BIOMASS AND BIOENERGY 34 (2010) 1597–1607

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Development of a biorefinery optimized biofuel supply curve for the Western United States

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ARTICLE INFO

Article history:
Received 3 July 2009
Received in revised form
21 May 2010
Accepted 6 June 2010

Keywords:
Biofuel
Supply assessment
Resource
Supply chain
GIS
Optimization

ABSTRACT

A resource assessment and biorefinery siting optimization model was developed and implemented to assess potential biofuel supply across the Western United States from agricultural, forest, urban, and energy crop biomass. Spatial information including feedstock resources, existing and potential refinery locations and a transportation network model is provided to a mixed integer-linear optimization model that determines the optimal locations, technology types and sizes of biorefineries to satisfy a maximum profit objective function applied across the biofuel supply and demand chain from site of feedstock production to the product fuel terminal. The resource basis includes preliminary considerations of crop and residue sustainability. Sensitivity analyses explore possible effects of policy and technology changes. At a target market price of 19.6 $ GJ^{-1}, the model predicts a feasible production level of 610–1098 PJ, enough to supply up to 15% of current regional liquid transportation fuel demand.

1. Introduction

Production of renewable transportation fuels from biomass holds great potential in the Western United States. Biofuels are an increasingly important ingredient in the region's energy policy goals including greenhouse gas emissions reductions, reduced dependence on petroleum in the transportation sector, and rural job creation [1–3]. The potential is limited by the resource availability (both quantity and type) and economics of the full biofuel supply chain. The research described here combines a geographic information system (GIS) resource model with a biorefinery siting optimization model to provide a clearer understanding of the contribution that biofuels might make to transportation energy requirements of the Western United States by 2015 and at what cost.

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0961-9534/$ – see front matter
doi:10.1016/j.biombioe.2010.06.007

Previous work has considered technically and/or sustainably harvestable biomass [4–7]. These studies have served to highlight the potential for biomass in the region and to demonstrate the importance of geographic factors in determining the resource base. For example, agricultural residue availability depends on cropping patterns, soil types, climatic factors and cultivation practices of the growers [8]. Forest biomass availability will depend on the ecological management of forest on federal lands and the management practices of the forest products industry on private lands [9], in addition to federal policies influencing market access. However, previous assessments of the potential of biomass in the region have not explicitly considered the costs of the complete biofuel system from feedstock supply through final demand for the fuel products.

Many studies considered the optimal sizing or siting of biomass-based conversion facilities [10–13]. Advances have been made in using precision spatial information [14–16] and in considering multiple products [17]. The literature shows that the optimal site, size and choice of technology for the utilization of biomass resources will depend on the distribution of the resources, the marginal cost of transportation, the economies of scale of the biorefinery and the local markets for the products. No work, to our knowledge, has attempted to provide a consistent study of multiple conversion technologies competing for a diverse set of biomass feedstock with real-world geographic data.

Table 1 – Biofuel pathways modeled.

Feedstock Category	Feedstock type	Conversion technologies[a]
Clean Lignocellulosics	Forest biomass	
	Herbaceous	
	Energy Crops	
	Straw and Stover	LCE
	Ag. Residues	
	Orchard/Vineyard Wastes	LCG
	Municipal Solid Wastes	LCMD
	-Clean Mixed Paper	
	-Clean Wood Wastes	
	-Clean Yard Wastes	
Lignocellulosics	Remainder of Biomass	LCG
	MSW	LCMD
Lipids	Seed Oils	FAME
	Yellow Grease	FAHC
	Animal Fats	
Cereal grains	Corn	Dry and Wet Mill Ethanol

a LCE - cellulosic ethanol through hydrolysis and fermentation; LCMD - Fischer Tropsch diesel; LCG - upgrading of pyrolysis oils to gasoline; FAME- fatty acid to methyl esters (FAME); FAHC - hydrotreatment of fatty acids to hydrocarbons.

2. Scope

We consider biofuels produced by technologies and from resources that are expected to be commercially viable by 2015. From the large set of possible biofuel pathways, we have chosen to model 30 pathways consisting of 12 feedstock types and 6 biofuel conversion technologies. More detailed information on conversion technologies and feedstock supply data is given below Table 1.

This study is limited to the Western United States and specifically the member states of the Western Governors' Association, a region consisting of the states including and to the west of Texas, Oklahoma, Kansas, Nebraska, South Dakota and North Dakota. This is a large and geoclimatically diverse region with significant quantities of biomass from both forest and agricultural sectors as well as from the municipal waste stream. The study uses a 2015 timeframe, which allows enough time for the development and initial deployment of second-generation biofuel production technologies. As a first approximation, a scenario is examined of an overnight build for 2015 based on a single representative year for resource and cost estimation. The model is sufficiently general to relax the constraints imposed in this analysis, and further development is underway for a full national-scale model. The analysis here follows on a previous assessment of the potential electricity generation from biomass in the western region [18].

3. Methodology

A geographically-explicit biomass resource assessment and infrastructure network model is integrated with technoeconomic models of the conversion technologies to yield a spatial distribution of resource supply and biofuel products across the region. The combination of the models finds an optimal configuration of the biofuel supply chain to produce biofuels.

This analysis has four main components – 1) geographically-explicit biomass resource assessments, 2) engineering/economic models of the conversion technologies, 3) models for multi-modal transportation of feedstock and fuels based on existing transportation networks, and 4) a supply chain optimization model that designs the fuel production system based on inputs from the other models. The optimization model is described below. The resource assessments, conversion technology models, and the spatial analysis are described later.

