Biomass and Bioenergy 104 (2017) 45–52

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Cost to produce liquid biofuel from invasive eastern redcedar biomass

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ARTICLE INFO

Article history:
Received 13 March 2017
Received in revised form
12 June 2017
Accepted 15 June 2017

Keywords:
Minimum selling price
Biofuel
Biomass
Eastern redcedar
Juniperus virginiana L.
Feedstock
Invasive species
Mathematical programming
Pyrolysis

ABSTRACT

Biomass harvested from invasive plant species has been proposed for use as lignocellulosic feedstock for the production of advanced biofuels as a way to mitigate the indirect land use issues associated with the production of dedicated energy crops. Encroachment of eastern redcedar (*Juniperus virginiana* L.) has reduced the forage productivity of North American Great Plains grasslands ranging from Texas in the South to Alberta in the North. The objective of this study is to develop and demonstrate a modeling system that can be used to determine the minimum selling price of biofuel. A fast pyrolysis process that exclusively uses eastern redcedar biomass to produce gasoline and diesel blend stock is assumed. A mixed integer mathematical programming model is constructed and applied to a 15 county case study region from which eastern redcedar may be collected. The modeling system considers the growth rate of unharvested trees to determine the optimal biorefinery location, the optimal harvest locations for each of 20 years, and the minimum selling biofuel price. To fulfill 2 Gg d^{-1} feedstock requirements for the expected life of the biorefinery, 73% of the trees growing in year zero in the case study region would be required. For a 313 dm^3 Mg^{-1} conversion rate, and with biorefinery ownership, operating and maintenance cost of 630 \$ m^{-3}, the expected cost to deliver feedstock is estimated to be 61 \$ Mg^{-1}, and the estimated minimum selling biofuel price is 830 \$ m^{-3}.

1. Introduction

Use of biomass residual products as lignocellulosic feedstocks for the production of advanced biofuels has been proposed as a way to mitigate the indirect land use issues associated with the production of dedicated energy crops [1,2]. Studies have been conducted to evaluate the efficacy of collecting forest and wood products residues for use as feedstock [3–5]. Invasive plant species such as kudzu (*Pueraria montana* (Lour.) Merr.) [6], water hyacinth (*Eichhornia crassipes* (Mart.) Solms) [7], honey mesquite (*Prosopis glandulosa* Torr.) [8,9], and eastern redcedar (*Juniperus virginiana* L.) [10,11] have also been proposed as potential biomass feedstock sources.

North American grasslands are substantially reduced from their historic pre-European settlement size in part because of Eastern Redcedar (ERC) encroachment that converts Great Plains prairie into brush land in a matter of years [12,13]. ERC is one of the most widely distributed native species in the USA [14,15]. It is spread by small mammals and birds [16]. Pre-European settlement in North America, ERC persisted on rocky bluffs, and in deep canyons and other areas where fire historically did not occur [17,18]. Fire was used by indigenous people to maintain the grasslands [19]. The fire can prevent the conversion of grasslands into woodlands [20,21]. Suppression of prairie fires enabled ERC to grow and spread in environments previously dominated by prairie grasses [17,18,22]. Engle et al. [12] reported that ERC has invaded Great Plains grasslands ranging from Texas in the South to Alberta in the North and is spreading at an insidious pace. They refer to the ERC invasion of grasslands as a green glacier [12]. In addition to the suppression of fire, the encroachment of ERC is due to its adaptability to growing in various types of soils and climatic conditions [12,14,16,23].

While prescribed burning of native prairie grasslands is an effective means to control ERC, safety issues, as well as legal concerns and liability issues limit prescribed burning as a management tool [24–27]. Over time ERC encroachment on native prairies left unchecked grows into a very serious and economically important problem by effectively destroying forage production capacity, increasing risk of wildfires, creating health problems for citizens who are allergic to ERC pollen, as well as destroying native

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Abbreviations: ERC, eastern redcedar (*Juniperus virginiana* L.); OOMC, biorefinery ownership, operating, and maintenance cost; NPV, net present value; GAMS, generalized algebraic modeling system; BIPROP, proportion of total eastern red cedar biomass assumed to be available for contracting in year zero.

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http://dx.doi.org/10.1016/j.biombioe.2017.06.008

ecosystems such as the habitat of grassland birds [28].

ERC biomass has potential as a biorefinery feedstock [10,28,29]. There are several potential advantages of ERC biomass as a source of feedstock. Relative to other invasive species, in some regions of the Great Plains, ERC is abundant. Relative to dedicated energy crops, ERC does not require expenditures for planting, cultivating, irrigation, and fertilization [8]. ERC can be harvested throughout the year facilitating a just-in-time delivery system. In addition, removal of ERC biomass from rangeland will result in improved forage production and wildlife habitat as well as increase the value of the land [8].

