Cost of Procuring Invasive Eastern Red Cedar Biomass for use as a Biobased Product Feedstock

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Abstract

Suppression of prairie fires enabled Eastern Red Cedar (ERC) to invade and thrive on more than 12 million infested acres previously dominated by native grasses. Feedstock procurement for a biorefinery designed to use ERC biomass, would be unique relative to energy crop production systems such as switchgrass that can be expected to harvest feedstock produced on the same unit of land each year. Density of ERC is heterogeneous. After cutting, ERC does not regrow and after ERC is removed landowners could be expected to take measures such as prescribed fire to control it. A mixed integer mathematical programming model is constructed to determine the cost to obtain the rights to harvest, harvest, and deliver a specified quantity of ERC biomass each year, for a period of 20 years, to a biorefinery location. The optimal strategy depends critically on several assumptions including the proportion of ERC biomass under contract enabling ERC harvest once during the 20 years; ERC growth rate; ERC density; discount rate; harvest and transportation cost; and quantity of biomass required per day. Optimal harvest strategy, optimal biorefinery location, and maximum daily biorefinery capacity, are sensitive to tree density and the proportion of ERC biomass in the region from which ERC can be removed. The expected cost of delivered biomass ranges from $41 to $92 per ton depending on the assumption of proportion of ERC biomass under contract, quantity of biomass required at the biorefinery, harvest cost, growth rate of unharvested trees under contract, and discount rate.

Keywords: biomass feedstock; eastern red cedar; invasive species; mathematical programming

JEL classifications: Q19, Q57

Introduction

Eastern Red Cedar (*Juniperus virginiana* L.) (ERC) is one of 13 juniper species native to the United States (Knezevic et al., 2005). Prior to the settlement of Europeans in North America, this species persisted on rocky bluffs, and in deep canyons and other areas where fire historically did not occur (Smith, 2011). Suppression of prairie fires enabled ERC to grow and thrive in environments previously dominated by prairie grasses (Smith, 2011; Oklahoma Forestry Service, 2014) The encroachment of brush or woody species on grasslands has been widely reported (Auken, 2000; Gibbens et al., 2005; Auken, 2009). The encroachment of ERC increased over the last 50 to 60 years. It has been estimated that 300,000 acres of native prairie grasses are invaded with ERC per year in Oklahoma (Drake and Todd, 2002). The encroachment of ERC is a problem in many areas of the Great Plains (Fuhlendorf et al., 2008; McKinley and Blair, 2008; Bihmidine et al., 2010; Starks et al., 2011; Stark et al., 2014). ERC reduces forage production on pasture lands, destroys native ecosystems such as the habitat of the endangered lesser prairie chicken (*Tympanuchus cupido*), and produces allergens that harm human health (Drake and Todd, 2002; Zhang and Hirizoglu, 2010; Coffey, 2013). Due to its volatile characteristics, ERC also increases the risk of wildfires and the risk of damages from wildfires (Bidwell et al., 1996; Drake and Todd, 2002; Oklahoma Conservation Commission, 2006; Oklahoma Conservation Commission, 2008; Oklahoma Forestry Services, 2014).

Drake and Todd (2002) reported that estimates of annual economic losses from invasive juniper species, primarily ERC, in Oklahoma were approaching a half billion dollars annually. This includes estimates of losses due to catastrophic wildfires, losses in forage production for livestock, and lease hunting, recreation, and water yield losses.

A number of potential uses have been identified for chipped ERC whole plant biomass including: particleboard, fiberboard, plywood faced panels, wood flour, mulch, animal bedding/litter, shavings, "cedar oil" for perfume, "cedar oil" for insect repellent, "cedar oil" for wood preservative, wood/plastic composites for window and door sills, or decking, and down hole loss circulation material in the drilling industry (Drake and Todd, 2002). Another potential use of the whole tree is as feedstock for bioenergy (McKinley, 2012).

Prior to investing in any of these potential businesses, prudence would require a business plan for obtaining annually the required quantity of chipped ERC whole plant biomass feedstock for the expected life of the processing facility. In addition, information regarding the expected cost to deliver the materials as well as the most cost-efficient location of the processing business would be essential.

Feedstock procurement for a biorefinery designed to use chipped ERC whole plant biomass exclusively, would be unique relative to dedicated energy crop production systems such as switchgrass that can be expected to harvest feedstock produced on the same unit of land year after year. In other words, every day for the life of the business, feedstock would have been grown at a unique location. When cut at ground level ERC does not regrow, and after it is removed, landowners would be expected to take measures to prevent re-infestation. It is unknown if there is a sufficient supply of material within a reasonable perimeter to provide biorefinery feedstock annual biomass requirements for the expected life of the facility. Another issue is related to the proportion of existing ERC biomass in a region that a biorefinery could obtain the rights from landowners to harvest.

