^2), we can obtain the area of forest in each hexagon/county by multiplying the number of forest pixels by the 900 m^2 pixel size. For example, if a hexagon contained three forest pixels, the forest area falling within this hexagon would be 2,700 m^2. Once the forest area of each hexagon/county was calculated, the available woody feedstock in each hexagon was derived by multiplying the ratio of forest feedstock yield by 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, if a hexagon has 2,700 m^2 of forest and the county has 27,000 m^2, that pixel is assigned 10% of the county-level yield.

Table 24 below lists all the woody residue in the study region.

Table 24 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)

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

Procurement cost of feedstock

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

Unlike collection of woody feedstock, which can be done 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 planners must determine the amount of land contracted for growing switchgrass before knowing its yield. We assume that a fixed, volume-independent, per hectare cost and a per-milligram-removed cost would be included in the contracting arrangements for switchgrass. The per hectare cost of switchgrass, in line with that given in Griffith et al. (2012), was composed of the establishing cost prorated over 10 years, annual maintenance, and operation costs. A total annual cash cost of $718 per ha was used to establish and maintain switchgrass.

The harvesting and collection method and associated costs (i.e., the per milligram cost) are based on the DOE uniform-format feedstock supply system (Hess et al. 2009). To harvest switchgrass, a self-propelled windrower with a disc header is assumed for cutting the switchgrass. The cut and conditioned switchgrass is deposited on the field, forming a windrow. Later, a square baler and self-propelled stacker are used to bale and move switchgrass. The conditioning process, which crushes the stem of the switchgrass, is used to speed up drying and reduce dry matter loss. Table 25 lists the equipment and estimated costs of harvest and collection operations.

Table 25 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 costs

Most harvested feedstock must be preserved to avoid deterioration and fire danger, particularly in a high rainfall region such as East Texas. If the large square bales are stacked and stored in a hoop barn structure, each barn hoop is 22 m wide by 10 m high and 36 m long (ISU 2017). Figure 29 shows the setup of the indoor storage facility assumed in the present study. Based on the ISU (2017) study, each hoop barn contains two stacks, and each stack is assumed to be placed in a 10 m by 10 m by 36 m formation (65’ by 30’ by 115’): four bales wide with the long-side of the bale, eight bales high 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 1000 mg of feedstock.[12] Stacks within a hoop barn are separated by a 2 m distance and hoop barns are assumed to be placed 15 m away to keep the fire from spreading to other stacks and to ensure access for fire-fighting equipment (PSU 2016). According to Darr and Shah (2012), the consequent deterioration rate of the hoop barn is approximately 3%.

In this study, each facility is assumed to have a capacity of 100,000 mg, which is equivalent to hold 100 hoop barns of feedstock at any one time. This study further assumes that the hoop barns are placed with a 10 m by 10 m formation in the storage facility, with a setback

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[12] 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

distance 18 m between each barn (Darr and Shah 2012). Thus, the land dimensions must be 392 m by 532 m. Based on the work of Darr and Shah (2012), the building cost of a hoop barn is \$120 per m^2 and the consequent fixed cost of building a hoop barn of this size is \$27,377,280. Assuming these barns can last for 20 years, the resultant annualized cost of building storage depots is \$2,584,000.

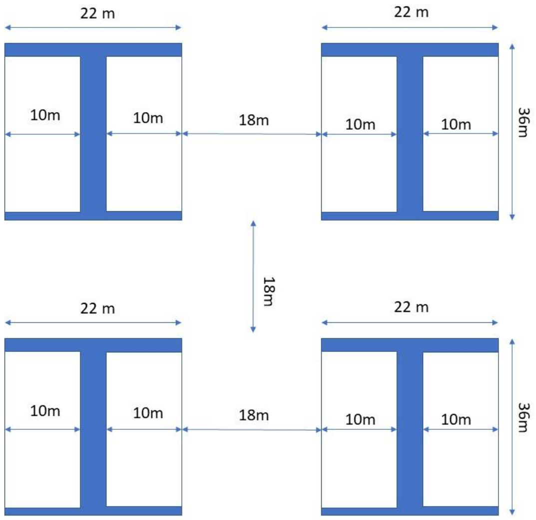

Figure 29 Formation of indoor storage for herbaceous biomass

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 non-pelleted feedstocks is identical. A telehandler collects the large square bales from the truck and stacks them in the formation described above, at a rate of 80 bales per hour. Table 26 below lists the variable bale storage costs.

Table 26 Storage costs 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)

It is noted that since woody feedstock can be collected from accessible piles year-round, it is assumed that wood does not require covered or offsite storage.

Size reduction option (pelleting)

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

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

Pellet storage is also considered, including the moving of pellet to storage bins and the cost of labor. The resultant variable and operating cost is $2.51 per mg. Table 27 and Table 28 list the capital costs of the pellet production plant equipment and the operating cost of production.

Table 27 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 28 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

Feedstock transportation and handling

Transportation and handling operations involve a fixed cost for loading and unloading, plus a variable cost per unit of distance. Given the transportation distances in this study are relatively short, usage of a truck is assumed for the base case. This is a 2.4 m wide by 16 m long, three-axle flatbed trailer used to move the large square bales, which means a truckload is 26 large square bales. The per unit loading cost is assumed to be $5.41 per mg, with a 25% moisture content assumption (Hess et al. 2009). The variable cost is a linear multiple of distance, in line with Mahmudi and Flynn (2006), which gives the estimated variable cost of truck transportation for bale as $0.148 per mg per km moved.

For transporting and handling wood, this study assumes the wood is shipped and that the transportation and handling costs are similar to those of moving grain. Based on the study of Ortiz et al. (2011), the total cost for chipping, loading using an auger, and unloading by opening gates and dumping is $2.74 per mg. For the variable cost of transporting wood chips by truck, we use the figure of $0.07 per mg per km, as estimated by Ortiz et al. (2011).

Preprocessing and handling at the biorefinery

Two conversion methods are commonly used to process lignocellulosic feedstock 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 assumes that all the feedstocks are converted into ethanol through a biochemical process. The capacity of the biorefinery is assumed to be 261.9 MLPY, based on operations of 24 hours a day for 310 days a year. The assumed capital cost of this type of plant is $220.1 million (Aden et al. 2002). The variable cost used in the study contains two parts: operating cost and the cost of purchasing enzymes. 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 29 lists the assumed capital cost components for a biochemical biorefinery.

The conversion rates for logging residue, thinning residue, and switchgrass through the bioconversion process are assumed to be 226.36 L per mg, 282.99 L per mg, and 272.32 L per mg, respectively (Foust et al. 2009). The logging residue yields are lower as we assume that they would contain limbs, branches, and bark and that this content would reduce the ethanol yield by 20% due to the lower enzymatic hydrolyzability (Frankó, Galbe and Wallberg 2015).

Table 29 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

Yield uncertainty considerations

Incorporation of yield uncertainty requires formation of an empirical probability distribution for the feedstock yields. This was done only for switchgrass, as the woody feedstock in the study region could be estimated before removal and more could be removed if supplies were short. The switchgrass yield probability distribution was developed using Texas-level historical records on hay[13] yield from 1950 to 2016. These historical data were first detrended to obtain the residual deviation of the crop yield in each year. The residuals for each year were then 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 to

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

estimate 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 presented in Table 30.

Table 30 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 for all required equipment. To incorporate those into our annual model, we calculated an estimate of the amortized cost of holding the items for one year by amortizing the cost. A 20-year life and a 7% discount rate were plugged into Equation (41), given in the previous chapter.

Table 31 lists the key parameters used in this study.

Table 31 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	718(2012)	768	$/Ha	(Griffith et al. 2012)
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	

We required an estimate of the number of days feedstock could be collected. Based on the study of Soloranzo-Campos (1990), the number of good working days in each month in the study region[14] is listed in Table 32.

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[14] 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 32 Probability of working days

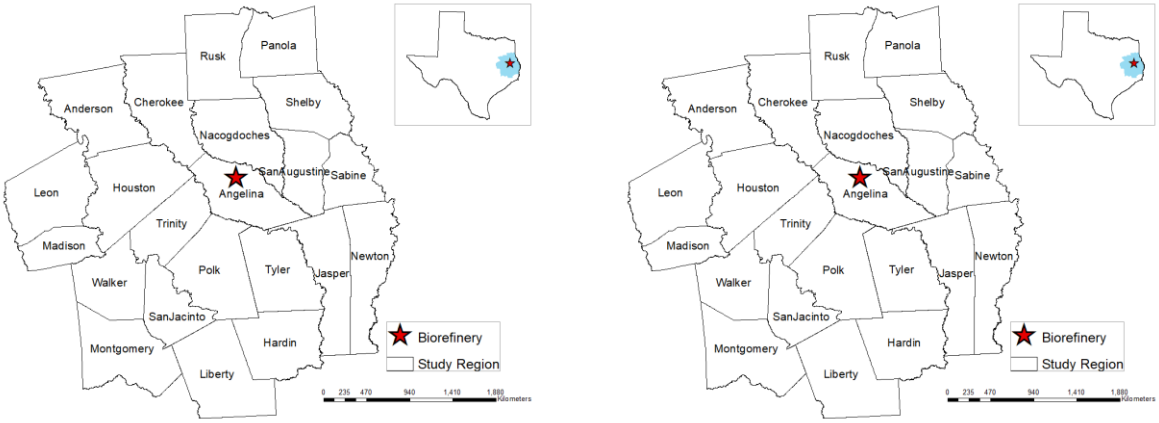
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Probability of working day	0.39	0.36	0.32	0.27	0.24	0.2	0.23	0.25	0.3	0.34	0.38	0.41
Actual days available	8.9	7.2	7.3	5.94	5.5	4.8	5.3	5.7	6.6	7.8	8.36	9.4

Analysis results

This section presents the results of the analyses conducted in this study. The first analysis involves a comparison of the results from the deterministic and the stochastic models to examine the impact of uncertainty on the supply chain design. Sensitivity analyses were conducted on the value of using multiple versus single types of feedstock, 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 contributes to supply chain analysis by incorporating high resolution spatial data into the proposed model. Although the potential for supply chain analysis at a fine spatial scale is increasingly recognized, such studies remain very limited and their potential has not yet been fully exploited. Further improving the capacity to draw spatial implications of supply chain analysis from high spatial resolution is essential. In fact, one of the challenges for previous studies was to precisely reflect the transportation cost of feedstock, since cellulosic feedstock is usually distributed widely. With a breakthrough in spatial analysis, substantial high-resolution geographical data and techniques can be employed in analyses to aid understanding of how feedstock distribution affects optimal facility placement and logistical decisions. Thus, an experiment of geographical scale was conducted to explore the impact of spatial data scale on the cellulosic biofuel supply chain design. The resultant model was executed on GAMS software, using CPLEX as solver, with a 0.1% tolerance gap between the best theoretical integer solution and the best objective value.

Comparison of the deterministic and stochastic model results

Figure 30 depicts the optimal locations of facilities in the solutions for the deterministic and stochastic models.



(a) Deterministic model (b) Stochastic model

Figure 30 Optimal locations in the deterministic and stochastic models

As shown in the figure, the biorefinery is optimally placed at the center of Angelina county in both models. No intermediate storage or pelleting plants are selected in either case. Only a small amount of switchgrass is stored at the biorefinery for emergency use and the rest is consumed within the harvest window. Outside the harvest window, woody materials are sent directly from supply region to biorefinery. In other words, the presence of woody materials year-round makes the use of stored switchgrass unattractive.

Table 33 below summarizes the costs of the stochastic and deterministic models. The main difference between the objective function values of the two models involves the costs of contracting land, purchasing thinning residue, dumping additional switchgrass, and moving feedstock. All these costs are higher with yield uncertainty.

