Spatially and Temporally Optimal Biomass Procurement Contracting for Biorefineries

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This paper evaluates the optimal composition of annual and perennial biomass feedstocks for a biorefinery. A generic optimization model is built to minimize costs – harvest, transport, storage, seasonal, and environmental costs – subject to various constraints on land availability, feedstock availability, processing capacity, contract terms, and storage losses. The model results are demonstrated through a case study for a midwestern U.S. location, focusing on bioethanol as the likely product. The results suggest that high-yielding energy crops feature prominently (70 to 80%) in the feedstock mix in spite of the higher establishment costs. The cost of biomass ranges from 0.16 to 0.20 $ l^{-1} (US$ 0.60 to $0.75 per gallon) of biofuel. The harvest shed shows that high-yielding energy crops are preferably grown in fields closer to the biorefinery. Low-yielding agricultural residues primarily serve as a buffer crop to meet the shortfall in biomass requirement. For the case study parameters, the model results estimated a price premium for energy crops (2 to 4 $ t^{-1} within a 16 km (10-mile) radius) and agricultural residues (5 to 17 $ t^{-1} in a 16 to 20 km (10 to 20 mile) radius.

Keywords: Cellulosic biofuels; Biomass; Biorefinery; Supply; Harvest shed

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INTRODUCTION

Future cellulosic biorefineries are expected mainly to be large-scale facilities using multiple sources of feedstocks. Determining the optimal combination of feedstocks for these biorefineries involves a number of considerations: (i) assuring a reliable supply and uniform quality of biomass over the entire productive lifetime of the biorefinery; (ii) lowering procurement costs (harvest, baling, transport, storage, and seasonal costs); and (iii) reducing the greenhouse gas (GHG) emissions to qualify as a cellulosic biofuel under the federal renewable fuels standard or similar regulations, and possibly for tradable GHG credits. The contractual terms may differ for annual and perennial feedstocks, requiring the biorefineries to take a lead role in developing and controlling their own feedstock supply. This article evaluates the optimal spatial and temporal characteristics of a vertically integrated biomass operation from the point of view of the biorefinery.

Biorefineries constructed in the Midwest are likely to draw from two major types of agricultural feedstocks: (1) energy crop biomass derived from perennial grasses such as switchgrass, *Miscanthus*, and mixed grasses, and (2) agricultural residue biomass derived from annual field crops such as corn, wheat, and barley. Differences between these two types of feedstocks have important feedstock sourcing implications for a biorefinery. Energy crops have higher biomass yield, greater density of biomass availability (more tons per unit area), and relative climate hardiness; such factors may enable a smaller biomass collection area (James *et al.* 2010; Khanna et al. 2008; Perrin *et al.* 2008). However, higher establishment costs of energy crops, longer time delay to achieve higher yields, the necessity to arrange long-term contracts due to lack of alternative markets for the biomass, and potential environmental problems, especially invasive nature of energy crops, hinder large scale cultivation of energy crops (Raghu *et al.* 2006). On the other hand, agricultural residues are already available as cheap byproducts of annual crops. Biorefineries have flexibility in contracting for harvesting agricultural residues, as such residues are only a secondary source of revenue for grain farmers. Furthermore, residues as byproducts of grain crops have lower allocated greenhouse gas (GHG) footprints. A major disadvantage of agricultural residues is the lower yield of biomass per acre compared to perennial energy crops, and this factor tends to increase the collection area radius and transport costs.

To address these tradeoffs, a general mathematical programming model is developed. The objective of the optimization problem is to minimize the cumulative discounted costs of biomass procurement over the biorefinery's productive life. We evaluate how the contracting arrangements for various feedstocks within the collection area (visualized as a series of concentric circular zones) would be affected by the production costs, harvest costs, transport costs, short-term *versus* long-term contractual commitments, and life-cycle GHG emissions.

The decision variables of this optimization model are the land areas of alternative feedstocks contracted for biofuel production; these can vary by their location within the harvest shed and the time of availability. A key constraint in the model is the length of contracts: land with perennial feedstocks is assumed to be under a decade-long contract to provide a reliable market for all biomass produced from such plantations; land with annual feedstocks are assumed to be available under annual contracts. Marginal croplands, such as pasture, fallow land, and Conservation Reserve Program (CRP) land, are assumed to be suitable for growing perennial grasses but not annual feedgrains.

Transport costs are estimated based on the amount of feedstocks used in the biorefinery operations. Because the amounts of alternative feedstocks are the decision variables of the optimization problem, the transport costs are endogenously determined in the model. The seasonal costs and environmental costs are also endogenously determined based on the time of year and transportation distance. Harvest costs and storage losses are assumed to be exogenous constants. Other parameters include biomass yield, ethanol conversion rates, life-cycle GHG emissions, crop production costs, harvesting costs, length of long-term contractual commitment needed to supply perennial feedstocks, and storage loss factor.

The results of the model are demonstrated for a case study location in Hugoton, in Southwestern Kansas. A biorefinery with an annual capacity of 200 M l (200 million liters or 53 million gallons) utilizing corn stover and *Miscanthus*, to represent annual and perennial feedstock, respectively is analyzed (Wright and Brown 2007).

LITERATURE REVIEW AND CONTRIBUTION

Extant studies employ a number of methods to estimate the quantity and price of biomass for biofuel production: enterprise budgeting (Atchison and Hettenhaus 2003; Genera Energy 2009; Perrin *et al.* 2008), supply curve analysis (De La Torre Ugarte and Ray 2000), simulation modeling (Sokhansanj *et al.* 2008, 2009), and mathematical optimization (Cundiff *et al.* 1997; Epplin 2009; Kang *et al.* 2010; Shastri *et al.* 2011; Wang *et al.* 2009). The estimated biomass cost per unit output of ethanol range from 0.10 to 0.12 $ l^{-1} ($0.40 to $0.45 per gallon) reported in techno-economic studies conducted by the US Department of Energy to 0.17 to 0.21 $ l^{-1} ($0.67 to $0.84 per gallon) of cellulosic ethanol – assuming 26.2 l t^{-1} ethanol yield (90 gallons per ton of biomass) – estimated using optimization models such as the Integrated Biomass Supply and Logistics (IBSAL) model (Kumar and Sokhansanj 2007; Sokhansanj et al. 2006). The biomass yield levels have been reported to be the key factors determining the optimal composition of multiple feedstocks (Dunnett *et al*. 2008; Jacobson *et al.* 2009).

Cundiff *et al*. (1997) estimated that harvest shed extended up to 22 km (~14 mile radius) to supply 67,200 t (74,000 tons) of switchgrass. Shastri *et al*. (2011) also estimated the costs of supplying single feedstock (switchgrass) to range from 45 to 49 $ Mg^{-1}; their optimization model suggested on-farm storage to create cost effective biomass supply. Epplin *et al.* (2007) and Mapemba *et al.* (2007, 2008) studied the optimal combinations of naturally grown perennial grasses and agricultural residues using a series of mixed integer linear programming models. Their model maximized the net present value of profits for a biorefinery that used the saccharification and fermentation process over a 20-year time frame. In their results, the proportion of energy crops was low due to lower yields of cellulosic biomass when energy crops were naturally grown in Conservation Reserve Program (CRP) lands. Other optimization models, such as FASOM and BEPAM, also estimate the optimal composition of multiple feedstock biomass at the national (U.S.) level (Khanna *et al.* 2010; McCarl *et al.* 2000). The BEPAM model predicted that energy crops could be competitive when grown in marginal croplands. Sharma *et al.* (2013a,b) provide a review of studies that use mathematical programming models and also analyze changes in biomass supply costs under various scenarios related to weather, available work hours during the harvest time, and other inputs.