3.1. *Supply chain optimization model formulation*

A biofuel supply chain optimization model was developed to consider explicit spatial distributions of biomass supply, competition among technologies for resources, and the economies of scale of conversion technologies in finding the best design for biofuel supply chains. The model locates, sizes, and allocates feedstock to biorefineries with the objective of maximizing the profitability of the industry as a whole. The profit considered is the sum of the profit for each individual feedstock supplier and fuel producer over the entire study region. Costs considered are those associated with feedstock procurement, transportation, conversion to fuel, and fuel transmission to distribution terminals. Fuel production and selling price determine industry revenue. The selling prices of the product fuels are input parameters that are varied to create a supply curve.

The model is formulated as a mixed integer-linear program Fig. 1. Decisions integrated into the model are whether to build a biorefinery of a given technology at a given site (X_{jt}); if built, how much feedstock is consumed (Yf_{jft}), how much fuel is produced (Yb_{jt}) and which supply points are exploited (F_{ijfp}). These decisions are made for all potential sites simultaneously with no double counting of resources. The objective of the program is to maximize the total annual profit of producing and delivering biofuels to the nearest distribution terminal. The profit is defined here as the annual revenue from the sale of biofuels less the annual cost of producing those biofuels. The annual profit equation is:

$$\text{Profit} = \sum_{jt} fuel\_price \cdot LHV_t \cdot Yb_{jt} - \text{Cost} \tag{1}$$

where

$$\text{Cost} = \sum_{ijfp} (PC_{ifp} + DC_{ijf}) \cdot F_{ijfp} + \sum_{jt} \left(a_t \cdot X_{jt} + \sum_f b_t \cdot Yf_{jft} \right) + \sum_{jt} TC_{jt} \cdot Yb_{jt} \tag{2}$$

the subscripts '*i*' and '*j*' correspond to locations of biomass supply points and potential biorefineries, respectively. The subscript '*f*' denotes the type of biomass feedstock, the subscript '*t*' denotes the conversion technology and the subscript 'p' represents a procurement price level.

The revenue is determined by the selling price of fuel (*fuel_price*). The value of all fuels is presumed to be equal on an energy content basis. The model was constructed in the local units based on the US gallon (3.7854 L). Fuel quantities are converted from gallons of fuel to units of energy (MJ) by the lower heating value of the fuel (LHV_t). The costs considered are the procurement of feedstock (PC_{ifp}), the transportation of feedstock to the biorefinery (DC_{ijf}), the transportation of the product fuel to the nearest distribution terminal (TC_{jt}) and the conversion cost. The conversion cost is dependent on the size of the biorefinery. We characterize it here as a binary-linear function with a fixed cost (a_t) if a facility is built and a variable cost (b_t) dependent on the capacity of the biorefinery expressed in terms of feedstock input (Yf_{jft}).

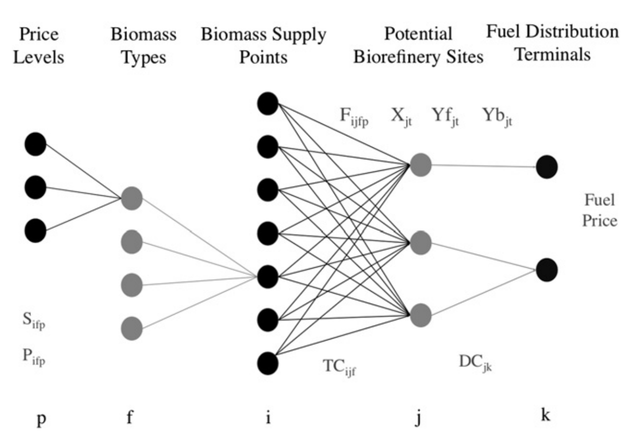

Fig. 1 – Simplified optimization model schematic–input parameters are listed at the bottom of the diagram and the decision variables are listed on the top.

The objective function is combined with a number of constraints representing the physical limitations or restrictions of the biomass industry in the mathematical model. The first set of constraints limit the biomass originating from a source at a price level to be less than the maximum supply of biomass of that type at that price level at that source ($Supply_{ifp}$).

$$\sum_j F_{ijfp} \le Supply_{ifp} \tag{3}$$

The biofuel produced at a biorefinery is equal to the quantity of biofuel that can be produced from the biomass entering the biorefinery given the conversion efficiency (h_{ft}) including handling loss. We also relate the biorefinery biomass input capacity to the biomass coming into the facility.

$$\sum_{ip} F_{ijfp} = \sum_t Yf_{jft} \tag{4}$$

$$Yb_{jt} = \sum_f \eta_{ft} \cdot Yf_{jft} \tag{5}$$

There can be no biorefinery size if the fixed cost has not been paid (binary variable at that site is 0). If the binary variable is 1 then the biorefinery can be no greater than its maximum allowable size for the technology (M_t).

$$\sum_f Yf_{jft} \le M_t \cdot X_{jt} \tag{6}$$

All variables representing physical quantities must take on either a zero or positive value.

$$F_{ijfp}, Yf_{jft}, Yb_{jt} \ge 0 \tag{7}$$

Each model run gives results of the industry-wide fuel production for a given price; which biorefinery locations are optimal and how big they are; and which biomass resources are used by which biorefineries. Multiple model runs are performed over a range of fuel prices. Plotting the industry production against fuel price gives the supply curve for each resource type, and each point on the supply curve represents a separate model run. The three supply curves for the three resource types (grains, lipids, and lignocellulosics) are combined to produce the regional and state specific supply curves for biofuels.

The biorefinery siting optimization model is solved using the MIP solving algorithm in CPLEX optimization software from ILOG using the GAMS model language [19,20]. The computational difficulty of the model depends on the number of variables with the number of binary variables being most important. To speed the process, the model was split into three models; one for the lignocellulosic resources, one for the lipid resources and one for grain resources. The lignocellulosic model was the largest of these models consisting of approximately 527 000 variables, with 582 binary variables and 11 365 constraints.

