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Analysis of environmental and economic tradeoffs in switchgrass supply chains for biofuel production

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ABSTRACT

This study considered the environmental advantages of switchgrass, along with the economic challenges in its logistics, in the design of a sustainable switchgrass supply chain in Tennessee. Applying a multi-objective optimization model to high-resolution spatial data, potential tradeoffs among the objectives of minimizing feedstock costs, GHG (greenhouse gas) emissions, and soil erosion were identified for a set of conversion facilities on an efficient frontier. The tradeoff relationship was primarily driven by the type of agricultural land converted to switchgrass. Hay and pasture lands were more cost effective but resulted in higher soil carbon losses and soil erosion after being converted to switchgrass. Converting crop lands reduced GHG emissions and soil erosion but caused higher feedstock cost primarily due to the higher opportunity cost of land use. The respective average costs of abating GHG emissions and soil erosion on the efficient frontier were \$2378 Mg^{-1} and \$10 Mg^{-1}. The compromise solution conversion facility site generated 63% higher feedstock cost compared to the cost minimizing location, while reducing soil erosion by 70 fold and diminishing GHG emissions by 27%. Reducing soil erosion may be a more cost effective environmental criterion than reducing GHG emissions in developing a sustainable switchgrass supply chain in Tennessee.

1. Introduction

Higher energy prices and the mandate set forth in the Renewable Fuel Standard of the Energy Independence and Security Act of 2007 [1] have driven growth in ethanol produced using corn (Zea mays L.). Changes in land use with expanded corn production have raised concerns about increased soil erosion, fertilizer and pesticide pollution, and greenhouse gas emissions [2]. Corn uses more fertilizer than other major crops and accounted for 46% of all fertilizer use in the United States in 2010 [3]. Tillage intensity is also higher for corn production than for other crop production, exacerbating water-induced soil erosion [2]. Therefore, the expansion of corn production on existing crop lands, set aside agricultural lands, and grasslands [4–7] has aggravated soil erosion [8,9] and losses of nutrients to the environment [10].

The US EPA (Environmental Protection Agency) has advocated the production of biofuels from LCB (lignocellulosic biomass) to overcome the aforementioned problems from using grain crops to produce biofuels. In addition, the US EPA's 2014 Clean Power Plan promotes the production of biofuels using LCB as a strategy to reduce GHG (greenhouse gas) emissions [11]. The agency requires that any advanced biofuel generate 60% fewer lifecycle GHG emissions than gasoline or diesel fuel when measured at 2005 levels [12]. Biofuels produced from LCB, including short-rotation woody crops, agricultural residues, and herbaceous grasses, have great potential for reducing GHG emissions relative to biofuels produced from grain crops (Farrell et al., 2006). Growing perennial grasses to produce biofuels also could reduce soil erosion on agricultural lands [13,14], an important objective of US agricultural policy [15].

Abbreviations: LCB, lignocellulosic biomass; GHG, greenhouse gas; USDA, US Department of Agriculture; EPA, Environmental Protection Agency; RUSLE, Revised Universal Soil Loss Equation; MRS, marginal rate of substitution.

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Switchgrass (Panicum virgatum), a herbaceous prairie grass native to North America, requires less fertilizer and chemicals, has better water use efficiency, and has greater tolerance to a wide range of environmental conditions when compared to field crops and other herbaceous species [16,17]. Because switchgrass is a perennial crop with a life span of 10 or more years, it provides year-round coverage of soils and enhances soils through its extensive root system that reduces water runoff and soil losses and by improving soil organic matter, soil structure, soil water holding capacity, and nutrient holding capacity [18]. Previous studies have suggested that biofuels produced using switchgrass could reduce GHG emissions by 60%–90% when compared with fossil fuels [19] and up to 50% when compared with biofuels produced using corn grain [20,21].

Despite the potential environmental and ecological advantages, the high cost of using switchgrass for biofuels production has impeded development of a switchgrass-based biofuels industry [22,23]. Biofuels produced using switchgrass costs 17.8% more than corn and 34.4% more than gasoline when measured on an energy equivalent basis in 2005 dollars [23,24]. Procurement costs in a switchgrass supply chain may constitute 30%–50% of the total cost of producing biofuels [22,25,26]. Important factors contributing to higher supply chain costs include low bulk density of switchgrass; increasing harvest, storage, and transportation costs; and losses of feedstock stored outdoors due to weathering if switchgrass is harvested only once a year [27].