Although prior models analyze the regional or national supply of biomass, the focus of this paper is on the harvesting and contracting decisions faced by a biorefinery procurement manager. The optimization models employed by Epplin *et al.* (2007) and Mapemba *et al.* (2007, 2008) partially address this issue; the model developed for this study extends their work with a focus on the spatial and temporal distribution of alternative feedstocks. The proposed model is more generic and can be adapted for different processing technologies as well as geographic locations. The emphasis is on the analysis of spatial and temporal patterns of harvesting contracting arrangements, optimal acreage, and additional price premiums, if any, payable for cellulosic biomass.

Other novel features of this modeling approach compared with existing studies are as follows. (i) Existing studies treat the available biomass quantities in the region as exogenously given and then try to minimize procurement costs. In comparison, the proposed model treats biomass acreage to be harvested as an endogenous decision variable subject to overall biomass availability constraints;[1] (ii) transport costs are also endogenously determined as a function of harvesting decisions, which is novel compared to existing studies; (iii) the temporal yield patterns of energy crops, which also affect feedstock acreage decisions, are modeled explicitly, unlike many other studies that use steady state average yields; (iv) the current model incorporates the flexibility available

[1] Mapemba *et al*. (2008) model acreage harvested as an endogenous variable. However, their analyses and results are specific to Oklahoma. This model extends their analysis by modeling a generic harvest shed around a biorefinery for any location as a number of concentric circles.

with agricultural residue harvest and the restrictions due to long-term contracts with energy crops; (v) the possible impacts of GHG emissions on feedstock sourcing decisions are also incorporated in the model; (vi) the model constraints enable computation of price premiums for feedstocks depending on the optimal spatial and temporal pattern of harvest shed. As a result, this model provides better insights into the realities of biomass procurement.

MODEL

Consider a generic biorefinery with ethanol production capacity PC (million gallons/quarter). The biorefinery's decision problem is to minimize the net present value of cumulative biomass procurement costs over a planning horizon (*e.g.*, 20 years based on the expected life of the biorefinery). The biomass procurement costs include payments made directly to farmers for biomass material (CM); payments made to contractors for harvesting (CH), transport costs (CT), and seasonal costs (CL); storage costs (CS); and internalized environmental costs (CE). The full model is provided in the appendix.

The harvest shed is assumed to be circular, with the biorefinery located at the center (Fig. 1). The harvest shed is divided into concentric circular production zones ($z = 1,2,\ldots Z$), each zone corresponding to a concentric circular zone of outer radius R_z and inner radius R_{z-1} measured in miles. Each zone contains both agricultural and non-agricultural land. Excluding the non-agricultural land and land unsuitable for producing cellulosic biomass, the available area is modeled as a fraction (σ) of the total geographic area in each zone (σ_{sz} for annual feedstocks (s) and σ_{gz} for perennial feedstocks (g) in zone z). The area available for harvest is assumed to be distributed uniformly within every zone of the harvest shed.

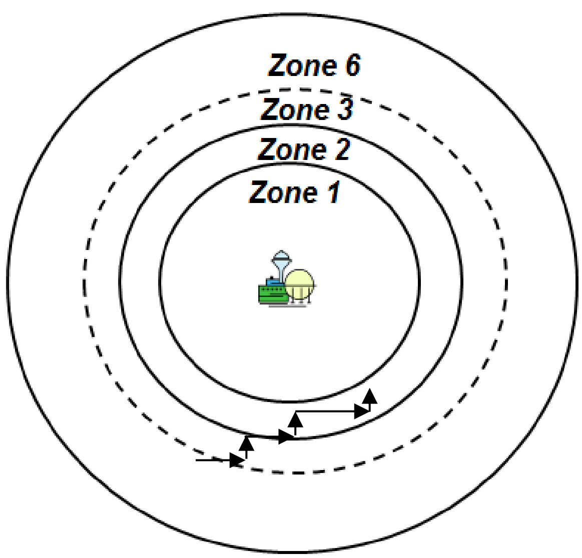

Fig. 1. Concentric circular harvest shed area around the biorefinery (arrows represent perpendicular roads used for transport)

The biomass requirements can be met with multiple feedstocks that include many annual residue feedstocks ($s = 1, 2, \ldots S$) and perennials ($g = 1, 2, \ldots G$). Once planted, perennials are assumed to produce biomass for τ_g years. Because of the lack of alternate markets and high establishment costs, it is assumed that perennial grass farmers seek long-term contracts extending up to τ_g years, which is a key constraint in determining the optimal feedstock.[2] Hence, in the model, if some acreage is planted with energy crops in year *t*, then that acreage will be retained with energy crops for the next τ_g years. The model is formulated over quarterly intervals (*q*) to study how seasonal cost differences and differences in the harvesting pattern of residues and perennial grasses, which usually extends over three to six months during a crop year, affect decisions.

The decision variables are (i) the acreage A_{szq} contracted to harvest agricultural residue *s* in quarter *q* in zone *z*, and the acreage A_{gztq} contracted to plant energy crop *g* in year *t* in zone *z*, and (ii) the amount of feedstock (*s*, *g*) processed during every quarter *q*.

The objective function of the sum of discounted costs over Q quarters is given below,

$$\sum_q \delta^q * [\sum_g \sum_z \sum_t CX_g * Y_{gtq} * A_{gztq}) + \sum_s \sum_z CX_s * Y_{szq} * A_{szq}) + (1+\omega q)\, CT_q + \sum_g CE_{gq} + \sum_s CE_{sq} + d * \sum_s X_{sq} + d* \sum_g X_{gq}] \qquad (1)$$

where the subscripts *g* and *s* refer to perennial and annual feedstocks, respectively, *t* and *q* refer to the time periods (year and quarter, respectively), and *z* refers to the concentric zone around the biorefinery. The cost components CX, CT, and CE refer to the sum of exogenous costs (material and harvest costs), transport costs, and environmental (limited to GHG emissions associated with biomass production, harvest, and transport in this case) costs, respectively. Constants δ, d, and ω are the discount factor, storage, and seasonal cost parameters, respectively. Other model parameters include the biomass yields of annual and perennial feedstocks (Y_s and Y_g, respectively), storage costs (d_s and d_g), proportion of biomass lost in storage (ε_s and ε_g), the minimum amount of biomass to be maintained in the inventory for continuous functioning of the biorefinery (*MIR*), ethanol yield per ton of annual and perennial feedstocks (K_s and K_g), fixed and variable cost components of transport costs per ton mile (a_0 and a_1), and the fraction of area available to plant either feedstock within each zone (σ_{sz} and σ_{gz}).