3.2. *Biomass resource assessment*

The methods for the biomass resource assessments are described below for each resource type. The methods vary between resource types due to the variation in constraints on each resource.

3.2.1. *Agricultural crop residues*

Agricultural crop residues are for the most part lignocellulosic biomass that remains in the field after the harvest of primary crops. Residues include stalks and leaves from corn (stover) and straw from wheat, barley, oats, and rye production. While agricultural crop residue quantities produced are substantial, only a fraction of them can potentially be sustainably collected for bioenergy use primarily due to their importance in protecting soil productivity, especially in reducing soil erosion. The amount of soil erosion that agricultural cropland experiences is a function of many factors: crop rotation, field management practices (tillage), timing of field management operations, physical characteristics of the soil type (soil erodibility), field topography (% slope), localized climate (rainfall, wind, temperature, solar radiation, etc.), and the amount of residue (cover) left on the field from harvest until the next crop planting. Recent analyses demonstrate that under certain conditions, agricultural residue removal can occur without exceeding tolerable soil loss limits [8].

We estimate the yield of sustainably removable residues for each county in the region based on soil erosion constraints. These values were estimated utilizing National Agricultural Statistics Service (NASS) corn, spring and winter wheat, barley, oats, and rye production (yield and area planted) data for 2000–2003 and employing a procedure that estimates crop residue retention levels after harvest subject to up to three different field management (tillage) scenarios (conventional tillage, CT; conservation/reduced tillage, RT; and/or no-till, NT) such that rainfall and/or wind erosion rates did not exceed NRCS soil-specific tolerable soil loss limits [8]. These numbers do not directly account for any carbon losses or concerns with soil moisture. Not all crop residues are included in this model mostly due to restricted producing regions, e.g., rice in California. Later implementations of the model will increase the number of residues considered.

The costs of harvesting these residues were generated using standard engineering and economic parameters for machinery that are typically used to harvest and/or field process, bale, and transport corn stover or small-grain straw to the field edge [21]. The yields and cost were aggregated into county-level supply curves expressed in terms of total mass of biomass available at the field edge at a given cost of production for each county in the region.

Residues (trimmings, dead wood, etc.) are generated from the growth and cultivation of orchard and vineyard crops produced in the western region. Production statistics (area planted and yields) and the average annual quantity of residue by crop were obtained from the 2002 Census of Agriculture [22] and data from an analysis performed in California [4]. The cost of residue pick-up and transport to the field edge is assumed for purposes here to be 33 $ t^{-1} dry basis [23].

3.2.2. *Animal fats and waste greases*

Edible and inedible types of tallow, byproducts of the meat processing/slaughter industry, are potential feedstocks for biodiesel production. Each has distinct characteristics and price structures. Statistics derived from two independent sources [24,25] give an average generation of tallow of 824 kt in the study area from approximately 50 separate locations in Arizona, California, Colorado, Kansas, Nebraska, Texas, Utah, and Washington. Prices for edible and inedible tallow at various locations throughout the U.S. were obtained from a national source [24] for a period of two years (July 2005 through June 2007).

Waste grease feedstocks (e.g. restaurant greases) are a secondary but accessible source of biodiesel feedstock. Estimates of this resource were made based on methodology developed by Wiltsee [7] using urban population statistics. Municipalities with populations greater than 100 000 according to the 2000 U.S. Census were included in this analysis. Population expansions were estimated for each city in 2015 using data for state population growth derived from data provided by the U.S. Census Bureau [26].

3.2.3. *Municipal waste biomass*

The biomass fraction of municipal waste was estimated at a municipal level for cities with populations greater than 100 000. Waste generation was assumed at 1.26 t^{-1} per capita based on a state-level survey of solid waste disposal and recycling [27]. The EPA estimates that 5.5% of MSW is clean wood wastes [28] of which we assume 75% is available for biorefineries. Sixteen percent of MSW is estimated to be unrecycled paper [28], of which we assume 50% is recoverable for feedstock. Yard and green wastes make up another thirteen percent of MSW [28], we assume 75% of the yard and green wastes are available. Costs for separating these fractions of MSW is estimated at between 27 $ t^{-1} dry basis and 33 $ t^{-1} dry basis for the paper and wood fractions and 11 $ t^{-1} dry basis for the yard/green waste fractions, which are source separated [29].

3.2.4. *Forest biomass*

Supplies of biomass from forests were estimated for resources associated with the thinning of timberland with high fire hazard, logging residue left behind after anticipated logging operations for conventional products, treatment of Pinyon Juniper woodland, general thinning of private timberland, precommercial thinning on National Forest land in western Oregon and Washington and unused mill residue. Estimates were guided by sustainability principles. In the context of biomass removal from forests, the question of sustainability requires consideration of a wide range of issues, including: nutrient cycling and soil productivity, maintenance of biodiversity, water quality, and wildlife habitat. These factors, and resulting constraints on forest operations, are generally very site-specific. Soil productivity in certain soil types, for example, may be more sensitive to micronutrient levels and thus require retention of some level of woody residue. Wildlife habitat requirements may stipulate retention of snags or maintenance of coarse woody debris.

