INL/JOU-23-70982-Revision-0

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November 2022

Changing the World's Energy Future

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http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Nth-plant scenario for forest resources and short rotation woody crops: biorefineries and depots in the contiguous US

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Abstract

Estimating the US potential of woody material is of vital importance to ensure cost-effective supply logistics and develop a sustainable bioenergy and bioproducts industry. We analyzed a mature conversion technology for woody resources for the contiguous US that takes advantage of economies of scale: the nth-plant. We developed a database to quantify the total accessible woody biomass within a distributed network of preprocessing depots and biorefineries considering both quality specifications for conversion and a target cost to compete with fossil fuels. We considered two categories of woody biomass: 1) forest residues from trees, tops and limbs produced from conventional thinning and timber harvesting operations as well as non-timber tree removal; and 2) short rotation woody crops such as poplar, willow, pine, and eucalyptus. A mixed integer linear programming model was developed to analyze scenarios with woody feedstock blends at variable biomass ash contents and cost targets at the biorefinery. When considering a target cost of $85.51/dry ton at the biorefinery, the maximum accessible biomass from forest residues in 2040 remained constant at 106 million dry tons regardless of ash targets. Including short rotation woody crops as part of the blend increased the total accessible biomass to 153 and 195 million dry tons at ash targets of 1% and 1.75%, respectively. We concluded from our analysis that woody resources could address about 55% of EPA's (Environmental Protection Agency) target of 16 billion gallons of cellulosic biofuel.

Keywords:

Forest residues, short rotation woody crops, biofuel, biorefineries

1. Introduction

Renewable energy can provide a sustainable solution to a changing climate with frequent extreme weather, decreasing soil and water quality, increasing pest outbreaks and resistance, and water scarcity while also meeting food, feed and energy demands of a growing population (Foley et al., 2011; Liu et al., 2013; Rockström et al., 2009; Schmidhuber and Tubiello, 2007; Tilman et al., 2002). Bioenergy is currently the largest renewable energy source worldwide supplying approximately 13% of energy demand (WBA, 2019). Resources such as agriculture, forestry, and waste materials have the potential to be a major contributor in future global energy paradigms that emphasize renewable energy over fossil-based energy. The US is the largest biofuel producer in the world, totaling 17.3 billion gallons, which is 17% of the US renewable energy mix (US EIA, 2020; US EIA, 2021). Corn-based biofuels are restricted to 15 billion gallons/year (US EPA, 2020) and an additional 16 billion gallons/year of renewable fuels are projected to come from cellulosic resources such as energy crops, municipal solid waste, and agricultural and forest residues (US EPA, 2020). Hossain et al. (2021) predicted that 168 million dry tons (7.4 million GGE) could be accessible to biorefineries in the US by 2040 where corn stover and Panicum virgatum L. (hereafter "switchgrass") feedstocks could meet specific cost and quality parameters at the biorefinery. The study presented herein quantifies the potential of forest resources and short rotation woody crops (SRWCs) to complement the ambitious EPA targets while also meeting quality expectations at the refinery. In this study we consider: 1) forest residues from trees, tops and limbs produced from conventional thinning and timber harvesting operations and from non-timber tree removal, and 2) SRWCs such as Poplar x Populus (hereafter "poplar"), Willow x Salix (hereafter "willow"), Pine x Pinus (hereafter "pine"), and Eucalyptus x Eucalyptus Globulus (hereafter "eucalyptus"). For simplicity, we refer to these two types of resources as woody biomass.

The US has the potential to produce 290 million tons of woody biomass by 2040 (US DOE, 2016). Protection of agricultural and forest lands from degradation, urbanization and desertification as well as sustainable innovation in crop yields will contribute to ensure the anticipated potential of the woody biomass. Approximately 5% of the agricultural land (240 million hectares) could be used for growing dedicated energy crops (e.g. SRWCs) by 2035 (Sheet, 2012). The environmental impacts of using forest resources are low compared to fossil fuels due to its lower energy requirements and inherent CO2 storage during photosynthesis. However, only 2% of the current US energy production comes from wood-based resources (Zhu, 2011). Sustainable forest management is one of the concerns contributing to current low utilization of wood-based resources for energy (Bioenergy IEA, 2018). One example of sustainable forest management is to balance carbon losses in forest stands with carbon growth in other forest stands through coordinated harvest activities and utilization of thinned trees or forest by-products as bioenergy. Other major contributors towards stranded woody resources are high costs of collecting, transporting and storing woody biomass. Processes include harvesting, felling, extraction, chipping, and loading (US DOE, 2011; Rummer & Darren, 2013). Tree felling is done using forage harvesters and feller-bunchers. Grapple skidders, forwarders or cable-yarding are used for extraction- the process of transporting large timbers from their origin to a loading zone. Processing generally consists of removing limbs and tops from felled trees using chainsaws, delimbers and buckers. Log sections are then loaded onto trailers. Grinders, hogs, and chippers are used for complex processing operations after log removal. Harvest operations and weather conditions impact the quality of woody biomass extracted.

Conversion facilities require low moisture content (<10%), low ash content (<1%) and small particle sizes (2mm chips) (Hartley et al., 2021). Kizha et al. (2018) found a drop of moisture content from 52% to less than 20% over a 12-month study period for timber operations. However, ash content tends to increase during piling and handling of logging residues due to soil impurities (Mcdonald et al., 2001). Heterogeneous feedstock quality such as varying ash, moisture and carbon content contribute to high operational costs at the biorefinery due to operational instability. This in turn, leads to system downtime, variable conversion yields, and challenges to process robustness (Hartley et al., 2020; Lin et al., 2016). Thus, transporting woody materials from loading zones near harvesting sites to facilities for conversion to fuel accounts for 47-50% of the total cost (Pan et al., 2008; Mcdonald et al., 2001). Considering coordinated decision making strategies, i.e., coordinated transport, supply chain integration, and higher truck payload can achieve cost savings of up to 3%, 24%, and 40% respectively (Kogler et al., 2021). Moreover, multimodal transport using both truck and rail terminals could increase the resiliency of the supply chain addressing supply uncertainties due to natural calamities, and equipment breakdown (Kogler

& Rauch, 2018; Kogler & Rauch, 2019). A resilient biorefinery should have a large supply radius and unit trains are the least expensive transportation mode for distances longer than 240 miles when barge is not an option (Gonzales et al., 2013).

Considering the complexities of harvesting, preprocessing and transporting woody materials, an efficient supply chain is imperative for our future bioeconomy. Acharya et al. (2014) and Mitchell (2000) developed a decision support system to estimate the delivery cost of wood fuel from forest resources in the state of Mississippi in the US and the UK respectively. Frombo et al. (2009) developed a strategic decision model for woody biomass considering different conversion technologies. The model determined how much biomass needed to be harvested in forest sites of Savona province in Italy and what plant capacity would be optimum. While there are many studies on biomass supply chain optimization, most of them considered only a centralized system where all biomass is shipped to one location (Akgul & Papageorgiou, 2012; Bai et al., 2011; Marvin et al., 2012). Very few studies analyzed distributed systems (Braimakis et al. 2014; Roni et al. 2019), a supply chain that includes collection facilities for preprocessing- also known as depots. Kim et al. (2011) optimized the number, location and capacity of processing plants from forestry resources for both distributed and centralized systems -a system where wood is delivered from the landing directly to the biorefinery. However, they only considered the Southern US. Patel et al. (2019) analyzed the distributed and centralized supply chain system to develop a single biorefinery using whole tree biomass in Canada. Since only one biorefinery was considered, the system was unable to take advantage of the availability throughout the country and was only focused on higher supply regions.

Most studies analyzed US regions rather than analyzing the contiguous US due to computational complexities of a large-scale analysis. A raster-based analysis of the contiguous US identified that analyzing the state of Texas in isolation of nearby states could result in an underestimation of 25% of the total accessible biomass in that state (Gonzales & Searcy, 2017). Blending biomass types help reduce ash content resulting in higher conversion yields (Hossain et al., 2021). Lan et al. (2021) determined the minimum fuel selling prices for a centralized and a distributed system in the southeastern US with blends of pine residues and switchgrass. Supply chain studies for woody biomass considering cost targets are also very rare. To our knowledge, there are no studies that include a blend of forest resources (from forestlands) and SRWCs (from croplands). This study addresses this research gap by developing a supply chain for forest residues and SRWCs considering a specified quality and cost target for conversion in the contiguous US.

In this manuscript we analyzed a blended system of centralized and distributed collection facilities for woody material conversion. Biomass is delivered from landing to depots for preprocessing into blended chips of various biomass types depending on quality specifications required by biorefineries. Similar to Hess et al. (2009), Kenney et al. (2013), Gonzales & Searcy (2017), Edmunds et al. (2018), and Hossain et al. (2021), the idea is to generate a uniform-format feedstock delivered to biorefineries, reduce biomass quality variability, and improve conversion performance. We quantified the total accessible wood resources to biorefineries by 2040 given a target cost and quality. In this process, we determined the optimal location and capacity of depots and biorefineries using a modified version of our published model (Hossain et al., 2021). This study aims to answer the following questions:

1. How do different blending ratios of forest residues and SRWC affect the woody biofuel economy?

2. Can wood-based resources take advantage of the economies of scale of an nth-plant scenario with a mature conversion technology?
3. How can we maximize the mobility of wood-based resources with a supply chain network of biorefineries and depots?

