Environmental and economic trade-offs of switchgrass supply chain for biofuel in Tennessee

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Abstract: The low efficiency of feedstock storage and transportation hinders the commercialization of a switchgrass-based biofuel industry although the feedstock has various environmental benefits. This study develops a sustainable switchgrass supply chain that balances its economic and environmental performance, including soil erosion, and GHG emissions using a multi-objective optimization model based on high-resolution spatial data in Tennessee. Results suggest that the best preferred location for biorefinery, plantation area, and the type of land converted to switchgrass are crucial to trade-off relation between industrial cost and environmental performance of the feedstock supply chain.

Keywords: Switchgrass, Biofuel, Supply Chain, Greenhouse Gas, Soil Erosion, Tradeoff

1 Introduction

Concerns over energy security and greenhouse gas (GHG) emissions are spawning interest in alternative sources to substitute for petroleum-based energy. The high percentage (85%) of the GHG emissions in 2011 produced by energy-related activities accelerated the development of more environmentally friendly sources from biomass (United States Environmental Protection Agency (US EPA) 2013). The Clean Power Plan proposed that biomass-derived fuels can decrease GHG emissions compared to burning conventional fossil fuels (McCarthy 2014). The Energy Independence and Security Act (EISA) established that a life cycle GHG emission threshold from cellulosic biofuel must be 60% less than the lifecycle GHG emissions of the 2005 baseline average gasoline or diesel fuel that it replaces. (US EPA 2010). Energy from lignocellulosic biomass (LCB), including short-rotation woody crops, agricultural residues, and herbaceous grasses, has great potential for GHG reduction (Farrell et al. 2006).

Switchgrass (*Panicum virgatum*), one of the native species in the North American Tallgrass Prairie, has the potential of higher productivity on barren soils, lower demand for fertilizer compared to conventional crops, better water use efficiency, and greater tolerance to a wide range of environmental conditions compared to other herbaceous species (McLaughlin and Adams Kszos 2005). Research has suggested that switchgrass-based fuel might reduce GHG emissions by 60% to 90% compared with regular fossil fuel sources (Monti et al. 2012), and up to 50% when compared with conventional annual crops rotations (Monti et al. 2009; Ziolkowska 2013). Additional environmental benefits of production switchgrass include lessening water demand (Dominguez-Faus et al. 2009), and correspondingly decrease soil erosivity and organic carbon loss from soil conservation (Khanal et al. 2013; Zenone et al. 2013).

Perennial grasses provide year-round soil cover, reduce water runoff and sediment loss and favor soil development process by improving soil organic matter, soil structure, soil water, and nutrient holding capacity (Kort et al. 1998). The seeding rate of grasses was reported improved in loess soil and decreased the discharged soil and scattered sediment (Ichizen et al. 2005). And switchgrass downgrades soil detachment capacity, rill erodibility, critical shear stress and relative soil detachment through network of fibrous roots in surface layer (Zhang et al. 2013). Soil loss decreases up to 12% relative to the baseline under a switchgrass production scenario, and over 60% of the area demonstrated improved soil conditions corresponding to the changes in rainfall erosivity and crop cover (Khanal et al. 2013). Root density was significantly greater under switchgrass than under corn or soybean with root depth from 60 cm to over 150 cm (Kort et al. 1998; Tufekcioglu et al. 1998). Other researchers found the late harvested spring-sown crops such as maize, sugar beet, potatoes and other vegetables are associated with relative high levels of erosion because of greater exposure to rain during autumn and winter (Evans et al. 1996; Stoate et al. 2001).

Despite the potential environmental and social advantages of supplying switchgrass for biofuel production, the cost of the switchgrass supply chain and cellulosic biofuel production has inhibited the deployment of the switchgrass-based biofuel industry (Khanna et al. 2008; Wesseler 2007). Production cost of 1 liter of gasoline equivalent from switchgrass was 17.8% higher than that from corn, and 34.4% higher than the cost of gasoline in year 2005 (Pimentel and Patzek 2005; Wesseler 2007). The relative low density of switchgrass increased the harvesting and collecting. Also, a large-scale storage area will be required for the bulky biofuel feedstock. Feedstock cost could constitute 30%-50% of total switchgrass-based biofuel production cost (Khanna et al. 2008; Yu et al. 2014; Zhang et al. 2013). The exposure of switchgrass bales to weather during storage might result in dry matter (DM) loss, which might result in additional feedstock cost (Mooney et al. 2012). In addition, the transporting feedstock from supply area to biorefinery is expected to generate significant truck flows due to low feedstock density. Yu et al. (2014) found about more than 20% of total feedstock plant-gate cost was attributed to feedstock transportation from supply area to the potential biorefinery.

Balancing the economic and environmental metrics for switchgrass feedstock supply chain has received recent attention driven by the need of creating a sustainable feedstock supply. Various multi-metrics were applied to reduce GHG emissions and improve aquatic environments in the design of the supply chain (Bernardi et al. 2012; Parish et al. 2012; Valdivia et al. 2012; You et al. 2012; Yu et al. 2014). Through the multi-objective optimization models, most of current studies focused on cost minimization and GHG reduction in LCB feedstock supply chain (Miao et al. 2012; Monti et al. 2012; Sadrul Islam and Ahiduzzaman 2012; Sanderson et al. 2006), also a growing interest in broader perspective of environmental benefits, such as reducing water stress and soil erosion (Eranki et al. 2013; Smeets et al. 2009).