Transport costs include loading, unloading, and trucking costs. Total transport costs (CT) and transport distance depend on the biomass harvested and used for biofuel production. Because 'acreage planted' is a decision variable, the transport costs are determined endogenously in the model; that is, CT_q is endogeneously determined based on the acreage decision variables A_{szq} and A_{gztq}. Average transport distance calculations for harvesting from concentric circular areas with perpendicular road system are based on previous studies by French (1960, 1977). The total transport costs CT_q are minimized along with other costs in the objective function

$$CT_q = \sum_z [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}] * [a_0 + a_1\, {}^2\!/_3\, w\, (R_z^3 - R_{z-1}^3)/(R_z^2 - R_{z-1}^2)] \qquad (2)$$

Current industry discussions indicate that biorefineries would most likely store the biomass on the field and transport them to the biorefinery when needed. This requires

[2] Biorefineries also would be willing to enter into long-term contracts to assure supply and to avoid competition for biomass with other processors.

transport at different times of the year, leading to seasonal costs. The seasonal costs (CL) are computed by multiplying the transport costs and harvesting costs with a factor ω_q that adjusts for cost differences (based on average diesel prices) over the four quarters. The environmental costs of biomass are based on the GREET model 1.8 (ANL 2007). The life cycle GHG emissions for corn stover are used here as the base line by setting it to zero. Incremental lifecycle GHG emissions are used for others, compared to corn stover, in the calculation of environmental costs. Both seasonal and environmental costs depend on the feedstock composition and hence are determined endogenously in the model.

The key constraints of the model are as follows:

(a) Land availability constraints:

$\sum_s A_{szq} \leq \sigma_{sz} ZA_z$; the acreage allocated to annual feedstocks is restricted to prime cropland area within the concentric circular area in zone z (ZA_z)

$\sum_g \sum_t A_{gztq} \leq (\sigma_{gz} + \sigma_{sz}) ZA_z$; the acreage allocated to perennial feedstocks is derived from both prime or marginal cropland in the concentric circular area in zone z (ZA_z)

(b) Biomass supply – demand balance constraint:

Biomass produced in quarter q + Stocks from previous quarter (q-1) = Biomass used for biofuel conversion in quarter q + Ending stock for quarter q

The other constraints in the model include non-negativity and terminal conditions, accounting relationships to compute costs CX, CE, and CT, and constraints to meet the cellulosic biofuel production input requirements throughout the entire operating period. (Detailed model is included in the appendix).

The cost minimization problem is coded in GAMS and solved. In this model, the objective function and the constraints are linear, hence, the results are globally optimal. The results from the optimization model include (i) the minimized total cost of biomass, expressed in terms of dollars per gallon of ethanol; (ii) acreages of all feedstocks (annuals and perennials) harvested in each quarter in each zone; (iii) variations in biomass quantities processed *versus* maintained in storage; and (iv) shadow prices or price premiums to expand land acreage of the preferred feedstock within each zone. Additional sensitivity analyses are conducted to assess the impact of changes in exogenous parameters (*e.g.*, land availability, change in material costs).

CASE STUDY

The results of the generic model are illustrated using a case study for a biorefinery of 200 M l^{-1} (200 million liters) per year target capacity located in Hugoton, Kansas. The time frame of operation is assumed to be 20 years (80 quarters), with the circular harvest shed extending up to a 80 km (50-mile) radius. The circular harvest shed around the biorefinery is sub-divided into six concentric zones (z) with outer radii at 8, 16, 24, 32, 48, and 80 km (5, 10, 15, 20, 30, and 50 miles). At an average conversion rate of 70 gallons per ton, this biorefinery would require about 172,000 t (190,000 tons) of biomass each quarter sourced from prime croplands and marginal lands. According to the USDA census database, suitable prime croplands are estimated at 12% of the geographic area and marginal croplands at 10% of geographic area (USDA - NASS 2009). These parametric assumptions on land area are later relaxed to evaluate how harvest shed acreage affects optimal feedstock portfolio.

Agricultural residues are assumed to be harvested once during the third quarter of every year; the yield of agricultural residues is assumed to be 280 g m^{-2} (1.25 tons per acre). For the energy crop *Miscanthus*, the biomass yield is estimated at 740 g m^{-2} (3.3 tons per acre) in year 1; 1480 g m^{-2} (6.7 tons per acre) in year 2; 2241 (10 tons per acre) in years 3 through 7; and 1793 g m^{-2} (8 tons per acre) in years 8, 9, and 10. Once planted, energy crops are assumed to be harvested for the next 10 years (τ_g=10 years or 40 quarters). That is, an energy crop established in year 1 will supply biomass during years 1 through 10, an energy crop established in year 2 will supply biomass during years 2 through 11, and so on. If the energy crops are planted in each of the 20 years, then there are potentially 120 choice variables related to energy crop acreage (20 years * 6 zones harvested each year). However, as the biorefinery nears its shut down at the end of 20 years, the farmers may be unwilling to establish new acreages of perennial energy crops. To reflect this unwillingness, establishment of new perennial crops is restricted to years 1 through 11; this ensures that there are no energy crop acreages planted in years 12 through 20 that fail to meet the contractual obligations by year 20. The energy crop is assumed to be harvested during the fourth quarter of every year due to their winter hardiness. A second set of decision variables are the quantity of biomass kept in storage, either at the biorefinery or on the field. For the last quarter (q = 80, denoted by Q), the storage level is restricted to zero for both feedstocks to reflect the terminal condition of multi-period optimization.

For the case study, the material costs of agricultural residues and energy crops are estimated at 24 and 33 \$ t^{-1} (\$22 and \$30 per ton), respectively.[3] Harvest costs such as chopping, raking, collecting, baling, hauling, and staging biomass within the farms are estimated at 15.4 and 17.6 \$ t^{-1} (\$14 and \$16 per ton), respectively, based on USDA reports. The harvesting costs for energy crops are slightly higher because of the intensive use of machinery in handling energy crop biomass (Epplin *et al.* 2007; Sokhansanj *et al.* 2006; Thorsell *et al.* 2004; Wang *et al.* 2009). Transportation costs are estimated at 0.192 \$ $(t\text{-km})^{-1}$ (\$0.28 per ton-mile). The seasonal cost adjustment factors (ω_q) for transport and harvesting costs are estimated as 105%, 108% and 109% for quarters 2, 3, and 4, respectively, relative to the first quarter, based on EIA estimates of diesel price indices(EIA - DOE 2010). For storage, a three-week supply of cellulosic biomass is assumed to be maintained in the biorefinery. Any additional biomass harvested would be stored on field at the expense and risk of the farmer. The storage costs and the amount of biomass lost in storage (both on-field and on-site) are estimated at \$12 per ton per year and 12% per year, respectively. The environmental costs are computed by multiplying the GHG emissions quantity with an estimated GHG price of 16.5 \$ t^{-1} (\$15 per ton) CO_{2e}.[4] We use life cycle GHG emissions for corn stover as the base line (set to 0) and use incremental lifecycle GHG emissions for *Miscanthus*, drawing on estimates in GREET version 1.8 (ANL, 2007). The parametric values for the case study are summarized in Table 1.