Finally, this study adds to the current literature by developing a database with origin-depot and depot-biorefinery location and allocation. We consider multiple scenarios by varying the blend ratio of forest residues and SRWCs as well as the targeted ash content required at the biorefinery.

2. Methods

2.1 Model Formulation

We modified our published mixed-integer linear program model (Hossain et al. , 2021) to solve for the maximum amount of woody feedstock delivered to biorefineries while meeting a set of quality characteristics, cost targets and facility capacity constraints (eq. 1). We assumed that in higher yielding regions, large depots will be co-located with a biorefinery. Smaller depots will collect woody biomass from lower yielding regions and ship preprocessed feedstock to biorefineries located in higher yielding regions. Given the relatively low ash content, high heating value and low sulfur content of woody materials, we assumed thermochemical conversions at the biorefineries and that quality requirements are based on ash content. Table 1 presents the data, parameters and decision variables in our formulation.

$$\max \qquad (1)$$

Hossain et al. (2021) identified biorefinery facilities of a fixed size, 725,000 dry tons per year (dt/year). In this study, we relaxed this capacity constraint to identify biorefineries and depots with various capacities. We assumed that a depot and a biorefinery could be as small as 25,000 dt/year and 725,000 dt/year respectively. Biorefineries could be as high as 2.9 million dt/year - four times the size of a biorefinery in Hossain et al. (2021). The depot capital cost was calculated using the preprocessing construction cost presented by Hartley et al. (2021), \$2.73/dt (2016\$) for a 725,000 dt/year capacity depot. Construction costs were scaled for varying sizes of depot using the rule of six-tenth (Guthrie et al., 1969) and expressed as a regression equation with an adjusted R-square of 0.9783 (eq.2). The total fixed cost was calculated using the summation of all the depot building costs.

Table 1. Data sets, parameters, and decision variables

Data sets	
F	Set of feedstock types
P	Set of feedstock prices
I	Set of origin locations
J	Set of potential depot locations
K	Set of potential biorefinery locations
J_i	Set of potential depot locations within 200 miles of origin i
K_j	Set of potential biorefinery locations within 200 miles of depot j
	Set of ash content per ton for feedstock f
	Set of available resources for origin i of feedstock type f at price p
	Set of minimum supply for origin i of feedstock type f

	Set of total variable cost from origin *i* to depot *j* to biorefinery *k*: farmgate price (*gr*), storage for logs and chips (*sl*, *sc*), transportation for logs and chips (*trl*, *trc*) , handling and queuing (*qh*), and preprocessing costs (*pr*)
	Set of distance between location *i* and location *j*
	Set of distance between location *j* to location *k*
	0 if = 0; 1 otherwise
Parameters	
G	Cost target at delivery
U	Required depot utilization factor (90%)
S	Maximum ash content at biorefinery
D	Constant multiplier for depot capacity
B	Constant multiplier for biorefinery capacity
P	Maximum percentage of SRWC
Continuous Decision Variables	
	Factor for depot capacity at location *j*
	Factor for biorefinery capacity at location *k*
	Amount of feedstock *f* purchased at price *p* from location *i*
	Amount of feedstock *f* shipped from location *i* to location *j*
	Amount of feedstock *f* shipped from location *j* to location *k*
Binary Decision Variables	
	1 if feedstock *f* is purchased at price *p* from location *i*; 0 otherwise
	1 if depot is built in location *j*; 0 otherwise
	1 if biorefinery is built in location *k*; 0 otherwise

Total variable cost (VC) to deliver biomass included farmgate price, storage, handling, transportation and preprocessing costs for logs and chips (eq. 3).

The modified set of constraints used in this study are listed in Table 2: Constraint (1) ensures that each feedstock is purchased only at a single price from each origin location. Constraint (2) puts a maximum limit to the amount of feedstock purchased from an origin location so that it does not exceed the total amount available at that origin. Constraint (3) ensures that the total amount shipped to a depot is within the capacity limit of that depot. Constraint (4) ensures that the total amount shipped to a biorefinery is within the capacity limit of that biorefinery. Constraint (5) is the flow balance between origin and depot. Constraint (6) sets a minimum utilization to the depot capacity. Constraint (7) is the flow balance between depot and biorefinery. Constraint (8) sets the maximum limit to the biorefinery capacity. Constraint (9) requires that the total ash content of all the different feedstocks supplied to a biorefinery is within the maximum allowable ash content. Constraint (10) enforces the required blending ratio of FLR and SRWCs in each biorefinery. The cost target is maintained using constraint (11) combining the total fixed as well as variable costs. The constraints in (11) ensures non-negativity of the continuous decision variables. The set of constraints in (13) are the constraints for binary decision variables.

Table 2. Model constraints

No.	Constraint Name	Mathematical Formulation
1	Feedstock purchase	
2	Maximum supply	
3	Depot Capacity	
4	Biorefinery Capacity	
5	Flow balance for origin-depot	
6	Depot Utilization	
7	Flow balance for depot-biorefinery	
8	Maximum Biorefinery Capacity	
9	Maximum Ash Content	
10	Blending Ratio	
11	Cost target	
12	Variable constraints	
13	Binary constraints	

2.2 Model Inputs

2.2.1 Available Resources

We considered county-level supply curve estimates for available resources at various roadside prices. Feedstock types analyzed include: 1) trees and forest residues from forest lands; and 2) SRWCs from agricultural lands. Roadside prices include the cost of stumpage plus harvesting costs. Roadside prices in the 2016 Billion-Ton Report (BT16) were presented in 2014$ and converted to 2016$ for this study. This conversion was performed using an inflation index applied to real feedstock prices as presented in Table C-2 in the BT16 (US DOE., 2016). We assumed a 3% dry matter loss for storage, handling, and transportation for forest residues and SRWCs.

Total forest land resources (FLR) assumed in this study include public and private land estimates in a medium-house-low-energy scenario (US DOE, 2016). Only estimates of forest resources with a roadside price less than or equal to $78/dt (2016$) are used in this study (Table 2). BT16 estimations for SRWCs were not well suited for this analysis as those simulations allowed herbaceous energy crops to compete with SRWCs, thereby restricting supply potential. To get the full economic potential of woody resources, we utilized the Policy Analysis System Model (POLYSYS), a partial-equilibrium linear programming model that simulates agricultural producer response to projected future market demands (De la Torre Ugarte & Ray, 2000, Langholtz et al., 2014, US DOE 2016). POLYSYS simulations have previously demonstrated that market-specific biomass demands can influence producer response and shape the potential future supply of biomass (Eaton et al., 2018, Oyedeji et al., 2021). To simulate market preference for SRWCs for the present analysis, herbaceous energy crops (e.g., Switchgrass, miscanthus) were removed as potential biomass energy crops, and only SRWCs were allowed to respond to simulated future market demand in the new simulations. Supply curve for year 2040 was considered based on biomass roadside prices (2018$) from $40 to $80/dt in ten-dollar increments (Davis, 2021).

For consistency, we expressed these prices into 2016$ roadside prices. County-level marginal potential woody energy crop supplies for each of the four species were made available at each marginal price point. However, no biomass was found available at less than $59/dt in the new price simulations. Given that processing cost of SRWCs was estimated at about $23.54/dt (Table 5), feedstock with a roadside price higher than $59/dt would not be feasible with a cost target at the biorefinery throat of $85.51/dt (2016$) or less. Therefore, we only considered available biomass that is less than or equal to $59/dt (2016$) at the roadside. Availability of woody materials across the US are shown in Figure 1.

Table 3. Available woody biomass based on roadside price (2016$) and land type used.

Land Type	Feedstock Type	Available Material at Roadside Price (million dt/year)					
		$29/dt	$39/dt	$49/dt	$59/dt	$68/dt	$78/dt
Forest	Residue	17.6	17.6	17.6	17.6	17.6	17.6
Forest	Tree	0	3.53	30.7	68.2	98.4	98.4
Land Type	**Feedstock Type**	**Available Material at Roadside Price (million dt/year)**					
		$30/dt	**$39/dt**	**$49/dt**	**$59/dt**	**$69/dt**	**$79/dt**
Crop	Willow	0	0	0	116	138	163
Crop	Pine	0	0	0	32.1	67.3	70.3
Crop	Poplar	0	0	0	5.62	22.0	36.7
Crop	Eucalyptus	0	0	0	3.67	5.58	15.1

Prices are in (2016$). dt: dry tons.

