Biomass Utilization Allocation in Biofuel Production: Model and Application

Jianbang Gan
C.T. Smith

Abstract

Various biomass sources can potentially be used for biofuel production, and many of these same biomass sources also have other uses. This raises an important question about biomass utilization allocation. We demonstrate an economic principle for biomass allocation by examining the profitability of woody biomass utilization in a simple two-product case. We then develop a mixed-integer programming model for allocating multiple biomass resources in the production of different biofuels and bioproducts. Our model combines biomass utilization allocation with biofuel supply chain optimization. The model is applied to solving the forest biomass utilization allocation problem for East Texas in the southern United States. We find that besides biofuel prices, production scale and CO_2 offset credits also significantly affect biomass utilization allocation. Our findings validate our integrative model approach to addressing biomass allocation and provide useful implications for enhancing the efficient utilization of forest biomass.

Keywords: forest biomass, biofuel supply chain, greenhouse gas offset, mathematical programming, southern United States.
Received 10 October 2010, Revised 20 July 2012, Accepted 24 October 2012.

Introduction

Several types of forest biomass can potentially be used for energy production. They include logging residues, thinning residues, milling residues, short-rotation woody crops and urban residues from trees and used wood, among others. Besides their possible use as biofuel feedstock, many of these woody biomass sources have other competing uses or play multiple roles in the economic and environmental systems. For example, logging residues can be utilized for energy, pulp or wood panel production (Gan and Smith 2006) or left at the harvest site to enhance soil and water conservation, carbon and nutrient cycling and wildlife habitat (Powers et al. 2005). Even for energy production, woody biomass can be used to produce different energy products (e.g., wood pellets, heat, electricity, liquid fuels, and so forth). This raises two important questions—how much forest biomass to harvest, and how to allocate the harvested biomass into the production of different bioenergy and wood products?

The answers to these questions will depend upon many factors, including at minimum the characteristics of forest biomass sources and the drivers or goals of their utilization. On the one hand, a feedstock needs to meet certain economic and environmental requirements for commercial-scale biofuel production. Sustainable biofuel feedstocks must be cost-competitive, relatively abundant and environmentally benign. Different biomass sources have different characteristics that affect their suitability as biofuel feedstocks. These characteristics need to be better understood so the advantages and disadvantages of a specific feedstock can be holistically assessed. For example, producing biomass by thinning fire-hazardous forest stands could be costly, whereas the quantity of this biomass is significant (Perlack et al. 2005, U.S. Department of Energy 2011). However, using this type of biomass for biofuel production can reduce wildfire risk as a result of reduced fuel-loading on forestlands, leading to the reduction of wildfire damage and the offsets of greenhouse gas (GHG) emissions from wildfire and the combustion of fossil fuels displaced by the biofuel produced from the biomass. This co-benefit is likely to offset (at least partially) the high cost of thinning overstocked forests. The cost offset will make the biomass more attractive for biofuel production while encouraging forestland owners to thin overstocked forests to reduce wildfire risk.

On the other hand, allocation of biomass among different uses is also influenced by market and nonmarket drivers. The production costs and prices of final fiber and energy products play a vital role in resource allocation. Additionally, there are other drivers of biofuels, including GHG emission offsets, national energy security, and economic development

Author information: Jianbang Gan (corresponding author), Department of Ecosystem Science and Management, Texas A&M University, College Station, Texas 77843-2138, USA, j-gan@tamu.edu. C.T. Smith, University of Toronto, 33 Willcocks Street, Toronto, Ontario M5S 3B3, Canada, tat.smith@utoronto.ca.

International Journal of Forest Engineering
ISSN 1494-2119 (print) and 1913-2220 (online)

(U.S. Congress 2007). These drivers are complex and sometimes conflict with one another in terms of their influence on biomass allocation. For instance, to offset GHG emissions, using biomass for power generation may be more beneficial than for producing liquid fuels. Producing liquid fuels with biomass, however, should be given a higher priority than power generation, if the primary goal is to enhance national energy security by reducing dependence on imported oil. The divergence in the impacts of these drivers calls for a systematic approach to determining biomass utilization allocation.

Yet literature on biomass use allocation is lacking, even though many studies have explored the supply chain management of forest products and biofuels (An et al. 2011). Most of the existing studies probe either biomass supply (Freppaz et al. 2006, Gan 2007) or logistics (Gunnarsson et al. 2003, Frombo et al. 2009, Kim et al. 2011) or both (Sokhansanj et al. 2006). Supply chains for multiple final products have also been analyzed (Chauhan et al. 2009). Among the studies on biomass/bioenergy logistics are analyses of techno-economic aspects (particularly facility siting) of bioenergy supply chains using various methods, including mathematic programming and spatial analysis tools (He and Zhang 2010, Rentizelas and Tatsiopoulos 2010, Tittmann et al. 2010). These studies, however, do not directly address biomass use allocation issues. And many of them incorporate neither environmental considerations nor the economies of scale.