Table 33 Expected costs in the deterministic and stochastic models

Item	Determinisitc	Stochastic	Unit
Expected cost of supply chain	97650.6	98656.5	$1,000
Annualized cost of biorefinery	22565.7	22565.7	$1,000
Annualized cost of storage	0.0	0.0	$1,000
Annualized cost of pellet plant	0.0	0.0	$1,000
Cost of contracting land	183.8	331.6	$1,000
Expected harvesting cost	30407.7	30767.7	$1,000
Expected dumping cost	0.0	481.8	$1,000
Expected storage cost	453.8	453.8	$1,000
Expected pelleting cost	0.0	0.0	$1,000
Expected conversion cost	31500.0	31500.0	$1,000
Expected transporting cost	12539.7	12556.0	$1,000
Profit form exporting pellet	0.0	0.0	$1,000
Average cost of ethanol	0.51	0.52	$/L

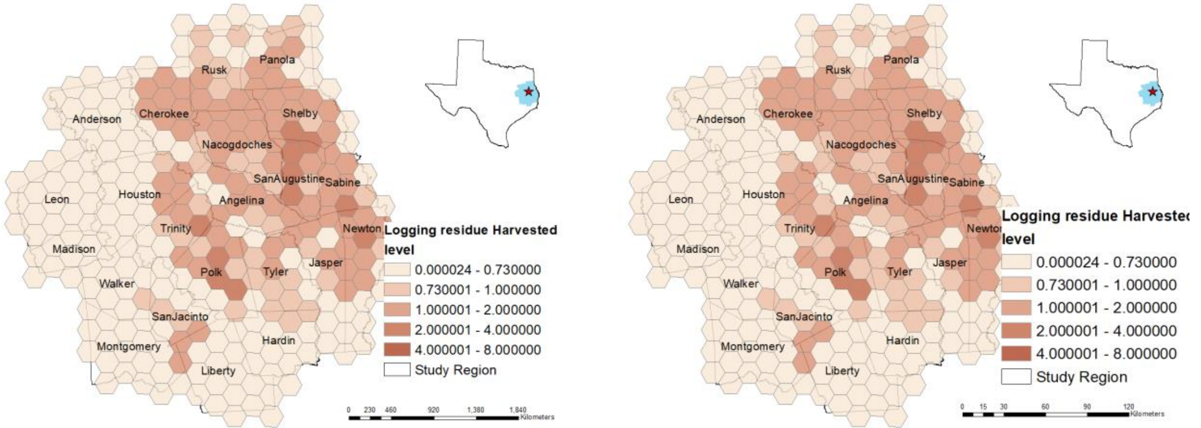
For the deterministic model, the fixed costs of biorefinery, collecting feedstock, ethanol production, and transportation account for 23.1%, 31.1%, 32.2%, and 12.8% of the objective function value, respectively. Of the total cost, 0.6% comes from emergency storage and land contracted for switchgrass. In the stochastic model, 22.8%, 31.1%, 31.9%, and 12.7% of the objective arise from fixed costs of biorefinery, collecting feedstock, conversion, and transportation. The cost of contracting land, dumping feedstock, and emergency storage accounts for the remaining 1.2% of the total. The expected cost of the stochastic model is 2.76% higher than that of the deterministic model.

Table 34 summarizes the key decisions in the deterministic and stochastic models.

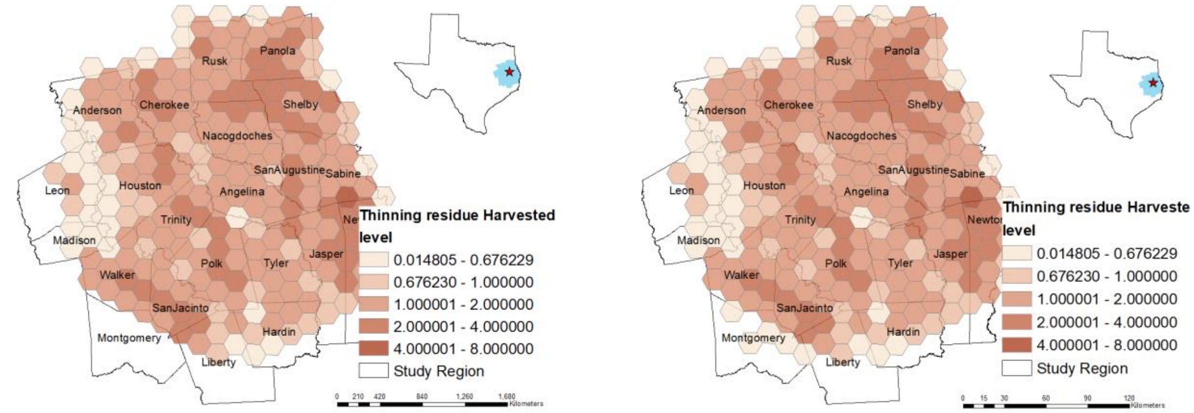
Table 34 Summary of decisions: the deterministic and stochastic models

Item	Determinisitc	Stochastic			Units
First Stage decision		Worst Yield	Best Yield	Average	
Total land contracted for biomass	17.5	31.5	31.5	31.5	1000Ha
Switchgrass	17.5	31.5	31.5	31.5	1000Ha
Second stage decision					
Total biomass harvested	722.7	721.5	722.5	722.5	1000Mg
Switchgrass	175.1	142.8	175.1	174.8	1000Mg
Logging residue	209.6	209.7	208.6	208.6	1000Mg
Thinning residue	338.0	369.0	338.8	339.1	1000Mg
Total biomass stored	0.0	0.0	0.0	0.0	1000Mg
Switchgrass	0.0	0.0	0.0	0.0	1000Mg
Logging residue	0.0	0.0	0.0	0.0	1000Mg
Thinning residue	0.0	0.0	0.0	0.0	1000Mg
Total biomass dumped	0.0	0.0	257.5	135.1	1000Mg
Switchgrass	0.0	0.0	257.5	135.1	1000Mg
Average biomass traveled distance	62.3	69.0	61.5	63.2	Km
Switchgrass	17.4	23.7	14.1	18.3	Km
Logging residue	74.6	74.7	74.6	74.7	Km
Thinning residue	77.8	83.3	77.8	77.9	Km
Total biomass processed	722.7	721.5	722.5	722.5	1000Mg
Switchgrass	175.1	142.8	175.1	174.8	1000Mg
Logging residue	209.6	209.7	208.6	208.6	1000Mg
Thinning residue	338.0	369.0	338.8	339.1	1000Mg

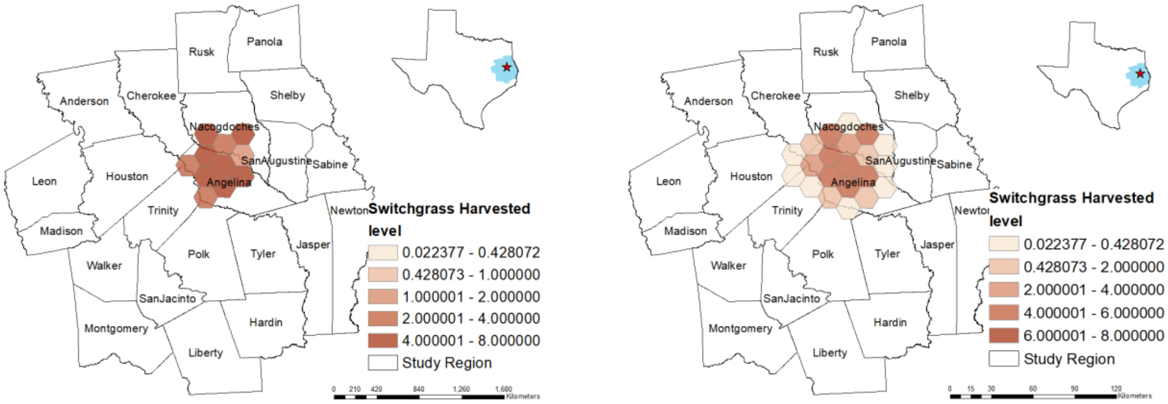
In the deterministic model, all decisions are made as if the switchgrass yield is equal to its average value. In the stochastic model, the contracted land is determined in advance, before the uncertainty is resolved, while different harvest, transport, and usage decisions are made depending on the realized yield state of nature. Consequently, there are 10 sets of decisions. Thus, rather than summarizing all the decisions, we choose to present the two extremes and the average. In the following tables, the first column in the stochastic model represents the resultant decisions when the worst yield state of nature is 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.



(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

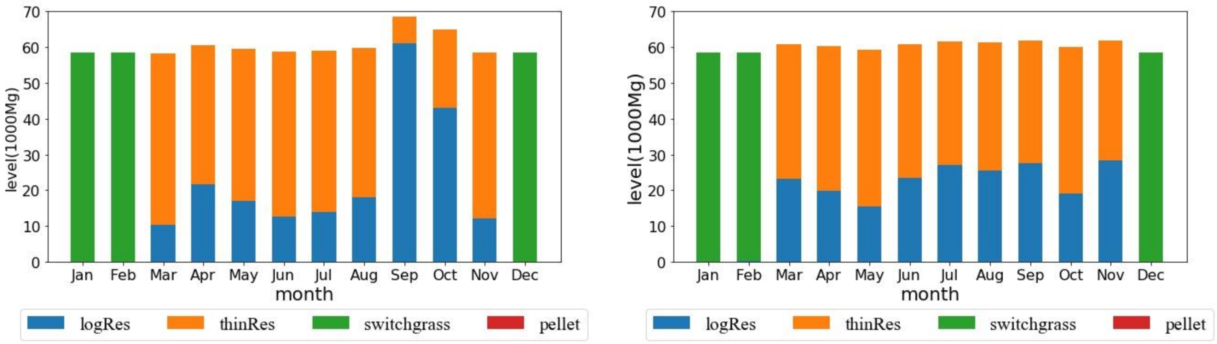


(e) Source for switchgrass in deterministic model (f) Source for switchgrass in stochastic model

Figure 31 Source of each feedstock in the deterministic and stochastic models

Figure 31 depicts the optimal land harvested for each feedstock for the deterministic and stochastic models. The amount and supply region of logging residue are essentially identical in both the deterministic and stochastic models and the supply area covers most of the study region. The harvesting level of logging residue near the biorefinery is the highest, decreasing as the hexagons move 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 is uncertain. The supply region of thinning residue in the stochastic model is effectively the same as its counterpart in the deterministic model, except for a slight enlargement in the southwest corner. The area of switchgrass harvested is almost double, although the expected harvesting level decreases slightly in the stochastic model. Under uncertain yields, 80% more land is contracted in the stochastic model than in the deterministic model to ensure sufficient available supply when the worst state of nature is realized. The different harvest levels across states of nature also affect the average distance of travel per milligram. When the worst scenario is resolved, the average distance traveled per milligram of feedstock is 69 km. In the best yield condition of switchgrass, the distance traveled falls to 61.5 km, as closer switchgrass can be relied upon under the good states of nature. However, the more distant switchgrass must be removed, and the model chooses to dump this rather than store or pelletize it.

Figure 32 depicts the monthly feedstock processed in the deterministic and yield uncertainty cases.



(a) Deterministic model

(b) Stochastic model

Figure 32 Monthly feedstock processed in the deterministic and stochastic models

In both cases, switchgrass is used as the major source of feedstock during its harvest window (January, February, and December), while a mix of logging and thinning residue are used as feedstock in other months. The exact source of the woody feedstock in both cases depends on the spatial distribution the relative ethanol yields. Feedstock beside the biorefinery is first consumed to the extent that the cost of obtaining this feedstock, plus shipping, divided by the conversion rate, is equal to the cost of the second-cheapest feedstock source. By the same token, once the delivery cost of the second-cheapest feedstock, divided by the conversion rate, becomes higher than that of the next cheapest feedstock, the model then switches to that feedstock and continues mixing until the demand of the biorefinery has been satisfied. For example, in the deterministic case above, the thinning residue near the biorefinery with the higher conversion rate is first used to satisfy the demand of the biorefinery, outside of the switchgrass harvesting window. As the cost of using thinning residue increases with the distance between supply region and the biorefinery, logging residue near the biorefinery is used. However, ultimately the price of the logging residue – plus moving cost and divided by its lower conversion rate – becomes equal to the delivery cost divided by the conversion rate of the farther away thinning residue. The model thus selects a different mix of logging and thinning residue until the minimum requirement is satisfied. It is also noted that the service area for thinning is larger than that for logging residue, which reflects the difference in conversion rates.