The process used models of silvicultural treatments to estimate total available biomass. The total available was then further reduced to reflect the material left on site to meet ecological constraints and the material that is otherwise impractical to remove. On federal lands, vegetation management projects are implemented within the framework of environmental analyses and regulations that ensure consideration of ecological effects and sustainability. While less restricted, treatments on private lands are also constrained through various environmental laws and regulations [30]. The potential forest biomass supply that is modeled here is a secondary output of other management objectives. Our attempts to reflect these guidelines are still rather gross and further evaluations will be needed to determine availability in local areas. A previous study [9] with limited environmental screens estimated 312 Mt of dry biomass are potentially available from fire hazard reduction thinnings, whereas with our additional base case screens we estimate 103 Mt of dry biomass are currently available. For each estimate it is assumed these amounts would be harvested over a period of years. Our base case would use about 11.8 Mt y^{-1} of dry biomass, which is an amount less than 25% of currently remaining net growth of growing stock [31].

Estimates are made under considerable uncertainty regarding the influences of endangered species, habitat preservation, water quality, and soil sensitivity, most likely making them overly conservative in some cases but not in all. Our analysis includes supply of biomass from federal lands, but this may not be viable because the Energy Independence and Security Act of 2007 [2] would not credit biofuels made from biomass removed from most federal lands toward the national renewable fuels standard (RFS). The only source that would not be notably reduced by this restriction would be the estimated 2.4 Mt y^{-1} to 3.9 Mt y^{-1} of dry biomass from thinning on private land.

3.2.5. *Commodity crops*

Potential area, price, and production of corn, soybeans, and canola that may occur in all counties in 2015 was estimated using 2006/2007 crop year planted area and yield data for corn, soybeans, and canola as reported by USDA's National Agricultural Statistics Service and projections of acreages and yields provided by the Food and Agricultural Policy Research Institute (FAPRI) [32,33]. Similar statistics exist from the USDA's Baseline Agricultural analysis [34]. Both sets of data could be used to develop estimates for national supply curves, but they would be at an extremely aggregated resolution and really only valid for a single year due to potential changes in exports, agriculture and energy legislation, and alternative fuel demand. County-level supply curves for individual grain crops are also subject to these factors, but especially local grain/oilseed prices, which are not accurately known. Therefore, due to these reasons, supply curves were not developed. Instead a sensitivity analysis on the price of corn is provided.

For each crop, FAPRI and the baseline analysis provide annual estimates of potential commodity crop yields and area planted for the crop years of 2007/2008 through 2015/2016. Projected production forecasts for each county in the study area in which corn, soybeans, and/or canola were produced were estimated by multiplying the percentage change in yield and planted area on a national basis for each of the three crops between the 2006/2007 crop year and the average of the 2014/2015 and 2015/2016 crop years. The crop years of 2014/2015 and 2015/2016 were used instead of one single year as decisions concerning 2015 plantings could be made in an earlier year. Yield and area projections were 14.5% and 13.6% for corn; −4.2% and 7.9% for soybeans; and 14.9% and 10.6% for canola and these were applied to 2006/2007 crop year statistics. Projections of agricultural commodities such as these are tenuous at best as agriculture, energy, and/or environmental legislation, market forces, and the world petroleum situation concerning supply and demand could very quickly render these numbers obsolete and therefore these projections should be evaluated and used with this in mind.

3.2.6. *Energy crops*

The method employed here to estimate the potential production of energy crops on marginal lands in the western region was to use production statistics of native grasses in unmanaged stands by soil type and county obtained from a USDA database. The database was populated by Natural Resources Conservation Service (NRCS) rangeland experts over many years and reflects possible production levels of a large number of herbaceous species, including switchgrass, under "non-managed" conditions (e.g., no fertilizer and/or chemical applications or dedicated field preparation that could potentially increase production). These data could possibly serve as a baseline or floor for future potential energy crop production. We include an increased management scenario with moderate amount of fertilizer applied as a sensitivity case.

Consultation with a number of USDA-related personnel with expertise in rangeland grass production revealed that inadequate and inconsistent production might occur at elevations of greater than 1372 m above sea level, field slopes greater than 15% and most importantly, in areas where average annual precipitation was less than 50.8 cm. Estimates for native grass production were made for lands classified as cropland, rangeland, or grassland and designated as land capability class III-VIII that met the above criteria for rainfall, slope and elevation. From this individual soil type production data, county-level supply curves were generated using economic and engineering parameters similar to those utilized for corn stover and small-grain straw baling and harvest.

3.3. *Biofuel conversion technologies*

Biofuel conversion technologies were modeled in two stages. First, detailed technoeconomic models were developed based on data from the literature. Second, the models were simplified into integer-linear functions dependent on the feedstock type and the capacity of the biorefinery. The technologies were chosen to be representative of the types of biofuel production processes that can be commercial in the mid term. The technology choices were based on significant differences in the relative benefits and challenges for each conversion process, status of the technology, and availability of published technology reports based on detailed engineering and cost analyses.

Analyses for current commercial production technologies are based on current cost and performance data [35–37], while advanced technologies models are based on detailed engineering design and performance modeling analyses, yielding cost and performance projections for the 2015 time period [38–53]. These projected costs are typically estimates for the nth plant, with accuracy in the range of +/− 25%–30%.

Spreadsheet models were created from data culled from literature. Efforts were made to conform the costs from each study to a common basis. In general, the key input variables for each model are the feedstock input type and quantity. Levelized non-feedstock production costs are calculated using a fixed charge rate (FCR) of 12.3%, calculated based on an economic lifetime of 25 years and a weighted cost of capital of 9.7%. Although it was relatively straightforward to convert the capital costs to 2006 US$, updating the energy and input resource portions of the O&M costs was not always possible due to varying levels of detail in the published studies. Where possible these values were updated using projected costs for the 2015 time period.

The detailed technoeconomic models are simplified into integer-linear annualized cost functions for use in the optimization model. Using the detailed models, we plot the annualized cost for each technology as a function of the input capacity of the biorefinery. A linear fit is found for the plot and the y-intercept (a_t) and slope (b_t) are parameters used in the optimization model.

