Society for Range Management

Cost of Removing and Assembling Biomass from Rangeland Encroaching Eastern Redcedar Trees for Industrial Use

By Nurul Nadia Ramli, Francis M. Epplin, and Tracy A. Boyer

On the Ground

- Eastern redcedar trees have encroached on Great Plains grasslands and are spreading at a glacial pace, reducing forage production, destroying native ecosystems, and producing human health harming allergens.
- The study was conducted to determine the expected cost to deliver a flow of feedstock to an optimal factory location for a business designed to use eastern redcedar biomass harvested from grasslands.
- Proportion of trees available for removal, quantity of feedstock required, harvest costs, and tree growth rate are critical factors.
- Assuring investors that a flow of eastern redcedar trees for industrial use would be attainable for 20 years at a reasonable cost may be challenging.

Keywords: eastern redcedar, encroaching species, economics, removal, business.

Rangelands 39(6):187–197
doi: 10.1016/j.rala.2017.09.002

Suppression of prairie fires enabled eastern redcedar (*Juniperus virginiana*) to encroach and thrive on thousands of U.S. Great Plains rangeland hectares. Eastern redcedar reduces forage production, destroys native ecosystems, increases the risk of wildfires, and produces allergens that harm human health. The species is costly to control. Researchers have investigated potential uses of the biomass in an attempt to incentivize entrepreneurs to assist landowners by harvesting the unwanted trees and using them as feedstock for a profitable business. Information regarding the quantity of biomass available for the expected life of a processing facility designed to use the trees as well as harvest and procurement cost would be required. The objective of this study was to determine for a case study region the potential available quantity and feedstock cost for a business designed to use eastern redcedar trees. A mixed integer mathematical programming model was constructed and used to determine the cost to obtain the rights to remove, harvest, and deliver a specified tonnage of eastern redcedar trees each year, for a period of 20 years, to an optimally located processing facility. The optimal strategy depends on tree density, proportion available for removal, growth rate, discount rate, harvest cost, transportation cost, and required tonnage.

Introduction

Eastern redcedar (*Juniperus virginiana*) (ERC) is one of 13 juniper species native to the United States.[1] 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.[2] Suppression of prairie fires enabled ERC to grow and thrive in environments previously dominated by prairie grasses.[2] The encroachment of ERC is a problem in many areas of the Great Plains.[3–8] Engle et al. reported that ERC has encroached on Great Plains grasslands ranging from Texas in the South to Alberta in the North and is spreading at an insidious pace.[9] They refer to the ERC encroachment on grasslands as a green glacier.[9] In addition to the suppression of fire, the encroachment of ERC is facilitated by its adaptability to growing in various types of soils and climatic conditions.[1,9–11]

ERC has become a very serious problem in the Southern Plains state of Oklahoma. It has been estimated that ERC becomes established on an additional 120,000 Oklahoma hectares (297,000 acres) each year.[12] ERC reduces forage production on pasturelands, destroys native ecosystems such as habitat of the lesser prairie chicken (*Tympanuchus cupido*) and produces allergens that harm human health.[8,12–14] ERC has low-hanging branches, and ERC foliage contains volatile oils that can easily be ignited by grass fires. Due to its volatile characteristics, ERC also increases the risk of wildfires and the risk of damage from wildfires.[12,15–18]

In 1933, Oklahoma farmers cropped more than 6.3 million hectares (annual crops and alfalfa hay). In 2016, only 2.9 million hectares were cropped, with another 291,779 hectares in the Conservation Reserve Program (CRP). Thus, more than 3.2 million hectares that were once cropped are no longer cropped and not in the CRP.[19] On average, since 1933, more than 36,000 hectares (89,000 acres) per year in Oklahoma have been removed from crop production and converted to pasture. This land that was once cropped is highly susceptible to ERC encroachment. It has no recent history of being managed to control ERC and no history of prescribed fire.