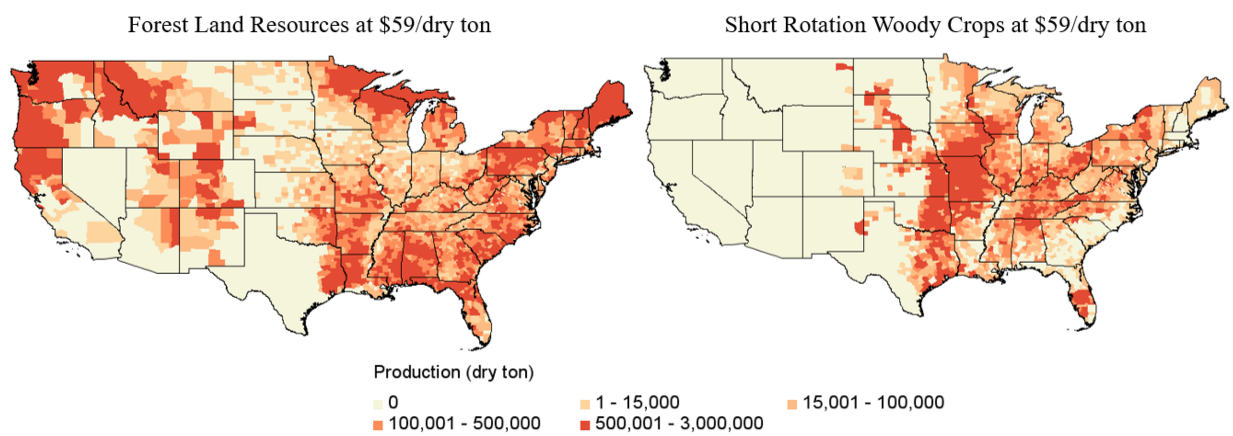


Figure 1. Woody biomass availability per county at a roadside price of $59/dt (2016$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

2.2.2 Candidate locations

After aggregating the two biomass datasets for FLR and SRWCs, 82% of the US counties, i.e. 2,606 counties, had positive values for biomass quantities. Each county was considered an origin point in our model. The computational complexity of our problem is further exacerbated with 6 feedstock types and 32 roadside price options to express biomass supply curves i.e. 31 different price options for FLR (Table 2) and one price option for SRWCs ($59/dt). To reduce our computational complexity, we reduced the number of county-candidates for the locations of depots and biorefineries by overlaying a fishnet of 100-mile grid in the contiguous US. The assumption for this reduction was that two biorefineries with a supply radius of 50-miles each, will most likely not be less than 100 miles apart. This approach reduced the potential candidates to 221 locations distributed over the contiguous US. Similar to our previous work (Hossain et al., 2021) and rather than using county centroids, the location of available FLR and SRWC per county was geo-referenced based on the location of the forest regions and cultivated crops in the 2021 National Land Cover Database, respectively. 2.2.3 Logistic costs

A maximum target cost of $85.51/dt (2016$) at the refinery gate was considered for the analysis based on the 2017 design case for the nth-plant scenario (Kenney et al., 2013). Harvesting prices presented in BT16 (US DOE, 2016) for the different forest regions and cutting operations were higher estimates when compared to a more recent study by Hartley et al. (2021). We adjusted harvesting prices based on the latest publication mentioned. This adjustment resulted in lower roadside prices as inputs to our model (Table 4). Table 4. Adjusted roadside prices (2016$/dt) for forest land resources

Feedstock	Roadside Price from BT16 (2016$)	Forest Region	Adjusted Roadside Price (2016$) based on Cutting Operation	
			Clear Cut	Thinning/ Partial Cut
Forest Residues	29	PNW	15.19	11.29
		IW	15.44	12.61
		NC, NE, S	15.57	12.65
	39	PNW	24.96	21.06
		IW	25.21	22.38
		NC, NE, S	25.34	22.42
	49	PNW	34.73	30.83
		IW	34.98	32.15
		NC, NE, S	35.11	32.19
	59	PNW	44.50	40.60
		IW	44.75	41.92
		NC, NE, S	44.88	41.96
	68	PNW	54.27	50.37
		IW	54.52	51.69
		NC, NE, S	51.73	51.73
Tree	39	IW, NC, NE, S	19.08	-
	49	NC	-	23.64
		IW, NC, NE, PNW, S	29.5	-
	59	IW, NC, NE, PNW, S	39.34	33.41
	68	IW, NC, NE, PNW, S	49.11	43.18
	78	IW, NC, NE, PNW, S	58.88	52.95

Forest regions: Northeast (NE), North Central (NC), South (S), Inland West (IW), and Pacific Northwest (PNW).

Operational costs such as storage, handling, queuing, preprocessing and transportation (Table 5) are based on the catalytic fast pyrolysis pathway presented by Hartley et al., (2021) and BT16 report (US DOE, 2016). Trees were assumed to be transported as logs from the landing and will be converted to 2 mm chips at the preprocessing facilities or depots (Hartley et al., 2021). Forest residues and SRWCs were assumed to arrive at the collection facility as chips from the landing and will be reduced in size at the depot.

Table 5. Adjusted roadside prices (2016$/dt) for forest land resources

Cost Description	Feedstock Format	Location	Feedstock Type		
			Forest Land Resources		Short Rotation Woody Crops
			Trees	Residues	
Adjusted Roadside Price	Logs/Chips	Origin	$19.08 - $58.88	$11.29 - $54.52	$59.09
Storage, Handling and Queuing	Logs/Chips to Chips	Depot	$2.65		
Storage, Handling and Queuing	Chips	Biorefinery	$0.85	$0.64	$0.85
Processing Cost	Logs/Chips to Chips	Depot	$27.32	$23.54	$23.54
Transportation Fixed Cost or Fieldside Handling and Queuing	Logs/Chips	Origin to Depot	$3.58	$1.81	$3.58
Transportation Variable Cost	Logs/Chips	Origin to Depot	$0.08[1]	$0.14[1]	$0.08[1]
Transportation Fixed Cost	Chips	Depot to Biorefinery	$1.81		
Transportation Variable Cost	Chips	Depot to Biorefinery	$0.14[1]		

[1]$ /mile/dry ton

2.2.4 Feedstock Quality

Table 6 specifies the assumed initial ash content values considered for each feedstock type (Thakaran et al., 2003). It is assumed that after preprocessing, logs and chips will have the targeted moisture and carbon contents for conversion. Afterwards, they will be blended to achieve the target ash.

Table 6. eedstock ash content based on feedstock type

Resource Type	Feedstock Type	Ash Content (%)
Forest land resources	Trees	0.8
	Forest residues	1.5
Short rotation woody crops	Pine	0.8
	Poplar	1.87
	Willow	1.997
	Eucalyptus	1.5

2.3 Scenarios

We analyzed different scenarios with varying required feedstock blends at the biorefineries, distinct ash contents required at the biorefineries, and different cost targets. Varying feedstock blending values were identified to analyze the potential of short rotation woody crops in a sustainable bioeconmy. Variations in ash contents and target costs were in line with previous studies supported by DOE as specified in this section.

Assumed feedstock quality attributes required at the conversion facility for optimization are moisture, ash and carbon as per the catalytic fast pyrolysis pathway presented by Hartley et al., (2021). These quality targets are presented in Table 7. Ash content quality targets were run at different values: 1% ash content based on the 2022 catalytic fast pyrolysis pathway projection (Hartley et al., 2018), and 1.75% ash content based on the 2020 catalytic fast pyrolysis pathway 2020 woody state of technology (Hartley et al., 2021)

Table 7. Feedstock quality targets at the biorefinery gate

Moisture Content (w.b)	**Carbon**	**Ash Content (%)**	
		Catalytic Fast Pyrolysis 2022 Projection	**Catalytic Fast Pyrolysis 2020 Woody State of Technology**
≤ 10%	≥ 50.51%	≤ 1%	≤ 1.75%

Feedstock blending scenarios were as follows: 1) Base case: biorefineries will only accept FLR since a market for SRWCs has not been established. 2) 75% FLR: biorefineries will accept both FLR and SRWCs with a required blending ratio of at least 75% incoming feedstock from FLR. 3) 50% FLR: biorefineries will accept both FLR and SRWCs with a required blending ratio of at least 50% incoming feedstock from FLR. 4) No constraint: biorefineries will accept both FLR and SRWCs with no constraint on blending ratio.

To compare model results with our previous publication on herbaceous biomass (Hossain et al., 2021), we also ran scenarios with a target cost of $79.07/dt (2016$) at the refinery gate. Additionally, we included scenarios with target costs of $70.31/dt for 1% ash and $67.03/dt for 1.75% ash to take into account the design case updates from the 2022 catalytic fast pyrolysis projection and the 2020 catalytic fast pyrolysis woody state of technology respectively (Hartley et al., 2018; Hartley et al., 2021). Combining roadside prices at $59.09/dt and a preprocessing cost of $23.54 for SRWCs (from Table 5) add up to $82.63/dt, leaving very little room for storage, handling and transportation costs to reach a target of $70.31/dt, let alone, $67.03/dt. Hence, we only ran these target costs at the base case simulation, where trees and residues are the only available resources. 3. Results

3.1 Accessible Resources

The MILP developed for this analysis has a supply resource curve as input options to locate facilities with resources for preprocessing and conversion. For a given feedstock type and location, only one roadside price and resource quantity combination is selected as accessible from the input supply curve in the solution. Herein, resources that are inputs to the model are referred to as available resources. Similarly, resource outputs of the model are referred to as accessible resources. Table 8 presents aggregations of the optimization model's outputs for the analyzed scenarios in this study. As expected, total accessible resources increased as the cost target increased. Note that an increase in targeted ash content at either target price did not result in an increase in accessible biomass when trees and residues were the only resources available, i.e. the base case scenarios. Total accessible biomass increases when SRWCs are introduced (base case scenarios vs. all other scenarios). Regardless of cost and ash targets, total accessible biomass was highest when there were no constraints for blending forest land resources and short rotation woody crops. And higher when the constraint was 50% for each compared to 75% for forest land resources.