3.4. *Spatial analysis*

3.4.1. *Biorefinery site screening*

Potential biorefinery locations were chosen to be suitable representative locations throughout the western states based on a specific set of criteria – namely population, access to major highways and railroads or existence of a similar facility. These are not necessarily exact locations, but rather areas that have the required infrastructure for a biorefinery. To limit the number of locations searched, biorefineries are limited to locations of existing cities and towns. City data were acquired from the National Atlas [54] and included each city's location, identification code, and population data for the year 2000. Not all cities include population estimates.

Potential locations that were very close to one another were merged to a single representative location to limit the search space for the optimization routine. Cities were selected first by identifying all cities with greater than 10 000 population. Then a 50 km travel distance was established around each city. If multiple cities were within the 50 km travel distance the city with the largest population was selected and all others within 50 km of the selected city were eliminated. These criteria use population as a surrogate for availability of water and other essential services, including trucking, skilled labor, and materials. In doing so, potential locations are included in the analysis that may not have the water necessary to support a biorefinery.

3.4.2. *Model of transportation costs*

To accurately calculate the costs of transporting feedstock and fuels along the supply chain, a comprehensive transportation network was assembled. The transportation network includes existing highways, rail lines, and marine transport routes, as well as inter-modal facilities. The inclusion of inter-modal facilities allows for the calculation of loading and unloading costs associated with the transfer of feedstock or fuel from one mode of transport to another. The network was built to enable the calculation of both time and cost of travel between two locations. Thus, each segment of the network is attributed with a mode and speed of travel. Data from a variety of sources was compiled to build the geographic and cost components of the transportation network. Biomass and liquid fuel transportation were modeled using three modes: truck, rail, and barge.

The costs of biomass and fuel transport by truck were developed from several sources [55–57]. Haulage costs are the same for all biomass on a total weight (moisture + dry biomass) basis, thus their moisture content differentiates the dry biomass transportation costs. The cost of transporting all liquids (oils, grease, and fuel products) is considered to be the same on a volumetric basis. The energy cost of diesel was 18.45 $ GJ^{-1}.

Rail costs used in this study are based upon a published mileage-based rate schedule for agricultural products [58]. The costs are fitted to a linear model. We have also included a loading and unloading cost. Marine transportation costs are based on a published rate schedule for river barge [59]. The rates were fitted to a linear function of distance similar to the rail rates above.

Many of the resources are reported at the county level and need an additional transportation cost added to account for the travel within the county. The intra-county transportation cost is calculated using the average "city-block" distance from any point in the county to the centroid. This geometric measure uses the perimeter of the county to estimate average travel distance. Additionally, it is assumed that the average travel speed along this route is 56 km h^{-1}. These intra-county costs are then combined with the county centroid-based network transportation model.

These data were incorporated into a geodatabase in the ArcGIS software environment. Once the network was built the Network Analyst extension was used to create an origin-destination cost matrix from all source origins to all potential biorefinery locations. Similarly, network analysis was used to calculate the least cost paths from all potential biorefinery locations to the nearest petroleum distribution terminals.

4. Results

Results are obtained and discussed in four principal categories: 1) cost and geographic distribution of the biomass resources, 2) influence of biofuel price on supply, 3) details of the biofuel system at a single price point (e.g., 19.6 $ GJ^{-1}), and 4) sensitivity analyses testing alternative scenarios.

4.1. *Biomass resources*

There are three categories of feedstocks – grain (corn), lipids (greases, oils) and lignocellulosics. The corn resource dedicated to fuel production is projected to have a maximum of 77 Mt. This is approximately thirty percent of the current U.S. production. The lipid resource consists of 161 kt of yellow grease, 824 kt of tallow and 3.5 Mt of oil seeds (soy and canola). Of the 120 Mt of lignocellulosic resources, 82.5 Mt are available at the field, forest plot or municipal material recovery facility (MRF) at or below 33 $ t^{-1} dry basis. Municipal waste, energy crops on marginal land, and forest resources are the most significant resources in the West. Below 20 $ t^{-1} dry basis, only source separated yard wastes and a portion of the forest resources are available Fig. 2.