Efforts have been underway for years to find a use for ERC biomass that would incentivize an entrepreneur, or a for-profit business, to willingly harvest and remove ERC trees from grasslands. A number of potential uses have been identified for ERC biomass, including particleboard, bioenergy feedstock, 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 for the drilling industry.[12,20]

The annual quantity of material required for any of these potential businesses to achieve size economies is unknown. It is not known if any of these potential businesses, even after achieving size economies, could compete with existing alternatives and achieve profitability. However, prior to investing in any of these potential businesses, due diligence would require a business plan for obtaining annually the required quantity of ERC tree tonnage for the expected life of the processing facility. In addition, information regarding the expected cost to deliver the feedstock as well as the most cost-efficient location of the processing business would be essential.

Feedstock procurement for a business designed to use ERC trees exclusively would be unique relative to typical crop or plantation forest production systems. When cut at ground level, ERC does not regrow; after it is removed, landowners would be expected to take measures to prevent re-infestation. Thus, every day for the life of the business, ERC trees would have to be acquired from a unique location. It is unknown if there is a sufficient supply of trees within a reasonable perimeter to provide feedstock requirements for the expected life of a processing business. Another issue is related to the proportion of existing ERC biomass in a region that a business could obtain the rights from landowners to harvest.

The objective of this study is to determine feedstock cost for a business designed to use ERC trees 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 ERC biomass to a processing location each year for a period of 20 years. The model is solved to produce solutions for several different combinations of annual feedstock 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 business location and harvest locations for each of 20 years that would minimize feedstock costs given initial ERC inventory.

Modeling, Data, and Assumptions

A mixed integer mathematical programming model is constructed to determine the cost, including the cost (or return) to secure harvest rights, harvest cost, and transportation cost to deliver a specified quantity of ERC biomass to a business location each year for a period of 20 years. The model is designed to produce least-cost delivered feedstock solutions for several different combinations of annual feedstock 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 business location. The model is solved using the generalized algebraic modeling system (GAMS) with the CPLEX solver.

Development of infrastructure for collecting and providing a flow of feedstock would be required for an ERC biomass processing industry. For the purpose of modeling, a vertically integrated system is envisioned. It is assumed that the company would acquire the rights to enter fields with ERC trees and clear-cut and remove ERC biomass once during a 20-year period. Then the company would centrally manage the harvest and transportation required to deliver feedstock to their processing facility.[21] The model is used to determine the quantity of biomass to be contracted in each county and the counties in which ERC trees are optimally removed each year. Trees under contract that are not removed in year t are expected to continue to grow and be available for harvest in year $t + 1$.

Case Study Region

The case study region includes 15 counties in the state of Oklahoma: Blaine, Canadian, Dewey, Ellis, Garfield, Kingfisher, Lincoln, Logan, Major, Noble, Okfuskee, Pawnee, Payne, Pottawatomie, and Woodward (Fig. 1). The estimated quantity of existing biomass was obtained from field data produced by Starks et al.[6] It is assumed that the growth rate of ERC trees not harvested is 8% per year.[22] The land areas with ERC trees in these counties have been estimated by the Natural Resources Conservation Service (NRCS).[23] Six of these counties (Blaine, Dewey, Pawnee, Payne, Canadian, and Logan) are considered prospective locations for the processing facility (Fig.1). These potential factory locations were selected based on the density of ERC biomass as well as the accessible road infrastructure. The factory is assumed to