The objective of this study is to determine feedstock cost for a biorefinery designed to use chipped ERC whole plant biomass exclusively. A model is constructed and used to determine cost, including the cost (or return) to secure harvest rights, harvest cost, and transportation cost, to deliver a specified quantity of chipped ERC whole plant biomass each year for a period of 20 years to a biorefinery location. The model is solved to produce solutions for several different combinations of annual biorefinery biomass requirements, proportion of existing ERC biomass in a county available for harvest, growth rate of unharvested trees, harvest cost, transportation cost, and discount rate. The model is used to determine the biorefinery location and harvest locations for each of 20 years that would minimize feedstock costs given initial ERC inventory.

Modeling, Data and Assumptions

The model is designed to produce least-cost delivered feedstock solutions for several different combinations of annual biorefinery needs, proportion of ERC biomass in a county available for harvest, growth rate of unharvested trees, harvest cost, transportation cost, and discount rate. Binary variables are included to enable the model to determine the least-cost delivered feedstock biorefinery location. The model is solved using the generalized algebraic modeling system (GAMS) with the CPLEX solver.

Infrastructure to harvest, chip, and transport ERC biomass does not exist. For the purpose of modelling, a vertically integrated system is envisioned. It is assumed that the company would acquire the rights to enter ERC infested fields and clear-cut and remove ERC biomass once during a 20 year period. The company is assumed to centrally manage the harvest and transportation required to deliver feedstock to their biorefinery (Epplin, 1996). The model is used to determine the quantity of biomass to be contracted in each county and the counties in which ERC should be harvested every year. Trees under contract that are not harvested in year t are expected to continue to grow and be available for harvest in year $t+1$.

Feedstock Supply Locations and Biorefinery

The case study region includes 15 Oklahoma counties (Fig. 1). The estimated quantity of existing biomass was obtained from field data produced by Stark et al. (2011). It is assumed that the ERC growth rate of trees not harvested is 8% per year (Engle and Kulbeth, 1992). The Natural Resource Conservation Service (NRCS) has produced estimates of the quantity of land infested with ERC in these counties. Six of these counties (Blaine, Dewey, Pawnee, Payne, Canadian, and Logan) are considered as prospective locations for the biorefinery (Fig.1). These potential biorefinery locations were selected based on the density of ERC biomass as well as the accessible-road infrastructure. The biorefinery is assumed to operate 350 days per year for 20 years. Three biomass feedstock requirement levels were modeled; 551, 1102, and 1653 tons per day.

Acquisition of Rights to Harvest ERC Biomass

Prior to building a biorefinery, it is assumed that the company would engage in contracts with landowners who own accessible land infested with ERC. ERC incursion imposes substantial costs on landowners who depend on their land to produce forage. Boyer and Ramli (2016) have found that some landowners are amenable to having ERC biomass removed from their property and are willing to pay to have it removed. The contracts would provide the company with the rights to enter infested fields at some time during the expected 20-year life of the biorefinery and clear-cut and remove ERC biomass. Landowners who are willing to do so, could enter bids as to the price they would be willing to pay to have ERC biomass removed. For example, the company could advertise to inform landowners in the counties of interest that bids are being solicited for cutting and removing ERC biomass. The company could screen the received bids based on objective measures including the bid rate, ERC biomass density, terrain, and distance from the anticipated biorefinery location.

Based on findings of a survey of landowners in the case study region conducted by Boyer and Ramli (2016) it is assumed that ERC biomass could be obtained from landowners willing to pay from $3.90 to $4.50 for each dry ton removed. Some landowners would not be willing to contract with the company and some infested land would be difficult to harvest. The proportion of existing ERC biomass in the region for which the harvest and removal rights could be secured is unknown. Three scenarios were modeled; 20%, 40%, and 60%. For the baseline, it is assumed that 20% of the initial inventory of ERC biomass in the case study region would be under contract. The contracts are assumed to be made in year zero and the model accounts for ERC biomass growth, after year zero, of trees under contract that remain to be harvested in future years.