Operations research methods have been widely used to evaluate the design of LCB supply chains using cost minimization or profit maximization as the objective of the decision maker (e.g. 25–26, 28). However, an increasing number of studies have examined economic and environmental tradeoffs in the design of a sustainable LCB supply chain [28–32]. Notwithstanding the growing literature evaluating tradeoffs in biofuels production, the imputed costs of mitigating environmental degradation or improving environmental quality with biofuels produced using LCB have only been examined on a limited basis [32]. The imputed cost is the proxy value of ecosystem services provided by LCB production such as reduced GHG emissions and soil erosion in the design of a sustainable supply chain [32,33].

An assessment of the sustainability of an LCB supply chain depends on the use of high-resolution spatial data to accurately model the characteristics of the supply chain [34]. Spatially oriented factors such as LCB availability, changes in fertilizer and chemical use with LCB production, and feedstock transportation costs and emissions influence the optimal configuration of a sustainable supply chain. Models that use high spatial resolution data generate more detailed predictions of the footprint of the LCB supply chain and are more useful for policy analysis and for private and public decision making [35]. Most multi-objective studies have not taken into account spatial characteristics, with only a few studies highlighting the value of geographic data in the economic and/or environmental optimization of the LCB supply chain [29,32,35,36].

A systematic assessment of the imputed costs of environmental services in a LCB supply chain will contribute to a better understanding by potential stakeholders of the cost-benefit tradeoffs of biofuels production. However, the existing literature lacks an integrated mathematical model valuation that incorporates high-resolution geospatial data on various environmental outputs from LCB supply chains. Acknowledging that gap in the literature, the present study combines the use of detailed spatial data and a multi-criteria optimization model to examine economic and environmental tradeoffs in a LCB supply chain. This study extends the typical tradeoff analysis in bioenergy literature to assess the value of various environmental outputs from LCB supply chains. The fine spatial details included in the LCB supply chains analysis enhances the determination of feedstock draw area and conversion facility location. The detailed data also improves the precision of soil erosion and greenhouse gas emissions estimation from the land use changes required to supply the biomass.

The analysis focuses on the optimal location and design of a switchgrass supply chain in Tennessee. The state of Tennessee has several characteristics that lend itself to an evaluation of economic and environmental tradeoffs in biofuels production: a humid subtropical climate that is well suited to the production of high yielding switchgrass, agricultural soils that are highly erodible, and a geographically diverse set of agricultural production activities and landscapes. Thus, the objectives of this study are: (1) to determine the potential tradeoffs required to minimize feedstock costs, GHG emissions, and soil erosion for a switchgrass supply chain in Tennessee, and (2) to evaluate the imputed costs of abating GHG emissions and soil erosion in the switchgrass supply chain. The valuation of GHG emissions and soil erosion can assist in the development of an economically and ecologically viable advanced biofuel production effort.

2. Methods and data

2.1. Supply chain assumptions

Minimization of total switchgrass cost was assumed to be the primary objective of conversion facility decision makers. High feedstock cost has been identified as an important impediment to the development of a switchgrass-based biofuel industry for private investors interested in maximizing profits [22,23]. The two environmental criteria, minimization of GHG emissions and minimization of soil erosion are driven by US EPA and USDA (US Department of Agriculture) policies aimed at reducing their levels [12,15]. The system boundary for calculating switchgrass costs, GHG emissions, and soil erosion produced in the supply chain was from the farm field to the conversion facility plant gate (Fig. 1).

The switchgrass conversion facility was assumed to produce 189.3 million liters (L) of ethanol year^{-1}. The five main feedstock cost components considered in the design of the supply chain were: (1) land resource allocation, (2) production, (3) harvest, (4) storage, and (5) transportation. Supply chain activities were modeled on a monthly time-step. Switchgrass was harvested between November and February after senescence, delivered to the facility or placed in storage during harvest, and delivered from storage to the facility for processing in the off-harvest period from March through October. Assuming a conversion rate of 287.7 L of ethanol dry Mg^{-1} of switchgrass [37], feedstock required for the facility was 600,892 dry Mg year^{-1}.

The potential switchgrass supply area in this study included all agricultural land in Tennessee and a buffer area of 80 km contiguous to the state border (Fig. 2). Locations for the conversion facility were limited to 150 industrial parks in the Tennessee Valley Authority database [38]. Candidate industrial parks had the required space and access to roads and water resources for the facility. The study area was downscaled to a 13 km^2 hexagon resolution, defined as the land resource unit, to capture variations in land resources, the transportation network, and other geographic features of the study area. The ratio of crop land to hay and pasture land by land resource unit in Fig. 2 indicates that west Tennessee is the major crop production area, while pasture and hay land is primarily located in the eastern region of the state.