[3] In 2009, farmers in south central Nebraska were paid an average of 24 \$ t^{-1} (\$22 per ton) as material cost for agricultural residues supplied to Energy Grains Biomass LLC. Mooney *et al.* (2008) and Wang *et al.* (2009) estimated the material costs of energy crops from 25 to 35 \$ t^{-1}

[4] GHG permit prices have been extremely volatile over the last few years, ranging from \$1 to \$55 per metric ton on the EU-ETS markets. While pricing of any of the GHG credits depends on the policy environment, these environmental costs are included in the cost minimization problem to account for social value created.

RESULTS AND DISCUSSION

The average biomass cost for biofuel production was estimated to be 0.16 $ l^{-1} ($0.61 per gallon)[5]. These estimates are similar to other studies, which estimate costs between 0.15 and 0.20 $ l^{-1} ($0.60 and $0.75 per gallon) of cellulosic biofuel (Sharma *et al.* 2013b; Solomon *et al.* 2007). Energy crops account for 73% of the total biomass requirements in the optimal supply feedstock mix. Energy crops appear prominently in the optimal portfolio of raw materials, indicating that high establishment costs, lower yields in the initial years, and higher material and harvesting costs are sufficiently offset by lower transport costs and the availability/suitability of marginal croplands (CRP) for energy crop cultivation.

Table 1. Parametric Values for the Case Study

Parameter	Level in base case scenario
Costs of storage, d (per metric ton per year)*	$12
Storage Loss (per year)*	12%
Energy crops and stover grown in separate fields	
% Land available for perennial energy crop cultivation in each zone (USDA – NASS 2009)	22%
% Land available for stover collection in each zone (USDA – NASS 2009)	12%
Discount rate*	2%
Minimum inventory maintained at the biorefinery facility (estimated based on corn ethanol operations; biomass worth 3 weeks of storage in a total of 12 weeks)	25%
Material costs (estimated using Atchison and Hettenhaus 2003)	
Energy crop (Mooney *et al*. 2008; Wang *et a*l. 2009)	33 $ t^{-1} ($ 30 per ton)
Stover	24.2 $ t^{-1} ($ 22 per ton)
Harvesting costs	
Grasses	17.6 $ t^{-1} ($ 16 per ton)
Stover	15.4 $ t^{-1} ($ 14 per ton)
Transport costs per ton mile	0.19 $ $(t\text{-km})^{-1}$ ($0.28/ton-mile)
Seasonal cost factors (EIA – DOE 2010)	Q1=1, Q2=1.05,Q3=1.08, Q4=1.09
Environmental costs*	16.5 $ t^{-1} ($15/ton) of GHG

* Assumptions

[5] Average cost per gallon = (cumulative discounted cost of biomass over 20 years)/(total amount of biomass ethanol produced over 20 years);

Figures 2 and 3 show the model solution for the optimal acres of annual agricultural crops and energy crops contracted for supply, respectively. As can be seen from Fig. 3, most energy crops enter into contract during year 1 to supply biomass for the next ten years of the crop cycle, and are replaced in year 11 to supply for the next ten years. Relatively small additional acres are contracted during intermediate years to cover shortfalls in energy crop yields in the ending periods of the initial plantings and the establishment years of the second cropping cycle.

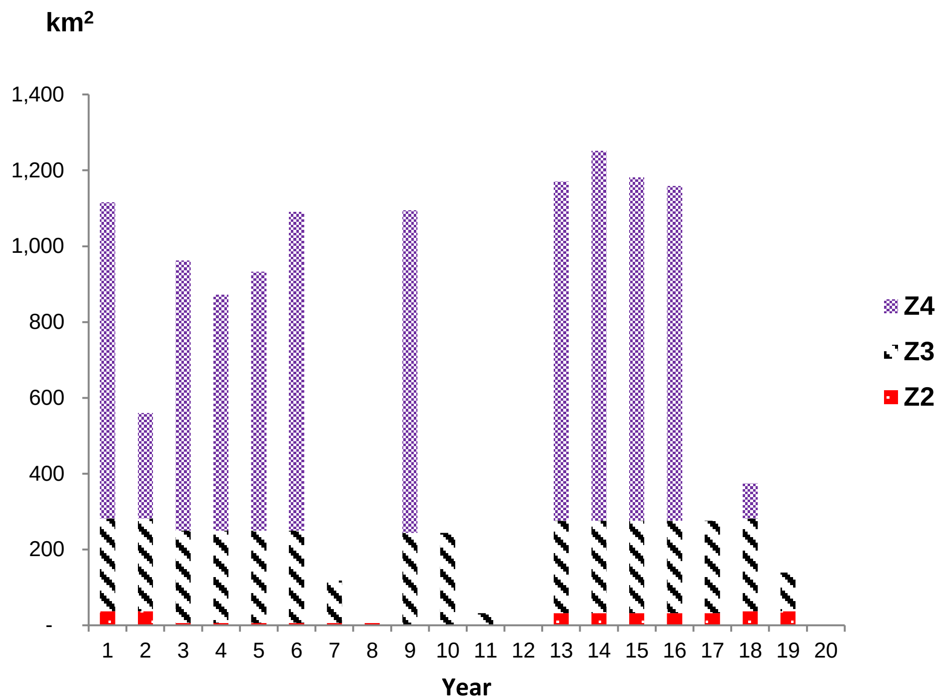

Fig. 2. Agricultural residue acreage (km^2) contracted in each zone Z by year

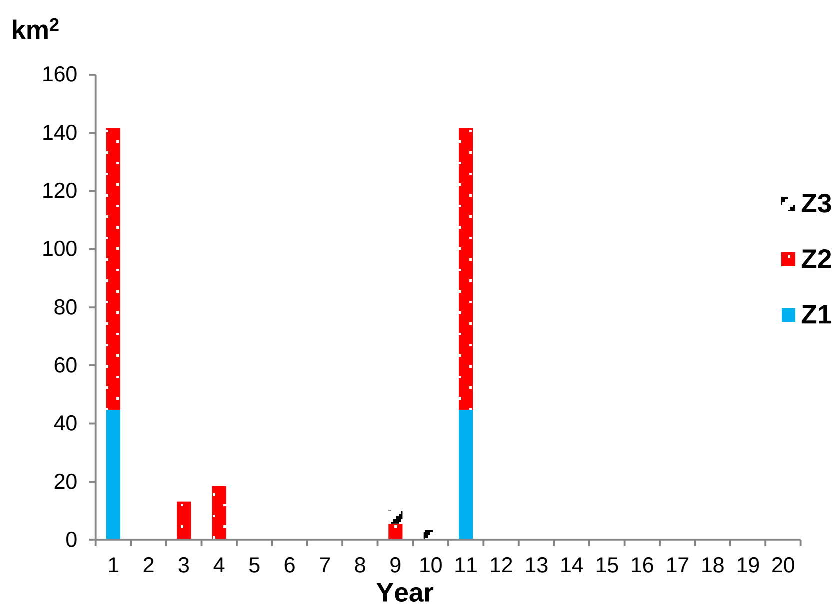

Fig. 3. Perennial energy crop acreage (km^2) contracted in each zone Z by year

The temporal distribution of cumulative acreage under contract for energy crops and agricultural residues is shown in Fig. 4. Agricultural residue contracts are mainly in zones 3 and 4, in the 16- to 32-km (10- to 20-mile) radius around the biorefinery. These results suggest that a relatively steady area under energy crops acts as a base load biomass source and agricultural residues are used to cover shortfall on an as and when required basis. The energy crop acreage is considerably less than that of agricultural residues due to higher yield rates per acre. Hence, energy crops account for a higher proportion of feedstock tonnage (Fig. 5) despite lower acreage (Fig. 4). These results lend support to the industry and USDA assertion that energy crops can play a major role in supplying raw materials for cellulosic biofuel.