This paper focuses on forest biomass allocation and utilization in terms of economic efficiency and environmental consequences, particularly GHG offsets. We will first summarize the general characteristics of major forest biomass feedstocks. We will then depict an economic principle of resource allocation, which is illustrated using a simple case of determining forest biomass allocation between wood pulp and biofuel production. This will be followed by the description of an empirical mixed-integer programming (MIP) model for determining biomass harvest levels and allocating different feedstocks into production of multiple final products (e.g., biofuels, biopower and bioproducts) with consideration of both the energy value and GHG credits of biofuels. Our model encompasses the supply chain of forest biofuels, allowing for (a) more comprehensive inclusion of biomass and biofuel production costs by incorporating the economies of scale and (b) the examination of interrelationships among different segments of the supply chain. Finally, the model will be applied to solving a biomass allocation problem in East Texas, USA. Although its application focuses on forest biomass, the model is applicable for allocations of non-forest biomass feedstocks in different regions.

Characteristics of Forest Biomass

Different forest biomass sources have different advantages and disadvantages in terms of production cost, availability and environmental impact. Here we briefly summarize general characteristics of forest biomass sources (Table 1), because these characteristics have implications for biomass utilization. In comparison with agricultural biomass (perennial plants or crop residues), forest biomass has another important advantage — it can be supplied almost year around.

Mill residues are relatively uniform in quality and physical characteristics and easily accessible, yet most of them have been used for power and heat generation, mainly by the forest products industry. Their current use patterns, however, can change at different market conditions and policy mandates.

Logging residues are relatively abundant and have proved to be a viable feedstock source in Nordic countries and other parts of the world. Their production cost varies with terrain conditions, spatial distribution density, and hauling distance. The major concern or uncertainty about collecting logging residues is possible negative impacts on long-term soil productivity and biodiversity (Lattimore et al. 2009). The mechanically recoverable rate of logging residues is about two-thirds. When long-term soil productivity loss is considered, the economically optimal removal rate could be lower than the mechanically recoverable rate (Gan and Smith 2010). Consideration of site quality would probably suggest that managers avoid taking leaves and needles from the harvest site.

Thinning residues include those from silvicultural thinning, such as early releases and precommercial and commercial thinning and forest fuel treatment thinning aimed at mitigating wildfire hazard. The amount of biomass that can potentially be derived from either type of thinning is significant in

Table 1. *Characteristics of forest biomass.*

Biomass sources	Production cost	Quantity	Environmental Impact	Other
Mill residues	Low	Most have been used, but could be re-allocated	Small	Ready for use, uniform
Logging residues	Medium	Large, not used	Varying with removal intensity	Site preparation benefits
Thinning residues	High	Large, not used	Varying with removal intensity	Benefits for timber production and/or fire mitigation
Small-diameter trees	Medium-high	Large, yet could be used as pulpwood	Varying	New use/market, stand improvement
Energy plantation	Medium-high	Potentially large	Varying	Additional land required and high input

the U.S. Yet production cost could be very high (Arriagada et al. 2008), as could soil nutrition-related risks. The benefits derived from silvicultural thinning and wildfire risk reductions, although hard to quantify, can at least partially offset the production cost.

Small-diameter trees left over after high grading harvests could also be a potential feedstock source for biofuel production. The exact amount of this biomass resource is yet to be assessed. Stand improvements may require removing these small-diameter and low-quality trees. The benefit from, or incentive for, stand improvement can lower the actual cost needed to be compensated for the biomass generated.

Short-rotation woody biomass plantations are another potential bioenergy feedstock resource. Availability will largely depend upon how much suitable land is available for such plantations. Possible high inputs and added pressure on land use are likely to increase the production cost of this biomass and cause some undesired environmental impacts. On the other hand, plantations will allow for easier machine operations, reducing the costs of growing and harvesting biomass, and can increase the spatial density of biomass, lowering feedstock transportation costs.

Materials and Methods

Allocation of a Limited Resource Among Competing Uses

In this context, the economic competitiveness is assessed with regard to the ceiling price of wood. The basis of the approach is the idea of increasing competition between different wood energy conversion pathways if shortages of wood supply arise. Wood prices are a well-accepted indicator of the scarcity of resources (Endres and Querner 1993, Hackett 2006). The various ceiling prices are calculated by applying the annuity method for a period of 20 years (with annuity factor a=0.1168). Therefore, the ceiling prices for wood (P_w) are determined by the capital expenditures ($I_i \times a$), operating expenditures ($O_i \times a$), subsidies in the form of tax reliefs or investment grants (S_i) and the revenues from heat sales (R_h) and/or feed-in tariffs (R_p). Regarding the co-firing of wood with hard coal, the savings from purchasing EU emission allowances are included, as well. In financial terms, it is the CO_2-emission avoidance (E_i) multiplied with the price of EU emission allowances at the European Energy Exchange (EEX) spot market (P_{eua}). Given all these parameters, Equation (1) describes the wood ceiling price as a function of the fossil fuel reference price (P_f).

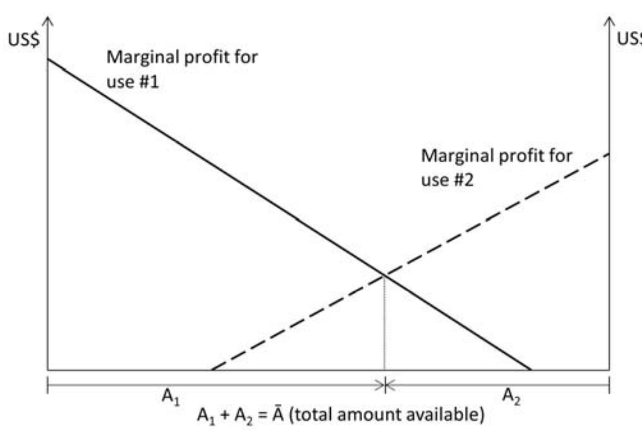

Figure 1. *Efficient allocation of a fixed amount of a resource between two competing uses*.