Comparison of multiple- and single-source feedstock scenario results

The following section discusses the impact of storage on the biofuel supply chain. Due to the relatively low energy density of feedstock, a large volume is required to produce usable quantities of energy. Thus, storage is commonly required in a supply chain system. A properly developed storage plan can help to balance issues of feedstock harvest timing, random supply shortages, and feedstock deterioration and loss. As shown in Texas High Plains chapter, storage plays a critical role in ensuring a sufficient supply of feedstock to the biorefinery when multiple sources of feedstock have different harvesting windows. However, unlike Texas High Plains, where energy crops and their residues are the major source of feedstock, readily available woody feedstock throughout the plan horizon makes East Texas an ideal place for a logistical system in which feedstock is delivered to the biorefinery "just in time" for use.[15] Most of the feedstock is sent to the biorefinery and consumed directly. However, a small portion of wood chips (12,698 mg) is stored at biorefinery, which can thus continue running for up to seven days, if necessary.

The impact of utilizing a single feedstock, as opposed to multiple sources, is examined and the results are presented below. In the multi-feedstock scenario, the biorefinery utilizes woody feedstocks and switchgrass; thus, with the exception of the emergency storage at the

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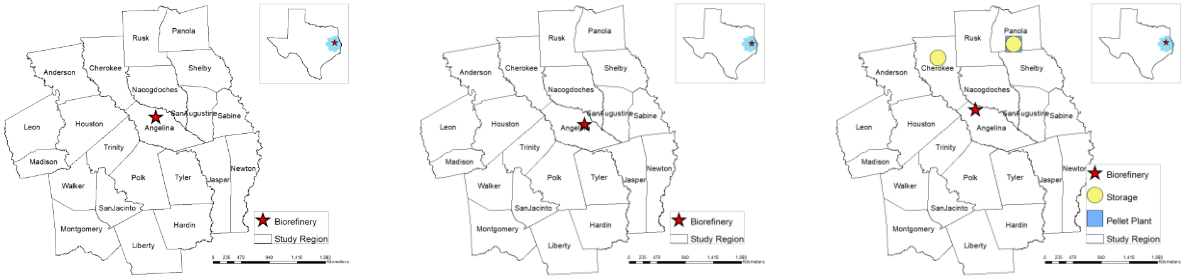
[15] "Just-in-time" delivery system refers to the system where no additional storage was required for feedstock except for the emergency use. Feedstock was sent directly from supply region and consumed without stored.

biorefinery, no additional storage is needed. When only switchgrass is available, storage plays a key role, due to the seasonality of the switchgrass harvest.

Next, we present the results on the optimal locations and then discuss the cost components and the optimal logistical decisions. The storage and the optimal locations for biorefinery, storage depots, and pellet plants for multiple- and single-source scenarios are depicted in Figure 33.

When either multiple feedstock or woody material alone is available, feedstock is sent directly to the biorefinery and no storage is required for switchgrass. Thus, the multi-feedstock scenario produces a significant saving in fixed costs for storage and transportation. When woody feedstock is available (with or without switchgrass), the supply chain setup is essentially the same, with the exception of the location of the biorefinery, as no storage or pellet plants are employed.



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

Figure 33 The optimal locations of facilities for single- and multiple-feedstock cases

In terms of the biorefinery location, the optimal location when no switchgrass is used moves 10 km to the southeast in the multi-feedstock case, as more thinning residue is distributed here.

The optimal biorefinery location in the switchgrass-only scenario is located in the northeast of Angelina county, closer to more pasture land. Additionally, six storage depots are selected to store the switchgrass for later use in the non-harvesting periods. Three of the six selected depots are placed in Cherokee county, and the remaining depots and a pellet plant are placed in Panola county. The pelleting plant in Panola county is used primarily to reduce transportation costs and avoid the costs of deterioration and storage. In the base scenario, the pelletizing option does not reduce the amount of feedstock dumped by removing it and moving it to the edge of field. As pelletizing cannot be exported and pellet manufacture costs are relatively high, the additional feedstock is dumped, rather than turned into pellets. However, if pellets can be exported, the storage/pellet depots can provide additional options for handling excess production and geographically stranded feedstocks that are not within an 80 km biorefinery radius.

Table 35 below summarizes the cost of each component in these scenarios.

The results indicate that the expected cost of the proposed supply chain when only switchgrass is available is 38% higher than when multiple feedstocks are available, while costs in the woody feedstock-only scenario are 3% higher than in the multiple feedstock case. The higher cost for switchgrass-only is due to more land being contracted for switchgrass, as well as the increased costs of constructing and operating new storage depots and pellet plants. On the other hand, the higher expected costs in the woody feedstock-only scenario are due to the increasing service area for woody feedstock and the associated transportation costs. Specifically, the cost of obtaining woody feedstock and transporting it to the biorefinery increases by 7.7% for thinning residue and 12.6% for logging reside, compared to the multi-feedstock case.

Table 35 Expected costs of each component in multiple- and single-source models

Item	all feedstocks	Only switchgrass	Only woody	Units
Expected cost of supply chain	98656.5	134746.8	101634.0	$1,000
Annualized cost of biorefinery	22565.7	22565.7	22565.7	$1,000
Annualized cost of storage		21868.8		$1,000
Annualized cost of pellet plant		378.6		$1,000
Cost of contracting land	331.6	1776.6		$1,000
Expected harvesting cost	30767.7	26454.3	33150.3	$1,000
Expected dumping cost	481.8	3204.1		$1,000
Expected storage cost	453.8	8493.5	280.5	$1,000
Expected pelleting cost		1162.8		$1,000
Expected conversion cost	31500.0	31500.0	31500.0	$1,000
Expected transporting cost	12556.0	17334.2	14137.5	$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, approximately nine times as much pasture land is contracted for switchgrass production in the switchgrass-only scenario. A key source of this is the fixed facility cost, which is almost double, due to the need to construct storage depots and pellet plants. Additionally, under switchgrass-only, the cost of storing increases by 5.6 times with respect to the multi-feedstock case, while dumping costs are 17.7 times higher than in the multi-feedstock case. A 36.5% higher transportation cost is also observed, since additional transportation is required between the supply region and storage, as well as storage and the biorefinery. Moreover, the average travel distance for switchgrass to the biorefinery is two to three times higher than in the base scenario, depending on the state of nature. Given the cost of transporting baled feedstock is higher than that of woody chips, due to the volume that can be transported per trip, the increasing use of switchgrass requires more travel by truck and contributes to a higher realized transportation cost in the single-source scenario.

Table 36 lists the optimal decisions when multiple and single sources of feedstock are available.

When all sources of feedstock are available, only switchgrass within a 40 km radius of the biorefinery is harvested, and the amount of switchgrass collected varies from 140,000 mg to 170,000 mg, depending on the yield states of nature. The amount of woody feedstock is 0.5% and 8.8% higher for logging and thinning residues, respectively, for worst case switchgrass yield than for best case. Given that thinning residue can produce more ethanol than logging residue, more thinning residue is used to meet the minimum requirements for the bad yield.

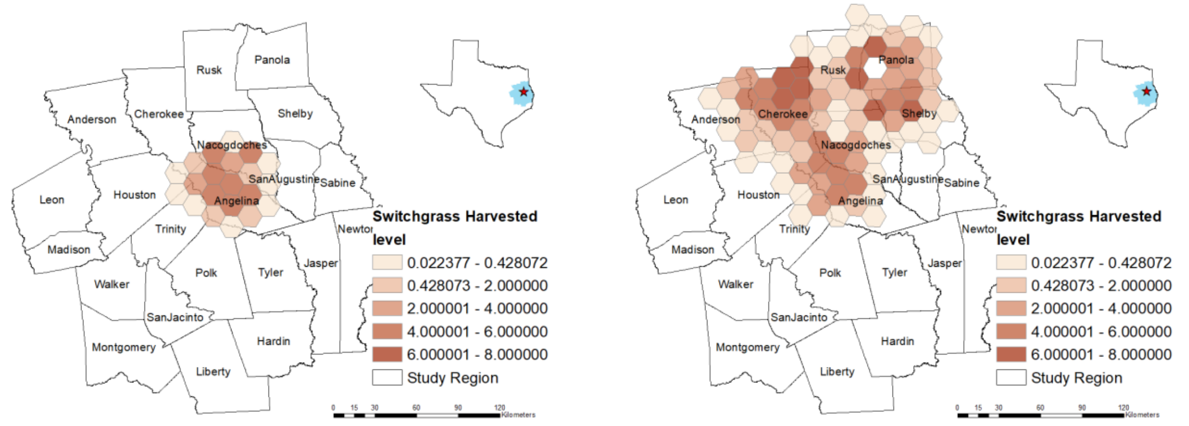
Table 36 Summary of decisions: multiple- and single-source feedstock scenarios

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 biomass	31.5	31.5	31.5	168.9	168.9	168.9	0.0	1000Ha
Switchgrass	31.5	31.5	31.5	168.9	168.9	168.9	0.0	1000Ha
Second-stage decision								
Total biomass harvested	721.5	722.5	722.5	765.3	777.4	777.2	746.0	1000Mg
Switchgrass	142.8	175.1	174.8	765.3	777.4	777.2	0.0	1000Mg
Logging residue	209.7	208.6	208.6	0.0	0.0	0.0	316.0	1000Mg
Thinning residue	369.0	338.8	339.1	0.0	0.0	0.0	430.0	1000Mg
Total biomass stored	0.0	0.0	0.0	1231.2	2486.2	2473.7	0.0	1000Mg
Switchgrass	0.0	0.0	0.0	1231.2	2486.2	2473.7	0.0	1000Mg
Logging residue	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Thinning residue	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Total biomass dumped	0.0	257.5	135.1	0.0	1540.5	883.4	0.0	1000Mg
Switchgrass	0.0	257.5	135.1	0.0	1540.5	883.4	0.0	1000Mg
Average biomass traveled distance	69.0	61.5	0.0	47.3	39.0	0.0	0.0	Km
Switchgrass	23.7	14.1	0.0	47.3	39.0	0.0	0.0	Km
Logging residue	74.7	74.6	0.0	0.0	0.0	0.0	70.2	Km
Thinning residue	83.3	77.8	0.0	0.0	0.0	0.0	80.3	Km
Total biomass processed	721.5	722.5	722.5	0.0	0.0	0.0	735.2	1000Mg
Switchgrass	142.8	175.1	174.8	0.0	0.0	0.0	0.0	1000Mg
Logging residue	209.7	208.6	208.6	0.0	0.0	0.0	305.2	1000Mg
Thinning residue	369.0	338.8	339.1	0.0	0.0	0.0	430.0	1000Mg
Pellet Produced	0.0	0.0	0.0	95.0	43.6	44.4	0.0	1000Mg
Pellet Processed	0.0	0.0	0.0	95.0	43.6	44.4	0.0	1000Mg

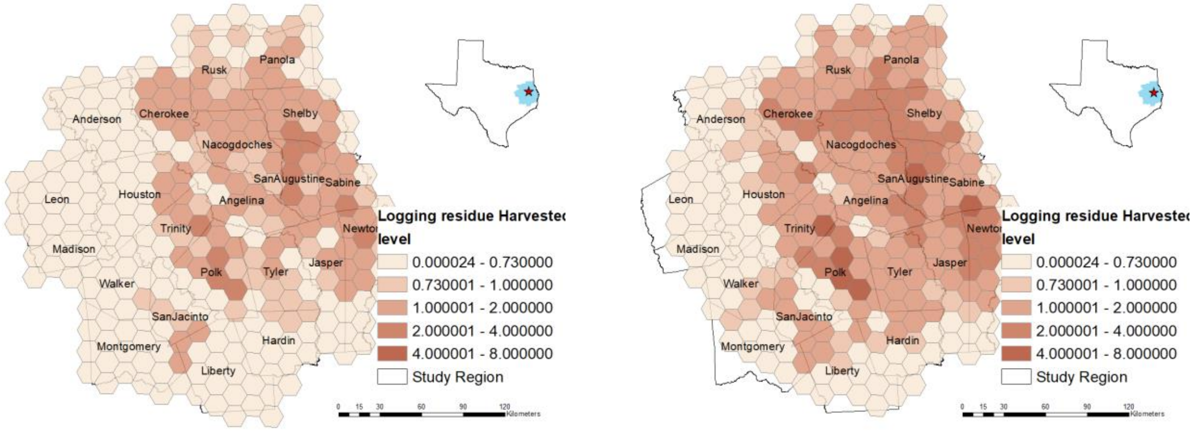
When only switchgrass is available, the area and amount of switchgrass harvested in the single-feedstock scenario is greater than in the multi-feedstock case. Switchgrass within a 40 km radius is sent to biorefinery and consumed during the harvesting season in both scenarios. However, switchgrass outside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

Figure 34 illustrates the supply region for switchgrass in the multi-feedstock and switchgrass-only scenarios.