To conduct a solid analysis of multiple environmental impact and economic cost of LCB feedstock supply chain, it is crucial to have detailed spatial data in high resolution, such as available land, transportation network, and crop yields for LCB feedstock and other conventional crops (McBride et al. 2011). The accuracy of sustainable assessment was dependent on location- and case-specific data to evaluate biomass availability and feedstock transportation emission (Jäppinen et al. 2011). Observation-calibrated model also enabled a study to better respond to market prices and public policies, and to generate prediction in greater detail than aggregated level models (Egbendewe-Mondzozo et al. 2011). However, only a few studies have incorporated the high resolution spatial data associated with multiple environmental issues into systematic assessment and optimization decision making (Parish et al. 2012). The information of multivariate environmental impacts and the associated imputed cost of a LCB feedstock supply chain can provide the farmer, industry, stakeholders and policy-makers better insight into the sustainable design of LCB feedstock supply.

The objective of this study is to determine the potential environmental impact (including greenhouse gases and soil quality) of supplying switchgrass to a potential conversion facility in Tennessee. In addition, the potential tradeoff between the economic and environmental metrics of the switchgrass supply chain will be evaluated associated with imputed cost of supplying switchgrass in Tennessee.

2 Methodology and Data

2.1 Study area

The cellulosic biorefinery facility is assumed having production capacity of 50 million gallons per year (MGY) of biofuel in Tennessee. With a conversion rate of 76 gallons of biofuel per ton of switchgrass in demand (Wang et al. 1999), the total demand of switchgrass feedstock is around 657 thousand tons. The candidate localities of biorefinery were selected within TN State boundary having sufficient access to water, power, and roads, as well as storage space given in Tennessee Valley Authority database (Smith 2011). The potential feedstock supply area may expand across the state boundary. Therefore the area under study also includes the buffer area of 50 miles width outside state border and around Tennessee (Figure 1). In order to underline the geospatial variation in land resource and emphasize the features in land utilization, the above region has a five square mile resolution of hexagon (land resource unit). The data input are mostly based on a land resource unit.

The biomass feedstock supply chain boundary for life cycle analysis under study is from field to farm gate. Figure 1b depicts how biomass is designed through the various main operations along the supply chain from fields to the biorefinery. The economic cost and considered environmental impacts will be calculated based on this supply chain design including the following sections: land resource allocation, production operation, harvest operation, storage, and transportation.

2.2 Model structure

2.2.1 Cost

Production and harvest operations are closely associated with the planting scale while the area of planting bioenergy crops determines transportation costs and the logistic pattern. In addition, the time schedule of production management practices also balances the supply and demand market throughout harvest and off-harvest seasons. The prior objective model of minimizing total cost for a switchgrass feedstock supply chain is therefore presented below:

$$\text{Min } TC = C_{opportunity} + C_{production} + C_{harvest} + C_{storage} + C_{transportation} \qquad (1)$$

Where $C_{opportunity}$, $C_{production}$, $C_{harvest}$, $C_{storage}$, $C_{transportation}$ are opportunity costs from land resource conversion, production cost, harvest cost, storage cost and transportation cost of switchgrass, respectively. Each cost component is associated with spatial-temporal elements and operational management. The definition of the parameter and determinant variable is listed in Table 1.

$$C_{opportunity} = \begin{cases} \sum_{ipb} [(Price_{ip} \times Yield_{ip} - PC_{ip}) \times \frac{XC_{ipb}}{Yield_{i}^{swg}}], & \text{if } (Price_{ip} \times Yield_{ip} - PC_{ip} - LR_{ip}) \geq 0 \\ \sum_{ipb} (LR_{ip} \times \frac{XC_{ipb}}{Yield_{i}^{swg}}) & , \text{ if } (Price_{ip} \times Yield_{ip} - PC_{ip} - LR_{ip}) < 0 \end{cases} \quad (2)$$

The opportunity cost ($C_{opportunity}$) is occurred when the targeted land was selected for switchgrass production, and is the net revenue that is forgone by not allocating that land resources to another alternative use. This shadow price of the land resources is therefore the profit of other alternative land uses. Therefore, two possibilities of implicit land use were considered: 1) When the profit of other crop land is greater than the county-level land economic rent, the original land will be used as crop land and $C_{opportunity}$ is equals to the profit of crop land; 2) If the profit of other cropland was less than the land rent, the land owner was assumed to rent the land area instead and earns the profit for other purposes.

$$C_{production} = \sum_{ipb} (\frac{Est + AM}{Yield_{i}^{swg}} \times XC_{ipb}) \quad (3)$$

The production cost for switchgrass production ($C_{production}$) in Equation 3 included the cost of establishment as well as the annual maintenance cost.

$$C_{harvest} = \sum_{ipb} (\frac{\sigma_{ib}}{Yield_{i}^{swg}} \times XC_{ipb}) \quad (4)$$

The labor, fuel and machinery input were involved in switchgrass harvest cost ($C_{harvest}$). Harvest technologies such as baling system influenced the cost since different machineries with different fuel consumption rates used (Equation 4). The switchgrass was assumed to be harvested annually from November to February.

$$C_{storage} = \sum_{mipbt}(\gamma_{ibt} \times NXS_{mipbt}) \tag{5}$$

$$C_{transportation} = \sum_{ib}(\theta_{ib} \times \frac{\sum_{mp} XTN_{mipb} + \sum_{mpt} XTO_{mipbt}}{1 - DML_t}) \tag{6}$$

Storage cost for switchgrass (γ_{ibt}) is the summation of both the usage cost of gravel materials and equipment/labor cost for storage operations such as bale stack and tarp (Equation 5). The transportation cost (θ_{ib}) using semi-trailer truck involved energy consumption, machinery maintenance, and labor during switchgrass loading/unloading and transportation. They were determined by the time consumed during each process. Loading/unloading time for square bale was adopted based on the study of Duffy (2007) and it was assumed that the round bale consumed 10% more time than the square bale. The distance and speed determined the time consumption during transportation. The maximum distance from field to biorefinery plant was set to 75 miles.