Harvest and Transportation

Estimates of ERC whole plant biomass harvest costs for the region have been produced by Craige et al. (2015). Trees are assumed to be cut and piled in the field for several months to allow for natural drying. After a period, the dried trees could be chipped and directly deposited into a transport truck for delivery from the field to the biorefinery (Park et al., 2012). Harvest and transportation activities are assumed to be centrally managed to facilitate the flow of biomass from fields to the biorefinery (Epplin, 1996). Machinery requirements for harvest include skid steers and whole tree chippers. Scheduled machine hours for both machines are 2000 hours per year. Use rate is assumed to be 65% for skid steers and 75% for whole tree chippers (Craige et al., 2016). Thus, the annual productive machine hours are estimated to be 1300 and 1500 for the skid steer and whole tree chipper, respectively. The working capacity of the budgeted skid steer is assumed to be 14.3 dry ton per hour for cutting and 7.7 dry ton per hour for moving the cut tree (skidding) to a site for drying and eventual chipping and loading. The working capacity of the budgeted chipper is assumed to be 12 dry ton per hour. Based on budgeted prices and capacities, the estimated cost to cut, move the cut tree to a pile for drying, chip the whole plant, and convey it into a truck is estimated to be $39 per dry ton (Craige, 2015).

It is assumed that the ERC biomass will be transported to the biorefinery using 18-wheel tractor-trailers with an assumed capacity of 12 dry ton of chipped ERC biomass. Craige et al., (2016) estimated transportation costs, including fixed costs, fuel, and labor, to be $2.25 per mile. Based on these estimates, field to biorefinery transportation cost is:

$$\tau_{ij} = \frac{2.25*(2*distance_{ij})}{12} \qquad (1)$$

where τ_{ij} is the transportation cost ($ per ton) from county *i* to biorefinery location *j*, $distance_{ij}$ is the distance (miles) from county *i* to biorefinery location *j*, and the average load is assumed to be 12 dry ton of ERC biomass.

Model Equations

The objective function is constructed to minimize the net present costs to deliver ERC biomass to a biorefinery. The objective function is specified as:

$$\min NPC_{X_{ijt}} = \left\{\sum_{t=1}^{T} \left(\sum_{i}^{I}\sum_{j}^{J}\gamma_i X_{ijt} + \sum_{i}^{I}\sum_{j}^{J}\tau_{ij} X_{ijt} - \sum_{i}^{I}\sum_{j}^{J}\rho_i X_{ijt}\right)\right\} * PVF_t \qquad (2)$$

where *NPC* is net present costs, γ_i is the cost to harvest ERC biomass in county *i* ($ per ton), τ_{ij} is the transportation cost from county *i* to biorefinery location *j* ($ per ton), ρ_i is the payment received from the landowners in county *i* for removing biomass ($ per ton), $PVF_t = (1 + r)^{-t}$ is the present value factor, r is the discount rate, *t* is year of harvest (t = 1…20), and X_{ijt} is the quantity of biomass to be harvested in county *i* and delivered to biorefinery *j* in year *t*. Equation (2) is minimized subject to a set of constraints. Equation (3) defines the quantity of ERC biomass under contract to the biorefinery in year 1 in county *i* ($BIOQTY1_i$) to be equal to the total year 1 inventory of biomass in county *i* ($BIOQTY_i$) times the proportion (*BIPROP*) assumed to be under contract.

$$BIOQTY1_i = BIPROP * \ BIOQTY_i \quad \forall\, i \tag{3}$$

Equation (4) restricts the quantity of biomass harvested and delivered to the biorefinery in year 1 from county *i* to not exceed the quantity of biomass in the county under contract.

$$\sum_j^J X_{ij1} - BIOQTY1_i \leq 0 \ \ \forall\, i \tag{4}$$

Equation (5) defines the quantity of biomass in county *i* available to harvest after year 1 to be equal to the quantity of biomass under contract minus the quantity harvested in year 1 plus the growth rate of unharvested trees under contract.

$$NH_{i,1} = (BIOQTY1_i - \sum_j^J X_{ij1}) * (1 + \text{Grwth}) \quad \forall\, i \tag{5}$$

Equation (6) restricts the quantity of biomass harvested in county *i* and year *t* other than year 1 to not exceed the quantity available for harvest.

$$\sum_i^I X_{ijt} \leq \ NH_{i,t-1} \ \ \forall\, i, t > 1 \tag{6}$$

Equation (7) defines the quantity of biomass remaining after year *t* other than year 1 to be equal to the quantity not harvested in year *t* plus growth.

$$NH_{i,t} = (NH_{t-1} - \sum_j^J X_{ijt}) * (1 + Grwth) \ \ \forall\, i, t \neq 1 \tag{7}$$