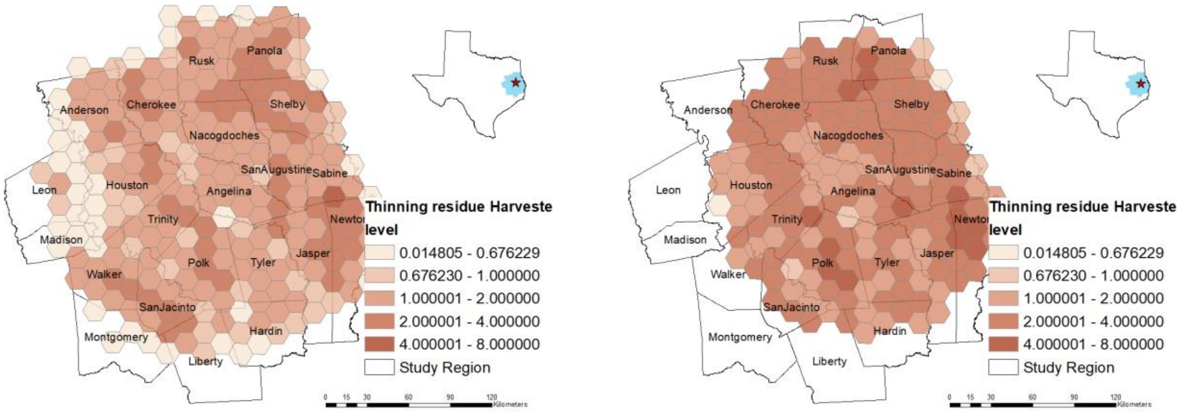
When only woody feedstocks are available, the use of both woody materials increases – although the increase is larger for thinning residue due to its higher ethanol conversion rate. Meanwhile, the collecting region of woody materials is reduced and the associated collecting level is higher than in the multi-feedstock case. For example, in Figure 34, (e) to (f) show the source of thinning residue in the multi-feedstock case and woody residue-only scenario. The source of thinning residue reduces from 100 km in the former to approximately an 85 km radius in the latter. Additionally, the same figures also depict that the collecting level in each hexagon is more intensive in the woody feedstock-only scenario, given that the color is darker and more evenly distributed than those in the multi-feedstock case. The change of collecting region and level are due to the distribution of woody materials. Given that woody materials are concentrated in the east part of the study region, the density of woody feedstock in each hexagon within the supply region in the woody feedstock-only scenario is higher than those in the multisource scenario. Thus, woody feedstock can be collected from a smaller area, incurring lower transportation costs. Therefore, as demand for woody material increases, more intensive collecting activities are observed in the region within an 85 km radius of the biorefinery in the woody feedstock-only scenario than in the multi-feedstock case.



(a) Switchgrass harvested in multi-feedstock scenario (b) Switchgrass harvested in single source scenario



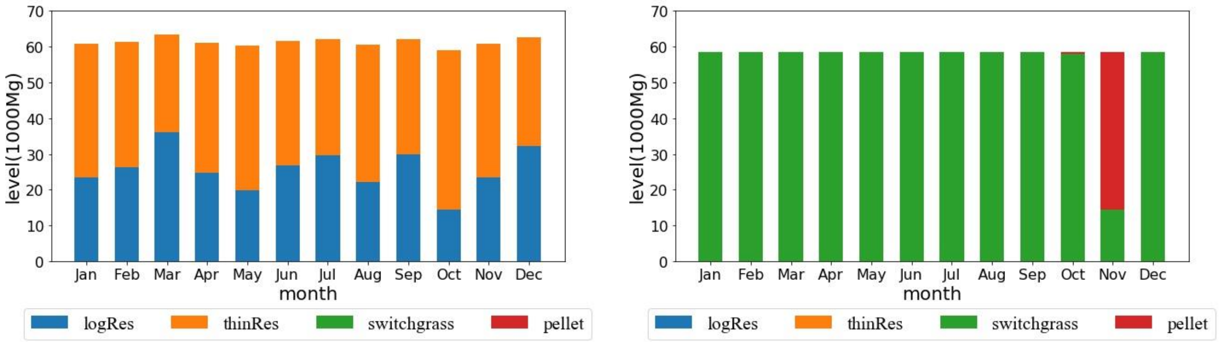
(c) Source for logging residue: multi-feedstock (d) Source for logging residue: woody feedstock only



(e) Source for thinning residue: multi-feedstock (f) Source for thinning residue: woody feedstock only

Figure 34 Amount of each feedstock harvested in no-storage and storage scenarios

Figure 35 shows the monthly feedstock process level for each feedstock.



(a) Only woody material scenario

(b) Only switchgrass scenario

Figure 35 Monthly feedstock processed in multiple- and single-source scenarios

In the multi-feedstock and switchgrass-only scenarios, switchgrass is converted to ethanol during the December to February harvest season. Outside that harvesting window, if not available, a mix of logging residue and thinning residue is used. When only switchgrass is available, baled switchgrass is processed into ethanol from April to September, while switchgrass pellets are consumed in October and November. The choice between pellets and stored switchgrass reflects assumptions of deterioration, storage, transport, and cost of pellet production. This manifests itself in a number of ways. First, the switchover after October is because the marginal cost of maintaining baled switchgrass exceeds that of maintaining pellets, thus the plant switches to pellets. Second, there is an increasing deterioration rate when feedstock is stored in baled form. Furthermore, the cost of moving pellet is cheaper than that of baled feedstock. Therefore, part of switchgrass is converted into pellets in February, stored from February to September, and then consumed before the beginning of harvesting season. The results indicate that, in both scenarios, the pellet option does not help to reduce the amount of feedstock dumped. Given that pellets cannot be exported in this scenario and the pelletizing costs are relatively high, the additional feedstock is simply dumped.

Impacts of ethanol conversion rate improvements

As discussed in the Texas High Plains chapter, an improvement in the conversion rate is expected due to R&D efforts. Based on the study of Mu et al. (2010), the improvement in conversion by the biochemical process is expected to range from 15 to 25%. To simulate the impact of conversion rate improvement, a sensitivity analysis is conducted to examine medium and high improvement scenarios (namely, 15% and 25%).

The optimal locations for facilities and types built in the different conversion rate scenarios are unaffected by improvements in biofuel conversion rates. Only one biorefinery is chosen, which is at the center of Angelina county, and no storage or pelleting facilities are constructed. Table 37 summarizes the total costs and the components, as well as the key logistical decisions for different conversion rate scenarios.

Table 37 Expected costs of each component in different conversion rate scenarios

Item	Base scenario	Medium improvement	High improvement	Units
Expected cost of supply chain	98656.5	91854.2	88527.4	1000.0
Annualized cost of biorefinery	22565.7	22565.7	22565.7	1000.0
Annualized cost of storage	0.0	0.0	0.0	1000.0
Annualized cost of pellet plant	0.0	0.0	0.0	1000.0
Cost of contracting land	331.6	185.9	171.0	1000.0
Expected harvesting cost	30767.7	26479.3	24206.5	1000.0
Expected dumping cost	481.8	87.4	81.1	1000.0
Expected storage cost	453.8	453.8	453.8	1000.0
Expected pelleting cost	0.0	0.0	0.0	1000.0
Expected conversion cost	31500.0	31500.0	31500.0	1000.0
Expected transporting cost	12556.0	10582.2	9549.3	1000.0
Profit form exporting pellet	0.0	0.0	0.0	1000.0
Average cost of ethanol	0.5	0.5	0.5	$/L

For the medium improvement scenario, the fixed cost of building the biorefinery is 24.5% of total cost, while the operating costs for obtaining feedstock, producing ethanol, and transportation account for 28.8%, 34.2%, and 11.5% of the average cost, respectively, across the states of nature. As for the high improvement scenario, 25.4%, 27.3%, 35.5%, and 10.78% of the expected objective costs cover fixed facility construction, obtaining feedstock, conversion, and transportation. The costs of contracting land, dumping feedstock, and emergency storage account for the remaining 0.8% and fall under the increased conversion rate.

While the optimal biorefinery locations in all three scenarios are identical, the expected total cost is reduced by 6.8% and 10.2% in the medium and high conversion rate improvement scenarios, respectively. The reduction is due to the lower costs of contracting, harvesting, transporting, and dumping excess feedstock, since less feedstock and growing acreage is required.

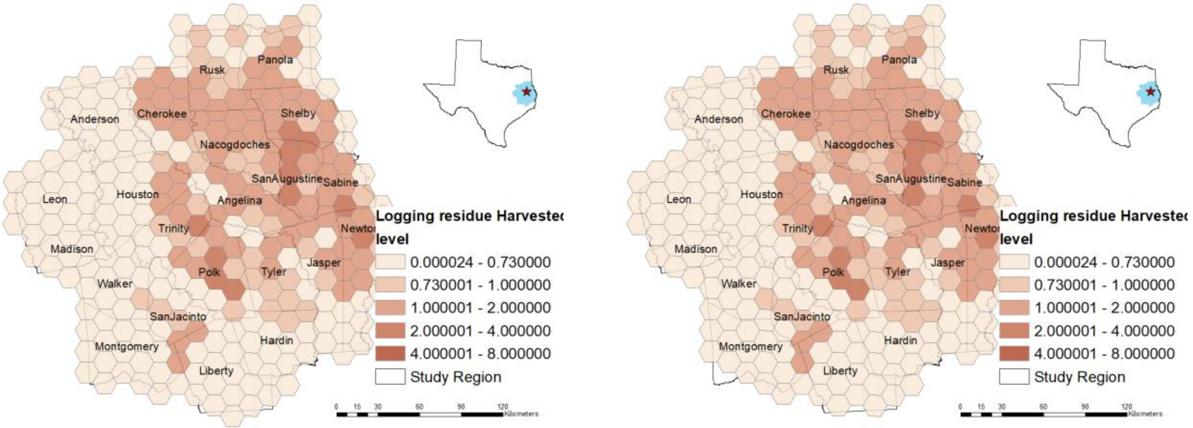
Table 38 below summarizes the key decision variables in the solutions in the ethanol conversion improvement scenarios. It is noted that the scenarios each produce a constant amount of ethanol. It is possible that the biorefinery may choose to collect the same level of feedstock as in the base case and thus produce more ethanol, but this scenario is not run here.

Based on the table and figure, the overall feedstock harvested decreases by 12.3% and 18.9% from the base scenario when the conversion rate increases by 15% and 25%. In terms of feedstock, the amount of logging residue utilized reduces by 0.4% and 1.6%, while switchgrass use is reduced by 15.9% and 22.7 % and thinning residue by 17.8 % and 27.7%.