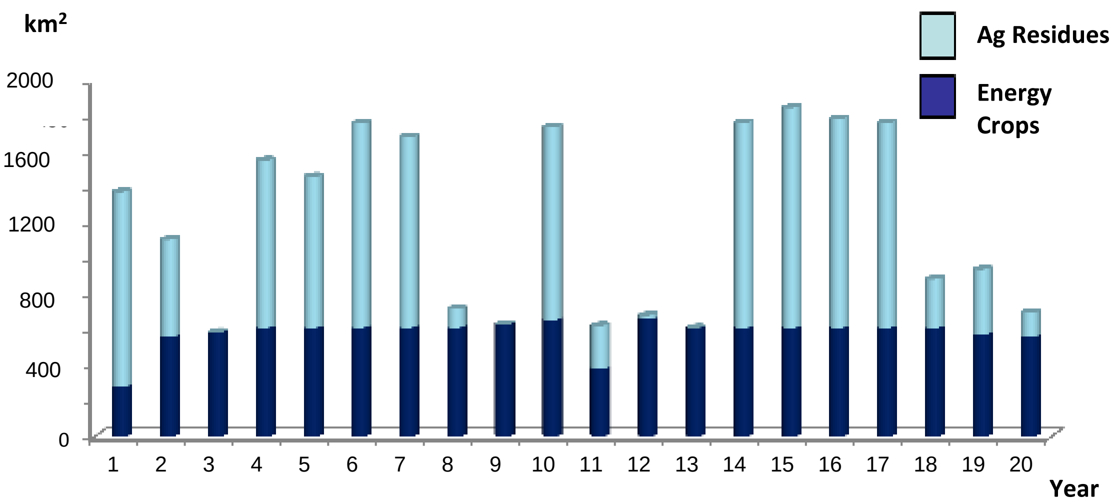

Fig. 4. Cumulative area under contract (km^2) to supply either feedstock

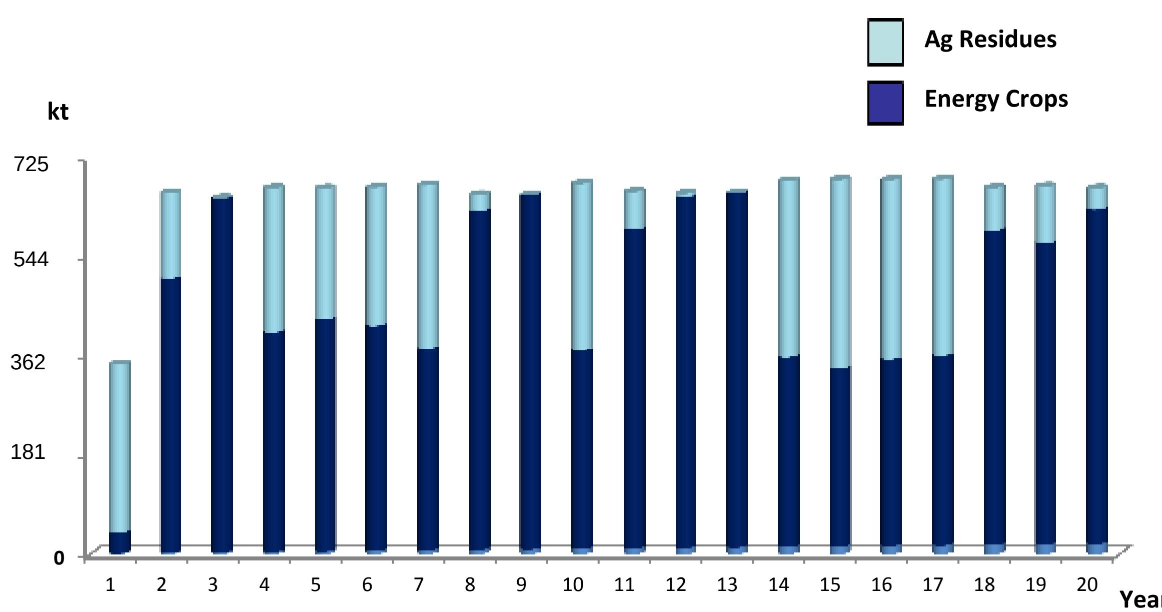

Fig. 5. Composition of biomass used for biofuel production (kt)

Figure 6 shows the spatial distribution of the harvest shed. The number on the right shows the total acreage (in sq km) in each zone available for biomass harvest. For the parameters used in this study, the harvest shed extends up to a 32- to 48-km (20- to 30-mile) radius around the biorefinery (zone Z_5). The optimization results indicate that almost all the available land in zones 1 and 2 will preferably be contracted to harvest perennial grasses. Agricultural residues are collected from fields and zones farther away. The high yields and savings in transport costs of energy crops dominate the lower material and harvest costs of agricultural residues, resulting in almost exclusive dependence on energy crops in zones closer to the biorefinery (corner solution). However, in zones that are farther away, contracting restrictions and the need to procure sufficient biomass during low productivity years of energy crops lead to feedstock composition that includes both energy crops and agricultural residues (interior solution).