Table 8. Analyzed scenarios using short rotation woody crops in absence of competition with herbaceous energy crops

Scenario		**Accessible resources (million dry tons/year)**						**Total accessible resources (million dry tons/year)**	**Numb. of Depots**	**Numb. of Biorefineries**
		Forest Land Res.		**Short Rotation Woody Crops**						
		Trees	**Residues**	**Pine**	**Poplar**	**Willow**	**Euc**			
Cost target $85.51/dry ton										
1% ash	Base case	91.2	14.8	N/A	N/A	N/A	N/A	106	113	72
	75% FLR	91.0	14.7	11.8	1.46	9.36	1.48	130	125	109
	50% FLR	90.6	14.7	24.7	1.54	9.66	1.21	142	122	112
	No const.	90.6	14.6	31.1	4.28	11.1	1.30	153	120	114
1.75 % ash	Base case	91.2	14.8	-	-	-	-	106	73	60
	75% FLR	91.0	14.8	6.84	1.18	23	1.01	138	131	111
	50% FLR	89.5	14.6	15.6	1.56	47.2	1.95	170	125	118
	No const.	86.0	14.5	25.3	2.92	64.4	2.46	195	136	134
Cost target $79.07/dry ton										
1% ash	Base case	88.7	14.3	N/A	N/A	N/A	N/A	103	94	93
	75% FLR	85.9	14.3	6.03	0.52	5.77	0.23	112	110	109
	50% FLR	83.6	14.3	9.76	0.5	4.99	0.19	113	106	105
	No const.	82.1	14.2	12.5	0.6	4.65	0.21	114	114	110
1.75% ash	Base case	88.4	14.6	N/A	N/A	N/A	N/A	103	110	91
	75% FLR	83.3	14.8	4.45	0.75	11.1	0.27	114	106	106
	50% FLR	78.7	14.1	5.57	0.6	16.7	0.74	116	107	107
	No const.	78.2	14.1	5.18	1.07	18	0.85	117	112	110
Cost target $70.31/dry ton										
1% ash	Base case	49.5	13.7	N/A	N/A	N/A	N/A	63	79	74
Cost target $67.03/dry ton										
1.75% ash	Base case	33.7	13.3	N/A	N/A	N/A	N/A	47	57	56

3.2 Facilities

For most of the scenarios, except for the $85.51/dt cost target scenarios, the number of depots and biorefineries have little difference between them. Since the maximum capacity of a depot and a biorefinery was 2.9 million dry tons, a high-capacity depot could be co-located with a high-capacity biorefinery. This implies that most of the depots are co-located with a biorefinery. In some cases, the number of depots or biorefineries will decrease even when total accessible resources increase as the model would identify higher facility capacities as part of the solution. Figure 2 and 3 (a) show the distribution of biorefinery capacities in each scenario.. The x-axis in Figure 2 and 3(a) were modified for better visualization. We added a small random variation to the location of each point, a process that is referred to as jittering, useful to handle over-plotting caused by discreteness in datasets. At a higher cost target ($85.51/dt), there were more biorefineries of higher capacity than at $79.07/dt, $70.31/dt, and $67.03/dt, regardless of available feedstock. Similarly, for the most part, as accessible biomass increases from the base case to the no constraint scenario, the number of biorefineries with high capacities increases.

3.3 Average Cost Per Ton of Biomass to Biorefineries

Figure 3(b) and 4 illustrate the distribution of the average cost per ton of biomass delivered to biorefineries for all the scenarios analyzed in this study. In general, only a few outliers were found in these scenarios. The most outliers were found in the scenario with the highest cost target ($85.05/dt) and lower ash target (1%). Similarly, the whiskers for maximum values are longest in the base case scenarios for $85.05/dt. Hence, the highest variability within average costs per ton of biomass in biorefineries was found in the base case scenario at $85.05/dt.

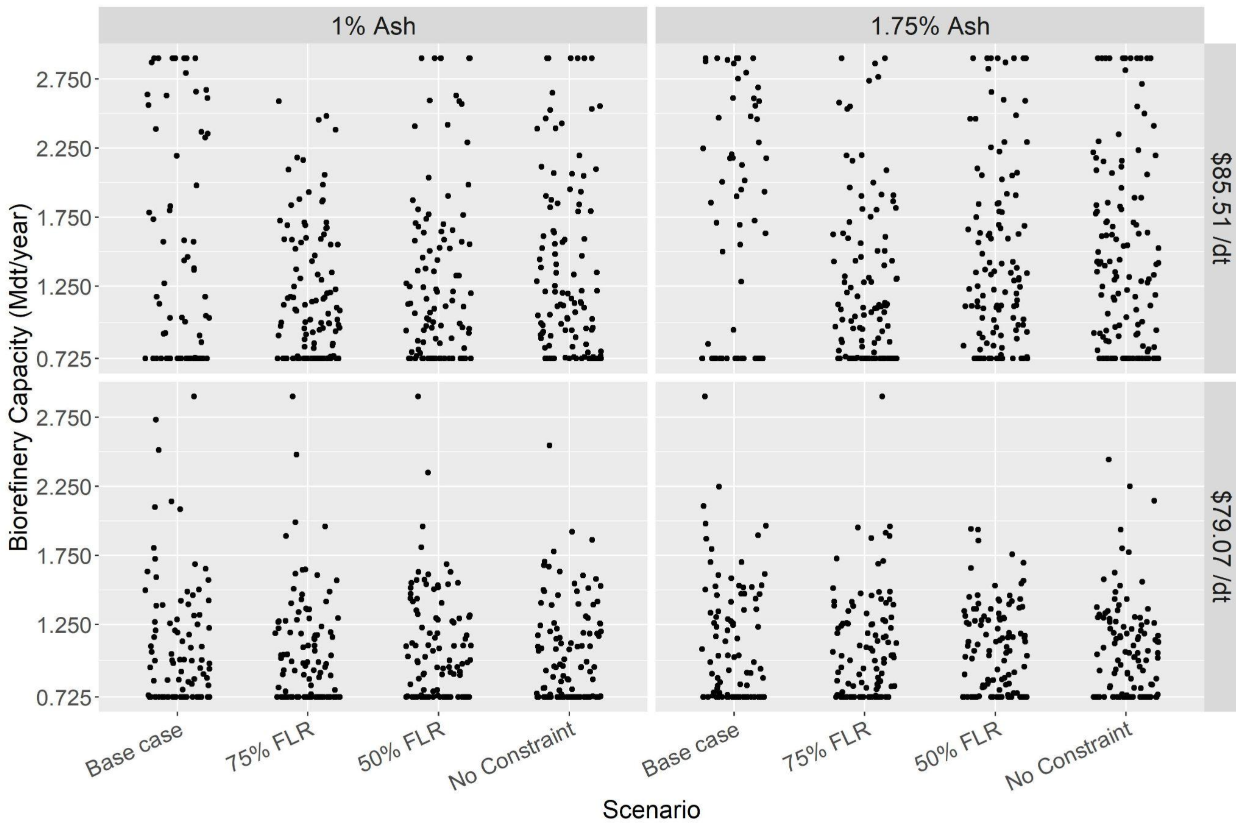
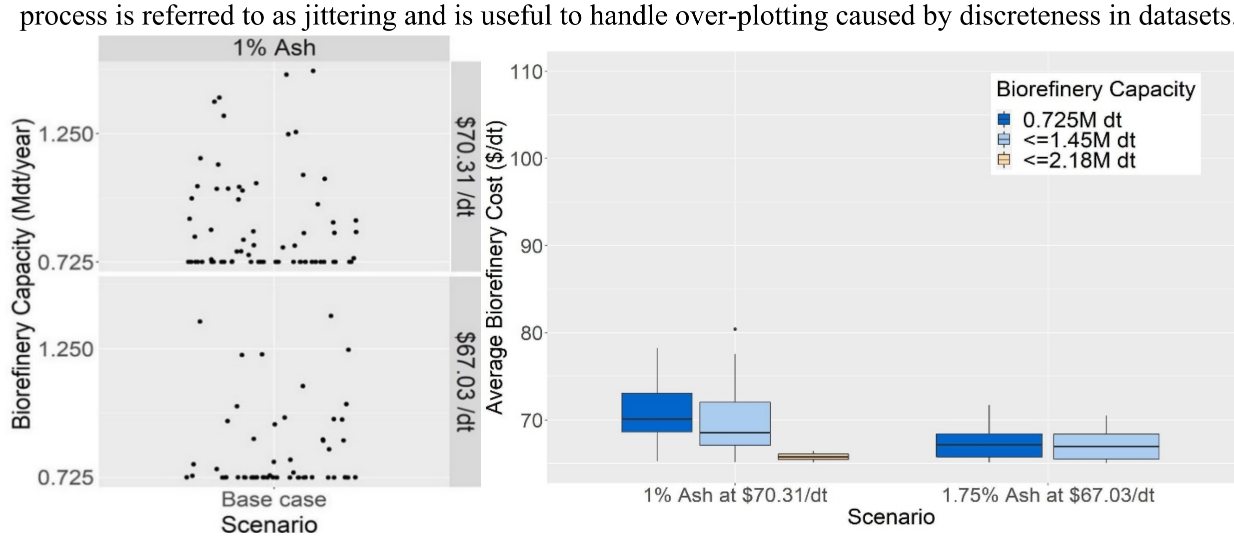


Figure 2. Biorefinery capacities for analyzed scenarios at $79.07/dt and $85.51/dt. The x axis was modified for better visualization by adding a small random variation to the location of each point. This process is referred to as jittering and is useful to handle over-plotting caused by discreteness in datasets.