Equation (8) restricts the quantity of biomass harvested and transported to the biorefinery location to be greater than or equal to the quantity of biomass required.

$$\sum_i^I X_{ijt} \ \geq \ D_{jt} \quad \forall\, j, t \tag{8}$$

Equation (9) restricts the choice variables to be non-negative.

$$X_{ijt} \geq 0 \tag{9}$$

Equation (10) restricts the biorefinery location variable to be binary.

$$Y_j = 0, 1 \qquad \forall j \tag{10}$$

Equation (11) forces the model to select one biorefinery location from among the six alternatives.

$$\sum_j^J Y_j = 1 \tag{11}$$

Table 1 and Table 2 include descriptions of set member elements, parameters, and variables

Results

The Cost of Delivered Feedstock

Table 3 includes a description of nine scenarios that include three alternatives for proportion of ERC biomass in the case study region under contract (20%, 40%, and 60%) and three alternatives for biorefinery size (551, 1102, and 1653 tons per day). These scenarios were further differentiated by harvest cost ($39 per ton and $78 per ton), payment received from the landowners ($3.90-$4.50 per ton depending on county and $0 per ton), annual growth rate of unharvested trees under contract (8%, 4%), and discount rate (3.5%, 7%).

Table 4 presents the percentage of ERC biomass in the 15 county case study region required to be under contract in year zero to provide the biorefinery requirement for 20 years for both 4% and 8% annual growth rate of unharvested trees under contract. If the biorefinery requires 551 tons of ERC biomass per day, 18.2% of year zero ERC biomass in the 15 county region must be under contract if unharvested trees add 8% to biomass each year. However, if the annual growth rate of unharvested trees is 4%, 24.2% of the year zero ERC biomass would be required under contract to provide 551 tons of ERC biomass per day for the expected 20 year biorefinery life. If the biorefinery has 100% access to ERC biomass in the 15 counties beginning in year zero, with an 8% per year growth rate of unharvested trees, the maximum quantity of ERC biomass available for harvest is 3029 tons per day. If the annual growth rate of unharvested trees is 4%, maximum daily harvest is 2272 tons per day. Access to biomass, and the risk of insufficient feedstock, would be a critical issue for a biorefinery in the region restricted to using biomass produced by ERC.

Table 5 includes estimates of the cost to deliver ERC biomass for each of the nine scenarios. For the assumptions included in the base model, it would be optimal to locate the plant in Dewey County. The estimated cost to deliver ERC biomass to the biorefinery ranges from $41 to $92 per ton depending on the proportion of ERC biomass under contract as well as the quantity of biomass required per day (Table 5). If the biorefinery requires 551 tons per day with the assumption that the company has contracted for 20% of the ERC biomass existing in the counties in year zero, the estimated cost to deliver is $53 per ton. The estimated cost to deliver feedstock decreases to $43 per ton and $41 per ton if the proportion under contract increases to 40% and 60%, respectively. Total feedstock delivered cost decreases in response to the reduction in the transportation cost from $19 per ton (20% under contract) to $6 per ton (60% under contract). The estimated average one way field to biorefinery transportation distance decreases from 50 miles to 16 miles as the proportion of ERC biomass under contract increases from 20% to 60% (Table 6).

If only 20% of the ERC biomass in the case study region can be placed under contract, with an 8% annual growth rate of unharvested material, the available biomass would not be sufficient to meet 1102 tons per day requirements. Fifty-five percent under contract in year zero would be required to fulfill a daily requirement of 1653 tons.

Doubling the expected harvest cost increases the expected cost to deliver feedstock by the level of the harvest cost increase ($39 per ton). However, the optimal biorefinery location,

location of trees to contract for in year zero, and harvest locations per year remain the same as with the base model. Similarly, changing the assumption that landowners would pay from $3.90 to $4.50 per ton (depending on county) to have the ERC biomass removed, to $0 per ton, changes the expected cost to deliver feedstock by the amount of the payment, but does not change the optimal biorefinery location, location of trees to contract for in year zero, or the harvest locations per year.

As shown in Table 4, the annual growth rate of unharvested contracted trees is critical. If the annual growth rate is 4% (rather than 8% as assumed for the base model) access to only 20% of the year zero ERC biomass would be insufficient to provide for the needs of a 551 tons per day biorefinery. Access to 60% would be insufficient to provide for the needs of a 1653 tons per day system. Access to 60% would be sufficient for a 1102 tons per day biorefinery but the cost would increase from $41 per ton for the base situation to $46 per ton (Table 5).