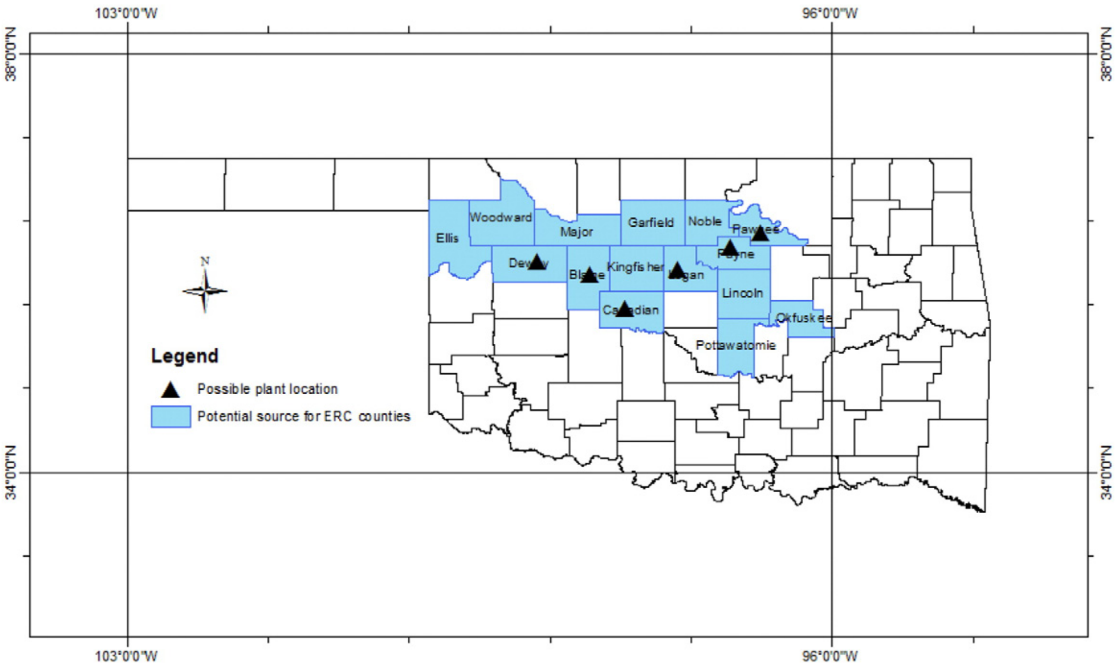

Figure 1. Case study region and potential factory locations.

process feedstock 350 days/year for 20 years. Three biomass feedstock requirement levels were modeled: 500, 1,000, and 1,500 Mg/day (551, 1,102, and 1,653 tons/day).

Acquisition of Rights to Harvest ERC Trees

Prior to building a processing facility, it is assumed that the company would engage in contracts with landowners who own accessible land with ERC trees. ERC encroachment imposes substantial costs on landowners who depend on their land to produce forage. The contracts could be designed to provide the company with the rights to enter fields at some time during the expected 20-year life of the factory and clear-cut and remove ERC biomass. Landowners who are willing to do so could enter bids for the price they would be willing to pay to have ERC trees 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 trees. The company could screen the received bids based on objective measures, including the bid rate, ERC biomass density, terrain, roads, and distance from anticipated processing facility location.

Based on findings of a survey of Oklahoma landowners, it is assumed that landowners would be willing to pay from \$4.76 to \$5.86 for each dry Mg (\$4.32 to \$5.32/dry ton) removed (Prof. T. Boyer, Oklahoma State University, personal communication, 24 January 2017). These findings are consistent with reports that some landowners in the region do engage in costly activities to reduce the deleterious effects of ERC and other woody species on forage production.[16] However, some landowners do not manage rangelands for forage production and may not be willing to contract with the company, and the company may refuse bids based on estimated costs to deliver feedstock from the site to the factory. 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 tree growth, after year zero, of trees under contract that remain to be removed in future years.

Harvest and Transportation

Estimates of ERC tree harvest costs for the region have been produced by Craige et al.[24] 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 a processing facility.[25] Harvest and transportation activities are assumed to be centrally managed to facilitate the flow of biomass from fields to the factory.[21] Machinery requirements for harvest include skid steers and whole tree chippers. Scheduled machine hours for both machines are 2,000 hours/year. Use rate is assumed to be 65% for skid steers and 75% for whole tree chippers.[24] Thus, the annual productive machine hours are estimated to be 1,300 and 1,500 for the skid steer and whole tree chipper, respectively. The working capacity of the budgeted skid steer is assumed to be 13 dry Mg/hour for cutting and 7 dry Mg/hour for moving the cut tree (skidding) to a site for drying and eventual chipping and loading. The working capacity of the budgeted