The cost analysis is subject to multiple constraints based on practical operations and rules of mass balance. Equations 7 and 8 restrict available land area and yield for LCB feedstock production in each production area. Equation 9 constrains the machine hours per month during harvest season, respectively. Equation 10 requires feedstock deliveries each month equals the summation of harvested feedstock in the given month after adjusting for transportation dry matter losses and feedstock harvested each month. Equation 11 assures that feedstock deliveries from storage cannot exceed available stocks in storage in each month. In addition, 12 and 13 maintain the balance of the cumulative storage of switchgrass after taking into account dry matter loss during both the harvest and off-harvest seasons. Lastly, feedstock deliveries to the biorefinery in each month must meet the demand for biofuel production by the biorefinery in equation 14. All parameters and variables in the model are nonnegative. All the constraints can be divided into 5 categories:

(1) Production

$$\sum A_{ipb} \leq Aa_{ip},$$

(Acreage constraint for production) (7)

$$XC_{ipb} \leq Yield_{ib} \times A_{ipb},$$

(yield constraint for production) (8)

(2) Harvest

$$Numb^{k}_{mb} \times Avehour_{m} - \sum_{i}\sum_{b}(MTB_{ib} \times AH_{mipb}) \geq 0,$$

(constraint on harvest machine working hours) (9)

(3) Transportation and Storage

$$XH_{mipb} = \frac{\sum_{j} XTN_{mipb}}{1-DML^{trans}} + \sum_{t} NXS_{mipbt}$$

(Harvest to shipment and storage balance) (10)

$$XS_{mipb} - \frac{XTO_{(m+1)ipbt}}{1-DML^{trans}} \geq 0$$

(Storage and shipment balance) (11)

$$XS_{(m+1)ipbt} = (1-DML^{stor}_{mbt}) \times XS_{mipbt} + NXS_{(m+1)ipbt}, \quad \text{Nov} \leq \text{m} \leq \text{Feb}$$

(cumulative storage balance during harvest season) (12)

$$XS_{(m+1)ipbt} = (1-DML^{stor}_{mbt}) \times XS_{mipbt} - \frac{XTO_{(m+1)ipbt}}{1-DML_{tran}}, \quad \text{March} \leq \text{m} \leq \text{Oct}$$

(cumulative storage balance during off-harvest season) (13)

(4) Biorefinery demand

$$\lambda(\sum_{i}\sum_{p}\sum_{b} XTN_{mipb} + \sum_{i}\sum_{p}\sum_{b}\sum_{t} XTO_{mipbt}) - Q_{m} = 0$$

(ethanol production requirement) (14)

(5) Sign constraint

$A, AH, XC, XH, XTN, NXS, XS, XTO, Numb^{k}_{mb} \geq 0$

2.2.2 GHG

The GHG emission (*TE*) analysis boundary is defined as the GHG emission caused by the economic activity in Equation 1. The major emission sources come from land use change (E_{luc}), energy consumption from switchgrass production, storage, and harvest (E_{energy}), transportation ($E_{transportation}$), and the production of seed, fertilizer, herbicide and machinery (E_{ind}). Equation 15 displays the second objective to minimize the total GHG emission from above sections.

$$\text{Min } TE = E_{luc} + E_{energy} + E_{transportation} + E_{ind} \tag{15}$$

$$E_{luc} = \sum_{p} \left(\sum_{mi} AH_{mip} \times (\Delta LUCO_{2,p} + \Delta LUCH_{4,p} + \Delta LUN_2O_{,p}) \right) \tag{16}$$

$$E_{energy} = \sum_{mipb} XH_{mipb} \times StorE + \sum_{mibp} AH_{mibp} \times (ProE + HarE) \tag{17}$$

$$E_{transportation} = \sum_{mi} TransE_{mip} \times \frac{\sum_{p} XTN_{mip} + \sum_{pt} XTO_{mip}}{Loadwt_{mip} \times (1 - DML^{trans})} \tag{18}$$

$$E_{ind} = \sum_{mip} (FertE + HerbE + SeedE) \times AH_{mip} + \sum_{mb} Numb^{k}_{mb} \times machE^{k} \tag{19}$$

2.2.3 Soil erosion

The soil erosion rate at a particular site is determined by the combination factors of physical structure of soil layers, land management, and climate pattern, which can be estimated through modeling of Universal Soil Loss Equation (USLE), that enable conservation planners to project limited erosion data to the objective localities and conditions that cannot completely be measured physically. The USLE model is developed and improved by the USDA soil conservation service to revised USLE (RUSLE) and has been the most widely used model since then (Wischmeier and Smith 1978). The model framework and availability of data factors across the country is also widely studied (Kokkinidis 2014; Renard et al. 1997). The model is designed to predict the longtime average soil losses in runoff from specific field areas in specified cropping and management systems:

$$SoilE = R \times K \times C \times P \times LS \tag{20}$$

where, potential long-term average annual soil loss (*SoilE*, ton/acre/yr) can be obtained by multiplying the following factors: *R*, rainfall and runoff factor by geographic location; *K*, soil erodibility factor; *C* crop/vegetation and management factor; *P* support practice factor; and *LS*, length and steepness of slope factor. All these factors are dimensionless and valuated empirically. The result of *SoilE* can be compared with existing database of soil loss tolerance (*T*, ton/acre/yr), which is the maximum amount of soil loss tolerated to assess the erosion hazard of that area, to appraise the soil erosion hazard (Soil Survey Staff).