We apply this principle to examining the allocation of woody biomass between the uses for biofuel production and traditional wood pulp production. Although wood pulp is an intermediate product, it seems more comparable with bioethanol in terms of production cost. The marginal profit (MP) for biofuel is $MP_e = p_e\ \partial V_e/\partial A_e$ - $MC(A_e)$, and the marginal profit for wood pulp is given by $MP_w = p_w\ \partial V_w/\partial A_w$ - $MC(A_w)$, where the subscripts e and w respectively denote biofuel and wood pulp, p is the price of the final product, V represents the physical output of the final product, $\partial V/\partial A$ (the first-order partial derivative of V with respect to A) is the marginal physical product (biofuel or wood pulp) of woody biomass, and MC is the marginal cost of biomass. Letting $MP_e = MP_w$, we can derive the relationship between p_e and p_w that ensures the equality of the marginal profits of producing either biofuel or wood pulp from one additional unit of biomass. Any combination of p_e and p_w that is not on the line represented by this relationship suggests that one use of the biomass is more profitable than the other (to be illustrated and further explained in the Result and Discussion section).

Estimating the profit of biofuels, however, can be complicated because their production cost can vary with many factors, such as technologies used, facility location, production scale, and so forth. Additionally, biofuel benefits may include the revenues from biofuel sales, GHG credits, and other associated benefits. To portray this whole picture, we need a more comprehensive and capable model for determining biomass allocation.

A Mixed-Integer Programming Model of Biomass Allocation

The model we propose is a nonlinear MIP model. It is intended to allow us to simultaneously determine the amount of biomass harvested from all basic spatial units in the study region, allocation of each biomass resource to the production of various biofuels, and location and size of biomass storage and conversion facilities.

Our model has several unique features. First, because biofuel production costs are sensitive to production scale or plant size, a nonlinear relationship between costs and plant size is embedded in our model. Second, the number of conversion and intermediate processing facilities has an integer value, thus leading to an MIP model. Third, besides the energy value of biofuels, GHG credits are accounted for and included in the model. Fourth, multiple feedstock sources and multiple final products are allowed. Finally, for simplification and tractability, it is assumed that for each basic spatial unit, biomass is supplied at a centralized point, whereas biomass is grown across the landscape of the spatial unit.

The symbols used to denote the variables and parameters in the model are described in Table 2. With these, the mathematic expression of the model can be written as follows.

Objective Function

$$Max\ \pi = \sum_{f} p_f Q_f + \sum_{jlft} p_c \delta_{lft} \eta_{lft} U_{jlft} - \sum_{il} cb_{il} X_{il} - \sum_{ijls} ct1_{ijls} Y1_{ijls} - \sum_{ikls} ct2_{ikls} Y2_{ikls} - \sum_{kjls} ct3_{kjls} Y3_{kjls} - \sum_{klm} cs_{klm} ZS_{klm} m - \sum_{jlfnt} cr_{jlfnt} ZR_{jlfnt} n \quad (1)$$

The objective function is to maximize the annual profit (π) of overall production of biofuels, biopower and bioproducts in a study region. The revenue will come from the sales of final products (biofuels, biopower and bioproducts) and the credits of GHG emissions offsets. The costs include those of growing, harvesting and transporting biomass to a centralized location in the basic spatial unit; biomass transportation from a centralized growing site to a refinery or storage and from a storage facility to a refinery; biomass storage; and biomass-to-biofuel conversion. The storage and conversion costs also account for the costs associated with the idle capacities of storages and refineries to ensure the appropriate sizes of storage and conversion facilities are built. For simplicity, we assume biomass will be supplied within a basic spatial unit at a constant price. Economies of scale are also incorporated in calculating storage and conversion costs. The unit cost function for storing or converting biomass at the scale S is $c(S) = c_o(S/S_o)^{\alpha-1}$, where c_o is the unit cost at the base scale S_o and α is the scale factor. The scale factor reflects the economies of scale in production, depending upon production technologies used and ranging from 0 and 1 (usually between 0.6 and 0.9) (Kumar et al. 2003, Gallagher et al. 2005, Gan and Smith 2011).