Table 1. Alternatives evaluated

Scenario	Proportion of ERC biomass in case study region placed under contract in year zero*	Quantity of biomass required per day (Mg)
20% 500 Mg	20%	500
40% 500 Mg	40%	500
60% 500 Mg	60%	500†
20% 1,000 Mg	20%	1,000
40% 1,000 Mg	40%	1,000
60% 1,000 Mg	60%	1,000
20% 1,500 Mg	20%	1,500
40% 1,500 Mg	40%	1,500
60% 1,500 Mg	60%	1,500

* *BIPROP* in model equation 3.

† The factory is assumed to operate at capacity 350 days per year for an expected life of 20 years. A 500 Mg per day facility would require 175,000 Mg ERC biomass per year, a total of 3,500,000 Mg ERC biomass for the 20-year life.

chipper is assumed to be 11 dry Mg/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 $42.71/dry Mg.[24]

It is assumed that the ERC biomass will be transported to the processing facility using 18-wheel tractor-trailers with an assumed capacity of 10.9 dry Mg. Craige et al.[24] estimated transportation costs, including fixed costs, fuel, and labor, to be $1.4/km ($2.25/mile). A detailed description of the mathematical programming model is included in the online Appendix.

Results

Cost of Delivered Feedstock

Table 1 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 factory size (500, 1,000, and 1,500 Mg/day). These scenarios were further differentiated by harvest cost ($42.71/Mg and $85.42/Mg), payment received from the landowners ($4.76/Mg to $5.86/Mg depending on county and $0/Mg), annual growth rate of unharvested trees under contract (8%, 4%), and discount rate (3.5%, 7%).

Table 2. Percentage of eastern redcedar biomass in the 15-county case study region required to be under contract in year zero to provide for the needs of a factory for 20 years for two tree annual growth rates

Factory size	Annual growth rate of trees remaining to be harvested	
Mg/day	8%	4%
	% Required under contract	
500	18.2*	24.2
1,000	36.4	48.5
1,500	54.6	72.7
2,000	72.8	97.0
2,061		100.0
2,748†	100.0	

*Contracts for 18.2% of the growing eastern redcedar trees available in year zero in the 15-county region would be required to provide 500 Mg per day for 20 years assuming an 8% annual growth rate of unharvested trees.

† If 100% of the existing eastern redcedar trees in the 15-county region were available, assuming an 8% annual growth rate of unharvested trees, 2,748 Mg per day would be available for 20 years.

Table 3. Estimates of the cost to deliver eastern redcedar biomass for three levels of proportion of land under contract (20%, 40%, 60%), three levels of biomass required per day (500 Mg, 1,000 Mg, 1,500 Mg), two levels of harvest cost ($42.71/Mg, $85.42/Mg), two levels of payment received from landowners ($4.76/Mg-$5.86/Mg, $0/Mg), 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	
	Factory location	**Cost $/Mg**	**Factory location**	**Cost $/Mg**	**Factory location**	**Cost $/Mg**	**Factory location**	**Cost $/Mg**	**Factory location**	**Cost $/Mg**
20% 500 Mg	Dewey	58	Dewey	101	Dewey	63	*		Logan	59
40% 500 Mg	Dewey	47	Dewey	89	Dewey	52	Dewey	52	Dewey	47
60% 500 Mg	Dewey	44	Dewey	87	Dewey	50	Dewey	47	Dewey	44
20% 1,000 Mg	†									
40% 1,000 Mg	Dewey	58	Dewey	101	Dewey	63			Logan	59
60% 1,000 Mg	Dewey	50	Dewey	93	Dewey	55	Dewey	58	Dewey	50
20% 1,500 Mg										
40% 1,500 Mg										
60% 1,500 Mg	Dewey	58	Dewey	101	Dewey	63			Logan	59

* With a 4% annual growth rate of unharvested trees, contracts for 20% of the existing eastern redcedar biomass at year zero would be insufficient to provide for factory needs for the 20-year expected life.