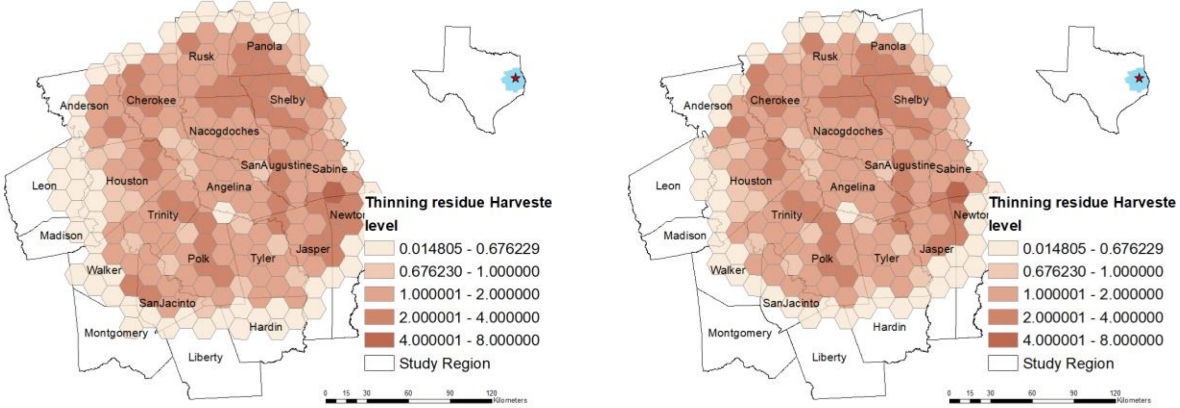
Table 38 Summary of decisions: different conversion rate scenarios

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	31.5	31.5	31.5	17.7	17.7	17.7	16.3	16.3	16.3	1000Ha
Switchgrass	31.5	31.5	31.5	17.7	17.7	17.7	16.3	16.3	16.3	1000Ha
Second-stage decision										
Total biomass harvested	721.5	722.5	722.5	631.2	633.7	633.5	583.7	585.8	585.7	1000Mg
Switchgrass	142.8	175.1	174.8	80.1	152.3	146.9	64.8	140.1	135.0	1000Mg
Logging residue	209.7	208.6	208.6	209.3	205.0	208.5	209.4	205.7	206.2	1000Mg
Thinning residue	369.0	338.8	339.1	349.9	275.7	278.0	309.5	239.9	244.5	1000Mg
Total biomass stored	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Switchgrass	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Logging residue	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Thinning residue	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Total biomass dumped	0.0	257.5	135.1	0.0	90.3	26.9	8.9	83.0	12.5	1000Mg
Switchgrass	0.0	257.5	135.1	0.0	90.3	26.9	8.9	83.0	12.5	1000Mg
Average biomass traveled distance	69.0	61.5	0.0	69.4	57.1	0.0	67.5	55.2	0.0	Km
Switchgrass	23.7	14.1	0.0	17.5	12.8	0.0	15.4	12.5	0.0	Km
Logging residue	74.7	74.6	0.0	74.7	74.2	0.0	74.6	73.2	0.0	Km
Thinning residue	83.3	77.8	0.0	78.4	68.8	0.0	73.7	64.3	0.0	Km
Total biomass processed	721.5	722.5	722.5	631.2	633.7	633.5	583.7	585.8	585.7	1000Mg
Switchgrass	142.8	175.1	174.8	80.1	152.3	146.9	64.8	140.1	135.0	1000Mg
Logging residue	209.7	208.6	208.6	209.3	205.0	208.5	209.4	205.7	206.2	1000Mg
Thinning residue	369.0	338.8	339.1	349.9	275.7	278.0	309.5	239.9	244.5	1000Mg

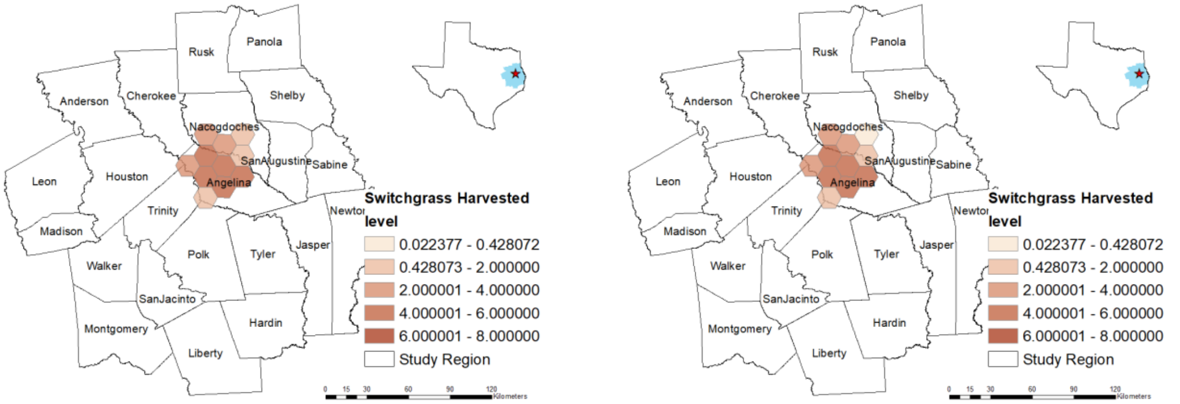
Figure 36 illustrates the supply regions for each feedstock in the different conversion rate scenarios. The results indicate that both the amount of feedstock harvested and land area used generally decreases as the conversion rate increases. The harvested area for logging residue does not change in the conversion rate scenarios. However, both the harvesting region and amount of thinning residue and switchgrass decrease as the conversion rate improves. For the thinning residue, the harvesting region is reduced from a 90 km radius to an 85 km radius, and then a 70 km radius of the biorefinery as the conversion rate improves. The harvesting area for switchgrass is reduced from a 30 km radius to a 10 km radius as the conversion rate is raised. For each feedstock, that closest to the biorefinery is used first.



(a) Logging residue medium improvement scenario (b) Logging residue high improvement scenario



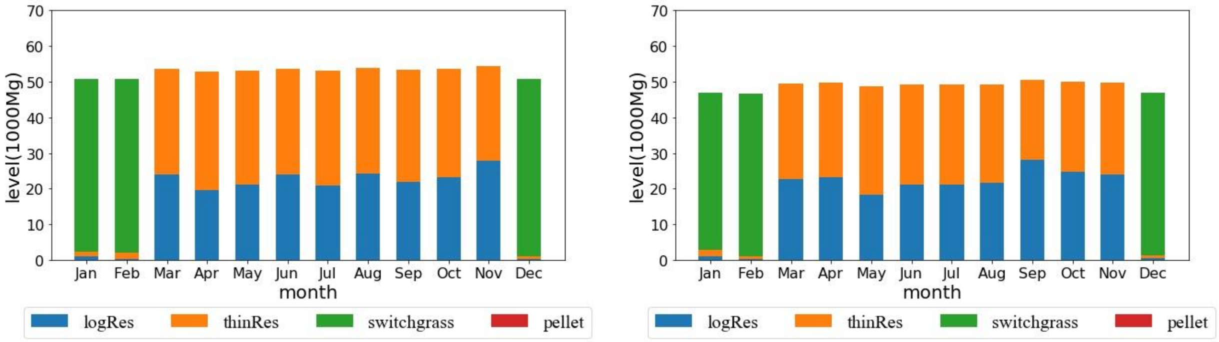
(c) Thinning residue medium improvement scenario (d) Thinning residue high improvement scenario



e) Switchgrass medium improvement scenario (f) Switchgrass high improvement scenario

Figure 36 Source of each feedstock in different conversion rate scenarios

Figure 37 below shows switchgrass is used as the major feedstock source during its harvesting window. Since the optimal solution does not include storage for all three conversion rate scenarios, switchgrass is not used outside of its harvest months. A mix of logging and thinning residue is used in this period. As ethanol can be made with decreasing feedstock as the conversion rate improves, the feedstock volumes become smaller.



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

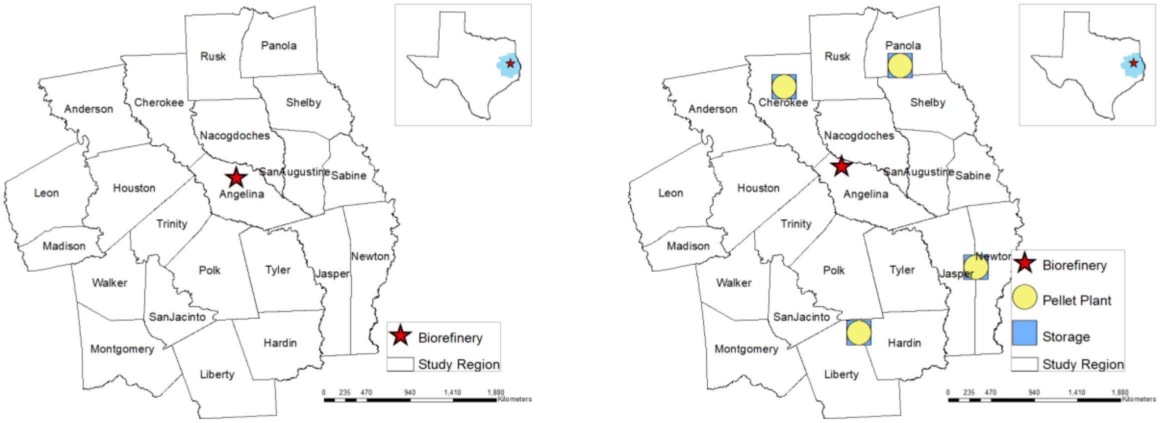
Figure 37 Monthly feedstock processed in different conversion rate scenarios

Impact of alternative pellet prices

The potential impact of higher pellet prices is examined to assess when pelleting is better than dumping. As shown above, pellets are not produced in the base case, but solely when switchgrass is the only feedstock available. However, a higher pellet price might change this result.

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

Figure 38 illustrates the optimal locations for the biorefinery, storage, and pelleting plants in the two pellet price scenarios.



(a) Base case/$100 per Mg Scenario

(b) $150 per Mg Scenario

Figure 38 Optimal locations for different price scenarios

When the pellet prices are either zero or $100 per mg, pelleting is not included and the solutions are the same as in the base case. Pelleting becomes viable when the price increases to $150 per mg. This, in turn, leads the model's choice 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. The storage depot pelleting plants are in Cherokee, Jasper, Liberty, and Shelby counties, with one plant in Jasper county and three in each of the other counties. It is assumed that each pelleting plant also has an associated storage depot.

Table 39 summarizes the expected cost components and the key logistical decisions for the pellet price scenarios. The solutions for the base case (zero) and $100 prices are identical, and no pellet is produced. However, when the export price is higher than $150 per mg, pellets are produced and exported. In turn, the profit from exporting the pellet helps to reduce the expected objective function value by 30.3% compared to the base scenario, despite cost increasing in every cost category.