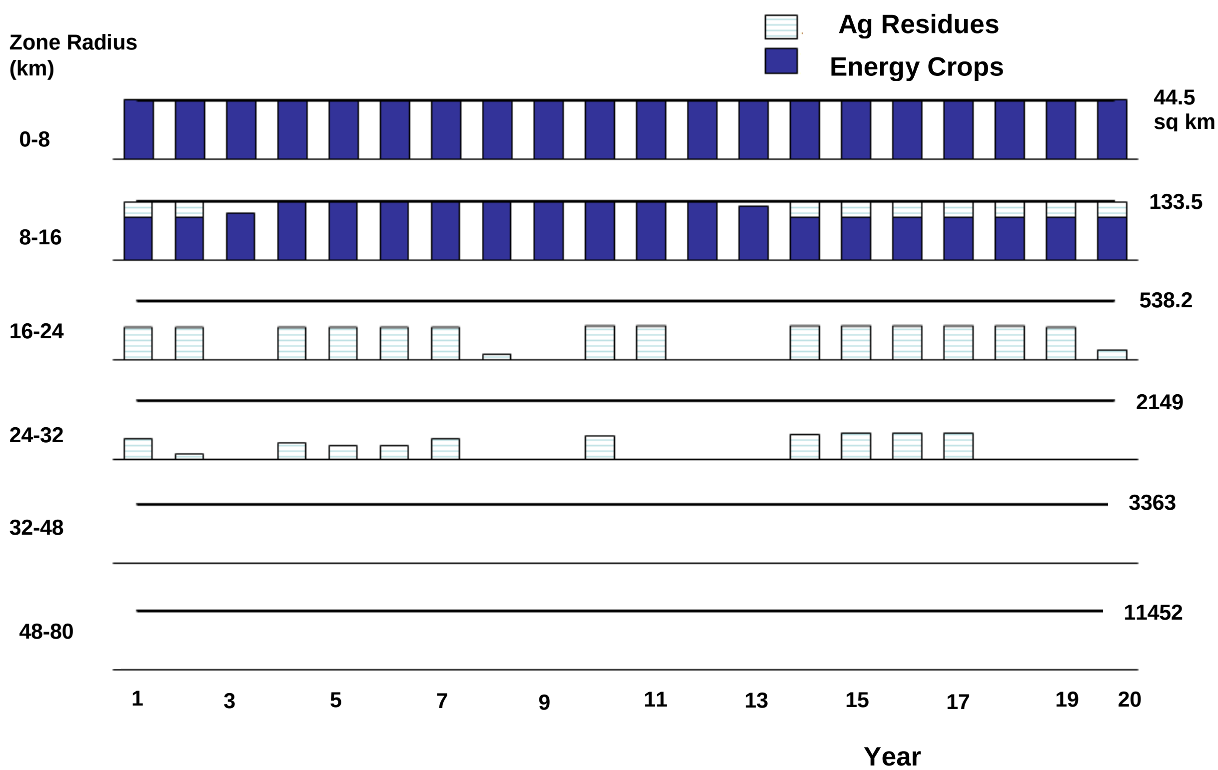

Fig. 6. Spatial and temporal distribution of harvest shed (km^2)

For the case study, all available land within a 15-mile radius would be contracted by the biorefinery. That is, the land acreage will become a constraining resource in this region. The biorefineries can pay a premium price to increase the land available within the 24-km (15-mile) radius. The price premium is the maximum amount that the biorefinery would be willing to pay to increase the land acreage by one more acre (in each zone) rather than sourcing the biomass from a more distant zone. These price premiums can be estimated as the shadow price of binding land constraints. The normalized price premium ($ t^{-1}) is obtained by dividing the shadow price ($ m^{-2}) by the biomass yield (t m^{-2}); they are shown in Fig. 7. The shadow prices depend on both the time and zone for both feedstocks. The price premium for additional land in zone 1 for energy crops is higher than that for additional land in zone 2 because the proximity of zone 1 to the biorefinery.

When the available land acreage is constraining, the model generates shadow prices; these shadow prices indicate the cost savings that can be achieved by increasing land under contract for a particular feedstock by an acre in a given concentric zone. For the case study parameters, the range of shadow prices is found to be 2.2 to 8.8 \$ t^{-1} (\$2 to \$8 per ton) for energy crops grown in fields located within a 16-km (10-mile) radius and 3.3 to 7.7 \$ t^{-1} (\$3 to \$7 per ton) for agricultural residues grown within a 16- to 32-km (10- to 20-mile) radius. The shadow prices for agricultural residues are higher when the energy crop output is lower (*e.g.* years 1 and 2), and these shadow prices of annual feedstocks decline gradually over time with the increase in supply of biomass from energy crops. The annual feedstocks are required mainly as buffer feedstocks to meet biomass demand when the energy crop output is low due to yield patterns. For energy crops, the contractual constraint that energy crops should be harvested during all 10 years after initial planting creates inflexibility and reduces the price premium. The shadow prices for energy crops increased after the establishment phase of 2 to 3 years. The shadow prices show a decline with increasing distance of the fields/zones from the processing plant, reflecting a transport cost premium for feedstocks grown closer to the biorefinery.

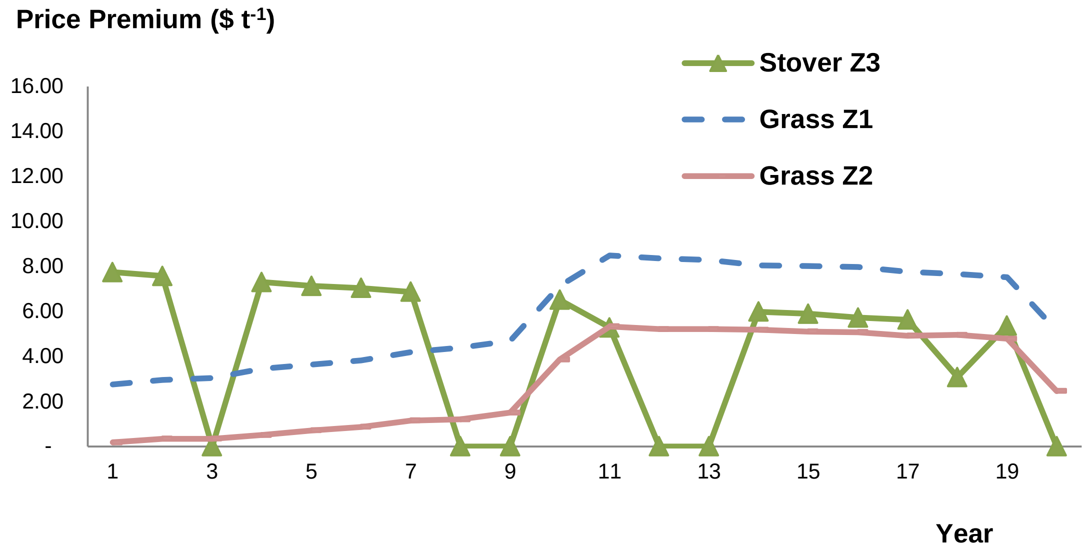

Fig. 7. Maximum price premium payable to expand harvest shed, by zone and year

SENSITIVITY ANALYSES

Under the base case scenario and when relative material costs are unchanged, energy crops account for 70 to 73% of the feedstock mix over 20 year time frame. The rate of substitution between the two feedstocks depends on the absolute values and relative values of costs used to parameterize the model. Table 2 shows how the proportion of energy crops changes when the material costs of agricultural residues and energy crops increase by 10 to 30%. Consider the ratio of material costs (CM_g divided by

CM_s): when energy crop material costs increase by 30% (from 33 to 43 \$ t^{-1} or \$30 to \$39 per ton) while keeping residue costs constant, the proportion of energy crops in the mix decreases drastically, from 72.9% to 48%. However, when the agricultural residue costs increase by 30%, to 31.5 \$ t^{-1} (\$28.60 per ton), the proportion of energy crops increases only slightly, from 72.9% to 81%.

Table 2. Proportion (%) of Energy Crops at Different Material Costs

	Agricultural residues \$ t^{-1} (\$/ton)			
	24.2 (22)	**26.7 (24.2)**	**29.1 (26.4)**	**31.5 (28.6)**
Energy crops \$ t^{-1} (\$/ton)	**Percentages**			
33 (30)	72.9	74	80	81
36.4 (33)	67	71	74	81
39.7 (36)	56	64	70	73
43 (39)	48	51	64	70

Table 3 demonstrates how the biomass total procurement costs (\$ per annual gallon) change when the farmers are paid different amounts for their cellulosic biomass. The biomass procurement costs are relatively stable between 0.16 and 0.18 \$ l^{-1} (\$0.60 and \$0.70 per gallon) of cellulosic ethanol across all cost scenarios.