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

Table 4. 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 $42.71/Mg, discount rate of 3.5%, growth rate of unharvested trees under contract of 8%, daily requirement of 500 Mg, optimal factory location in Dewey County (000 Mg)

County	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Blaine							61	175	151
Canadian				44	135				
Dewey									
Ellis						9	114		
Garfield					40	51			
Kingfisher						115			
Lincoln	40								
Logan				130					
Major									
Noble			61	1					
Okfuskee									
Pawnee	135	82							
Payne		93	114						
Pottawatomie									
Woodward									24

Table 2 presents the percentage of ERC biomass in the 15-county case study region required to be under contract in year zero to provide the factory requirement for 20 years for both 4% and 8% annual growth rate of unharvested trees under contract. If the factory requires 500 Mg/day of ERC biomass, 18.2% of year zero ERC biomass 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 500 Mg/day of ERC biomass for the expected 20-year factory life. If the factory has 100% access to ERC biomass in the 15 counties beginning in year zero, with an 8%/year growth rate of unharvested trees, the maximum quantity of ERC biomass available for harvest is 2,748 Mg/day. If the annual growth rate of unharvested trees is 4%, maximum daily harvest is 2,061 Mg/day. Access to biomass, and the risk of insufficient feedstock, would be a critical issue for a factory in the region restricted to using ERC trees.

Table 3 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 factory in Dewey County. The estimated cost to deliver ERC biomass to the factory ranges from $44/Mg to $58/Mg ($40 to $53/ton) depending on the proportion of ERC biomass under contract, as well as the quantity of biomass required per day (Table 3). If the factory requires 500 Mg/day with the assumption that the company has contracted for 20% of the ERC trees growing in the counties in year zero, the estimated cost to deliver is $58/Mg. The estimated cost to deliver feedstock decreases to $47/Mg and $44/Mg 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 $21/Mg (20% under contract) to $7/Mg (60% under contract). The estimated average one-way field to factory transportation distance decreases from 80 km to 26 km as the proportion of ERC biomass under contract increases from 20% to 60%.

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 1,000 Mg/day requirements. Fifty-five percent under contract in year zero would be required to fulfill 1,500 Mg daily requirements.

Doubling the expected harvest cost increases the expected cost to deliver feedstock by the level of the harvest cost increase ($42.71/Mg). However, the optimal factory 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 $4.76 to $5.86/Mg (depending on county) to have the ERC biomass removed to $0/Mg changes the expected cost to deliver feedstock by the amount of the payment, but it does not change the optimal factory location, location of trees to contract for in year zero, or the harvest locations per year.

As shown in Table 2, 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),

Table 4. *(Continued)*

Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
			101	175	175	175	175	175	175	175
	33	175	74							
175	142									

access to only 20% of the year zero ERC biomass would be insufficient to provide for the needs of a 500 Mg/day factory. Access to 60% would be insufficient to provide for the needs of a 1,500 Mg day system. Access to 60% would be sufficient for a 1,000 Mg/day factory, but the cost would increase from $50/Mg for the base situation to $58/Mg (Table 3).

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 16%. The reduction in growth rate reduces the available biomass, increases average field to factory transportation distance, and consequently increases the cost to deliver the feedstock. Optimal harvest locations are thus different from those of the base scenario.

For the 20% 500 Mg, 40% 1,000 Mg, and 60% 1,500 Mg scenarios, doubling the discount rate from 3.5% to 7% changes the optimal plant location from Dewey to Logan County (Table 3). However, doubling the discount rate changes the cost to deliver feedstock for each of these three scenarios by only $1/Mg. The change in plant location increases average one-way transportation distance from 80 km to 86 km. The net effect of the higher discount rate is to reduce future costs relatively.