If the annual growth rate is 4% (rather than 8% as assumed for the base model), the total cost to deliver feedstock for feasible scenarios increases from 6 to 14%. The reduction in growth rate reduces the available biomass, increases average field to biorefinery transportation distance and consequently increases the cost to deliver the feedstock. Optimal harvest locations are thus different from base scenario.

For the 20% 551 tons, 40% 1102 tons, and 60% 1653 tons scenarios, doubling the discount rate from 3.5% to 7% changes the optimal plant location from Dewey to Logan County (Table 5). However, doubling the discount rate changes the cost to deliver feedstock for each of these three scenarios by only $2 per ton. The change in plant location increases average one way transportation distance from 50 miles to 53 miles. The net effect of the higher discount rate is to reduce future costs relatively.

The Optimal Locations for Harvest

The result from base scenario find that in the earlier years it would be optimal to harvest contracted ERC biomass from counties most distant from the plant location (Table 7). If the biorefinery requires 551 tons per day, with access restricted to 20% of year zero biomass, feedstock would be required from all counties in the case study region except for Okfuskee and Pottawatomie (Table 7). In the first 13 years, the optimal harvest pattern would include harvest from Blaine, Canadian, Dewey, Ellis, Garfield, Kingfisher, Lincoln, Logan, Major, Noble, Pawnee, Payne, and Woodward. From years 13 through 20 it would be optimal to harvest from Dewey County, in which the biorefinery is located (Table 7).

As the proportion of trees under contract increases, the company has access to more ERC trees in each county. As a result, biorefinery requirements can be met by harvesting from counties in closer proximity to the facility. For example, if the company has 40% access for each county, the optimal harvest locations are Blaine, Dewey, Ellis, Major and Woodward (Table 8). If 60% of the year zero biomass could be placed under contract, and only 551 tons per day are required, the optimal harvest locations would involve only three counties, Dewey, Major and Woodward. The optimal harvest locations for each of the 20 years vary depending on proportion of trees under contract and quantity of biomass required at the biorefinery. For the parameter levels evaluated, the model solves for eight unique transportation flows.

Discussion

Prior to investing in a biorefinery designed to use chipped ERC whole plant biomass feedstock, prudence would require a business plan for obtaining annually the required quantity of feedstock for the expected life of the processing facility. A rational investor would not invest in a factory that did not have a reasonable plan for obtaining the feedstock (Griffith et al., 2014). One alternative would be for the biorefinery to engage in contracts with the landowner to acquire the rights to obtain sufficient quantity of ERC biomass from the trees under contract for the expected plant life. The models presented in this paper follow from the assumption that feedstock harvest and delivery is managed by the biorefinery for a period of 20 years. The model is designed to produce solutions for several different combinations of annual biorefinery needs, proportion of ERC biomass in a county available for harvest, growth rate of unharvested trees, harvest cost, transportation cost, and discount rate. The model was used to determine optimal biorefinery location and optimal harvest locations for each of the 20 years. Based on the assumptions in the models, the optimal plant location was either in Dewey or Logan County. Proportion of trees under contract, quantity of biomass required, growth rate and discount rate are critical factors that determine the optimal plant location as well as the optimal harvest location. For the base model the estimated feedstock delivered cost for ERC biomass ranges from $41 per ton to $53 per ton depending on the assumptions of proportion of ERC trees placed under contract in year zero as well as the quantity of ERC biomass required.

If only 20% of the ERC biomass in the 15 county case study region can be placed under contract for possible harvest during the 20 year life of the biorefinery, with an 8% per year growth rate of unharvested trees, the quantity of biomass available would not be sufficient to fulfill a 1102 tons per day biorefinery requirement. The proportion of trees under contract is a critical factor.

Biomass required per day is also a crucial factor. To provide for the feedstock needs of a biorefinery that requires 2205 tons per day, 73% of the ERC trees in the case study region would be required if an annual growth rate of 8% is achieved. If the annual growth rate is 4%, 97% of the ERC trees in the 15 county region in year zero would be required to provide for the 20 year requirements of the biorefinery.