Table 3. Cellulosic Biomass Procurement Costs

	Agricultural residues \$ t^{-1} (\$/ton)			
	24.2 (22)	**26.7 (24.2)**	**29.1 (26.4)**	**31.5 (28.6)**
Energy crops \$ t^{-1} (\$/ton)	**\$ l^{-1} (\$ per gallon)**			
33 (30)	0.16 (0.61)	0.161 (0.61)	0.164 (0.62)	0.164 (0.62)
36.4 (33)	0.166 (0.63)	0.169 (0.64)	0.169 (0.64)	0.172 (0.65)
39.7 (36)	0.172 (0.65)	0.174 (0.66)	0.177 (0.67)	0.179 (0.68)
43 (39)	0.177 (0.67)	0.179 (0.68)	0.182 (0.69)	0.185 (0.70)

Sensitivity analysis with respect to the environmental costs, shown in Table 4, indicates that environmental costs have only a minor effect on the optimal feedstock portfolio. Even when the GHG prices increase from 16.5 to 55 \$ t^{-1} (\$15 to \$50 per ton) of carbon dioxide equivalent, the proportion of energy crops decreases slightly, from 72.9% to 69%. This decline in share of energy crops with increase in GHG prices may appear counter-intuitive because energy crops have significantly lower life cycle GHG emissions compared to corn. However, energy crop GHG performance relative to residues depends on how much of the corn production related emissions are allocated to residues. The GREET model, that we draw on in our estimates, treats corn-stover as a waste by-product and allocates none of the corn production related emissions to stover. Only incremental emissions associated with stover collection and additional fertilizer use to compensate for stover removal are considered. As a result energy crops have higher environmental (GHG) costs compared to residues; consequently the proportion of energy crop declines when GHG prices increase. But these declines are not substantial because even at these GHG prices, environmental costs account for a relatively small fraction of overall costs.

Table 4. Impact of Higher Greenhouse Gas Prices on Optimal Feedstock Portfolio

GHG price $ t^{-1} ($/ton)	Proportion of energy crops (percentage)	Biomass total procurement cost $ l^{-1} (US$ per gallon)
16.5 (15)	72.9	0.160 (0.606)
27.5 (25)	70.7	0.161 (0.611)
55 (50)	69.0	0.164 (0.623)

Table 5 presents how the proportion of energy crops changes when the available land area is altered. An increase in the acreage of marginal lands increases the proportion of energy crops (along the columns from top to bottom); an increase in the acreage of prime croplands decreases the proportion of energy crops (along the rows from left to right). In either case, the proportion of energy crops stays relatively high, at 70% or more. The sensitivity analysis indicates that the proportion of energy crops in the feedstock mix is robustly high under different conditions, reinforcing the argument that energy crops will be the preferred feedstock for future biorefineries.

Table 5. Proportion (%) of Energy Crops under Different Land Availability

Prime cropland + Marginal cropland supplying energy crops	Prime cropland supplying agricultural residues		
	5% of geographic area	**10% of geographic area**	**15% of geographic area**
14% of geographic area	78.6	72.0	NA
22% of geographic area	80.6	72.9	71.2
30% of geographic area	81.9	77.2	74.2

CONCLUSIONS

1. Decisions about the optimal feedstock mix for biorefineries involve tradeoffs among material costs, transport costs, storage costs, and most importantly, costs of entering into long-term contracts with energy crop producers, while agricultural residues do not need long-term contracts.
2. Analyses using representative case study parameters suggest that energy crops will likely account for a significant proportion of the optimal feedstock mix, despite higher establishment costs and the need for long-term contracts. Higher yields/acre and associated lower transport costs offset the higher costs of feedstock production. Agricultural residues are likely to be used primarily to cover shortfalls in energy crops.
3. Energy crops will be contracted closer to the biorefinery, while agricultural residues will likely be collected from the fringe areas. Shadow price analyses indicate that available land near the biorefinery will receive price premiums for growing energy crops.
4. Overall analyses suggest that energy crops will be preferred feedstocks for future biorefineries. Policies aimed at supporting energy crops and overcoming barriers to

commercial production of energy crops will be critical for the success of the biofuel industry and should be promoted.

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APPENDIX

Subscript notation:

s — Annual agricultural residue feedstocks such as straw or stover [s = 1, 2, … S]
g — Perennial grass feedstocks such as *Miscanthus*, switchgrass [g = 1, 2, … G]
z — Concentric circular production zone [z = 1, 2, … Z]
q — Production/harvesting time period (quarter) [q = 1, 2... Q]
t — Year in which perennial crops are planted [t = 1, 2, … T]. Perennial crop *g* is assumed to supply biomass for τ_g years following establishment; hence, the perennial crop *g* established in year 3 (t=3) will supply biomass starting in year 3 until $3 + \tau_g$

Parameters:

CM_s, CM_g — Unit material cost of feedstocks s and g (dollars per ton, price paid to farmers)

CH_s, CH_g — Unit harvest cost of feedstocks s and g (dollars per ton)

CT_z Unit transport cost of feedstock from zone z to the biorefinery located at the center (dollars per ton)

CS_{sq}, CS_{gq} Unit storage cost of feedstocks s and g in quarter q (dollars per ton per quarter)

CE_{gq} Unit incremental environmental cost of perennial feedstock g in quarter q (dollars per ton) relative to corn stover

CE_{sq} Unit incremental environmental cost of annual feedstock s in quarter q (dollars per ton) relative to corn stover

CX_{szq} Total exogenous costs of annual feedstocks s processed in quarter ($CM_s + CS_s + (1+\omega_q)\ CH_s$, dollars per ton)

CX_{gzq} Total exogenous costs of perennial feedstocks g processed in quarter ($CM_g + CS_g + (1+\omega_q)\ CH_g + CE_g$, dollars per ton)

Y_{gtq} Yield of perennial feedstock g, planted in year t, for quarter q [Fixed pattern of yields in tons per acre per quarter; e.g. in scenario B, *Miscanthus* crop planted in year t = 3 will yield 746 g m^{-2} (3.33 tons/acre) in quarter 12, 1495 g m^{-2} (6.67 tons/acre) in quarter 16, 2241 g m^{-2} (10 tons/acre) every fourth quarter during quarters 20 – 36, 1793 g m^{-2} (8 tons/acre) every fourth quarter during quarters 40 – 48, and 0 tons in all other quarters. If *Miscanthus* crop were planted in year t = 5, then the same yield pattern will be shifted from quarters 20 through 56. The amount of biomass available in quarter q depends on the planting year (t) of *Miscanthus*]

Y_{szq} Yield of annual agricultural residues *s* that remains constant – harvested only once in a year either during the third or during the fourth quarter)

Ψ_{sq}, Ψ_{gq} Quantity of feedstock (s, g) produced within the entire harvest shed during quarter q (tons)

D_{sq}, D_{gq} Quantity of feedstock s and g processed at the biorefinery during quarter q (tons)

ω_q Factor to compute seasonal costs related to transporting; second quarter is taken as the reference season, *i.e.* $\omega_{q=2}$ is normalized at 1 (Table 4.5)

δ Quarterly discount factor

d Storage cost parameter (dollars per ton per quarter)

ε_s Rate of loss of agricultural residue due to storage (percentage per quarter)

ε_g Rate of loss of perennial grasses due to storage (percentage per quarter)