By definition, most landowners could be expected to prefer land free of invasive species. Indeed, they may be willing to pay to have an invasive species removed from their property. However, collection and transportation of a flow of biomass from an invasive species for the expected working life of a biorefinery would not be easy. It is not known if a biofuel business designed to exclusively use ERC biomass could compete with existing alternatives and achieve profitability. Prior to investing, due diligence would require cost estimates and a business plan for obtaining annually the required quantity of chipped ERC whole plant biomass feedstock for the expected life of the biorefinery. In addition, information regarding the expected cost to deliver the materials as well as the most cost-efficient location of the biorefinery would be essential.

Feedstock procurement for a biorefinery designed to use chipped ERC whole plant biomass exclusively, would be unique relative to that for a dedicated energy crop. A dedicated perennial energy crop such as switchgrass (*Panicum virgatum* L.) may produce feedstock for harvest on the same unit of land year after year. When cut at ground level, ERC does not regrow, and after it is removed, landowners would be expected to take measures to prevent reinfestation. Hence, every day for the life of the business, ERC feedstock would have to be acquired from a unique location. It is unknown if there is a sufficient supply of material within a reasonable perimeter to provide biorefinery biomass requirements for the expected life of the facility. Another issue is the means by which a biorefinery could obtain harvest and removal rights from landowners and the willingness of landowners to grant rights.

A rational investor would not invest in a biorefinery that did not have a reasonable plan for obtaining the feedstock [30]. The available quantity of ERC biomass is highly dependent on access to infested land that is mostly 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 ERC infested land. It remains to be determined if a sufficient quantity of landowners would be willing to agree to long term contractual arrangements that would provide the biorefinery company with the rights to enter infested grasslands 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.

The objective of this study is to develop and demonstrate a modeling system that can be used to determine the minimum selling price of biofuel when using biomass from invasive ERC as the exclusive feedstock. The modeling system enables determination of the proportion of biomass inventory that must be placed under contract in year zero, the optimal biorefinery location and the optimal harvest locations for each of 20 years. Given the uncertainty regarding biorefinery ownership, operating, and maintenance cost (OOMC), and the uncertainty regarding the quantity of biofuel that could be produced per unit of biomass, the minimum selling biofuel price is computed for two levels of daily feedstock requirements, two levels of OOMC, and two biomass to biofuel conversion rates. The model is used to determine the liquid biofuel price necessary for a biorefinery to breakeven when using ERC as the single feedstock to produce biofuel. Also, the model is used to determine the optimal biorefinery location and harvest locations for each of 20 years.

2. Model

A mixed integer mathematical programming model is constructed to determine the minimum selling price of biofuel for a biorefinery designed to process ERC biomass into gasoline and diesel blend stock as described by Dutta et al. [31]. The objective function of the model is to maximize the net present value (NPV) of the system that includes all activities from obtaining ERC harvest and removal rights from landowners, to the production of the bio-based gasoline and diesel blend stock. The minimum selling biofuel price is found by iteratively changing the biofuel price in the model to determine the price level at which the net present value of the system is equal to zero [32]. Binary variables are included to enable the model to determine the optimal biorefinery location. The model is solved using the generalized algebraic modeling system (GAMS) with the CPLEX solver.

The objective function is constructed to maximize the net present value of the system. The objective function can be specified as:

$$\max_{X_{ijt}} NPV = \left\{ \sum_{t=1}^{T} \left(\rho Q_t + \sum_{i}^{I} \sum_{j}^{J} \delta_i X_{ijt} - \sum_{i}^{I} \sum_{j}^{J} \gamma_i X_{ijt} - \sum_{i}^{I} \times \sum_{j}^{J} \tau_{ij} X_{ijt} - (OOMC) Q_t \right) * PVF_t \right\} \tag{1}$$

where NPV is net present value (\$), ρ is the biofuel price (\$ m^{-3}), Q_t is the quantity of biofuel produced in year t (m^3), δ_i is the payment received from the landowners in county i for removing biomass (\$ Mg^{-1}), γ_i is the cost to harvest ERC biomass in county i (\$ Mg^{-1}), τ_{ij} is the transportation cost from county i to biorefinery location j (\$ Mg^{-1}), $OOMC$ is biorefinery ownership, operating and maintenance cost (\$ m^{-3}), $PVF_t = (1+r)^{-t}$ is the present value factor, r is the discount rate, t is year of harvest ($t = 1 \ldots 20$), and X_{ijt} is the quantity of biomass to be harvested in county i and delivered to biorefinery j in year t (Gg). Equation (1) is maximized subject to a set of constraints.

Equation (2) 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.

$$BIOQTY1_i = BIPROP * BIOQTY_i \ \forall\ i \tag{2}$$

Equation (3) 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.

$$\sum_{j}^{J} X_{ij1} - BIOQTY1_i \le 0 \ \forall\ i \tag{3}$$

Equation (4) 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.

$$NH_{i,1} = \left(BIOQTY1_i - \sum_{j}^{J} X_{ij1} \right) * (1 + \mathrm{Grwth}) \quad \forall\ i \tag{4}$$