(a) (b)

Figure 3. Distribution of (a) biorefinery average costs and (b) biorefinery capacities for the base case scenarios at $70.31/dt and $67.03/dt. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

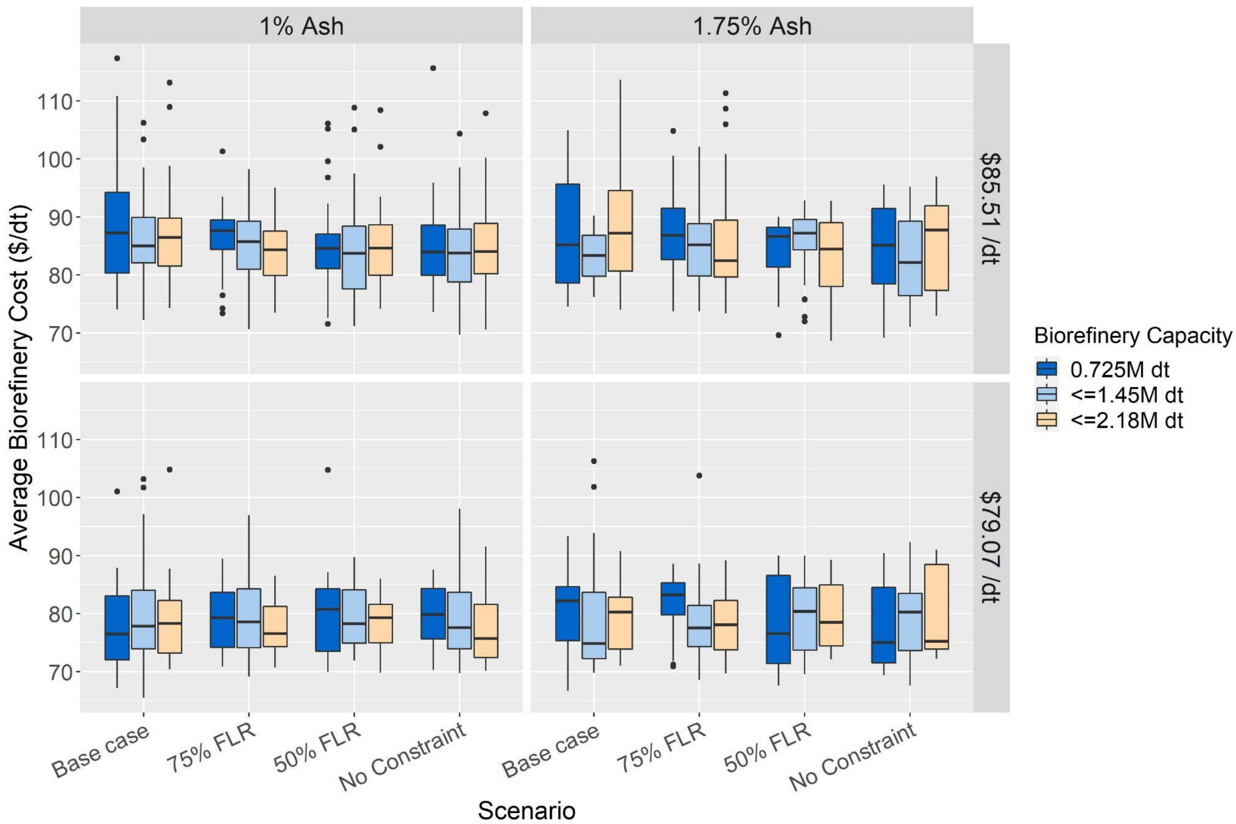


Figure 4. Distribution of average biomass costs to biorefineries for different scenarios at $79.07/dt and $85.51/dt cost targets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

3.4 Stranded Resources

Given that our optimization model is constrained to select one price and quantity combination from the supply curve for a given feedstock type and location, quantifying the total stranded resources is not straightforward. Table 9 illustrates the maximum stranded resource quantities for the base case scenario at 1% and at a target cost of $85.51/dt. Values presented in Table 9 may be interpreted as cumulative stranded resources, but rather the amount stranded is correlated to the respective roadside price. For example, 498 dt/year were stranded at a roadside price of $20/dt.

Table 9. Stranded woody feedstock by roadside price ($2016)

Forest Land Resources	Price ($/dt)	Stranded (dt/year)
Trees	20	498
	24	299
	30	241,102
	34	45,588
	40	1,126,454

	44	461,727
Forest Residues	12	162
	13	225
	13	85,782
	16	47,036
	16	11,660
	16	93,596
	23	190,002
	26	1544
	26	10,595
	26	13,346
	36	765
	46	293

3.5 Feedstock Ratio

Figure 5 illustrates the feedstock proportions found to be optimal for each scenario. For most scenarios, more than 50% of the accessible feedstock came from trees. tSince willow has a high ash content, the proportion of willow increases when higher ash targets are allowed at the biorefinery displacing accessible trees and pine resources.

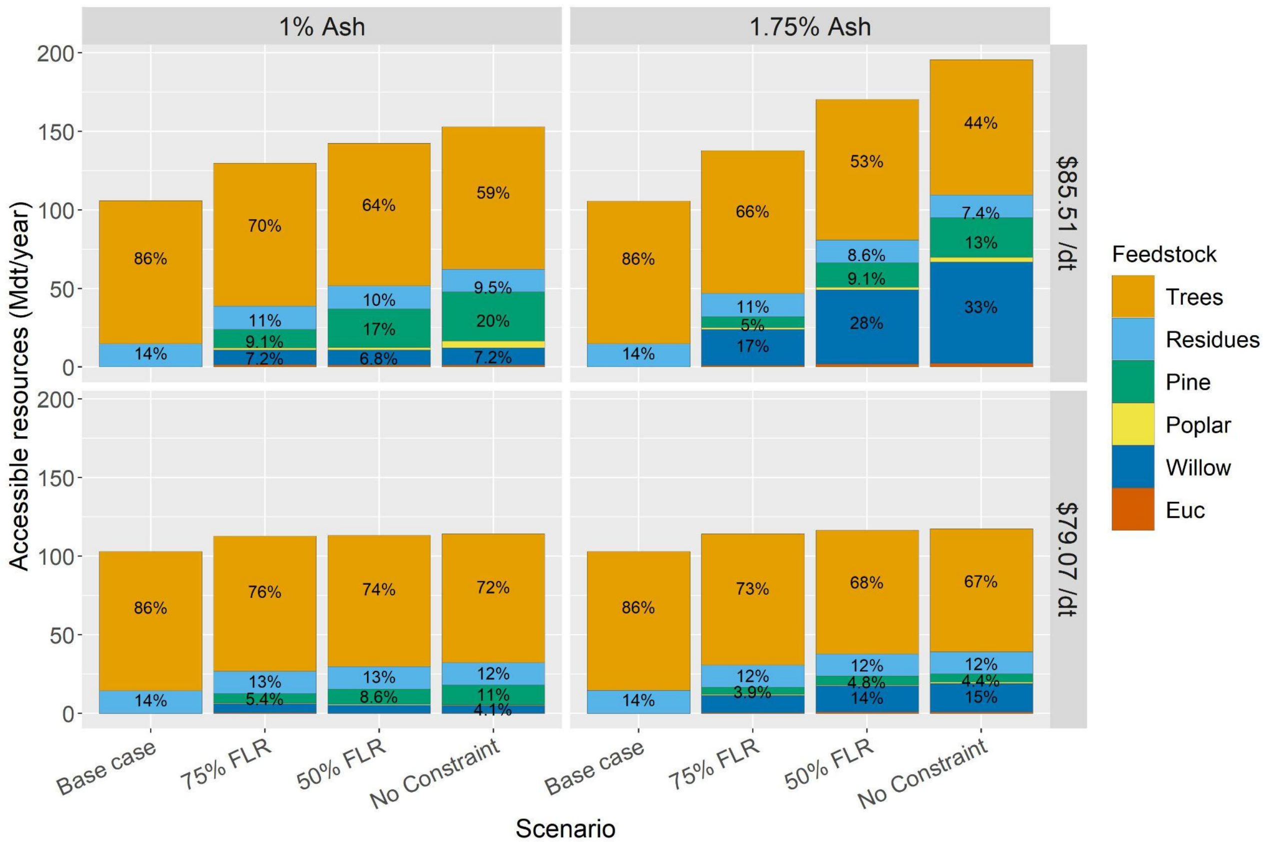


Figure 5. Feedstock blend accessible for the analyzed scenarios at $79.07/dry ton and $85.51/dry ton. Poplar and eucalyptus supply proportions vary from 0.2% - 3%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

3.6 Depot and Biorefinery Locations

Figures 6 and 7 show the location of biorefineries and depots for all the scenarios at $85.51/dry ton target cost. The radius of the circle represents the capacities of the depots. Very few biorefineries were located in the forest land resources of the northwest. Depots in that region also have a low capacity compared to the Midwest region. As we introduce the constraint on feedstock blending ratio, accessible SRWC increases, which is evident with the establishment of a higher number of biorefineries and depots in the agricultural lands of the Midwest. Similar graphical observations were made for scenarios with target costs of $79.07/dt, $70.31/dt and $67.03/dt and are included in the appendix.