The available quantity of ERC biomass is highly dependent on access to infested land of which most is privately owned. This study is based on the assumption that prior to building a biorefinery, the company would engage in contracts with landowners who own accessible land infested with ERC. An online survey conducted by Boyer and Ramli (2016) found that some landowners in the case study region are amenable to having ERC biomass removed from their property and are willing to pay to have it removed. However, it remains to be determined if a sufficient quantity of landowners would be willing to agree to long term contractual arrangement that would provide the company with the rights to enter infested fields at some time during the expected 20-year life of the biorefinery and clear-cut and remove ERC biomass. Costs associated with arranging and managing these contracts have not been included in the estimates of cost to deliver feedstock.

Conclusion

The analysis highlights several issues that would pose challenges to the establishment of a biorefinery in the case study region designed to process biomass produced by invasive ERC trees exclusively. First, prior studies have found that the minimum size of a biorefinery required to achieve size economies required to be economically competitive is expected to require 2205 tons per day (Lynd et al., 1996; Kaylen et al., 2000; Wu et al., 2010; Dutta et al., 2015). With the assumed annual growth rate of 8%, access to 73% of the ERC trees growing in year zero would be required to provide 2,205 tons per day for 20 years. It could be difficult to obtain access to 73% of the trees. Second, contracts with thousands of individual landowners may be required. The study did not include a charge for the transactions, management, and enforcement cost of the contracts. Third, there is no precedent for contracts for the rights to enter property sometime during the next 20 years to remove ERC. Landowners willing to pay to have ERC removed are not likely to be inclined to passively wait up to 20 years to have it done. They may find other means to remove the ERC and restore the productivity of the land. Fourth, there is a risk that uncontrolled wild fires may destroy contracted feedstock. Fifth, construction of a biorefinery and assemblage of a management team to obtain and process ERC feedstock would require a substantial investment. Capital acquisition may be difficult given the number of uncertainties associated with ERC biomass procurement.

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Table 1. Description of sets and variables used in the model

Symbol	Description
Sets	
J	Prospective biorefinery locations: j = {Blaine, Canadian, Dewey, Logan, Pawnee, Payne}
I	Biomass source counties: i = {Blaine, Canadian, Dewey, Ellis, Garfield, Kingfisher, Lincoln, Logan, Major, Noble, Okfuskee, Pawnee, Payne, Pottawatomie, Woodward}
T	Year: t = {1-20}
Variables	
NPC	Net present cost
X_{ijt}	Biomass harvested and transported from county i to biorefinery at location j in year t
Y_j	Binary variable for biorefinery at location j (1 if built, 0 otherwise)
$NH_{i,t}$	Quantity not harvested in year t plus growth available for use in year $t+1$

Table 2. Description of parameters used in the model

Parameter	Description
γ_i	Harvest cost ($ per ton)
τ_{ij}	Round-trip cost of transporting biomass from county i to biorefinery location j ($ per ton)
ρ_i	Payment received from landowners ($ per ton) in county i
r	Discount rate
$BIOQTY1_i$	Initial quantity of biomass available from county i in year 1
$BIPROP$	Proportion of biomass in year zero available to harvest
$Grwth$	Biomass growth rate of trees not harvested
D_{jt}	Biomass required at biorefinery j in year t

Table 3. Alternatives evaluated.

Scenario	Proportion of ERC biomass in case study region placed under contract in year zero[a]	Quantity of biomass required per day (tons)
20% 551 tons	20%	551[b]
40% 551 tons	40%	551
60% 551 tons	60%	551
20% 1102 tons	20%	1102
40% 1102 tons	40%	1102
60% 1102 tons	60%	1102
20% 1653 tons	20%	1653
40% 1653 tons	40%	1653
60% 1653 tons	60%	1653

[a] *BIPROP* in model equation (3).

[b] The biorefinery is assumed to operate at capacity 350 days per year for an expected life of 20 years. A 551 tons per day facility would require 192,850 tons of ERC biomass per year; a total of 3,857,000 tons of ERC biomass for the 20 year life.

Table 4. Percentage of ERC biomass in the 15 county case study region required to be under contract in year zero to provide for the needs of a biorefinery for 20 years for two ERC tree annual growth rates.

Biorefinery Size tons per day	Annual Growth Rate of ERC Trees Remaining to be Harvested 8%	4%
	% Required Under Contract	
551	18.2[a]	24.2
1102	36.4	48.5
1653	54.6	72.7
2205	72.8	97.0
2272		100.0
3029[b]	100.0	

[a] Contracts for 18.2% of the growing ERC trees available in year zero in the 15 county region would be required to provide 551 tons per day for 20 years assuming an 8% annual growth rate of unharvested trees.

[b] If 100% of the existing ERC trees in the 15 county region were available, assuming an 8% annual growth rate of unharvested trees, 3029 tons per day would be available for 20 years.