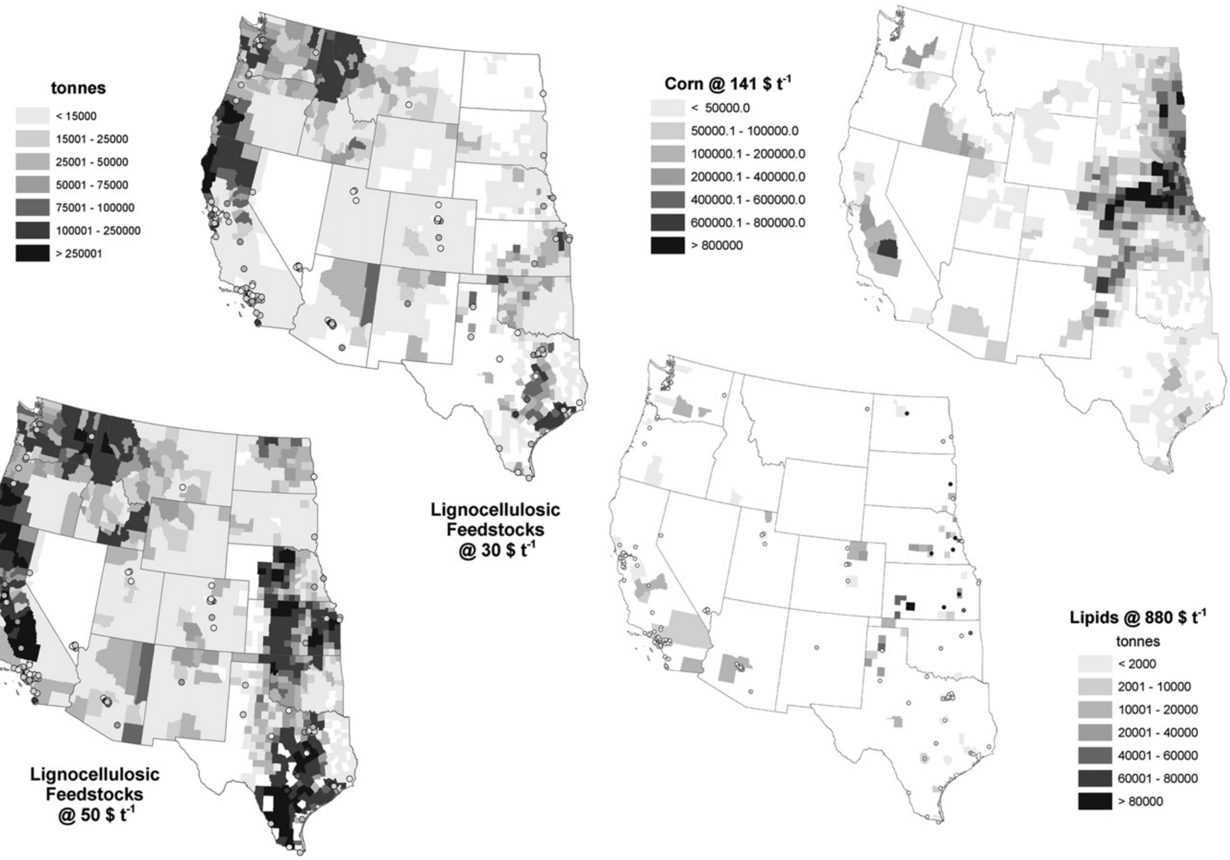

Fig. 2 – Distribution of lignocellulosic biomass feedstock in the study area.

The biomass resources are not uniformly distributed over the region. Large arid sections in the middle of the region have little to no resource while the areas with high population or significant amounts of forest or agricultural activities have significant resource available. The Pacific Northwest has a high concentration of forest resources, while the eastern border of the region has significant potential for agriculture-based biofuel feedstock in the form of corn or energy crops. In fact the restriction to the western region precluded for this analysis imports or exports across the eastern boundary, a limitation that would be removed by implementing at the national level.

4.2. *Biofuel price and supply*

The supply curve for biofuel over a range of fuel prices predicted by the model is shown in Fig. 3. For interpretation, it is important to note that the spatial distribution of demand and local fuel delivery are not included in the supply chain analysis. The local fuel delivery would likely add 1.6 $ GJ^{-1} to 2.9 $ GJ^{-1} in cost depending on the volumetric energy density of the fuel. By not including the spatial distribution of demand in the analysis, we have ignored the potential need to transport biofuels significant distances to reach the appropriate fuel markets. This would further increase fuel cost.

The supply curve has three regions of interest. The first region – between 10.2 $ GJ^{-1} and 16.3 $ GJ^{-1} – has a gradual increase in biofuel quantity with price, mainly exploiting low-value waste resources. The second region is a highly elastic area where 50 percent of the total potential can be brought on over a cost differential of 4 $ GJ^{-1}. This region is likely to overstate the elasticity of biofuel supply due to constant corn prices and constant land values for the energy crops that begin to play significant role at these prices. The final region consists of the last 30 percent of supply. As the lower cost resources are exhausted more expensive feedstock and technologies are needed. At high demand the curve becomes steep as resources considered in the

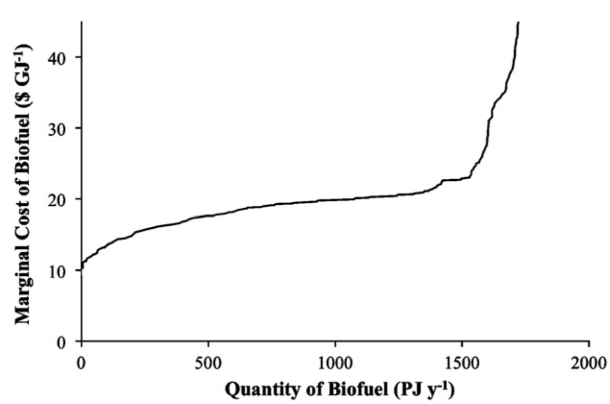

Fig. 3 – Supply curve of biofuels in Western U.S.

assessment are exhausted. While this is an artifact of the study boundaries, it can be interpreted as a loose sustainability constraint.

The supply curve represents the quantity of biofuels that could be produced at or below a given cost. The result is derived from the resource assessment, conversion technology models and the deterministic approach to supply chain optimization. It does not account for risks of uncertainty in resource supply, fuel demand and conversion technology performance. It is, therefore, an optimistic assessment of biofuel potential in 2015.

The resource types that are consumed to produce biofuel vary over the supply curve Fig. 4. Many of the resource types become fully exploited over a small range of prices. Market dynamics and diversity not captured in the model would likely increase the range of prices needed for full exploitation. Note that introduction of sustainability standards, inclusion of indirect land use and other market mediated effects, and other sustainability conditions might significantly alter conclusions regarding corn and energy crop resources. Indirect land use changes have been the subject of recent debate and analysis [61–64], and are incorporated into rulemaking for both the national RFS [65] and California low carbon fuel standard (LCFS) [66].