Table 39 Expected costs of each component in different pellet price scenarios

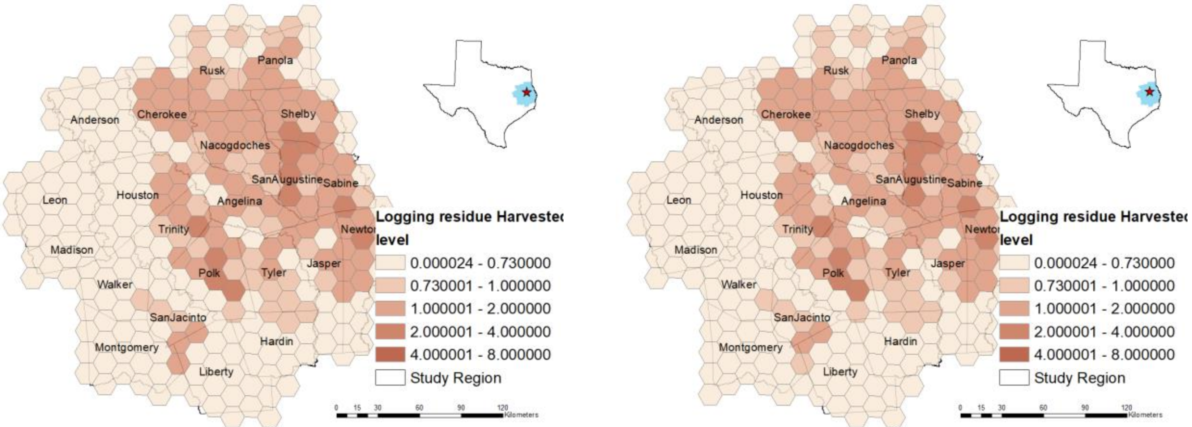
Item	Base sceanrio	$100/Mg scenario	$150/Mg scenario	Units
Expected cost of supply chain	98,656.5	98,656.5	68,739.4	$1,000
Annualized cost of biorefinery	22,565.7	22,565.7	22,565.7	$1,000
Annualized cost of storage			36,447.9	$1,000
Annualized cost of pellet plant			3,786.1	$1,000
Cost of contracting land	331.6	331.6	1,495.5	$1,000
Expected harvesting cost	30,767.7	30,778.0	60,721.1	$1,000
Expected dumping cost	481.8	1,209.0	844.9	$1,000
Expected storage cost	453.8	453.8	1,415.1	$1,000
Expected pelleting cost			24,257.9	$1,000
Expected conversion cost	31,500.0	31,500.0	31,500.0	$1,000
Expected transporting cost	12,556.0	12,556.0	24,533.4	$1,000
Profit form exporting pellet			-138,828.3	$1,000
Average cost of ethanol	0.51	0.51	0.36	$/L

Table 40 below lists the optimal solutions to the key decisions. Based on the results, the use of logging and thinning residue decreases when the price is $150 per mg, with switchgrass becoming the major source of feedstock. The average amount of land harvested for switchgrass is three times greater than in the base scenario. All the switchgrass harvested is within a 35 km radius of the biorefinery or pelleting plants. The switchgrass takes on a different pattern, clustered around the pelleting operations and not in proximity to the biorefinery. The supply region for the logging residue is unchanged across the scenarios, while the thinning residue area is reduced. The amount of feedstock dumped increases with higher prices, while the percentage that is dumped falls. In the base case, approximately 9% of switchgrass is dumped, while just 5.5-6% of switchgrass is dumped when the pellets can be exported at a high price. With the option of exporting pellets available, oversupply of switchgrass can be used more efficiently by converting it into pellets and exported. More feedstock is dumped in the high pellet price scenario relative to the low price scenario due to the limitation on the number of pellet plants allowed in the study region. In this study, a constraint on the total number of storage/pellet plants is applied to increase computation efficiency. Thus, given that all the available locations for pellet plants near the biorefinery are selected in the high pellet price scenario, the remaining feedstock must be dumped once the pellet production capacity is reached.

Table 40 Summary of decisions: different pellet price scenarios

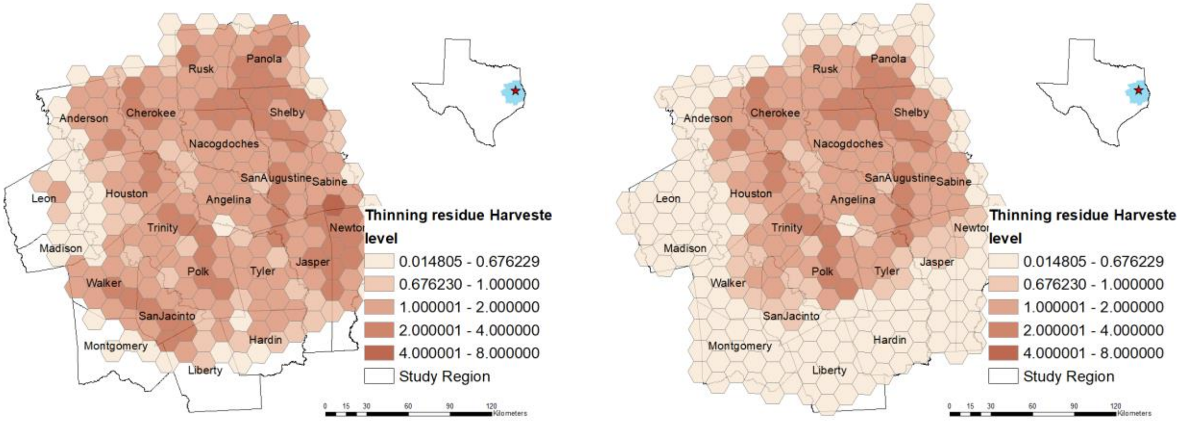
Item	Base/ $100 per Mg scenario			$150 per Mg scenario			Units
	Worst yield	Best yield	Average	Worst yield	Best yield	Average	
First-stage decision							
Total land contracted for biomass	31.5	31.5	31.5	142.2	142.2	142.2	1000Ha
Switchgrass	31.5	31.5	31.5	142.2	142.2	142.2	1000Ha
Second-stage decision							
Total biomass harvested	721.5	722.5	722.5	1222.9	1750.6	1704.0	1000Mg
Switchgrass	142.8	175.1	174.8	644.2	1486.4	1290.6	1000Mg
Logging residue	209.7	208.6	208.6	209.7	160.5	188.9	1000Mg
Thinning residue	369.0	338.8	339.1	369.0	103.7	224.5	1000Mg
Total biomass stored	0.0	0.0	0.0	899.0	349.6	290.4	1000Mg
Switchgrass	0.0	0.0	0.0	899.0	349.6	290.4	1000Mg
Logging residue	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Thinning residue	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Total biomass dumped	0.0	257.5	135.1	0.0	464.8	107.3	1000Mg
Switchgrass	0.0	257.5	135.1	0.0	464.8	107.3	1000Mg
Average biomass traveled distance	69.0	61.5	0.0	46.4	32.2	0.0	Km
Switchgrass	23.7	14.1	0.0	28.3	26.1	0.0	Km
Logging residue	74.7	74.6	0.0	43.2	71.2	0.0	Km
Thinning residue	83.3	77.8	0.0	84.4	50.2	0.0	Km
Total biomass processed	721.5	722.5	722.5	703.1	723.6	719.3	1000Mg
Switchgrass	142.8	175.1	174.8	233.5	459.4	331.8	1000Mg
Logging residue	209.7	208.6	208.6	100.6	160.5	163.0	1000Mg
Thinning residue	369.0	338.8	339.1	369.0	103.7	224.5	1000Mg
Pellet Produced	0.0	0.0	0.0	492.1	950.0	925.5	1000Mg
Pellet Processed	0.0	0.0	0.0	0.0	0.0	0.0	1000Mg
Pellet Exported	0.0	0.0	0.0	492.1	950.0	925.5	1000Mg

Figure 39 identifies the amount and area of each feedstock harvested in different price scenarios.



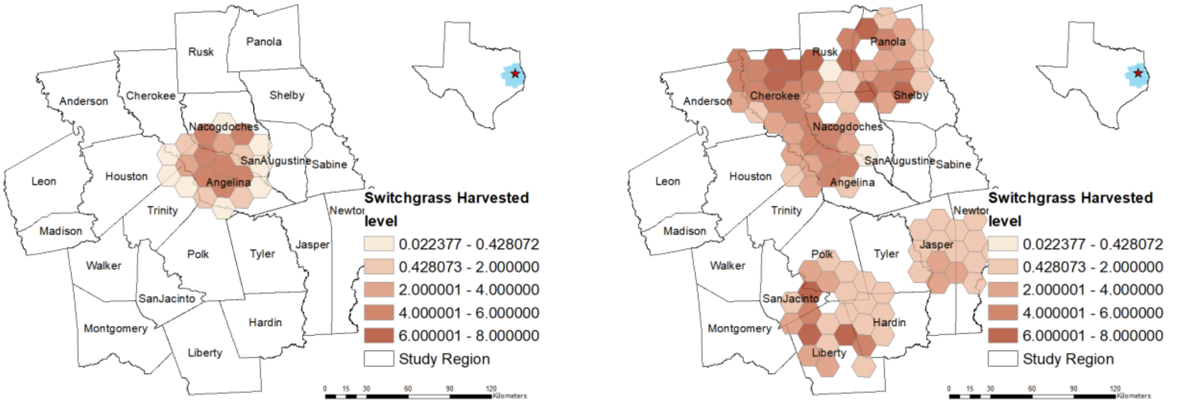
(a) Logging residue $100/Mg scenario

(b) Logging residue $150/Mg scenario



(c) Thinning residue $100/Mg scenario

(d) Thinning residue $150/Mg scenario



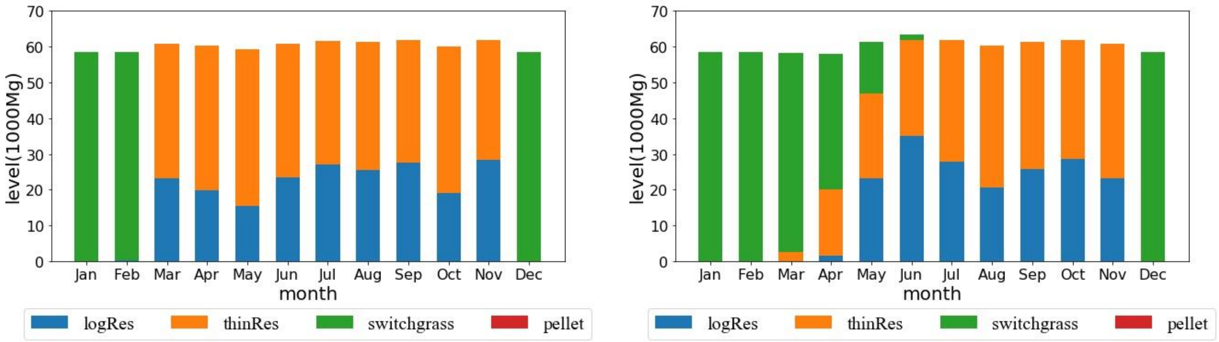
(e) Switchgrass $100/Mg scenario

(f) Switchgrass $150/Mg scenario

Figure 39 Source of each feedstock in different pellet price scenarios

The amount of each feedstock used by the biorefinery throughout the analysis period is depicted in Figure 40.

Here, we see that the pellet price is $150 per mg. Switchgrass is used outside of the harvest window both as a feedstock and as a source of material for pellet production. In fact, with high pellet price in the market, pellets are increasingly made for export, rather than for use in ethanol production. Additional switchgrass is stored in baled form and used in March, April, and May. The mix of logging and thinning residue is the major feedstock 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 40 **Monthly feedstock processed in different pellet price scenarios**

Impact of increases in accessible forest area

The potential impact on the supply chain of increasing accessible forest area is also examined. Until now, we have assumed that only the forest area within half a kilometer of the forest road system can be used, resulting in feedstock availability in approximately 75% of the overall forest area. Here, we examine cases where the accessible forest increases from that within a half-kilometer of a road to that within 1 km (90% of the overall forest area) and 1.6 km (98% of the overall forest area).

Table 41 below summarizes the cost breakdown and key logistical elements in the accessible area scenarios.