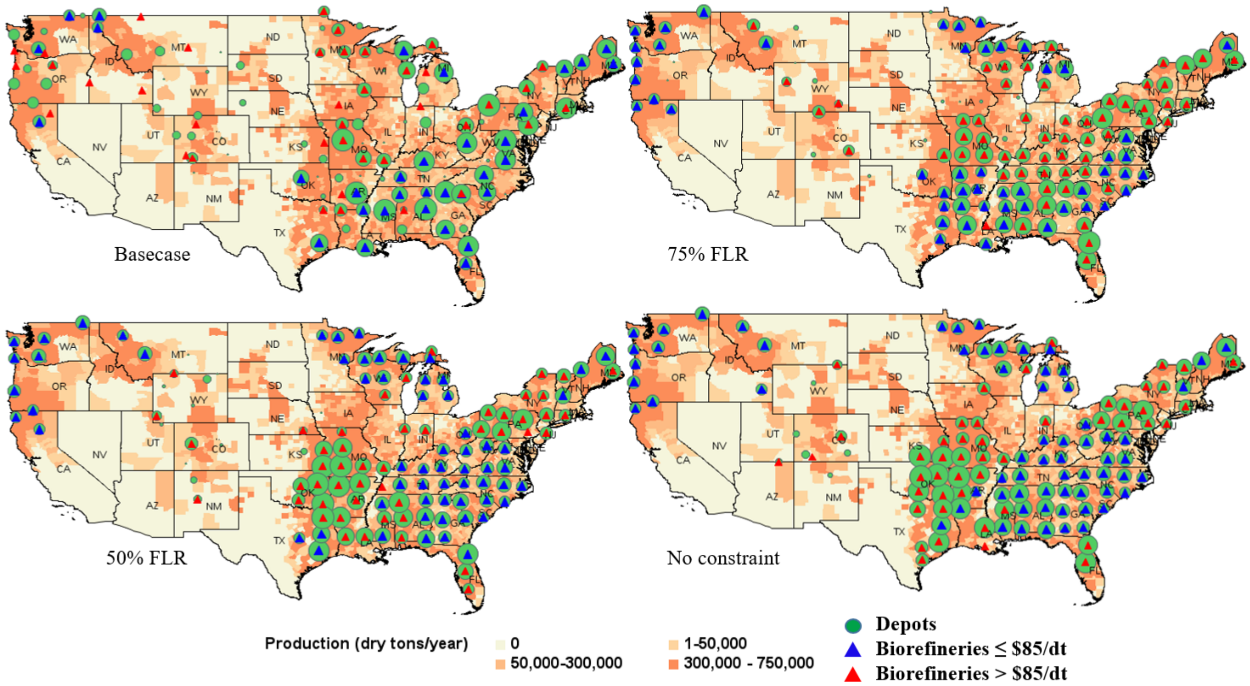


Figure 6. Depot and biorefinery locations for 1% ash blend scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

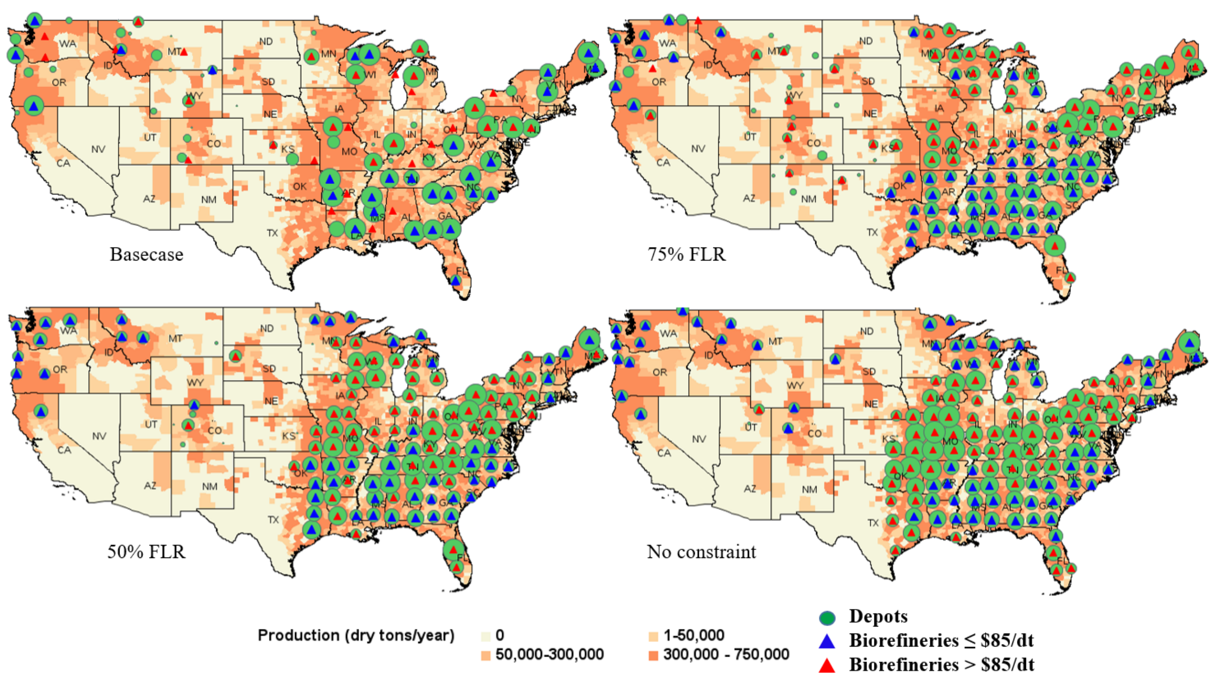


Figure 7. Depot and biorefinery locations for 1.75% ash blend scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

4. Discussion

4.1 The Potential of Woody Resources

One of the main goals of this study was to compare the baseline scenario with FLR to the scenarios where we have both the SRWC and the FLR, i.e. how the blend of SRWC and FLR might affect the supply. The presence of SRWC markets increases the total accessible biomass to biorefineries from 106 to 153 and 195 M dt/year at ash targets of 1% and 1.75%, respectively. Thus, the total delivered feedstock could have almost a two-fold increase in the presence of SRWCs. Our results also indicated access to stranded resources using a distributed supply network of depots and biorefineries. Especially for scenarios where target cost was high ($85.51/dt), there were several depots that were not co-located with the biorefinery (Table 8). These stand-alone depots were able to ship preprocessed biomass to biorefineries which otherwise would have remained stranded. For lower target cost scenarios, a centralized system might be ideal for woody biomass collection since most depots and biorefineries are co-located.

Analyzed scenarios illustrate that the maximum accessible forest residue is approximately 106 M dt/year regardless of ash content values required at the biorefinery and of desired feedstock blending ratio. In the presence of SRWC markets, scenarios where biorefineries are willing to accept resources from either forest lands or SRWCs maximizes accessible resources. Scenarios with a 1% ash target had the lowest resource accessibility while the ones with 1.75% had the highest. This can be attributed to the combination of high ash percentage of willow and poplar (Table 6) and high feedstock availability of these resources (Table 2). For example, if we compare the scenario with no blending constraints with a cost target of $85.51/dt, the collection of SRWCs increased from 48 to 95 M dt/year as the ash target was increased -about a 100%. The increase in willow alone was almost six-fold, from 11 to 65 M dt/year and it was the major contributor in increasing accessible SRWCs.

Since short rotation woody crops are most available at a higher price compared to trees and residues, the lower cost targets were able to access only a limited amount of those resources. Total accessible resource reduction between the two cost targets was mainly due to a significant decrease in the supply of pine and willow. Lowering the cost target at the biorefinery by about $6 ($85.51 to $79.07/dt) resulted in a 3% reduction of total accessible FLR in the base case, from 106 to 103 Mdt/year. The $6 reduction in target costs was most impactful in scenarios that include SRWCs, resulting in 14-40% reduction in total accessible resources. The highest reduction was observed when comparing results for these two cost targets with 1.75% and no blend constraints; total accessible resources decreased from 195 to 117 Mdt/year.

With a cost target of $79.07/dry ton at the biorefinery gate, 47% of EPA's cellulosic demand could be fulfilled by 2040 using corn stover and switchgrass (Hossain et al., 2021). Based on the analysis presented in this paper, approximately 117 M dt/year of woody resources could be delivered to biorefineries at $79.07/dt which addresses 33% of EPA's target goal of 16 billion gallons for cellulosic biofuel. Similarly, with a target cost of $85.51/dt (a $6/dt increase), woody resources alone could address 55% of EPA's target goals with 195 M dt/year. Woody resources can thus serve as a potential feedstock to boost the cellulosic biofuel production in the long simulation.

4.2 Contrasting our analysis with Previously Published Studies

To evaluate our study with the previously published studies, we ran our model with a cost target of $79.07/dt using BT16 (US DOE., 2016) published SRWC data (summarized in Table 10). We compared the non-competing scenario from the new price simulations data (Davis, 2021) with the estimates for SRWCs presented in BT16. Since the baseline year for BT16 was 2015 as opposed to the baseline year of 2018 for the new price simulations dataset (three years later), we compared the new simulations with estimates for year 2037 presented in BT16. Simulations in BT16 had an underlying assumption to limit eucalyptus development to be grown only in Gulf Coast states. This assumption led to low forecasted eucalyptus quantities (Table 10). Willow took over the land that was allocated to Miscanthus and switchgrass in BT16. Similarly, eucalyptus took over some land for Sorghum and energy cane allocated in BT16.

Due to the large stump growth of coppice crops (willow and eucalyptus), it is costly to change a coppice crop land to non-coppice crop land. Therefore,counties with willow and eucalyptus would not be expected to go back to producing poplar and pine which is reflected in the higher production of coppice crops than non-coppice crops in Davis (2021) price simulations. It also has a lower supply of poplar compared to BT16 due to model assumptions favoring the low ash content pine growth out of the non-coppice crops. As expected, the total supply in the new price simulation without the competition in herbaceous energy crops is higher than BT16. Since BT16 (US DOE., 2016) had availability at lower prices, the model was able to find more accessible biomass (Table 11) compared to the POLYSYS price simulation scenarios (Table 6).