Table 2. *Symbols for variables and parameters used in the model.*

Symbol	Description
Subscripts	
f	Type of final products including biofuels, biopower, heat and bioproducts
i	Site where biomass is grown (although it denotes centralized spatial points, it represents an area or a basic spatial unit in the model)
j	Location of conversion plants or refineries
k	Location of biomass storages
l	Type of biomass
m	Size of storages
n	Size of refineries
s	Type of transportation mode
t	Type of conversion technology
Parameters	
cb_{il}	Unit cost of biomass l supplied at site i (including biomass growing, harvesting and transporting to the centralized location within a basis spatial unit or a county in our case study shown later)
$ct1_{ijls}$	Unit cost of transporting biomass l from feedstock site i to refinery location j via transportation mode s
$ct2_{ikls}$	Unit cost of transporting biomass l from feedstock site i to storage location k via transportation mode s
$ct3_{kjls}$	Unit cost of transporting biomass l from storage location k to refinery location j via transportation mode s
cr_{jlfnt}	Unit cost of converting biomass l to product f at scale n and refinery location j using technology t
cs_{klm}	Unit cost of storing biomass l in the storage of size m at storage location k
p_f	Price of final product f
p_c	Price of GHG (CO_2-equivalent) offset
$\bar{x}_{il}$	Maximum available amount of biomass l grown at site i
θ	Proportion of biomass lost during storage
η_{lft}	Conversion rate from biomass l to product f using technology t
δ_{lft}	Life-cycle GHG (CO_2-equivalent) balance of product f converted from biomass l using technology t
Decision variables	
Q_f	Quantity of final product f produced
U_{jlft}	Amount of biomass l allocated to the production of product f at refinery location j using conversion technology t
X_{il}	Amount of biomass l produced/supplied at site i
$Y1_{ijls}$	Amount of biomass l transported from feedstock site i to refinery location j via transportation mode s
$Y2_{ikls}$	Amount of biomass l transported from feedstock site i to storage location k via transportation mode s
$Y3_{kjls}$	Amount of biomass l transported from storage site k to refinery location j via transportation mode s
ZR_{jlfnt}	Number of refineries of size n that convert biomass l to biofuel f at refinery location j (integer) using conversion technology t
ZS_{klm}	Number of storages of size m for biomass l at storage location k (integer)
Other symbol	
π	Annual profit

Constraints

The model is subject to several constraints, including the maximum amount of biomass that can be harvested from each basic spatial unit, biomass transportation constraints and storage and refinery capacity constraints. The biomass harvest constraint is

$$X_{il} \leq \bar{x}_{il}. \quad (2)$$

Inequality (2) imposes a limit on the total harvest of a given biomass type at a specific biomass growing/supply site (basic spatial unit) so that actual harvest will not exceed the maximum allowable level.

Biomass can be transported either from a harvest site to a refinery directly, or from a harvest site to a storage location and then to a refinery. There are two subsets of biomass transportation constraints. The first one is to ensure that the amount of each biomass type shipped to all the refineries and storage facilities from a biomass supply site does not exceed the amount of biomass harvested from the site, i.e.

$$\sum_{jls} Y1_{ijls} + \sum_{kls} Y2_{ikls} \leq X_{il}. \quad (3)$$

The other transportation constraint deals with inflows and outflows of biomass to/from a storage facility. The total amount of biomass shipped to a storage facility from all biomass growing sites, adjusted for handling loss, should be equal to the amount of biomass shipped out to all refineries, i.e.

$$(1-\theta)\sum_{is} Y2_{ikls} = \sum_{js} Y3_{kjls} \quad (4)$$

where θ is the proportion of biomass lost during storage. Equation (4) implies that biomass storage is temporary, i.e., biomass stored in a facility will eventually have to be delivered to a refinery.

The capacity constraints for storage and refineries take the following forms:

$$\sum_{is} Y2_{ikls} \leq \sum_{m} ZS_{klm} m \quad (5)$$

$$\sum_{is} Y1_{ijls} + \sum_{ks} Y3_{kjls} \leq \sum_{fnt} ZR_{jlfnt} n. \quad (6)$$

Constraint (5) states that the total amount of biomass shipped to a storage facility ($_k$) should be within the limit of the total storage capacity available at that location. And inequality (6) implies that the amount of biomass shipped to a refinery location should not be over the limit of the total refinery capacity available at that location.

Additionally, the feedstock allocation/utilization constraint can be expressed as

$$\sum_{ft} U_{jlft} = \sum_{is} Y1_{ijls} + \sum_{ks} Y3_{kjls}. \quad (7)$$

Equation (7) is to ensure that the total amount of a type of biomass ($_l$) used to produce all types of final products at a given refinery location ($_j$) is equal to the amount of biomass shipped to that location from all feedstock supply sites and storage facilities. This constraint serves as an accounting equation, providing direct answers to the biomass use allocation question. It also enables us to model the choice of conversion technologies.

Finally, the quantity of final products produced can be written as

$$Q_f = \sum_{jlt} \eta_{lft} U_{jlft}. \quad (8)$$

All variables are non-negative, and ZSkm and ZRjfnt are integers. (1)-(8) plus the non-negativity and integer constraints of variables constitute an MIP problem.

Study Area, Simulation Scenarios and Data Sources

The model was applied to East Texas to test its applicability to regional biomass use allocation. The study area, located north to the Gulf of Mexico, consists of 48,000 km^2 of timberland (Smith et al. 2004) and is an important part of the U.S. southern forest region. Forestry and the forest products industry have traditionally played a significant role in its rural economy, with an average annual timber harvest of 19 million m^3 (Gan and Smith 2007). Faced with the challenge of recent weak pulpwood and timber markets, the region is actively seeking alternative uses of its productive forests and abundant forest biomass, including development of forest bioenergy. A power plant fueled by forest biomass has just been commissioned in East Texas. Additionally, the energy sector is another key economic player in the area, where several nationally significant petroleum refineries are located. Hence, East Texas is an excellent region in which to base this study.

The model was run for a base scenario that represents the most likely market and technology conditions for biofuels in the near future. In addition, several variations associated with the base scenario were also simulated, including changes in the scale factor and CO_2 price.