The Optimal Locations for Harvest

Base scenario results find that in the earlier years it would be optimal to harvest contracted ERC trees from counties most distant from the factory location (Table 4). If the factory requires 500 Mg/day, with access restricted to 20% of year zero biomass, trees would be required from all counties in the case study region except for Okfuskee and Pottawatomie (Table 4). 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 factory is located (Table 4).

As the proportion of trees under contract increases, the company has access to more ERC trees in each county. As a result, factory 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. 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 factory.

If 60% of the year zero biomass could be placed under contract, and only 500 Mg/day are required with the growth rate of 4%, the optimal harvest locations would involve only four counties, Blaine, Dewey, Major, and Woodward (Table 5). On the other hand, if 20% of year zero biomass could be placed under contract and 500 Mg/day are required with the discount rate of 7%, the optimal factory location

Table 5. The optimal quantity of eastern red cedar biomass harvested per county per year if 60% in each county in year zero is contracted for harvest sometime during the 20-year period; estimated harvest cost of $42.71/Mg, discount rate of 3.5%, growth rate of unharvested trees under contract of 4%, daily requirement of 500 Mg, optimal factory location in Dewey County (000 Mg)

County	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Blaine	175	175	73						
Canadian									
Dewey									117
Ellis									
Garfield									
Kingfisher									
Lincoln									
Logan									
Major						56	175	175	58
Noble									
Okfuskee									
Pawnee									
Payne									
Pottawatomie									
Woodward			102	175	175	119			

switches to Logan County. The optimal harvest locations involve all counties in the case study region except Ellis (Table 6).

Discussion

Prior to investing in a factory designed to use ERC biomass feedstock, due diligence 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.[26] One alternative would be for the factory 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 life of the factory.

The model presented in this paper follows from the assumption that ERC tree harvest and delivery is managed by the factory for a period of 20 years. The model is designed to produce solutions for several different combinations of annual factory 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 factory location and optimal harvest locations for each of the 20 years. Based on the assumptions and parameter levels, the optimal factory location is 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 factory location and optimal harvest location and timing of harvest.

For the base model, the estimated feedstock delivered cost ranges from $44/Mg to $58/Mg 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 factory, with an 8%/year growth rate of unharvested trees, then the quantity of biomass available would not be sufficient to meet a 1,000 Mg day factory 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 factory that requires 2,000 Mg/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 region in year zero would be required to provide for the 20-year requirements of the factory.

The available quantity of ERC biomass is highly dependent on access to land of which most is privately owned. This study is based on the assumption that prior to building a factory, the company would engage in contracts with landowners who own accessible and unwanted ERC trees. However, it remains to be determined if a sufficient quantity of landowners would be willing to agree to long-term

Table 5. ***(Continued)***

Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
175	175	175	175	175	175	175	175	175	175	175

contractual arrangement that would provide the company with the rights to enter fields at some time during the expected 20-year life of the factory and clear-cut and remove ERC trees. 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 factory in the case study region designed to process biomass produced by ERC trees exclusively. First, an economically competitive use for the collected material is required. Additional research would be required to determine if a profitable business model could be formed for any of the potential uses. 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, it may be difficult for a company to contract for a sufficient quantity of biomass to fulfill feedstock requirements for the expected life of the processing facility. Fourth, 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 trees and restore the productivity of the land. Fifth, there is a risk that uncontrolled wild fires may destroy contracted feedstock. Sixth, construction of a factory and assemblage of a management team to obtain and process ERC feedstock may require a substantial investment. Capital acquisition may be difficult given the number of uncertainties associated with feedstock acquisition. Seventh, if a for-profit company that processes ERC biomass into a marketable product exists, landowners may expect a payment for the material rather than being willing to pay to have it removed.

Given the external consequences of ERC encroachment, waiting for a private company to mitigate the problem may not be good public policy. The study did not compute or consider the external cost of ERC and did not address public policies that may be used to internalize these costs. Additional research would be required to determine the level of costs incurred by the public from ERC encroachment and public policies that may be implemented to address these costs.