PC_q Quarterly ethanol processing capacity (gallons)

K_s, K_g Ethanol output for feedstock s and g respectively (gallons per ton)

MIR Minimum Inventory Requirement (tons)

Q Terminal time period

P_{GHG} Price for one ton of greenhouse gas ($ per ton of CO_2 equivalent)

GC_g Greenhouse gas credit for using perennial feedstocks, relative to using corn stover (tons of GHG per million gallon of cellulosic ethanol)

GC_s	Greenhouse gas credit for using annual feedstocks, relative to using corn stover (tons of GHG per million gallon of cellulosic ethanol)
a_0	Fixed component of transport costs ($ per ton of feedstock)
a_1	Variable component of transport costs ($ per ton-mile)
σ_{sz}	Fraction of total land area available in zone z to harvest annual feedstock s (in percentage)
σ_{gz}	Fraction of land area available in zone z to harvest all perennial feedstocks g (in percentage)
ZA_z	Total geographic area within zone z (acres)
R_z	Outer radius of zone z (miles)
w	Factor to convert radial distance to road distance; with perpendicular road network, w equals $\sqrt{2}$

Objective function:

Minimize discounted cumulative feedstock procurement costs over Q quarters:

$$\sum_q \delta^q * [\sum_g \sum_z \sum_t CX_g * Y_{gtq} * A_{gztq}) + \sum_s \sum_z CX_s * Y_{szq} * A_{szq}) + (1+\omega q)\, CT_q + \sum_g CE_{gq} + \sum_s CE_{sq} + d * \sum_s X_{sq} + d * \sum_g X_{gq}]$$

where CX refers to exogenous costs of cellulosic biomass, CT refers to endogenously determined transport costs and d*X refers to storage costs

with respect to decision variables:

A_{szq}	Acreage contracted to harvest annual feedstock s in quarter q, zone z (in acres)
A_{gztq}	Acreage planted with perennial feedstock g in year t, zone z (in acres)
X_{sq}, X_{gq}	Storage levels (stock variable, either at the biorefinery or on farm fields) of feedstock s and g at the end of quarter q (in tons)
D_{sq}, D_{gq}	Quantity of feedstock (stover s, grasses g) processed/demanded in quarter q – which are implicitly determined as residuals upon choosing X_{sq}, and X_{gq} subject to the following accounting relationships (E1-E4) and constraints (E5-E10):

Accounting relationships:

E1: Zone area ZA_z (in acres) around the biorefinery extending from zonal radius R_{z-1} to zonal radii R_z (in miles); the constant 640 converts square miles of area to acres

$$ZA_z = 640\, \pi\, (R_z^2 - R_{z-1}^2)$$

E2: Total biomass produced during every quarter (Ψ_q) is computed by multiplying the acreage harvested (A_{szq}, A_{gztq}) with yield (Y_{szq}, Y_{gtq})

$$\Psi_{sq} = \sum_z Y_{szq} * A_{szq}$$

$$\Psi_{gq} = \sum_z \sum_t Y_{gtq} * A_{gztq}$$
$$\Psi_q = \sum_s \Psi_{sq} + \sum_g \Psi_{gq}$$

E3: Transport costs (equation (3) from section 3):

$$CT_q = \sum_z [a_0 + a_1\ {}^2/_3\ w\ (R_z^3 - R_{z-1}^3)/(R_z^2 - R_{z-1}^2)] * [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}]$$

E4: Environmental costs of perennial feedstocks (CE_{gq}) and annual feedstocks (CE_{sq}) are computed based on expected GHG prices (P_{GHG}) and GHG credit (GC_g and GC_s).[6]

$$CE_{gq} = P_{GHG} * GC_g * D_{gq} * K_{gq}/1000000$$
$$CE_{sq} = P_{GHG} * GC_s * D_{sq} * K_{sq}/1000000$$

Constraints:

E5: Land availability constraints for perennial feedstocks:

The acreage harvested with grasses (A_{gztq}) and agricultural residues (A_{szq}) should be less than the available area from crop lands ($\sigma_{sz}\ ZA_z$) and marginal ($\sigma_{gz}\ ZA_z$) croplands. This constraint has to be satisfied in every quarter q across all zones z.[7]

$$\sum_g \sum_t A_{gztq} \le \sigma_{gz}\ ZA_z$$

Land availability constraints for annual feedstocks

$$\sum_s A_{szq} \le \sigma_{sz}\ ZA_z \qquad \text{for all q and z}$$

E6: Biomass mass balance constraints: Biomass supplied from fields and storage should equal the sum of biomass processed and inventoried in each quarter:

Biomass produced in quarter q (Ψ_q) + Stocks from previous quarter (q-1) = Biomass used for biofuel conversion in quarter q ($D_{gq} + D_{sq}$) + Ending stock for quarter q

$$\Psi_q + [(1 - \varepsilon_s) * \sum_s X_{s\ q-1} + (1 - \varepsilon_g) * \sum_g X_{g\ q-1}] = D_{gq} + D_{sq} + [\sum_s X_{sq} + \sum_g X_{gq}]$$

E7: Biofuel produced has to meet or exceed the processing capacity (PC_q) in every quarter:

$$\sum_s K_s * D_{sq} + \sum_g K_g * D_{gq} \ge PC_q \qquad \text{for all q}$$

[6] The division by 1000000 converts ethanol gallons to million gallons.

[7] A different formulation of land allocation is where both feedstocks can be harvested from all available lands. The restriction to source agricultural residues from prime croplands and energy crops from marginal croplands can be relaxed in the following manner. When all feedstocks can be grown in both prime and marginal croplands, the constraint E5 is replaced with the following. The total proportion of available (prime and marginal) cropland in every zone will be σ_z where $\sigma_z = \sigma_{sz} + \sigma_{gz}$. The summation over years (t) adds up the acreage allotted to energy crops that are planted at different times during the years 1 – 11. This constraint should be satisfied in every quarter q across all zones z.

$$\sum_s A_{szq} + \sum_g \sum_t A_{gzt} \le \sigma_z\ ZA_z \quad \text{for all q and all z}$$

E8: Biomass stored at the biorefinery has to meet the minimum inventory required (MIR) at the biorefinery – only this quantity of biomass incurs storage costs. The excess biomass, if any, would be stored on field without storage costs.

$$\sum_s K_{sq} * X_{sq} + \sum_g K_{gq} * X_{gq} \geq MIR * PC_q \qquad \text{for all } q$$

E9: Terminal conditions for the last quarter (Q) are imposed by restricting the final period storage to zero after meeting the biomass processing requirements
Biomass supplied from the fields in final quarter Q + supply from the storage in quarter (Q-1) – Biomass used for conversion in Q = Ending stock for quarter Q = 0

$$\Psi_Q + \sum_s (1 - \varepsilon_s) X_{s\,Q-1} + \sum_g (1 - \varepsilon_g) X_{g\,Q-1} - D_{sQ} - D_{gQ} = \sum_g \sum_s (X_{sQ} + X_{gQ}) = 0$$

E10: Non negativity constraints of acreage and storage decision variables:

$$A_{szq} \geq 0; A_{gztq} \geq 0; X_{sq} \geq 0; X_{gq} \geq 0$$