Table 41 Expected costs for different forest access rates scenarios

Item	Base scenario	90% accessible	98% accessible	Units
Expected cost of supply chain	98,656.5	96,279.1	95,772.0	$1,000
Annualized cost of biorefinery	22,565.7	22,565.7	22,565.7	$1,000
Annualized cost of storage	0.0	0.0	0.0	$1,000
Annualized cost of pellet plant	0.0	0.0	0.0	$1,000
Cost of contracting land	331.6	213.8	213.8	$1,000
Expected harvesting cost	30,767.7	29,691.7	29,215.6	$1,000
Expected dumping cost	481.8	106.3	107.3	$1,000
Expected storage cost	453.8	453.8	453.8	$1,000
Expected pelleting cost	0.0	0.0	0.0	$1,000
Expected conversion cost	31,500.0	31,500.0	31,500.0	$1,000
Expected transporting cost	12,556.0	11,747.9	11,716.0	$1,000
Profit form exporting pellet	0.0	0.0	0.0	$1,000
Average cost of ethanol	0.52	0.51	0.50	$/L

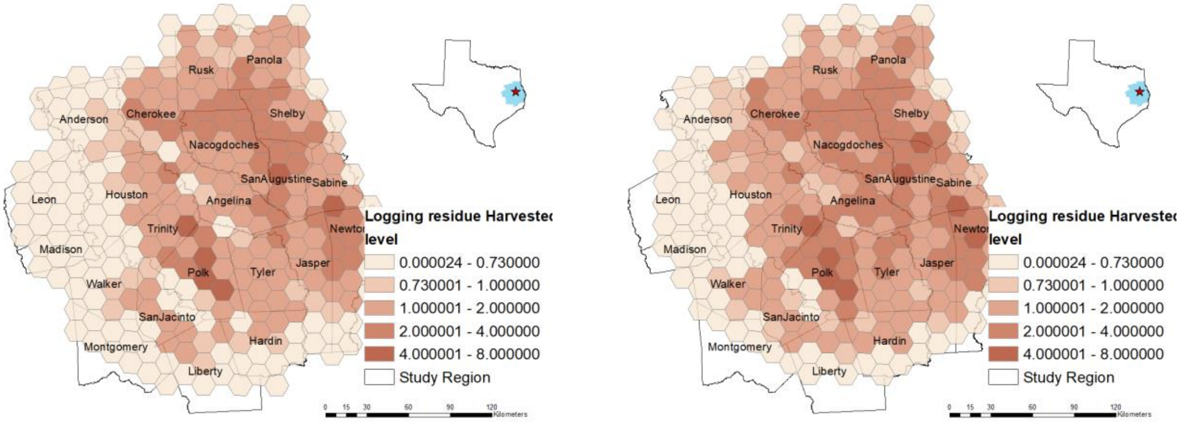
At optimality, the biorefinery location is insensitive to the accessible forest rate alternatives. While the optimal settings for each scenario are the same, the expected supply chain costs fall as the accessible area increases. The accessible forest increases from a base level of 75% to 90% and 98%. In turn, the expected cost falls by 2% and 2.9%. The cost reduction is due to the replacement of switchgrass with more thinning and logging residue closer to the biorefinery.

Table 42 summarizes the key decisions, and Figure 41 depicts the feedstock supply locations.

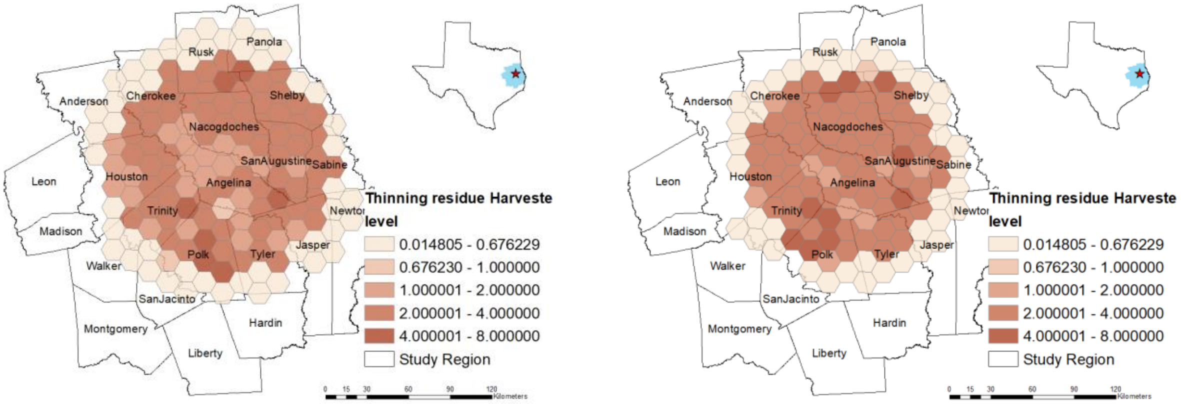
The sourcing areas for each feedstock become smaller with the usage of logging and thinning increasing. For logging residue, usage increases by 48% and 68% in the 1.0 and 1.6 km scenarios. This lowers the amount and cost of contracting land for switchgrass, with less switchgrass harvested, dumped, and transported. The amount of logging residue that is collected in 100 km and 80 km radius in the 1-km and1-mile scenarios, respectively. The harvesting region for thinning residue decreases from an 80 km radius to 60 km, while the harvesting region for switchgrass remains within the area, with a 15 km to 20 km radius.

Table 42 Summary of decisions: different forest access rates scenarios

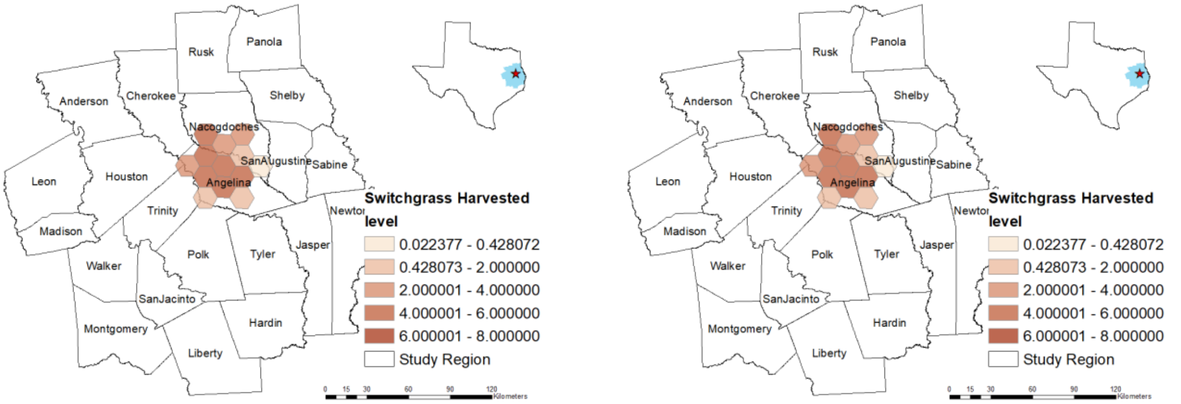
Item	Base scenario			90% accessible scenario			98% accessible scenario			Units
	Wrost yield	Best yield	Average	Wrost yield	Best yield	Average	Wrost yield	Best yield	Average	
First-stage decision										
Total land contracted for biomass	31.5	31.5	31.5	20.3	20.3	20.3	20.3	20.3	20.3	1000Ha
Switchgrass	31.5	31.5	31.5	20.3	20.3	20.3	20.3	20.3	20.3	1000Ha
Second-stage decision										
Expected biomass harvested	721.5	722.5	722.5	739.1	742.7	742.5	748.6	751.5	751.3	1000Mg
Switchgrass	142.8	175.1	174.8	20.7	175.1	168.2	8.2	175.1	168.1	1000Mg
Logging residue	209.7	208.6	208.6	320.4	309.3	309.6	370.3	353.4	353.9	1000Mg
Thinning residue	369.0	338.8	339.1	397.9	258.2	264.6	370.1	222.9	229.3	1000Mg
Expected biomass dumped	0.0	257.5	135.1	0.0	103.8	31.6	0.0	103.8	31.8	1000Mg
Switchgrass	0.0	257.5	135.1	0.0	103.8	31.6	0.0	103.8	31.8	1000Mg
Average biomass traveled distance	69.0	61.5	0.0	68.7	52.4	0.0	66.6	51.2	0.0	Km
Switchgrass	23.7	14.1	0.0	9.2	14.1	0.0	1.9	14.1	0.0	Km
Logging residue	74.7	74.6	0.0	74.5	72.2	0.0	74.3	71.5	0.0	Km
Thinning residue	83.3	77.8	0.0	67.1	54.6	0.0	60.4	48.1	0.0	Km
Expected biomass processed	721.5	722.5	722.5	739.1	742.7	742.5	748.6	751.5	751.3	1000Mg
Switchgrass	142.8	175.1	174.8	20.7	175.1	168.2	8.2	175.1	168.1	1000Mg
Logging residue	209.7	208.6	208.6	320.4	309.3	309.6	370.3	353.4	353.9	1000Mg
Thinning residue	369.0	338.8	339.1	397.9	258.2	264.6	370.1	222.9	229.3	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

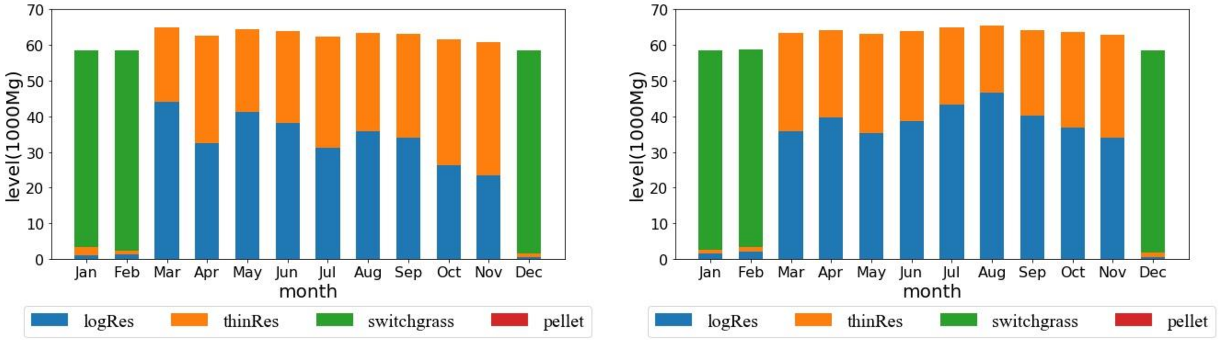


(e) Source of switchgrass 90% access rate scenario (f) Source of switchgrass 98% access rate scenario

Figure 41 Source of each feedstock in different forest access rates scenarios

The amount of each feedstock processed by month is depicted in Figure 42 in the accessibility scenarios.

Again, switchgrass is used in its harvesting season (January, February, and December). In the remaining months, a mix of logging residue and thinning residue are used. The increase in accessible forest region provides more thinning and logging residue closer to the biorefinery, replacing the more distant switchgrass. Similarly, as the accessible forest increases, the thinning residue farthest away is replaced by additional logging residue near the biorefinery. Therefore, a significant decrease in switchgrass and thinning residue is observed as more forest becomes accessible.



(a) 90% access rate scenario

(b) 98% access rate scenario

Figure 42 Monthly feedstock processed in different forest access rates scenarios

Experiments with geographic scale

Another analysis examines the consequences of using the finer scale hexagon-based information, as opposed to relying on county information. In this case, we ran a version of the model that specified the county level and another using the hexagons, as above. We then examined 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 the higher resolution spatial data naturally give more detailed information on the regions selected for feedstock production and more precise identification of transportation routes, but also lead to different estimates of transportation costs. Table 43 below presents a comparison of the costs for each of the supply chain components. There are essentially identical costs for each supply chain element, with the exception of transportation. This is because the movements are generally set in the county-level model from the centroids of the counties, while the more detailed model gives a more accurate representation of county heterogeneity and the locations of feedstock production, which raises the costs. With high-resolution spatial data, transportation costs are 4% higher than they are when using county-level data.