Because the difficulty to quantify and capture the soil erosion caused by manufacturing operations and other management operations other than land management, it is assumed that these operations sections not having soil erosion hazards. Therefore the hexagon-level resolution of soil loss estimation based on the land use change is displayed below, which is the third environmental impact objective to be minimized:

$$\text{Min} \quad TSoilE = \sum_i \{(R_i \times K_i \times LS_i \times P_i) \times \sum_p [(C_{swg} - C_p) \times \sum_b A_{ipb}]\} \tag{21}$$

As the land use type alters from cropland into switchgrass, the only soil erosion factor change will be crop management factor C in Equation 20. Switchgrass has a deep root system and abundant root biomass that significantly decrease the soil detachment with relative lower C factor for switchgrass. *R* factor is constant after the land use change, and the climate pattern will remain the same in a short run. Soil erodibility (*K*) and length steepness of the slope factor (*LS*) is geographically fixed and remains the same evenness with alternative cover crops. Support practice factor (*P*) is also fixed by the same upslope or downslope tillage with same flow pattern, grade, and direction of surface runoff after the land use changes to switchgrass. *C* factor therefore is the only factor that will change when the cover crop alters.

2.3 Eps-constraint method in multi-objective program

In this study, an improved augmented ε-constraint method (Mavrotas and Florios 2013) was applied to derive the tradeoff relationship between the three objectives considered by interpolating values between the extreme optima. By setting up priority objective function of cost, and release the other two environmental metrics as constraints, the multi-objective problem could find the trade-off middle point between the extreme optima. While AUGMON2 method still generates more surplus and repeating solutions (Mavrotas and Florios 2013), the algorithm is further developed by reducing the iteration times and increases the computation efficiency by more than 90%.

The Pareto Frontier was developed to evaluate the potential tradeoff among multiple objectives: cost minimization, GHG minimization, and soil erosion minimization. The best preferred point from the frontier was determined by Compromise Solution Method where the solution is closest to the ideal point (Ramos et al. 2014).

The other implication from the multi-objective problem includes: 1) location of the biorefinery and associated feedstock supply region; 2) amount of land converted from conventional crops or hay land; and 3) best management plan for consumption of energy, fertilizer, herbicide, seed and farm machinery and maintain the sustainability of switchgrass feedstock logistic system.

2.4 Data

2.4.1 Cost analysis

Crop yields were obtained from the SSURGO Database at the sub-county level (U.S. Department of Agriculture Nature Resources Conservation Service 2012). Switchgrass yield was simulated by Jager et al. (2010). Area in each land resource unit for each crop type was derived from the Cropland Layer Database (U.S. Department of Agriculture 2011). The prices of crops were three-year average prices for 2010-2012 (U.S. Department of Agriculture 2013). Production costs for crops were from the US Department of Agriculture (U.S. Department of Agriculture 2013) and Policy Analysis System (POLYSYS) model (De La Torre Ugarte et al. 1998). Simulated switchgrass yields were obtained from the Oak Ridge Energy Crop County Level Database (Jager et al. 2010) and were disaggregated to the land resource unit level using an index of soil quality. Production and harvest costs for switchgrass were from Larson et al. (2010) and the University of Tennessee (2014). The transportation cost of switchgrass included labor, energy consumption, semi-truck maintenance, and loading/unloading. The energy, labor and maintenance costs for operating equipment and capital costs were calculated based on the American Agricultural Economics Association Cost and Return Handbook (American Agricultural Economics Association 2000) and

American Society of Agricultural Engineers Standards (American Society of Agricultural and Biological Engineers 2006).

2.4.2 GHG estimation

To estimate the GHG emissions from land use change, the DAYCENT model, a daily time-step version of the CENTURY (Parton et al. 1994) biogeochemical model, was adopted to simulate the soil carbon uptake and CH_4 and N_2O emission factors due to the conversion of different types of land into switchgrass production. The soil carbon stock change is calculated based on IPCC guideline(Aalde et al. 2006). The management practice is scheduled according to the Field Crop Budgets (University of Tennessee 2014). The daily weather data from 1900 to 2012 for Tennessee was acquired from the DAYMET model maintained by the Oak Ridge National Laboratory[1]. The soil property data used in the DAYCENT were from SSURGO database (U.S. Department of Agriculture Nature Resources Conservation Service 2012). To show the spatial difference in emission potential, the state of Tennessee is divided into three Grand Divisions legally, geographically, and culturally (Tennessee General Assembly 2014) of East Tennessee, Middle Tennessee, and West Tennessee.

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (Argone National Laboratory 2013) provided the emission factors for all the three GHG gases from all machinery or vehicle combustion during LCB harvest. GHG emissions from transportation were estimated using the Motor Vehicle Emissions Simulator

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[1] http://daymet.ornl.gov/

(MOVES) developed by U.S. Environment Protection Agency (U.S. Environment Protection Agency). In addition to travel distance, local weather, travel speed and the slopes of road were considered when estimating the truck emissions of switchgrass from farm gate to the conversion facility. The version used to estimate vehicle emissions was MOVES2010b. Indirect emissions from the production of agricultural machinery, fertilizer, herbicide, and seed were calculated based on the emission factors from GREET model.

2.4.3 Soil erosion estimation

As mentioned in Equation 9, the five estimators of USLE model are available through different databases with high solution: The county level *R* factor can be obtained through RUSLE2 model[2]; *K* factor and slope angle is given in the SSURGO database[3]; *C* factor is referred from the TN bulletin with an assumption that the crop management follows traditionally routines (Jent et al. 1967). For cultivated cropland in TN, the relationship between the steepness and P factor has been found in Jent et al. (1967). The topographic factor LS is calculated and replaced by the drained area and slope angle (Mitasova et al. 2001; Mitasova et al. 1996).