Table 5. Estimates of the cost to deliver ERC biomass for three levels of proportion of land under contract (20%, 40%, 60%), three levels of biomass required per day (551 tons, 1102 ton, 1653 tons), two levels of harvest cost ($39 per ton, $78 per ton), two levels of payment received from landowners ($3.90-$4.50 per ton, $0 per ton), two growth rates of unharvested trees (8%, 4%), and two discount rates (3.5%, 7%).

	Base		Doubled Harvest Cost		Zero Payment from Landowners		Growth Rate of Unharvested Trees Halved (4%)		Doubled Discount Rate	
	Biorefinery Location	Cost $ per ton	Biorefinery Location	Cost $ per ton	Biorefinery Location	Cost $ per ton	Biorefinery Location	Cost $ per ton	Biorefinery Location	Cost $ per ton
20% 551 tons	Dewey	53	Dewey	92	Dewey	57	a		Logan	55
40% 551 tons	Dewey	43	Dewey	82	Dewey	47	Dewey	48	Dewey	43
60% 551 tons	Dewey	41	Dewey	79	Dewey	45	Dewey	43	Dewey	41
20% 1102 tons	b		b		b		b		b	
40% 1102 tons	Dewey	53	Dewey	92	Dewey	57	b		Logan	55
60% 1102 tons	Dewey	46	Dewey	85	Dewey	50	Dewey	53	Dewey	46
20% 1653 tons	b		b		b		b		b	
40% 1653 tons	b		b		b		b		b	
60% 1653 tons	Dewey	53	Dewey	92	Dewey	57	b		Logan	55

[a] With a 4% annual growth rate of unharvested trees, contracts for 20% of the existing ERC biomass at year zero would be insufficient to provide for biorefinery needs for the 20 year expected life.

[b] A blank in the cost column indicates that the contracted quantity in year zero would not provide sufficient feedstock; the scenario is infeasible.

Table 6. Estimates of average one-way transportation distance from the field to the biorefinery for each of the 27 feasible scenarios (miles).

	Base	Doubled harvest cost	Zero payment from landowner	Growth Rate of Unharvested Trees Halved (4%)	Doubled Discount Rate (7%)
20% 551 tons	50	50	50	a	53
40% 551 tons	22	22	22	35	22
60% 551 tons	16	16	16	23	16
20% 1102 tons	a	a	a	a	a
40% 1102 tons	50	50	50	a	53
60% 1102 tons	30	30	30	50	30
20% 1653 tons	a	a	a	a	a
40% 1653 tons	a	a	a	a	a
60% 1653 tons	50	50	50	a	53

[a] Infeasible scenario.

Table 7. The optimal quantity of eastern red cedar biomass harvested per county by year if 20% in each county in year zero is contracted for harvest sometime during the 20 year period; estimated harvest cost of $39 per ton, discount rate of 3.5%, growth rate of unharvested trees under contract of 8% per year, daily requirement of 551 tons, optimal biorefinery location in Dewey County (‘000 tons)

County	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Blaine							67	193	166											
Canadian				49	149															
Dewey													111	193	193	193	193	193	193	193
Ellis						10	126													
Garfield					44	56														
Kingfisher						127														
Lincoln	44																			
Logan				143																
Major											36	193	82							
Noble			67	1																
Okfuskee																				
Pawnee	149	90																		
Payne		103	126																	
Pottawatomie																				
Woodward									26	193	157									

Table 8. The optimal quantity of eastern red cedar biomass harvested per county per year if 40% in each county in year zero is contracted for harvest sometime during the 20 year period; estimated harvest cost of $39 per ton, discount rate of 3.5%, growth rate of unharvested trees under contract of 8% per yer, daily requirement of 551 tons, optimal biorefinery location in Dewey County (‘000 tons).

County	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Blaine	154	193	184																	
Canadian																				
Dewey								65	193	193	193	193	193	193	193	193	193	193	193	193
Ellis	39																			
Garfield																				
Kingfisher																				
Lincoln																				
Logan																				
Major						99	193	128												
Noble																				
Okfuskee																				
Pawnee																				
Payne																				
Pottawatomie																				
Woodward			9	193	193	94														

Table 9. The optimal quantity of eastern red cedar biomass harvested per county per year if 20% in each county in year zero is contracted for harvest sometime during the 20 year period; estimated harvest cost of $39 per ton, discount rate of 7%, growth rate of unharvested trees under contract of 8% per year, daily requirement of 551 tons, optimal biorefinery location in Logan County ('000 tons).