The values of key parameters for the base scenario are shown in Table 3. The values of key techno-economic parameters were taken from Antares (2008). The GHG emissions and net balances of forest bioenergy were derived from Gan and Smith (2010a, 2010b), reflecting the life-cycle consequences of forest bioenergy. Additionally, the maximum amount of available forest biomass feedstock, including logging residues, thinning residues and mill residues, were drawn from Gan and Smith (2006), VanderSchaaf (2009), and Gan et al. (2013). The base CO_2 price reflects the average daily closing price traded at the Chicago Climate Exchange from its inception to November 2008 (Gan and McCarl 2010).

This model was written in GAMS and solved using the MINLP solver (GAMS Development Corporation 2012).

Table 3. *Values of key parameters for the base simulation scenario.*

Parameter	Value
Bioethanol price	US$0.53 L^{-1}
Electricity price	US$100 MWh^{-1}
CO_2 price (credit)	US$2.50 t^{-1}
Unit cost of logging residues at the centralized location in a basic spatial unit	US$ 30 bdt^{-1}
Unit cost of fuel treatment thinning residues at the centralized location in a basic spatial unit	US$ 50 bdt^{-1}
Unit cost of mill residues at the centralized location in a basic spatial unit	US$ 10 bdt^{-1}
Biomass storing cost at the base scale	US$10 t^{-1}
Bioethanol conversion cost at the base scale	US$0.35 L^{-1}
Bioelectricity generation cost at the base scale	US$30 MWh^{-1}
Energy content of biomass	19 GJ bdt^{-1}
Ethanol yield	334 L bdt^{-1}
Efficiency of converting feedstock to electricity	0.30
Cost of transporting biomass from harvest sites to storage facilities or conversion plants	US$0.14 t^{-1} km^{-1}
Cost of transporting biomass from storage facilities to conversion plants	US$0.10 t^{-1} km^{-1}
Biomass loss during storage	6%
Base scale of conversion plants	50 MW (electricity) $8.5x10^7$ L yr^{-1} (ethanol)
Scale factor of storages and conversion plants	0.80

Note: L=liter, MW=megawatt, MWh=megawatt per hour, t=tonne=1000 kilograms, bdt=bone dry tonne, GJ=gigajoule, km=kilometer, and yr=year.

Results and Discussion

Woody biomass should be allocated between the production of bioethanol (or bioelectricity) and wood pulp based on $MP_w=MP_e$ when profit maximization is the sole objective (Figure 2). When prices of bioenergy and wood pulp are above the $MP_w=MP_e$ line, all biomass should be used for wood pulp production to maximize the profit. On the other hand, when prices of bioenergy and pulp fall below the $MP_w=MP_e$ line, bioenergy is more profitable than pulp. Finally, when the prices of bioenergy and pulp are on the $MP_w=MP_e$ line, biomass can be used for either bioenergy or pulp production or both.

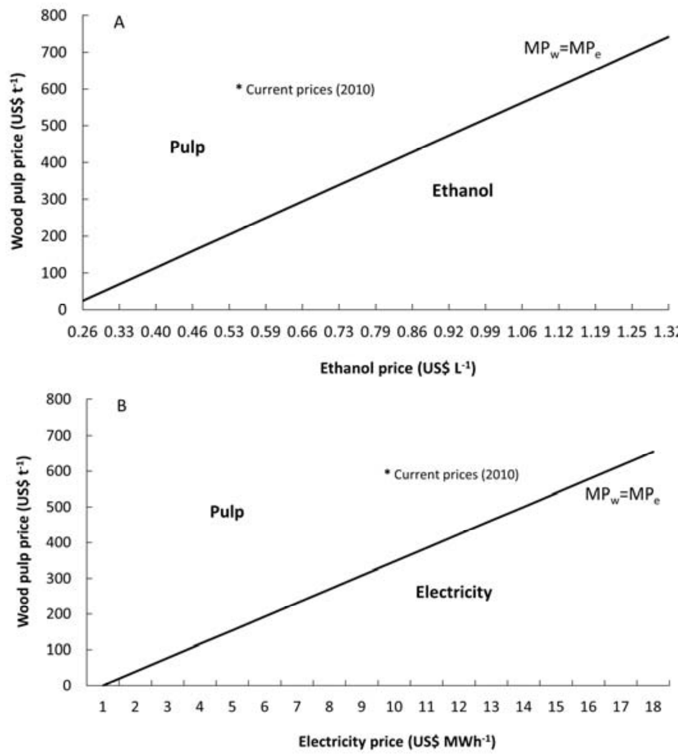

Figure 2. *Allocation of woody biomass to ethanol, electricity and pulp production when profit maximization is the sole objective, using marginal profit (MP) analysis.*

At current (2010) technologies and market prices of bioenergy and wood pulp, woody biomass that has traditionally been used for pulp production would continue to be used for that purpose. Bioenergy is not yet competitive with wood pulp in terms of profitability, because the current price points are above the $MP_w=MP_e$ line (Figure 2). Accounting for co-benefits of bioenergy, such as GHG offsets and reduced reliance on imported oil, could change this result. Although these co-benefits are not directly included in Figure 2, they can be added to the bioenergy price in the horizontal axis. If the bioenergy price is considered as a composite price that includes bioenergy price and co-benefits, then Figure 2 can also be used to determine biomass allocation in a context of multiple benefits. For instance, if the electricity price is US$100 MWh^{-1} and 1 MWh bioelectricity displaces 1 metric ton (t) of CO_2

that is valued at US$25 t^{-1}, then the composite price of the bioelectricity is US$125 MWh^{-1} (the sum of the electricity price (US $100 MWh^{-1}) and the CO_2 credit (US $25 MWh^{-1})).