Table 10. Available Short Rotation Woody Crops at Roadside for Year 2037 (US DOE, 2016)

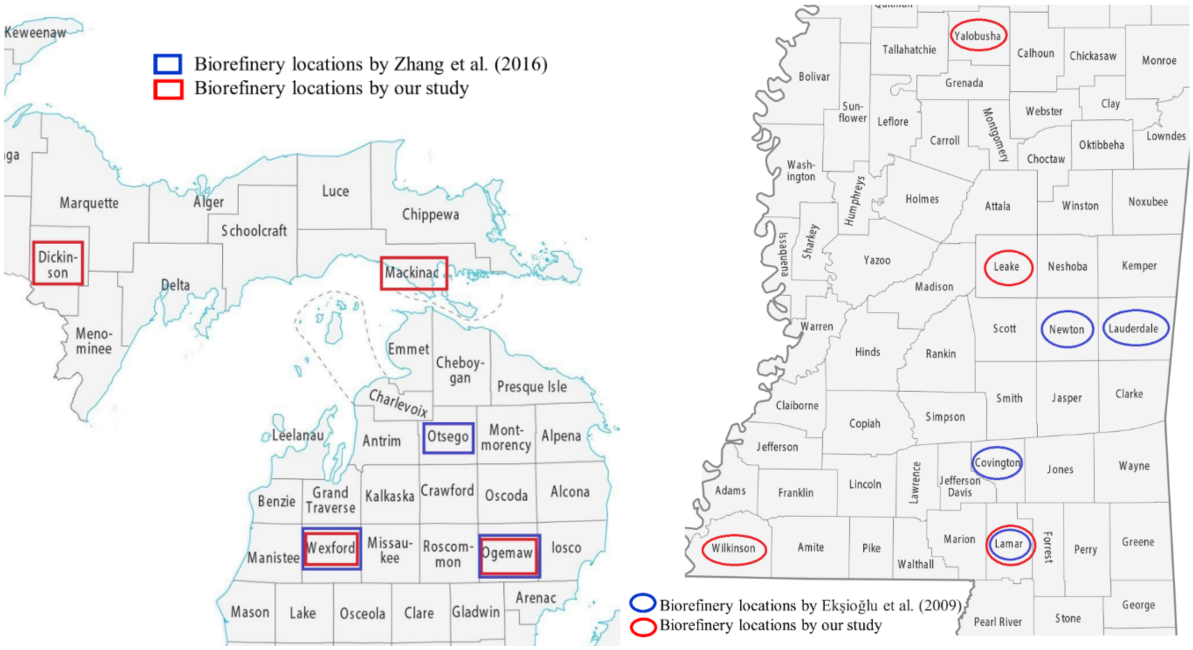
Resource Type	Available Material at Roadside Price (million dt/year)			
	$29/dt	$39/dt	$49/dt	$59/dt
Willow	0.925	5.60	23.7	31.2
Pine	0	0	0.010	0.116
Poplar	0	6.95	23.4	45.7
Eucalyptus	0	0	341	0.626

Table 11. Analyzed scenario using available short rotation woody crops at roadside for year 2037 (US DOE, 2016)

Scenario		Accessible Resources (M dry tons/year)						Total accessible resources (M dry tons/year)	Numb. of Depots	Numb. of Biorefineries
		Forest Land Res.		Short Rotation Woody Crops						
		Trees	Residues	Pine	Poplar	Willow	Euc			
Cost target $79.07/dry ton										
1% ash	Base case	88.53	14.33	N/A	N/A	N/A	N/A	103	94	93
	75% FLR	78.1	12.56	0.1	4.94	3.8	0.52	115	104	99
	50% FLR	78.02	12.5	0.1	5.02	3.88	0.48	115	117	106

	No const.	77.8	12.5	0.1	5.42	3.68	0.52	116	110	99
1.75% ash	Base case	88.35	14.57	N/A	N/A	N/A	N/A	103	110	91
	75% FLR	67.4	10.98	0.08	11.36	9.72	0.44	133	111	109
	50% FLR	55.54	9.08	0.06	20.72	14.24	0.38	161	118	112
	No const.	53.94	8.8	0.06	22.6	14.22	0.36	164	73	67

Most of the previous studies designing woody biofuel supply chains limited their scope to US states or regions. Zhang et al. (2016) developed a multi-stage, mixed integer programming model using multimodal transport to design forest biofuel supply chain for the state of Michigan using pulpwood. According to the most optimized scenario, three biorefineries were found in northern Michigan in the counties of Wexford, Otsego and Ogemaw considering a biofuel conversion rate of 40 gallons/ton (80 gallons/dt) since the assumed moisture content in the study was 50%. All three biorefineries had the capacity to produce 100 million gallons of biofuel/year, which translates to 1.25 million dry tons of feedstock collected, totaling 3.75 million dry tons of pulpwood. For the most optimistic condition in our analysis, ($85.51/dt cost target - 1.75% ash content with no feedstock blending constraint), we found four biorefineries in northern Michigan and one in southern Michigan. We also located biorefinery in Ogemaw and Wexford counties similar to Zhang et al. (2016) but with higher capacity (Figure 8a). Northern Michigan mostly has forest biomass whereas southern Michigan has a higher supply of short rotation woody crops (Figure 1). Since we considered both forest biomass resources as well as short rotation woody crops, we were able to find biorefinery locations both in northern and southern Michigan. A total of 5.77 million dry tons have been shipped to Michigan biorefineries in our analysis which is higher compared to Zhang et al. (2016) due to multiple feedstock choices, and preprocessing biomass at depots into a more flowable format to transport further distances. Moreover, Zhang et al. (2016) considered only Michigan counties as supply origins. Whereas, in our study, biorefineries in Michigan were able to procure biomass from Illinois, and Ohio due to the scope of our analysis. Similarly, we compared our analysis with a case study in Mississippi by Ekşioğlu et al. (2009) as illustrated in Figure 8b. Lignocellulosic biomass including corn stover and woody biomass (forest residues, pulpwood and sawtimber) were considered with a conversion rate of 80 gallons/dt. For the most optimistic scenario, a total of 170 million gallons of biofuel/year was expected to be produced in four biorefineries located in the counties of Newton, Lauderdale, Covington, and Lamar for which 2.13 million dry tons of biomass was shipped. For the most optimistic scenario in our study, we found four biorefineries in Lamar, Leake, Wilkinson, and Yalobusha counties collecting a total of 5.54 million from trees, residues and pine. Wilkinson county is located on the southern end of Mississippi which is collecting biomass from Louisiana as it is rich in trees and residues. Consideration of large-scale biorefineries in our study increased the biomass accessibility compared to other studies.



(a) (b)

Figure 8. Comparing our analysis with (a) Michigan case study and (b) Mississippi case study

Moreover, Xie et al. (2013) incorporated multimodal transport into a mixed integer programming model to design a cellulosic biofuel supply chain for California using corn stover and forest residues. Four biorefineries were identified, two of which were located in northern California, one in central valley and another one in southern California collecting a total of 545 thousand dt of corn stover and 2.5 million dt of forest residues. The biorefinery in central valley procured all the corn stover and some forest residues having the biggest capacity of 1.35 million dt/year. In our case, two biorefineries were selected in northern California in Del Norte and Tehama counties accessing a total of 2 million dt of trees and residues. Since corn stover was not a feedstock choice for our analysis, no biorefineries were found in the central valley. Xie et al. (2013) considered several transportation methods such as truck, single railcar and unit train which reduced the transport cost by 10.6% allowing higher biomass procurement compared to our study.

Bacenetti et al. (2016) analyzed different clones of poplar and willow to produce woody biofuel in Italy using experimental field test data over 12 years. Considering higher biomass yield and lower environmental impact, willow had better performance than poplar for growing in Italy. According to our study, out of the four short rotation woody crops, willow also has the potential to be the major contributor in terms of supply in US lands (Figure 5). Similar to the findings of our study, investment opportunities for large-scale biorefinery plants utilizing wood chips have also been found in the UK and Finland (Natarajan et al., 2014; Sharifzadeh et al., 2015).

5. Conclusion

This study used a mixed-integer linear programming model to design the supply chain network using single mode transportation (truck) identifying the location and capacity of both mid-scale as well as large-scale biorefineries to produce woody biofuel. Considering the contiguous US instead of doing a state specific analysis increased the computational complexities of our model. However, it allowed us to overcome the limitations of political boundaries which would impose a constraint of transferring biomass from one state to another. Hence, facilitating managerial decisions to invest capital in locations that will have a higher feedstock supply resilience. The study also demonstrated how a distributed network of depot across the whole US can facilitate managerial and operational decisions by increasing supply resiliency to a biorefinery with uniform-format stable woody resources. It was able to make tactical (short-term) decisions regarding how much biomass should be collected from each node (counties) and the amount shipped between each node of the supply chain. Although the findings of this study are applicable to US scenarios only, the formulated model is universal to any region or country. Adjusting the cost, supply input and candidate location of the facilities, the model can be used to develop biomass supply chain networks for any region/country and can help identify the logistics cost as well as the hot spots for future facility locations.