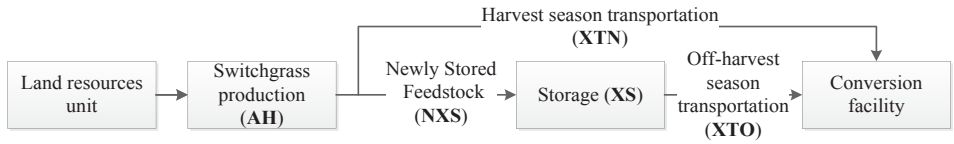

Fig. 1. System boundary of switchgrass supply chain: field to conversion facility.

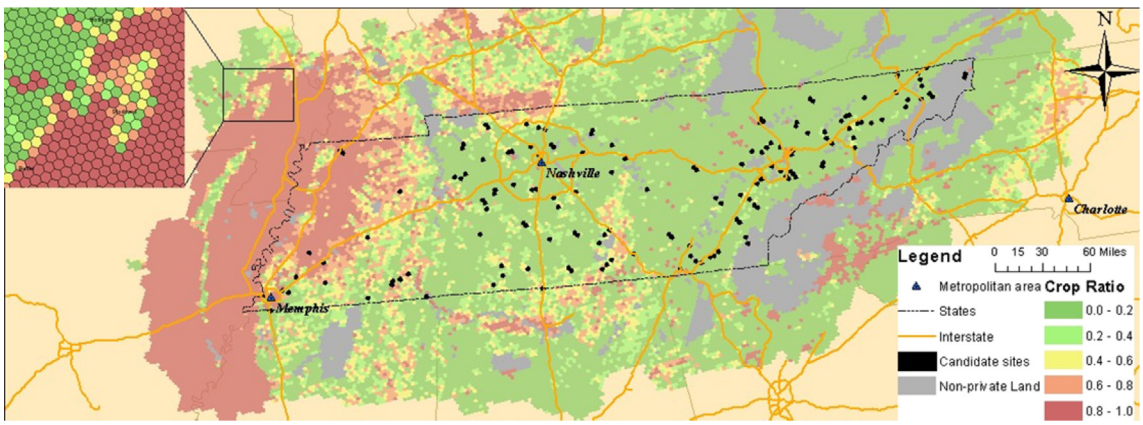

Fig. 2. Potential switchgrass supply area and industrial park sites for conversion facilities. Note: Crop ratio is the ratio of crop land to hay and pasture lands.

The payoff table method was used to determine the most preferred solution [39] of the multi-objective feedstock cost, GHG emission, and soil erosion minimization model. The supply chain model considering the aforementioned feedstock cost components was solved for each individual objective for each of the 150 industrial park sites in the study area. Optima and nadir values and the ranges obtained from solving for each individual objective were used in an improved augmented ε-constraint method [40] to solve the multi-objective function for each potential conversion facility site. Feasible and efficient solutions for all 150 sites in the study area form the efficient frontier (also called the Pareto-optimal) set of conversion facilities for the study area. The compromise solution method [41] was used to identify the most preferred conversion facility site and the switchgrass draw area for the supply chain on the frontier. Costs of abating GHG emissions and soil erosion in the supply chain were imputed using the frontier solution.

2.2. Model structure

2.2.1. Cost minimization

Following Larson et al. [42], minimization of feedstock cost at the conversion facility plant gate (TC, \$) for the switchgrass supply chain was modeled using Equations (1)–(6):

$$\text{Min } TC = C_{opportunity} + C_{production} + C_{harvest} + C_{storage} + C_{transportation}, \tag{1}$$

$$C_{production} = \sum_{ip}((Est + AM) \times \mathrm{AH}_{ip}), \tag{3}$$

$$C_{harvest} = \sum_{ip}(\sigma_i \times \mathrm{AH}_{ip}), \tag{4}$$

$$C_{storage} = \sum_{mi}(\gamma_i \times \mathrm{NXE}_{mi}), \text{and} \tag{5}$$

$$C_{transportation} = \sum_{i}\left(\theta_i \times \left(\sum_{m}\mathrm{XTN}_{mi} + \sum_{m}\mathrm{XTO}_{mi}\right)/(1 - DML^{trans})\right). \tag{6}$$

Costs for production ($C_{production}$), harvest ($C_{harvest}$), storage ($C_{storage}$), and transportation ($C_{transportation}$) activities in Equation (1) included equipment ownership, maintenance, labor, fuel, and materials used for farm field to plant gate activities in the switchgrass supply chain.

Definitions of the cost parameters and decision variables are listed in Table 1. The key parameters in the equations in this section and subsequent Sections (2.2.2 and 2.2.3) are summarized in Appendix Table A.