Solutions of the MIP Model for East Texas

Before presenting our model simulation results, we would like to clarify three simplifications that were made in the theoretical model that was applied to this case study. First, no wood pulp production is included in the MIP model simulation. This simplifies the analysis and also is justifiable. A recent national assessment reveals that it does not make economic sense to use pulpwood for biofuel production under current technology and market conditions and even in the near future (U.S. Department of Energy 2011). On the other hand, the forest biomass resources modeled are primarily residues that traditionally are not used for pulping. Additionally, East Texas, as well as the entire U.S. South, has experienced the reductions of pulping capacity in recent years due to the weak domestic market for paper products. Hence, it is unlikely the paper industry will use these residues for pulping.

Another simplification is related to co-products. The type and amount of co-products from biofuel products varies with feedstock type and conversion technology employed. And tradeoffs exist between yields of ethanol and co-products. To our knowledge, to date there is no valid technical and economic data on co-products from commercially operated biorefineries. This creates a challenge for incorporating co-products into analysis. Frederick Jr. et al. (2008) reported that for loblolly pine (*Pinus taeda* L.) at a 75% ethanol conversion efficiency (equivalent to the ethanol yield used in this study), the value of co-products is about US$0.02 L^{-1}. We used this data for our case study.

The last simplification is related to the potential sites of storages and conversion plants. We assumed that a storage site and/or a conversion plant can be located in any of these counties in the study region. This assumption is reasonable for East Texas, given its existing transport network, terrain conditions and access to raw materials, labor supply, water resources and final-product markets.

Solution under the base scenario

Under the base scenario, most of the logging and thinning residues in East Texas would be used for ethanol production (Table 4). Only one power plant of 100 MW fired by forest biomass would be built in the region, and four ethanol mills ranging from 3.79×10^8 L yr^{-1} (100 million gallons per year (MGY)) to 1.136×10^9 L yr^{-1} (300 MGY) would be established. All forest feedstocks would be transported directly from harvest sites to conversion plants without being stored at a separate location. There would be no need for a storage facility because the region is relatively small, and biomass loading, unloading and storage add significant costs to feedstock. Biomass storage can help reduce the impact of irregularities in feedstock production and supply. Such an impact of storage, however, is not modeled in this paper.

Under the base scenario, conversion plants would be scattered across the region. The power plant would be located in the northeast area (Bowie County) of the region, and the four ethanol mills would be scattered from north to south.

Almost all forest biomass (including logging, thinning and milling residues) physically available would be harvested and used for bioenergy production. The only exception is biomass from fuel treatment thinning, for which the amount to be procured for bioenergy production would be slightly less (1%) than the maximum amount physically available from thinning operations. All mill residues would be used, but 92% of them would be diverted to ethanol production instead of power and heat generation.

Impacts of scale factor on siting and size of conversion plants

The model solution appears very sensitive to changes in the scale factor (Table 4). As the scale factor increases from 0.8 to 0.9, while keeping everything else unchanged, more and

Table 4. *Conversion plant locations and sizes at different scale factor values*

Scale Factor	Type	Size	Number	Location(s)
0.8	Power plant	100 MW	1	Bowie
	Ethanol mill	3.79×10^8 L yr^{-1}	1	Cherokee
		4.54×10^8 L yr^{-1}	1	Marion
		9.46×10^8 L yr^{-1}	1	San Jacinto
		1.136×10^9 L yr^{-1}	1	San Augustine
0.9	Power plant	25 MW	2	Leon and Red River
		50 MW	3	Houston, Hardin and Liberty
		75 MW	1	Cherokee
	Ethanol mill	1.89×10^8 L yr^{-1}	2	Sabine and Cass
		3.79×10^8 L yr^{-1}	2	Montgomery and Jasper
		4.73×10^8 L yr^{-1}	1	Polk
		5.68×10^8 L yr^{-1}	1	Nacogdoches
		6.62×10^8 L yr^{-1}	1	Upshur

smaller conversion plants would be built across the region. There would be six power plants ranging from 25 MW to 75 MW and seven ethanol mills ranging from 1.89×10^8 L yr-1 (50 MGY) to 6.62×10^8 L yr^{-1} (175 MGY). Besides the size and number of conversion plants, their locations would be quite different from those under the base scenario. The high sensitivity of conversion plant size and site to changes in the scale factor is due to the scale factor having a big impact on feedstock transportation radii and costs (Gan and Smith 2011).

Similar to the base scenario, all available biomass—but 1% of thinning residues—would be used for bioenergy production. Eighty-four percent of the total harvested biomass would be used for ethanol production, and 91% of mill residues would be redirected to ethanol production.

Impacts of CO_2 Price and Co-Products on Biomass Utilization

Biomass utilization varies considerably with CO_2 price. As CO_2 price goes up, more biomass would be utilized for electricity production (Figure 3). This is because switching biomass from ethanol production to electricity generation would lead to a net gain in GHG offset. Under the base scenario and without consideration of co-products, when the benefit of GHG offset is not valued, all biomass would be used for ethanol production. At a CO_2 price of US\$2.50 t^{-1}, only about 6% of the total forest biomass would be converted to electricity. However, as the CO_2 price reaches US\$10 t^{-1} or above, all the biomass would be used for electricity generation (Figure 3(a)).