Limitations of our study include using geographical distances with a winding factor of 1.2 to calculate the road distances for transportation. For future analysis, actual road networks can be used to have accurate estimation on the transportation cost. Due to computational difficulty, we reduced the number of candidate locations for biorefineries and depots, which may have limited our results. Only 20% of the counties that had woody biomass available, were used as depot and biorefinery candidates. Future analysis could include a larger number of candidate locations using high performance computing resources and/or explore other solvers and developer platforms. Since the model identified very large capacity biorefineries i.e. 2.75 Mdt/year, future research directions could include multi-modal transportation (truck and rail) to take advantage of economies of scale using high-capacity transportation modes. The authors acknowledge that the robustness of our results and conclusions are subject to the projections and analysis of previous studies, including potential changes in embedded climate and natural disaster predictions resulting in changes to available forest resources and short rotation woody crop yields.

Increasing the use of woody resources for biofuel production is important from an environmental, social, and economical perspective. Wood resources have the potential to supply one-third of the nation’s cellulosic biofuel demand, displace our petroleum energy use and increase the economies of rural communities. According to the findings of our study, forest land resources will play a major role in shaping the future woody biofuel economy. However, forest managers and administrators need to ensure that this feedstock is not exploited. It is not recommended to harvest long-rotation high quality stemwood for bioenergy or cutting an entire forest region. Emerging bioenergy markets can support investment in maintaining healthy and productive forests while increasing the forest carbon reserve. Findings from this study can be used to ensure a reliable supply network of woody resources to help policy makers and investors with long-term and short-term managing decisions.

6. Acknowledgements

This work was funded by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) Bioenergy Technology Office under DOE Idaho Operations Office Contract DE-AC07-05ID14517 and USDA Hatch Project funds. The views expressed in this publication do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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Appendix A

Depot and Biorefinery locations at $79.07/dry ton

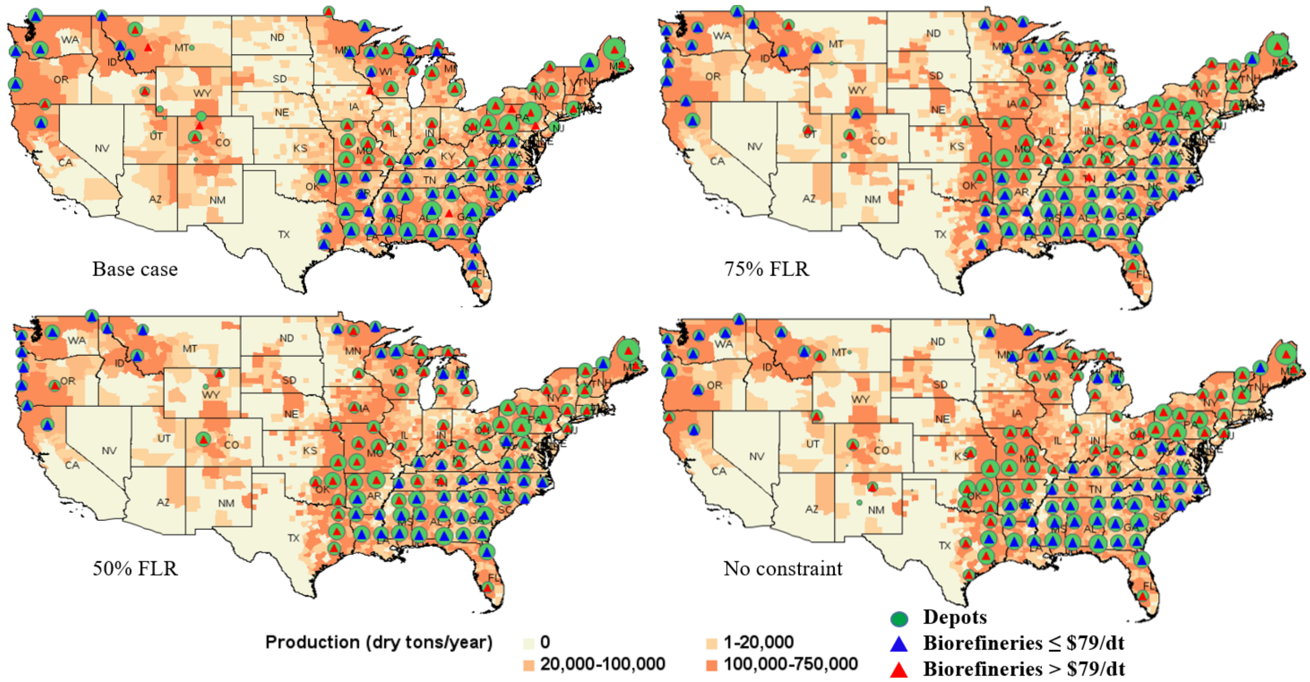


Figure 9. Depot and biorefinery locations for 1% ash blend scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

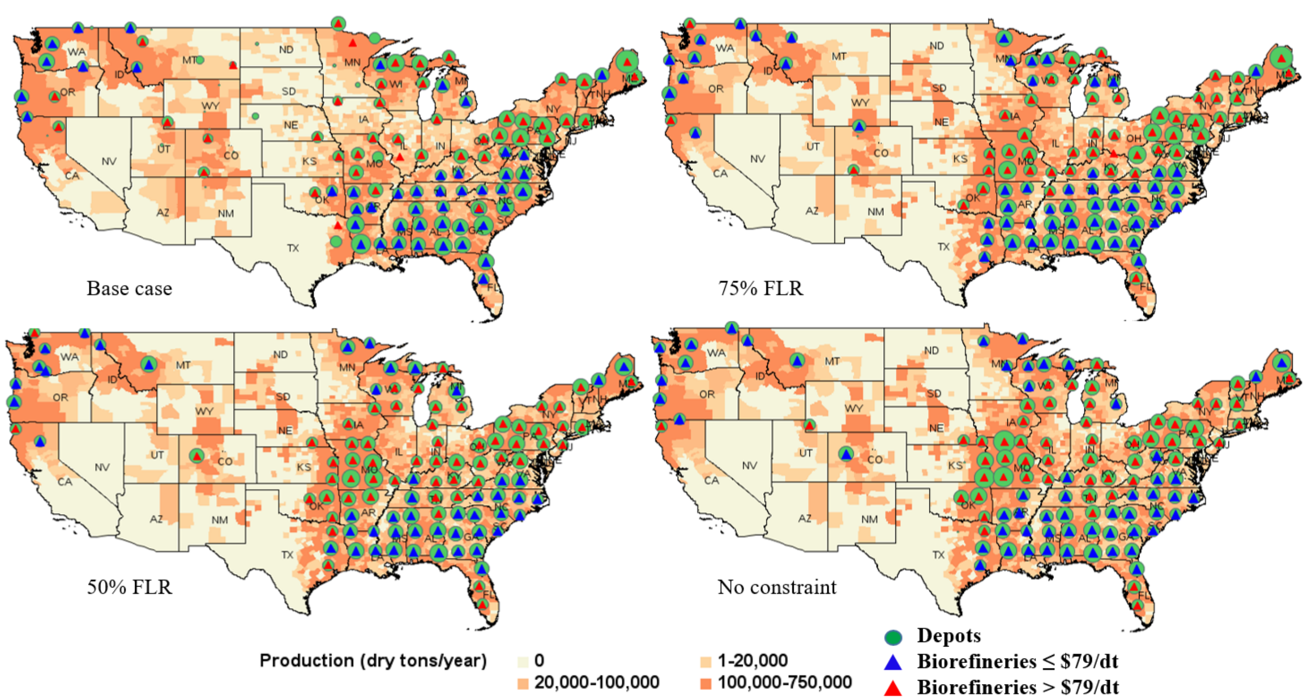
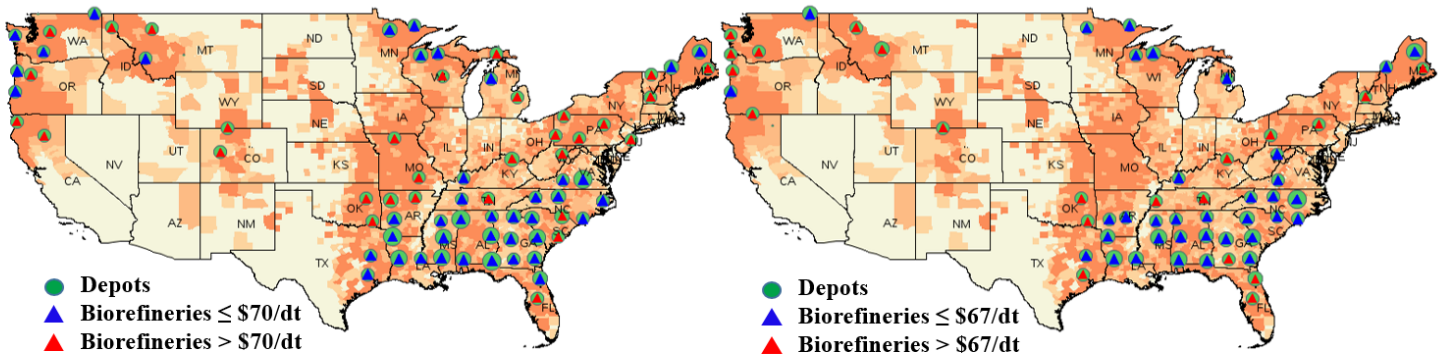


Figure 10. Depot and biorefinery locations for 1.75% ash blend scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)



(a) (b)

Figure 11. Depot and biorefinery locations of base case scenarios for (a) 1% ash blend at $70.31/dt and (b) 1.75% ash blend at $67.03/dt. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)