Table 43 **Cost comparison between county- and hexagon-level data in East Texas**

	County-level spatial data	Hexagon spatial data	Unit
Expected cost of supply chain	98160.0	98656.1	$1,000
Fixed cost	22565.7	22565.7	$1,000
Cost of contractin land	331.6	331.6	$1,000
Collecting/harvesting cost	30767.7	30767.7	$1,000
Storage cost (on site)	453.8	453.8	$1,000
Dumpping cost	481.0	481.0	$1,000
Pelleting cost	0.0	0.0	$1,000
Transportation cost	12060.3	12556.4	$1,000
Ethanol production cost	31500.0	31500.0	$1,000
Averaged production cost	0.52	0.52	$/L

Concluding comments

In this chapter, an exploration of supply chain design uses a cost-minimizing, two-stage stochastic mixed integer model. The model is subjected to scenarios concerning a) whether to include uncertainty in crop yield, b) an improved feedstock-to-ethanol conversion rate, c) alternative pellet export prices, d) whether the biorefinery handles single or multiple feedstock, and e) forest accessibility. Important observations from these results are summarized below.

First, we find that uncertainty is a key factor affecting the contracting of feedstock and handling of excess supplies in terms of dumping costs. With uncertainty, 80% more land must be contracted for switchgrass, so biorefinery demand is met even under the worst yield outcomes. Additionally, when the best yield state of nature is realized, approximately 175 mg of switchgrass is used as feedstock, while 135 mg or 15.7% of total available feedstock is dumped. In conclusion, one must not only consider bad yield outcomes, but also the handling of excess feedstock when higher yields occur.

Further analyses examine the impact of different feedstock-to-ethanol conversion rates. Here, we find that the feedstock facilities are invariant to increases, but the supply regions become smaller as conversion rates increase. Improving conversion rates and fixed output levels directly lead to reduced need for feedstock, which in turn reduces feedstock contracting, transport, and processing costs. The average cost of fuel production falls from $0.51 per L to $0.36 per L as the conversion rates improves.

Analyses of alternative pellet export prices reveal no effect of prices below $100, but a strong reaction to a price of $150. A high price affects both the optimal locations of facilities and the feedstock usage pattern. Additional model runs (not reported here) find the critical price to stimulate pelleting is between $110 and $120 per mg. When pellets are exported, the biorefinery location moves to the northwestern corner of Angelina county, nearer to available pasture land for growing switchgrass. Additionally, we find that when the pellet price is sufficiently high, the dumping of excess yield of switchgrass is reduced by pelletizing and exporting.

Consideration of differential accessibility of forests residues indicates that a change in accessible forest does not alter biorefinery location or cause storage depot and pelleting plants to be constructed. However, it does affect the area and harvesting volumes of the feedstock types.

The harvested area becomes smaller for each feedstock as the accessible forest area becomes larger. The harvesting level of logging and thinning residue also becomes larger due to a smaller supply region. The harvesting results for switchgrass are unchanged.

These results indicate that the average cost of cellulosic biofuel ranges from $0.51 L to $0.71 L in the absence of pellet export revenues. When pellet price is $150, the average cost falls to $0.36 L, but this remains above the current average starch-based ethanol production cost of $0.33 L. However, if government subsidies are considered, the proposed supply chain system becomes more competitive. For example, the CWC on cellulosic ethanol set by EPA is currently used to provide incentives to produce ethanol. According to EPA (USEPA, 2018), the CWC price in 2018 was $1.96 per gal or $0.52 per L. If the assumptions used in our modeling are accurate and the CWC is considered, the cellulosic ethanol is still not profitable under base conditions, but becomes profitable in some of the alternative scenarios.

In addition to the impact of different key parameters, different supply chain designs are discussed in this study. Multiple feedstock, woody materials-only, and switchgrass-only scenarios are compared to examine the impact of overall costs on the supply chain. Based on the results of these three scenarios, this study finds that total costs can be significantly reduced if wood is allowed, as we assume that it does not require covered storage. Given that it can be collected from accessible piles year-round, a just-in-time system can be employed to avoid the fixed costs of building storage depots and pelleting plants and to eliminate substantial variable storage costs. On the other hand, a switchgrass-only system requires this storage and raises costs by 36% above the multi-feedstock case and 24% above the wood-only case. Therefore, the ability to provide both seasonal switchgrass and year-round woody materials in East Texas would be a beneficial outcome of a low-cost cellulosic supply chain.

Moreover, we find that (a) advances in the conversion rates of feedstock-to-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 costs, thus they are notably competitive.

We also find it beneficial to use a more aggregate representation of the region, as opposed to a county-level risk presentation, because this gives a more complete image of the appropriate supply chain design, with more precise optimal facilities locations, supply region, feedstock mix, inventory level, and transportation routes. In addition, although the overall cost of managing a biofuel supply chain is not significantly affected when finer spatial units are applied, agricultural feedstock is usually distributed unevenly across the study region. Thus, when managing a biofuel supply chain, using the results of the analysis without accounting for the heterogeneity of feedstock distribution could lead to inefficient decision-making.

CHAPTER VI

CONCLUSIONS

This dissertation addresses the supply chain design required for supplying lignocellulosic feedstock to an ethanol plant. A flexible, two-stage stochastic MIP model was developed and implemented to represent a multi-feedstock ethanol supply chain under conditions of feedstock yield uncertainty. The model minimizes expected costs by determining the optimal values of the design decisions.

The model was implemented in two separate case studies, and several findings are noted. We found the use of multiple feedstocks to be superior, particularly when there is inherent seasonality of the feedstocks, resulting in a significant cost of storage. We also found feedstocks with a year-round harvest window to be highly desirable, as with logging and thinning residues in the East Texas case, as a just-in-time supply chain system could be developed to greatly reduce total costs, without the need for expensive storage. In contrast, due to increased storage need, the total cost rose by more than 36% when using only seasonally harvested switchgrass. Comparing the results across the two case studies in which multiple feedstocks are available, we found the cost per liter of ethanol when storage is not required to be \$0.520 L in East Texas and \$0.602 L in Texas High Plains.

Second, this study compares the use of remote facilities with a system using only centralized facilities. In the Texas High Plains case, the logistical decisions in the centralized storage scenario are essentially unchanged.

Studies with and without pelleting highlight no change from the base assumptions in the Texas High Plains case. However, the results indicate that the availability of high-priced pellet export possibilities provides options for the exploitation of geographically stranded feedstocks that are too far from the biorefinery locations to be moved directly. Our results in the Texas High Plains case study indicate that the corn stover collection area moves from an 80 km radius to 200 km when pellets can be exported at $150 per mg. With the larger radius, the remote stover collected is sent to a remote combined storage depot and pellet plant and then converted into pellets and mostly exported. Similarly, more switchgrass is harvested and exported in pelleted form at the $150 per mg export price. This study also notes that pellet export substantially reduces the price of fuel production, with the cost falling by up to 26.5% compared to the base scenario.

Further analyses examine the impact of different feedstock-to-ethanol conversion rates. The types of feedstock facilities chosen are invariant to increases, but the supply region for each biomass becomes smaller as the conversion rates increase. The improving conversion rates directly lead to reduced need for feedstock, which in turn reduces feedstock contracting, storage, disposal, and transport costs across the supply chain, with a change in feedstock mix reducing the use of distant supplies. In turn, improved conversion rates cause the average cost of fuel production to fall from $0.60 L to $0.54 L in the Texas High Plains and from $0.51 L to $0.36 L in East Texas. It is noted that we assume the biorefinery will produce identical amounts of cellulosic biofuel as the conversion rate improves, whereas expanding production might be an alternative.

Another finding concerns the importance of incorporating yield uncertainty. In particular, such uncertainty affects the need for feedstock contracting, excess feedstock dumping costs, feedstock mix, and tactical supply chain operations. In both case studies, more land for feedstocks is contracted in conditions of uncertainty as a safety margin to keep the refinery running when yields are low. However, when high yields occur, the model must incorporate excess feedstock. In the Texas High Plains and East Texas case studies, approximately 736,000 mg and 722,510 mg of total feedstock are used in refining, while 621,000 mg and 135,120 mg of excess feedstock are dumped at a cost. In the East Texas case, the amount of feedstock dumped is much less than in the Texas High Plains because the presence of year-round feedstock, such as logging and thinning residues, for which we assume non-stochastic yields.

Additionally, due to the high fixed costs and constant requirement for feedstock across the states of nature, total cost is not sensitive to the variations in contracting and dumping, with the cost of ethanol produced only varying by one cent per liter between the deterministic and the stochastic models ($0.59 L versus $0.60 L in the Texas High Plains and $0.51 L versus $0.52 L in East Texas). However, with other representations of yield distribution, the impact of the variation could be greater than seen here.

In terms of methodology, the results of the spatial resolution experiment showed that scale consistently influences transportation patterns and the resultant costs. Specifically, when high-resolution, sub-county level spatial data is used, transportation costs increase by 6.3% in the Texas High Plains and 4.1% in East Texas, compared to the county-level resolution. Additionally, the higher-resolution data stimulate a change in the storage locations in the Texas High Plains due to the altered precision of feedstock density portrayal. Thus, we conclude that the biofuel supply chain design and logistical decisions are sensitive to geographic scale and that more precise data will improve the supply chain design.

Limitations

The model presented in this dissertation has several limitations that suggest future research directions. A number of these are covered in the case study chapters, thus only the major and common examples will be mentioned here. First, the model assumes that the firm can readily use multiple feedstocks and thus does not introduce any fixed costs by adding others. For example, maintaining different handling and chemical treatment processes needed for the utilization of wood, switchgrass, or corn stover, and so on. This gap provides a possible basis 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. Biorefinery planners are assumed to be risk-neutral, as they consider the probability distribution of outcomes. However, they may well be risk-averse. Thus, a further analysis of risk preference could be conducted.

Yield uncertainty is another area in which the work could be extended. Here, we assume perfect correlation in yields across all land parcels in the collection region, but this may not be the case. We also use state-level data to set the yield distribution, but local data may be more variable (Kim and McCarl 2005). Furthermore, a four-step probability distribution is introduced for each crop, while a more detailed one might be desirable. Again, these are considerations for future research.

In terms of feedstock production, this study assumes that the production costs per milligram are fixed and consistent across the region; while, in reality, they are likely to vary with volume and from year-to-year, due to weather, pests, and other conditions. Additionally, assumptions on the disposition of excess feedstocks may not represent the on-the-ground situation. These may be examined in future studies.

Moreover, in this study, biofuel producers are assumed to own the entire supply chain. However, it is common for different segment of a proposed supply chain to be owned and operated by other stakeholders. Therefore, the impact of different ownerships on supply chain design are of interest.

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

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APPEENDIX A

LIST OF SYMBOLS

Sets

i	Feedstock 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 harvesting feedstock b
a_b/a_{bs}	Yield of feedstock b/ Yield of feedstock b under state of nature s
β_b	Cost of storing feedstock type b
c_{bi}	Cost of contracting a hectare land at location i for feedstock b
d_b	Cost of dumping a Ha of feedstock b at location i
γ_b	Cost of pelleting feedstock b
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_b	Pelleting yield (% of raw material)
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
$Prof$	Profit of exporting a Mg of pellet

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_{bi}	Amount of land contracted for feedstock b at supply region i (1000 hectare)

Second stage decision variables

$N_{bit}/N_{bit}(s)$	Amount of land for feedstock b harvested at supply region i in month t
$OBR_{bijt}/OBR_{bijt}(s)$	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)
$PLBR_{ljt}/PLBR_{ljt}(s)$	Amount of feedstock b sent from pellet station l to biorefinery location j 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)
$R_{blt}/R_{blt}(s)$	Mg of feedstock b that are pelleted at pelleting plant l 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)
$U_{jt}/U_{jt}(s)$	Amount of ethanol being produced at biorefinery location j in month t (Liter)
$W_{bit}/W_{bit}(s)$.	Amount of feedstock b being dumped at supply location i in month t (under states of nature s) (Mg)

Acronyms

CLC	Contracting cost for feedstock
CBP	Feedstock production cost
CST	Feedstock storage holding cost
CPL	Pelleting cost
CTP	Transportation cost
CAP	Capital cost of biorefinery, storage and pellet plant
$DUMP$	Overall dumping cost
EX	Profit from exporting pellet