Acknowledgments

The authors acknowledge the assistance of resources provided by the Oklahoma Agricultural Experiment Station. This research is based on work that is supported in part by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2014-38502-22598 through South Central Sun Grant Program. The project was also supported by the USDA National Institute of Food and Agriculture, Hatch grant number H-3028, and by the Jean & Patsy Neustadt Chair. Support does not constitute an endorsement of the views expressed in the paper by the USDA.

Table 6. 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 $42.71/Mg, discount rate of 7%, growth rate of unharvested trees under contract of 8%, daily requirement of 500 Mg, optimal factory location in Logan County (000 Mg)

County	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9
Blaine								119	175
Canadian									
Dewey	80	175	175	12					
Ellis									
Garfield									
Kingfisher									
Lincoln							153	56	
Logan									
Major				87	69				
Noble									
Okfuskee	36								
Pawnee					106	175	22		
Payne									
Pottawatomie				76					
Woodward	59								

Table A1 Description of parameters and levels evaluated

Parameter	Description	Levels evaluated
γ_i	Harvest cost ($/Mg)	$42.71/Mg; $85.42/Mg
τ_{ij}	Round-trip cost of transporting biomass from county *i* to factory location *j* ($/Mg)	$1.4/km/Mg * round trip km
ρ_i	Payment received from landowners ($/Mg) in county *i*	$4.76-$5.86/Mg depending on county and zero
r	Discount rate	3.5%; 7%
$BIOQTY1_i$	Initial quantity of biomass available from county *i* in year 1	Starks et al. 2011[6]
BIPROP	Proportion of biomass acquired via contract in year zero	20%; 40%; 60%
Grwth	Biomass growth rate of trees not harvested	4%; 8%
D_{jt}	Biomass required at factory *j* in year *t*	175,000 Mg; 350,000 Mg; 525,000 Mg

References

1. Knezevic, S., S. Melvin, T. Gompert, and S. Gramlich. 2005. Integrated management of eastern redcedar. Lincoln, NE, USA: University of Nebraska Lincoln Extension EC186.
2. Smith, S. 2011. Eastern Red-cedar: Positives, negatives and management. Ardmore, OK, USA: Samuel Roberts Noble Found1-8.
3. Fuhlendorf, S.D., S.A. Archer, F.E. Smeins, D.M. Engle, and C.A. Taylor. 2008. The combined influence of grazing, fire, and herbaceous productivity on tree – Grass interactions. In: Van Auken OW, editor. Western North American juniperus communities: A dynamic vegetation type. New York, NY, USA: Springer Science + Business Media. p. 219-238.
4. McKinley, D.C., and J.M. Blair. 2008. Woody plant encroachment by Juniperus virginiana in a mesic native grassland promotes rapid carbon and nitrogen accrual. *Ecosystems* 11:454-468.
5. Bihmidine, S., N.M. Bryan, K.R. Payne, M.R. Parde, J.A. Okalebo, S.E. Cooperstein, and T. Awada. 2009. Photosynthetic performance of invasive Pinus ponderosa and Juniperus virginiana seedlings under gradual soil water depletion. *Plant Biology* 12:1-10.
6. Starks, P.J., B.C. Venuto, J.A. Eckroat, and T. Lucas. 2011. Measuring eastern redcedar (*Juniperus virginiana* L.) mass with the use of Satellite Imagery. *Rangeland Ecology & Management* 64:178-186.
7. Starks, P.J., B.C. Venuto, W.A. Dugas, and J. Kiniry. 2014. Measurements of canopy interception and transpiration of eastern redcedar grown in open environments. *Environment and Natural Resources Research* 4:103-122.
8. Leis, S.A., C.E. Blocksome, D. Twidwell, S.D. Fuhlendorf, J.M. Briggs, and L.D. Sanders. 2017. Juniper invasions in grasslands: Research needs and intervention strategies. *Rangelands* 39:64-72.