3 Preliminary Results and Discussion

Figure 2 shows the relationship among the cost, GHG emission, and soil erosion for the cost minimization location in TN. Cost and environmental output are summarized in Table 2. Under the cost minimization case, total plant-gate feedstock cost was $43.4 million with 50.7

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[2] RUSLE2 model website: http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm
[3] SSURGO database: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053627

million kg of GHG and causes 34.0 thousand tons of soil erosion per year for the facility located in Wilson County. Hay/pasture is primarily converted to switchgrass with lowest opportunity cost, while this conversion likely release more GHG and reduce soil stability. The dot-line curves are pairwise projection plots of feasible solution. The cost-GHG and cost-soil erosion curves show that both GHG and soil loss mitigated when cost increased (Figure 2a). The surface plot in Figure 2b also shows the tradeoff relationships in the space. When the color map turns dark and purple, more soil can be conserved.

The solutions of all candidate nodes over Tennessee are shown in Figure 3. The regional Pareto frontier (envelope surface) was obtained encompassing the tradeoff curves of all candidate nodes (Figure 3a). The Pareto surface plot (Figure 3b) represents a bow-shaped surface which is the interpolated smooth surface based on feasible solution points. The best solution was determined by the Compromised Solution Method, where locates nearest to ideal point using weighted distance value. The result showed that, at a preferred point located in Lincoln County, the total cost increased by 53% from the cost minimization case while GHG emissions reduced by more than 68%. In addition, about additional 4.76 million tons/year of soil erosion was prevented compared to the cost minimization case. The tradeoff relation between GHG emission and soil erosion from Figure 4b showed a positively correlation between these two environmental metrics, and diverged when both metrics leaving from cost minimizing point. The divergence also indicates wider variation corresponding to increased cost.

The draw area for switchgrass production for scenarios of most preferred scenario and single objective scenarios are provided in Figure 4. Point B and O converted mainly crop lands to switchgrass saving GHG and soil erosion impact, while leave opportunity cost surge significantly.

4 Conclusion

Expediting the development of environmentally friendly alternative energy sources using switchgrass has been strongly promoted by State and federal government agencies over the past decades. However, technical barriers to the development of a cost-effective feedstock supply chain impede the sustainability of a bioenergy sector in the United States. This study identified an efficient Pareto frontier to minimize the industrial cost and generate interlaced environmental benefit. The trade-off relation considering both economic and multiple environmental metrics using multi-objective model provided information for policy makers to allocate the land use and optimize the management.

Results showed that land change into switchgrass production is crucial to both plant-gate cost and environmental impact of feedstock supply. Converting croplands to switchgrass incurred higher opportunity cost from land use change but stored more soil carbons and generated less soil erosions. The opportunity cost for converting hay/pasture land to switchgrass was lower but likely released more soil GHG emissions and caused higher soil losses. Tradeoff between feedstock costs and environmental benefits in switchgrass supply chains is also related to the changes of land use. The preferred location for the conversion facility generated modest increases in feedstock cost but improved the negative environmental impact greatly in the feedstock supply chain.

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Table 1 Definitions of Subscripts, Parameters and Variables

	Unit	Definition
Subscripts		
i		locations of switchgrass production field
j		location of the biorefinery
m		month
p		crops (hay & pasture, corn, soybean, wheat)
b		harvest method (square baler, round baler)
t		storage protection method
k		type of machinery (tractor, mower, loader, rake, baler)
Parameters		
$Price_{ip}$	$/unit	traditional crop price
$Yield_{ip}$	ton/area	tradition crop yield
PC_{ip}	$/acre	production cost of traditional crop
$Yield_i^{swg}$	ton/acre	yield for switchgrass in each hexagon
LR_{ip}	$/acre	land rent of traditional crop
Est	$/acre	Establishment cost in the first year
AM	$/acre	Annual maintenance cost
$Sigma_{ib}$	$/acre	cost of harvesting switchgrass
BEP_{ipb}	$/acre	breakeven price of land conversion to switchgrass
γ_{ibt}	$/ton	cost per unit of storing switchgrass
θ_{ib}	$/ton	cost per unit of transporting switchgrass from field to biorefinery
$LUCO_{2,p}$	CO_2e kg/acre	CO_2 emission from land conversion of crop to switchgrass
$LUCH_{4,p}$	CO_2e kg/acre	CH_4 emission from land conversion of crop to switchgrass
$LUN_2O_{,p}$	CO_2e kg/acre	N_2O emission from land conversion of crop to switchgrass
$StorE$	CO_2e kg/ton	GHG emissions from energy usage during storage
$HarE$	CO_2e kg/acre	GHG emissions from energy usage during harvest
$ProE$	CO_2e kg/acre	GHG emissions from energy usage during production
$FertE$	CO_2e kg/ton	GHG emissions from fertilization production
$HerbE$	CO_2e kg/ton	GHG emissions from herbicide production
$SeedE$	CO_2e kg/ton	GHG emissions from seed production
$MachE$	CO_2e kg/unit	GHG emissions from machinery production
$TransE_{mip}$	CO_2e kg /truck/route	GHG emissions from energy usage during transportation
$Loadwt_{mib}$	ton/truck	tonnage of switchgrass delivered per truck
Aa_{ip}	acre	cropland available in each hexagon for each crop
$CapUnit$	gal/year	annual capacity of a biorefinery
λ	gal/ton	switchgrass-ethanol conversional rate
$rateava_m$	%	ratio of working hours in each month to total