When co-products from ethanol production are considered (Figure 3(b)), almost all biomass in the region would be used for ethanol production when the CO_2 price is below US\$12.50 t^{-1}. At the CO_2 price of US\$15 t^{-1}, about one-third of the biomass would be used for ethanol production. As the CO_2 price rises to US\$17.50 t^{-1}, no biomass would be used for ethanol production. Obviously, inclusion of co-products would lead to more biomass allocated for ethanol production ceteris paribus.

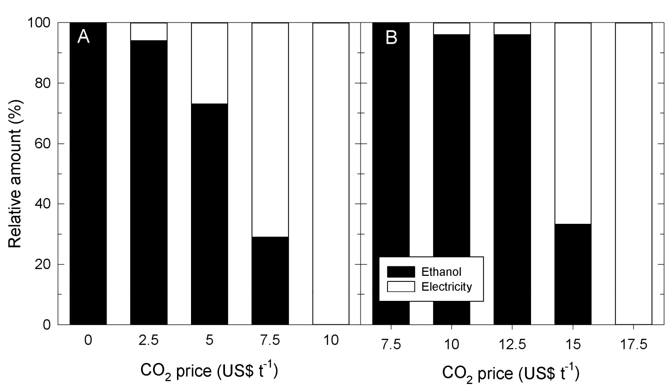

Figure 3. *Biomass allocation at different CO_2 prices without inclusion of co-products (A) and with inclusion of co-products (B).*

Conclusion

Many biomass feedstocks, including forest biomass, have competing uses; hence, their allocation among different uses must be strategically determined. By examining the profitability of wood pulp and bioenergy production, we illustrate an economic principle for allocating biomass among a variety of utilization alternatives. We further develop an MIP model for allocating various forest biomass feedstocks among the production of different final products. Our model can simultaneously determine the allocation of biomass to competing utilization options, as well as the optimum location and size of conversion plants and the selection of conversion technologies and transportation modes. It accounts for the costs of biomass harvesting, transport, processing and conversion and the benefits of CO_2 offsets, in addition to energy value. Additionally, this model incorporates the economies of scale into production cost estimates, a novelty of this paper.

The model was applied to determining allocation of forest biomass to alternative utilization options in East Texas. Marginal profit analysis suggests that wood pulp is a more profitable use of traditional pulpwood than bioenergy at current market and technology conditions in the U.S. South. However, without considering the use of forest residues for pulping, our simulation results lead to the following conclusions:

- Mill residues currently used for power generation should probably be redirected to ethanol production to increase profits;

- Allocation of forest biomass to electricity production will increase with CO_2 price and decrease with added value of co-products derived from ethanol production; and

- The location and size of conversion plants are highly sensitive to changes in the scale factor.

This study can be expanded in several dimensions. First, although bioelectricity has an advantage in GHG offset over bioethanol, the latter can help reduce reliance on imported oil, thus enhancing national energy security. Future work can incorporate this benefit into biomass allocation analysis. Second, this model can be expanded by adding a time dimension. For example, biomass supply constraints in different time periods could be included to ensure the stable supply of feedstock across various time periods. Third, although our theoretical model is capable of dealing with joint production of multiple products, as in the case of integrated biorefineries, it was not fully incorporated in the empirical simulations because of the lack of data from commercially viable operations. This modeling approach could be improved as more data from commercial operations of biorefineries become available. Finally, the application of the model was illustrated using a forest biomass case, but our model could be applied to other biomass sources including agricultural and urban biomass feedstocks. With multiple types of feedstocks, the model may need some modifications—for example, by including facility and process requirements for handling multiple or mixed feedstocks.

Acknowledgments

This paper was originally presented during one of the technical sessions of the International Workshop "Sustainability Across the Supply Chain of Land-Based Biomass," which was hosted jointly by IEA Bioenergy Task 43 Biomass Feedstocks for Energy Markets and the Long-Term Soil Productivity Study (LTSP) in Kamloops, BC, Canada on 1-4 June 2010.

The study leading to this paper was financially supported in part by the U.S. Department of Agriculture, Texas A&M AgriLife Research and the University of Toronto.

Literature Cited

An, H., Wilhelm, W.E. & Searcy, S.W. 2011. Biofuel and petroleum-based fuel supply chain research: a literature review. *Biomass and Bioenergy* 35: 3763-3774.

Antares Group, Inc. 2008. *Strategic assessment of bioenergy development in the west: bioenergy conversion technology characteristics.* Technical report, Western Governors' Association.

Arriagada, R.A., Cubbage, F.W., Abt, K.L. & Huggett, R.J. Jr. 2008. Estimating harvest costs for fuel treatments in the west. *Forest Products Journal* 58(7/8): 24-30.

Chauhan, S.S., Frayret, J.M. & LeBel, L. 2009. Multi-commodity supply network planning in the forest supply chain. *European Journal of Operational Research* 196: 688-696.