Land area devoted to the production of biofuels increases as the price of biofuels increases. At maximum, biofuels are produced on 12.1 Mha of marginal lands in native grass production and 9.5 Mha in corn production.

4.3. Biofuel production at single price point: 19.6 $ GJ^{-1}

At 19.6 $ GJ^{-1} the model predicts approximately 931 PJ of biofuel production. For reference, 7870 PJ of transportation fuels were sold in the WGA states in 2005 [60]. Of the total, 58 percent is from cellulosic ethanol, 38 percent from corn ethanol and the remainder is renewable diesel from yellow grease and tallow. The resulting biofuel production system shows areas on the east and west of the region are the most significant producers of biofuels in keeping with resource and population (water) distributions Fig. 5.

Lipid resources are converted to diesel via hydrotreatment at petroleum refineries to take advantage of low costs for hydrogen. In the model, the advantages of co-location and economies of scale outweigh the added cost of transportation.

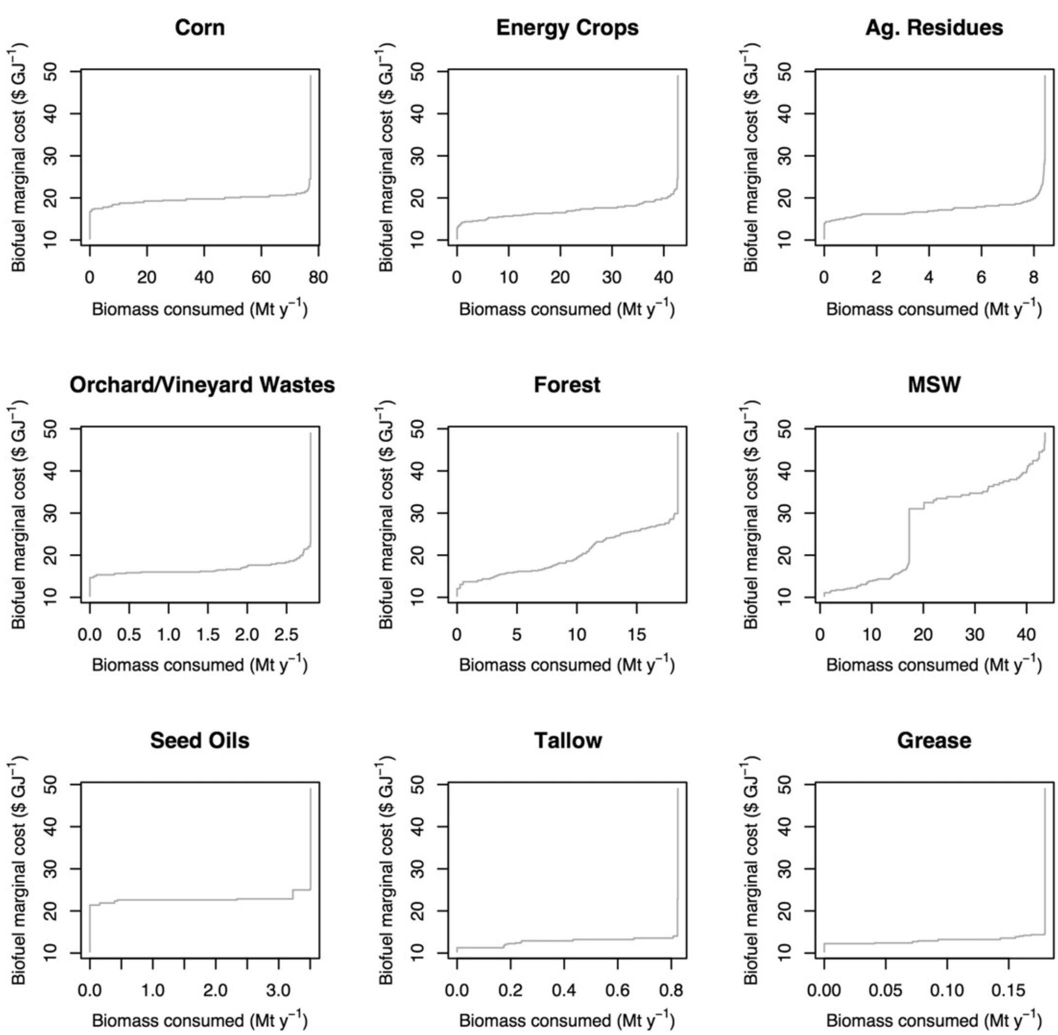

Fig. 4 – Biomass used for production of biofuels over the supply curve – rapid increase in consumption for MSW biomass resource near 32 $ GJ^{-1} is due to the deployment of the FT diesel technology consuming the mixed fraction of MSW (only biomass included in estimate).