$Avehour_m$	hour	average working hours of machinery in each month
MTB_{ib}	hour/acre	machine time per acre for each machinery
PAS_p	%	maximum percent of land converted
DML^{trans}	%	dry matter loss during transportation
DML^{stor}_{mbt}	%	dry matter loss during storage
Q_m	gal/month	monthly demand for ethanol
τ_i	head/acre	density of cattle one per acre of hay and pasture land
Variables		
A_{ipb}	acre	acres of switchgrass produced annually
AH_{mipb}	acre	acres of switchgrass harvested monthly
XC_{ipb}	ton	switchgrass produced annually
XH_{mipb}	ton	switchgrass harvested monthly from November to February
XTN_{mipb}	ton	switchgrass transported directly to the biorefinery after harvest
NXS_{mipbt}	ton	switchgrass newly stored monthly in harvest season
XS_{mipbt}	ton	switchgrass stored in harvest season
XTO_{mipbt}	ton	switchgrass transported from storage to the biorefinery
$Numb^{k}_{mb}$	unit	number of equipment used during harvest

Table 2 Summary of yearly itemized cost and environmental metrics

	Total cost min (A)	GHG min (B)	Middle point (O)
Opportunity Cost ($)	111,050,39	7,280,450	20,090,189
Harvest Cost ($)	22,395,721	22,621,306	22,542,500
Storage Cost ($)	2,774,796	2,774,796	2,774,796
Transportation Cost ($)	8,306,579	11,105,039	12,541,042
Production Cost ($)	8,606,186	8,779,434	8,718,912
Total cost ($)	**43,416,968**	**52,561,026**	**66,667,440**
GHG (kg)	**50,705,295**	**24,461,159**	**30,077989**
SoilE (ton)	**33,981**	**-2,721,296**	**-4,732.468**

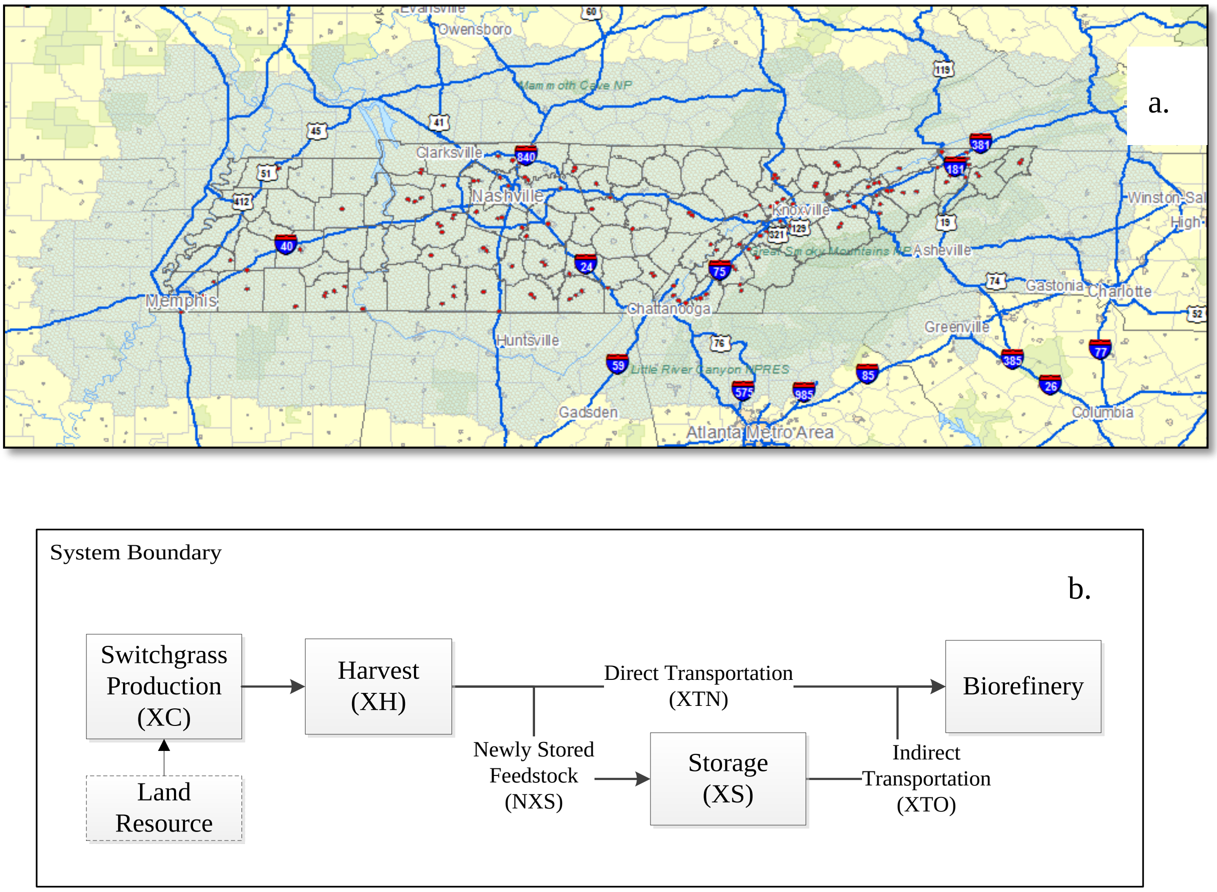

Figure 1 Potential feedstock area and industrial parks (a) and flow diagram of switchgrass supply chain from field to biorefinery (b)