Table 6. ***(Continued)***

Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
117										
58	175	56								
		119	33							
							169	107		
								68	175	175
						164	6			
			142	175	175	11				

9. Engle, D.M., B.R. Coppedge, and S.D. Fuhlendorf. 2008. From the dust bowl to the green glacier: Human activity and environmental change in Great Plains grasslands. In: Van Auken OW, editor. Western North American juniperus communities: A dynamic vegetation type. p. 253-271.
10. Hiziroglu, S., R.B. Holcomb, and Q. Wu. 2002. Manufacturing particleboard from eastern redcedar. *Forest Products Journal* 52:72-76.
11. Meneguzzo, D.M., and G.C. Liknes. 2015. Status and trends of eastern redcedar (Juniperus virginiana) in the Central United States: Analyses and observations based on forest inventory and analysis data. *Journal of Forestry* 113:325-334.
12. Drake, B., and P. Todd. 2002. A strategy for control and utilization of invasive juniper species in Oklahoma, final report of the Redcedar Task Force. Oklahoma City, OK, USA: Oklahoma Department of Agriculture, Food and Forestry.
13. Zhang, D., and S. Hiziroglu. 2010. Impact assessment and utilization of eastern redcedar. *American Journal of Applied Sciences* 7:1032-1037.
14. Coffey, A.J. 2011. Private benefits of eastern redcedar management and the impact of changing stocker value of gain [thesis]. Stillwater, OK, USA: Oklahoma State University.
15. Oklahoma Forestry Services, 2014. Frequently Asked Questions about Eastern Redcedar. [Available at: http://www.forestry.ok.gov/Websites/forestry/images/Redcedar_FAQs_web_version.pdf] Accessed March 13, 2017.
16. Bidwell, T.G., D.M. Engle, and M.E. Moseley. 1996. Invasion of Oklahoma rangelands and forests by eastern redcedar and ashe juniper. Stillwater, OK, USA: Oklahoma Cooperative Extension Service. Circular E-947.
17. Oklahoma Conservation Commission, 2006. Eastern redcedar trees add to fire danger. Conservation Conversation 51:1-4.
18. Oklahoma Conservation Commission, 2008. Eastern redcedar invading the landscape. The growing threat affecting the environment, safety and health. Oklahoma City, OK, USA: Oklahoma Conservation Commission.
19. U.S. Department of Agriculture, National Agricultural Statistics Service, 2016. Oklahoma Agricultural Statistics. Oklahoma City, OK, USA: Oklahoma Department of Agriculture, Food and Forestry.
20. Mckinley, C.R. 2012. The Oklahoma Redcedar Resource and Its Potential Biomass Energy. Stillwater, OK, USA: Oklahoma Cooperative Extension Service. NREM-5054.
21. Epplin, F.M. 1996. Cost to produce and deliver switchgrass biomass to an ethanol-conversion facility in the Southern plains of the United States. *Biomass and Bioenergy* 11:459-467.
22. Engle, D.M., and J.D. Kulbeth. 1992. Growth dynamics of crowns of eastern redcedar at 3 locations in Oklahoma. *Journal of Range Management* 45:301-305.
23. Natural Resource Conservation Service, 2009. Redcedar canopy cover maps [Available at: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/ok/technical/?cid=nrcs142p2_000527] Accessed March 13, 2017.
24. Craige, C.C., M.D. Buser, R.S. Frazier, S.S. Hiziroglu, R.B. Holcomb, and R.L. Huhnke. 2016. Conceptual design of a biofeedstock supply chain model for eastern redcedar. *Computers and Electronics in Agriculture* 121:12-24.
25. Park, S.C., R.J. Ansley, M. Mirik, and M.A. Maindrault. 2012. Delivered biomass costs of honey mesquite (Prosopis glandulosa) for bioenergy uses in the South central USA. *Bioenergy Research* 5:989-1001.
26. Griffith, A.P., M. Haque, and F.M. Epplin. 2014. Cost to produce and deliver cellulosic feedstock to a biorefinery: Switchgrass and forage sorghum. *Applied Energy* 127:44-54.