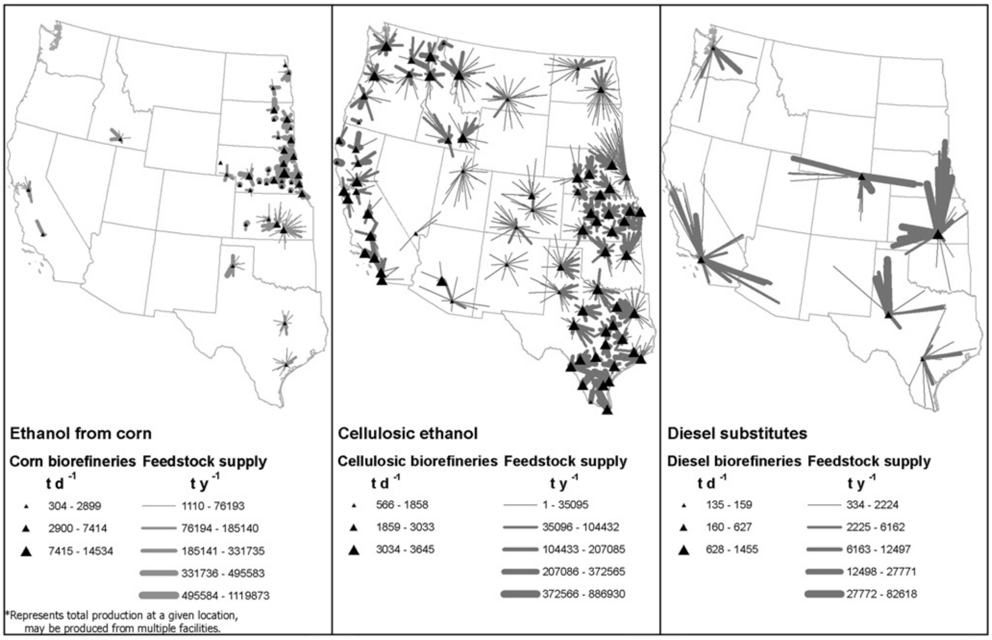

Fig. 5 – Location and biomass supply of biorefineries sited by the model for a biofuel selling price of 19.6 $ GJ^{-1}.

The technoeconomic models used result in lignocellulosic resources being converted to ethanol. 75 percent of the cellulosic ethanol biorefineries are between 2250 t d^{-1} and 3175 t d^{-1} of feedstock input. To serve these moderately large facilities, the distance from source to the biorefinery is larger than has been assumed in most technoeconomic assessments of lignocellulosic biofuels. The majority of biorefineries in the model basis have feedstock sheds (areas from where their resource is drawn) of greater than 160 km in maximum extent.

4.4. *Sensitivity analysis*

One limitation of this analysis is the treatment of corn supply as available at a single projected commodity price. The baseline case uses a price of 141 $ t^{-1} dry basis from the FAPRI projections for supply and price for 2015. The single commodity price causes corn ethanol to have a very flat supply curve. The corn price will be set by many factors aside from ethanol demand. We show a sensitivity case (Fig. 6) with corn price at 232 $ t^{-1} dry basis to indicate how corn prices impact the total biofuel supply curve.

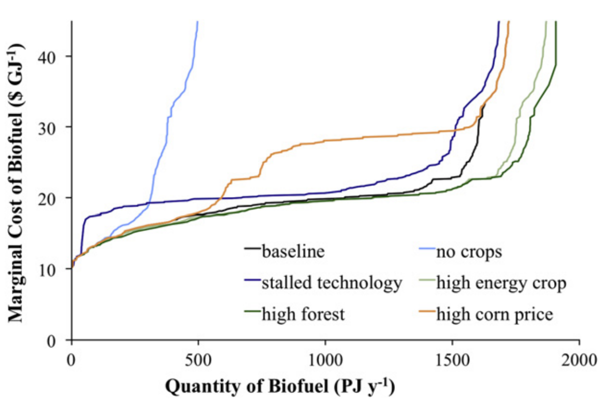

Fig. 6 – Sensitivity analysis results – high corn price (232 $ t^{-1}), exclusion of crop-based biofuels, stalled technology, increased energy crop yield, increased forestry activity.

Recent work [59,62] has called into question greenhouse gas emission benefits attributed to biofuels produced from crops (corn, seed oils and herbaceous energy crops) due to induced land use changes, including indirect effects. If these findings prove to be valid for the crops grown in the western region, the biofuel industry could have a significantly smaller resource base that satisfies the qualifications for "renewable biomass" under the federal Renewable Fuel Standard. For the same price point of 19.6 $ GJ^{-1}, removing corn, seed oils and herbaceous energy crops from consideration reduces the production of biofuels by 40% of the baseline, and the maximum production potential is greatly reduced to 29% of the baseline potential.

In addition, we considered cases where the development of cellulosic ethanol technology stalls and does not meet the projected performance targets, the case of more intensive energy crop production (described in 3.2.6) and the case of increased production of forest biomass (described in 3.2.4). Increasing the intensity of production of both energy crops and forest resources led to gains of biofuel production of 140 PJ and 150 PJ, respectively, within the price range of 20.5 $ GJ^{-1} to 22.5 $ GJ^{-1}. The stalled technology case had relatively small impact, increasing the cost by 1.6 $ GJ^{-1} and reducing the total production.

5. Conclusions

A robust model for biorefinery siting optimization has been developed for use with GIS-based spatial distributions of biomass resource. Model analysis over the western region of the United States shows there is a substantial potential for producing biofuels from agricultural, forest, urban, and energy crop biomass. Above a market price of 19.6 $ GJ^{-1}, the largest share of biofuel is predicted to come from energy crops. However, concerns over sustainability of energy crop production make this estimate uncertain.

The coupling of the GIS resource model with the mixed integer-linear optimization model for biorefinery siting provides capability for modeling a wide range of policy scenarios and testing sensitivity to changes in resource type, biomass production yield, capacity and efficiency, refinery type and performance, and fuel product and quality, as well as costs and revenues throughout the feedstock supply, conversion, and biofuel supply and use value chain. Further work is in progress to extend the model across the U.S. including regional fuel demands, stochastic and temporal effects, and competing feedstock demand sectors, especially electricity generation. Work is also underway to incorporate a more extensive spatial assessment of the sustainability of feedstock and bioenergy production.

Acknowledgements

We would like to thank Mui Lay for assistance with geographic analysis and mapping. This work was conducted under the Strategic Bioenergy Assessment of the Western Governors' Association. Support for this work was provided by the United States Department of Agriculture and the Sustainable Transportation Energy Pathways (STEPS) program at UC Davis.

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