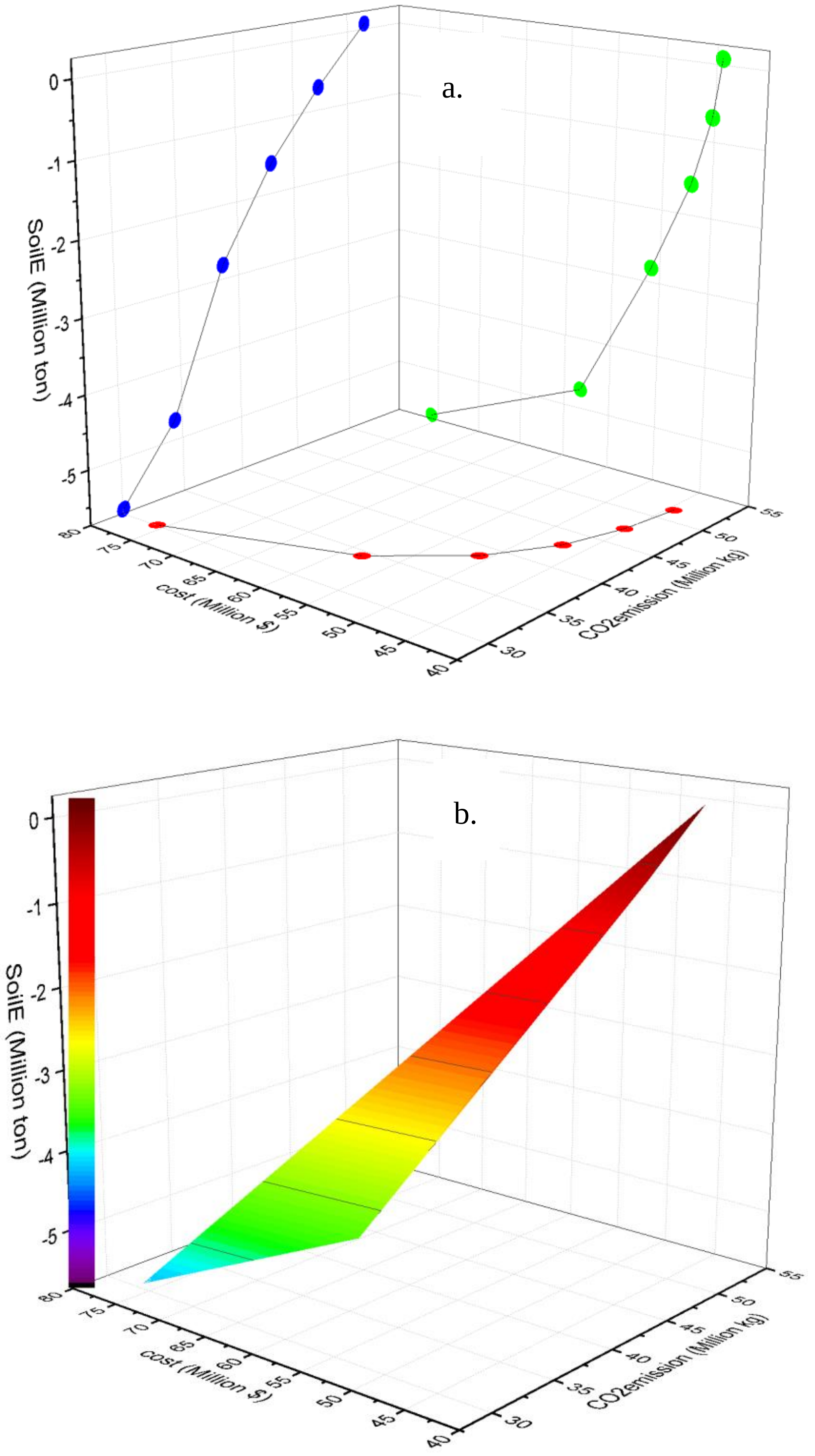

Figure 2 Solution of a single candidate point (a: solution projection on each coordinator panel; b: 3D surface)