Frederick, W.J. Jr., Lien, S.J, Courchene, C.E., DeMartini, N.A, Ragauskas, A.J. & Iisa, K. 2008. Production of ethanol from carbohydrates from loblolly pine: a technical and economic assessment. *Bioresource Technology* 99: 5051-5057.

Freppaz, D., Minciardi, R., Robb, M., Rovatti, M., Sacile, R. & Taramasso, A. 2004. Optimizing forest biomass exploitation for energy supply at a regional level. *Biomass and Bioenergy* 26: 15-25.

Frombo, F., Minciardi, R., Robba, M., Rosso, F. & Sacile, R. 2009. Planning woody biomass logistics for energy production: a strategic decision model. *Biomass and Bioenergy* 33: 372-383.

Gallagher, P., Brubaker, H. & Shapouri, H. 2005. Plant size: capital cost relationships in the dry mill ethanol industry. *Biomass and Bioenergy* 28: 565-571.

GAMS Development Corporation. 2012. *GAMS—a user's guide*. Washington, DC. Retrieved June 16, 2012, from www.gams.com/dd/docs/bigdocs/GAMSUsersGuide.pdf.

Gan, J. 2007. Supply of biomass, bioenergy, and carbon mitigation: Method and application. *Energy Policy* 35: 6003-6009.

Gan, J. & Smith, C.T. 2006. Availability of logging residues and their potential for electricity production and carbon displacement in the U.S. *Biomass and Bioenergy* 30: 1011-1020.

Gan, J. & Smith, C.T. 2007. Co-benefits of utilizing logging residues for bioenergy production: the case for East Texas, USA. *Biomass and Bioenergy* 31: 623-630.

Gan, J. & McCarl, B.A. 2010. *Forestry and carbon: market, measurement and management*. In, Gan, J., Grado, S. & Munn, I. (Eds.). Global Change and Forestry: Economic and Policy Impacts and Responses. New York: Nova Science. pp. 1-15.

Gan, J. & Smith, C.T. 2010a. Integrating biomass and carbon values with soil productivity loss in determining forest residue removals. *Biofuels* 1(4): 539-546.

Gan, J. & Smith, C.T. 2010b. Coupling life-cycle analysis with supply chain optimization in determining biofuel plant size. *Silva Fennica* 44(3): 497-510.

Gan, J. & Smith, C.T. 2011. Optimal plant size and feedstock supply radius: a modeling approach to minimize bioenergy production costs. *Biomass and Bioenergy* 35: 3350-3359.

Gan, J., Jarrett, A. & Johnson, C. 2013. Forest fuel reduction and biomass supply: perspectives from southern private landowners. *Journal of Sustainable Forestry* 32(1-2): 28-40.

Gunnarsson, H., Rönnqvist, M. & Lundgren, J.T. 2003. Supply chain modeling of forest fuel: production, manufacturing and logistics. *European Journal of Operational Research* 158: 103-123.

He, J. & Zhang, W. 2010. Techno-economic evaluation of thermo-chemical biomass-to-ethanol. *Applied Energy* 88: 1224-1232.

Kim, J., Realff, M.J., Lee, J.H., Whittaker, C. & Furtner, L. 2011. Design of biomass processing network for biofuel production using an MILP model. *Biomass and Bioenergy* 35: 853-871.

Kumar A., Cameron, J. & Flynn, P. 2003. Biomass power cost and optimum plant size in western Canada. *Biomass and Bioenergy* 24: 445-464.

Lattimore, B., Smith, C.T., Titus, B.D., Stupak, I. & Egnell, G. 2009. Environmental factors in woodfuel production: opportunities, risks, and criteria and indicators for sustainable practices. *Biomass and Bioenergy* 32(10): 1321-1342.

Mayfield, C.A., Foster, C.D., Smith, C.T., Gan, J. & Fox, S. 2007. Opportunities, barriers, and strategies for forest bioenergy and bio-based product development in the southern United States. *Biomass and Bioenergy* 31: 631-637.

Perlack, R., Wright, L., Turhollow, R., Graham, R., Stokes, B. & Erbach, D. 2005. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A., Page-Dumroese, D., Elioff, J.D. & Stone, D.M. 2005. The North American long-term soil productivity experiment: findings from the first decade of research. *Forest Ecology and Management* 220: 31-50.

Rentizelas, A.A. & Tatsiopoulos, I.P. 2010. Locating a bioenergy facility using a hybrid optimization method. *Internal Journal of Production Economics* 123: 196-209.

Smith, W.B., Miles, P.D., Vissage, J.S. & Pugh, S.A. 2004. *Forest resources of the United States, 2002*. Gen. Tech. Rep. NC-241. St. Paul, Minnesota: USDA Forest Service North Central Research Station.

Sokhansanj, S., Kumar, A. & Turhollow, A.F. 2006. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). *Biomass Bioenergy* 30: 838-47.

Tittmann, P.W., Parker, N.C., Hart, Q.J. & Jenkin, B.M. 2010. A spatially explicit techno-economic model of bioenergy and biofuels production in California. *Journal of Transport Geography* 18: 715-728.

U.S. Congress. 2007. The Energy Independence and Security Act of 2007. Washington, DC.

U.S. Department of Energy. 2011. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. Oak Ridge, Tennessee: Oak Ridge National Laboratory.

VanderSchaaf, C. 2009. *Biomass from logging residue and mill residue in East Texas, 2008*. College Station, Texas: Texas Forest Service.