County	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Blaine								131	193	129										
Canadian										64	193	62								
Dewey	88	193	193	13																
Ellis																				
Garfield												131	36							
Kingfisher																	186	118		
Lincoln							169	62												
Logan																		75	193	193
Major				96	76															
Noble																181	7			
Okfuskee	40																			
Pawnee					117	193	24													
Payne													157	193	193	12				
Pottawatomie				84																
Woodward	65																			

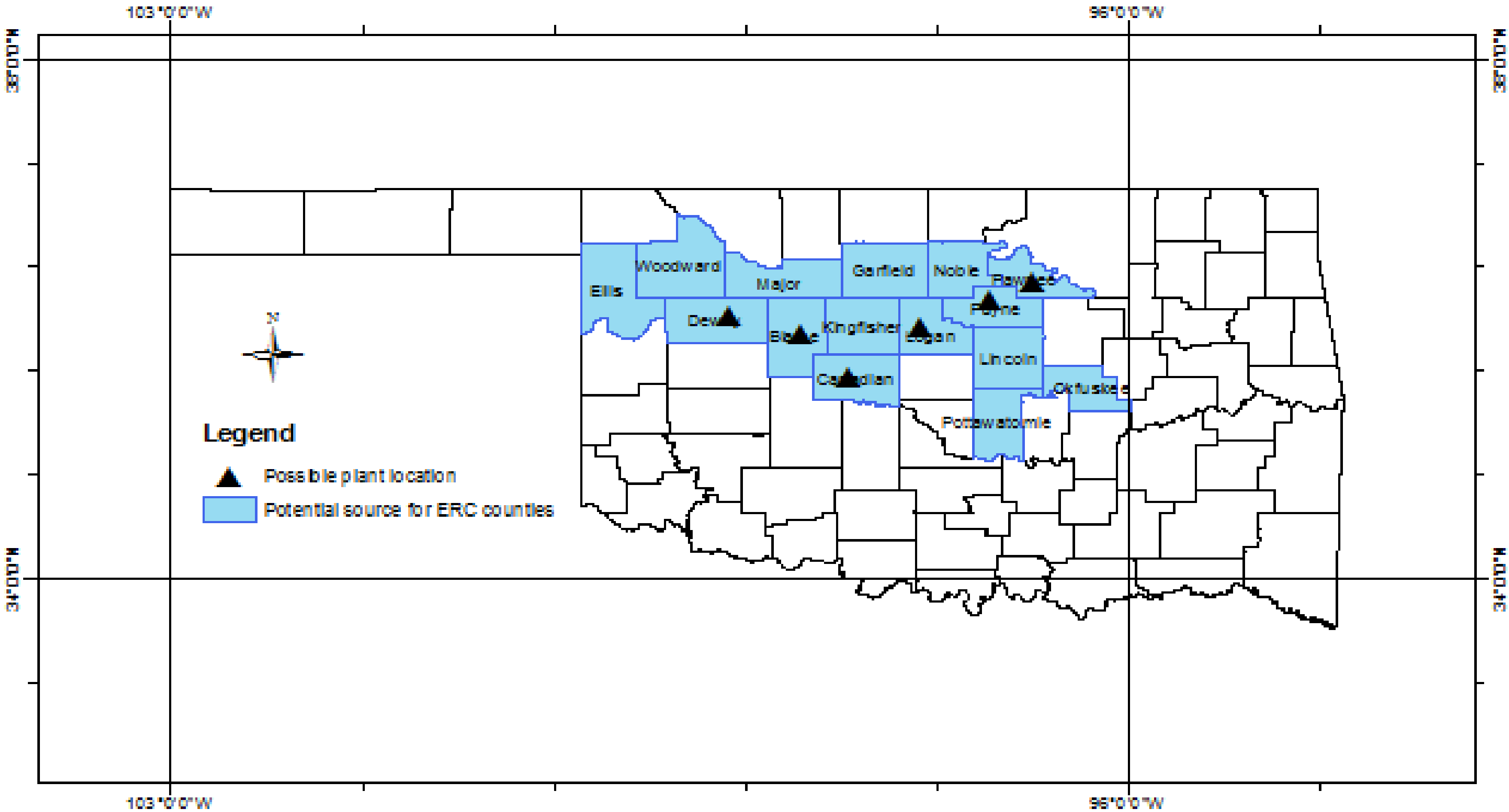

Figure 1. Potential source of ERC biomass and possible plant locations