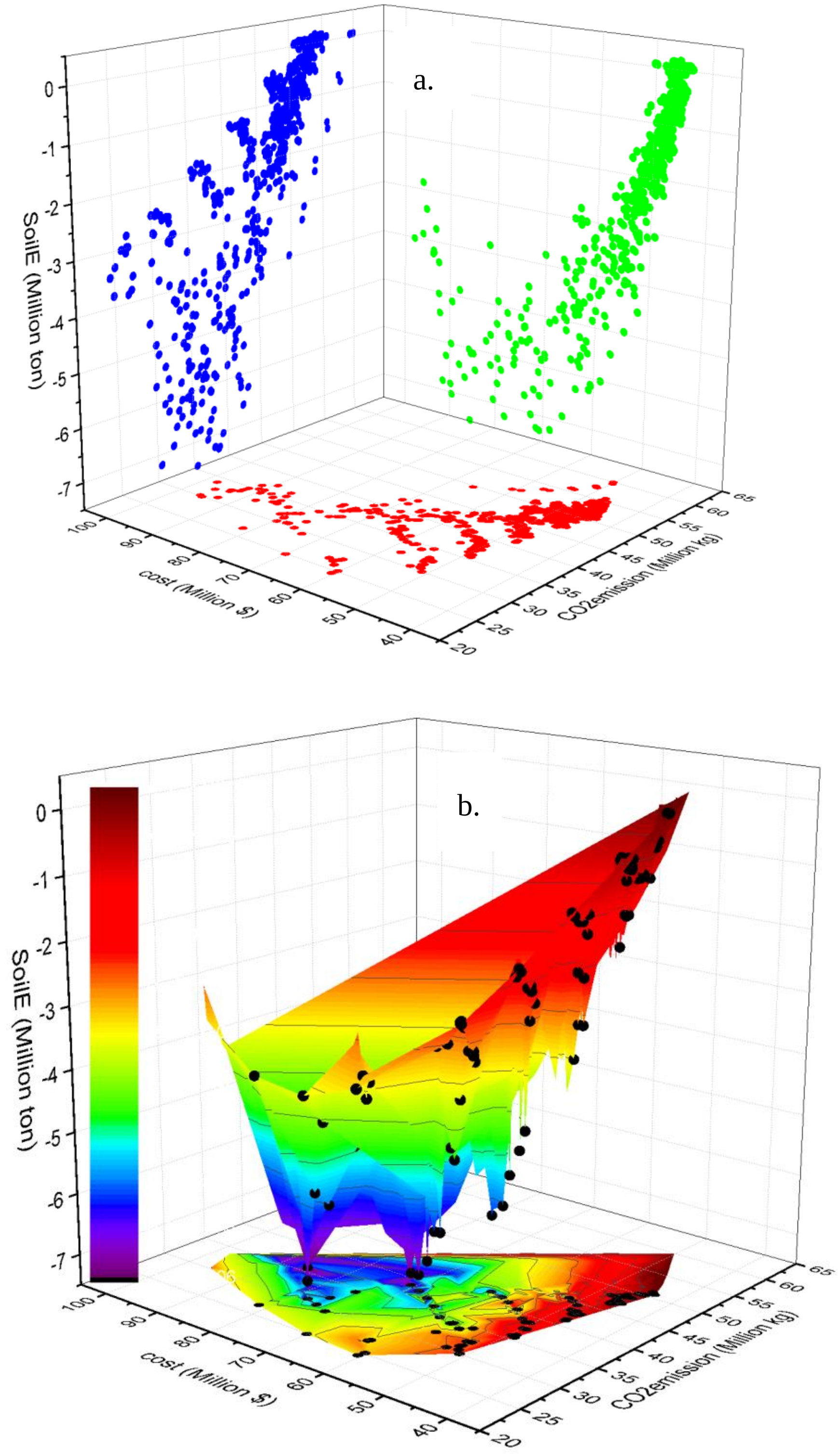

Figure 3 Regional feasible solution (a: solution projection on each coordinator panel; b: 3D Surface with regional Pareto curve in black dots)

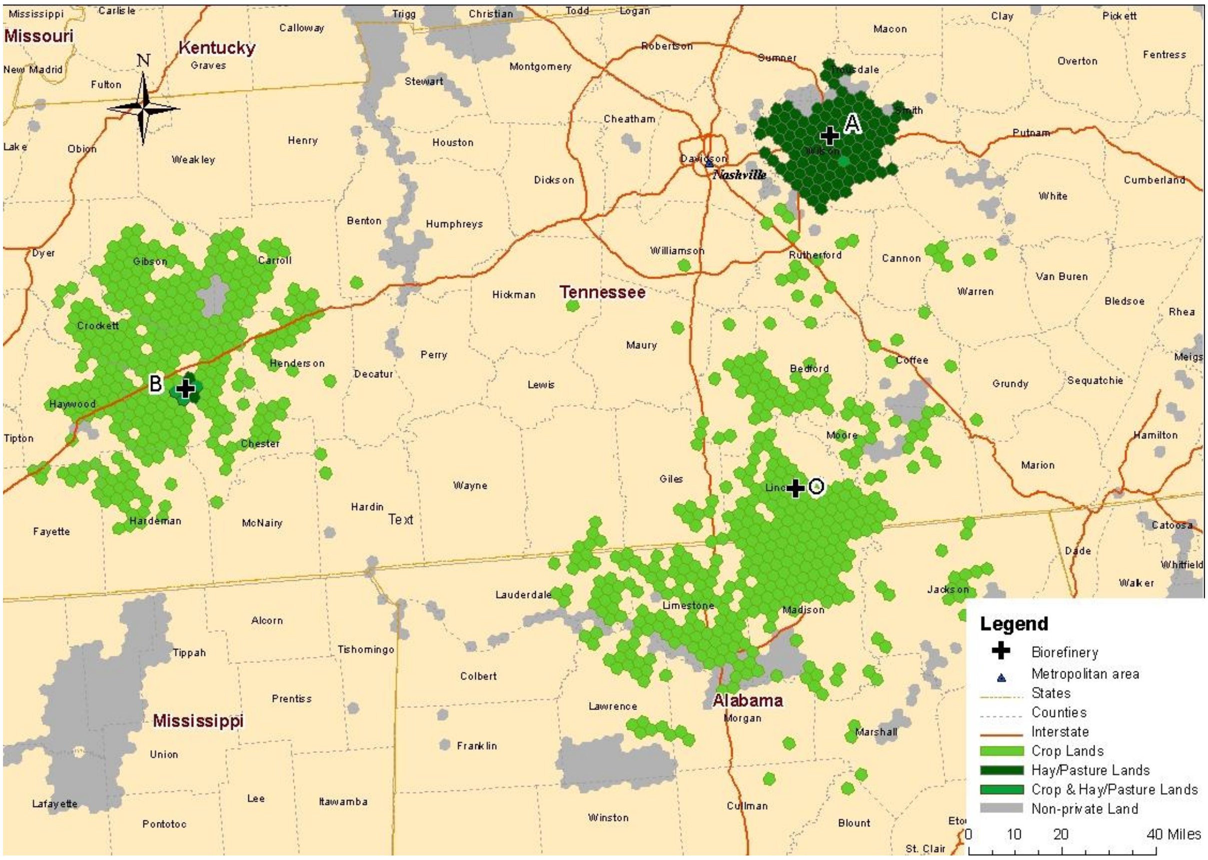

Figure 4 The draw area for switchgrass under different scenarios (A: Cost minimization; B: Emission minimization; O: Most preferred optimal point)

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