Opportunity cost ($C_{opportunity}$) in Equation (2) was defined as the forgone profit from crop, hay, and pasture production activities from the prior land use or the market rental rate for the land [42]. Cost of switchgrass production ($C_{production}$) in Equation (3) included the annualized establishment cost and annual maintenance cost.

$$C_{opportunity} = \begin{cases} \sum_{ip}[(Price_{ip} \times Yield_{ip} - PC_{ip}) \times \mathrm{AH}_{ip}], & \text{if } (Price_{ip} \times Yield_{ip} - PC_{ip} - LR_{ip}) \geq 0 \\ \sum_{ip}(LR_{ip} \times \mathrm{AH}_{ip}), & \text{if } (Price_{ip} \times Yield_{ip} - PC_{ip} - LR_{ip}) < 0 \end{cases}, \tag{2}$$

Table 1
Definitions of subscripts, parameters and variables.

	Unit	Definition
Subscripts		
i		Land resource units
j		Industrial park sites for conversion facility
m		Month
p		Type of crop land (hay and pasture, corn, soybean, wheat, sorghum, cotton)
k		Type of machinery (tractor, mower, loader, rake, baler)
Parameters		
Price	$\$ \text{Mg}^{-1}$	Crop prices
Yield	Mg ha^{-1}	Crop yields
PC	$\$ \text{ha}^{-1}$	Crop production costs
Yield	Mg ha^{-1}	Switchgrass yields
LR	$\$ \text{Mg ha}^{-1}$	Land rent
Est	$\$ \text{ha}^{-1}$	Switchgrass establishment cost
AM	$\$ \text{ha}^{-1}$	Annual maintenance cost
σ	$\$ \text{ha}^{-1}$	Cost of harvesting switchgrass
γ	$\$ \text{ha}^{-1}$	Cost per unit of storing switchgrass
θ	$\$ \text{ha}^{-1}$	Cost per unit of transporting switchgrass
DML	%	Dry matter loss during transportation
Aa	ha	Crop land available in each land resource unit
Avehour	Hour	Average working hours of machinery in each month
DML	%	Dry matter loss during storage
MTB	hours ha^{-1}	Machine time ha^{-1} for each machinery
Λ	L Mg^{-1}	Switchgrass-ethanol conversional rate
Q	L month^{-1}	Monthly demand for ethanol
$\Delta LUCO_2$	$CO_2\text{e kg ha}^{-1}$	CO_2 emission from land conversion
$\Delta LUCH_4$	$CO_2\text{e kg ha}^{-1}$	CH_4 emission from land conversion
ΔLUN_2O	$CO_2\text{e kg ha}^{-1}$	N_2O emission from land conversion
ProE	$CO_2\text{e kg ha}^{-1}$	GHG emissions factor from energy use during Switchgrass production
HarE	$CO_2\text{e kg ha}^{-1}$	GHG emissions factor from energy usage during harvest
StorE	$CO_2\text{e kg ha}^{-1}$	GHG emissions factor from energy usage during storage
MachE	$CO_2\text{e kg unit}^{-1}$	GHG emissions factor from machinery production
TransE	$CO_2\text{e kg route}^{-1}$	GHG emissions from energy usage during transportation
Loadwt	Mg truck^{-1}	Switchgrass delivered per truck
FertE	$CO_2\text{e kg Mg}^{-1}$	GHG emissions factor from fertilizer production
ChemE	$CO_2\text{e kg Mg}^{-1}$	GHG emissions factor from chemical production
SeedE	$CO_2\text{e kg Mg}^{-1}$	GHG emissions factor from seed production
U		Upper bound values for certain objective
L		Lower bound values for certain objective
R		Range of certain objective
Variables		
AH	ha	Area of switchgrass harvested
XTN	Mg	Switchgrass transported directly to the biorefinery
NXE	Mg	Switchgrass stored during harvest season
XE	Mg	Cumulative switchgrass storage
XTO	Mg	Switchgrass transported from storage to the biorefinery
NM	Unit	Number of equipment used for harvest

Harvest cost ($C_{harvest}$) in Equation (4) assumes switchgrass was processed into large rectangular bales. Storage cost for switchgrass (γ_i) in Equation (5) included materials, equipment, and labor for rectangular bale staging and storage operations. Transportation costs (θ_i) in Equation (6) assumed the use of semi-trailer trucks and trailers to transport switchgrass from storage to the conversion facility. Costs for transportation were determined by the time required to perform each activity. Loading and unloading times for bales were taken from a study by Duffy [43]. Distance and truck speed based on highway speed limits were used to determine transportation time. Maximum travel distance to transport switchgrass to the conversion facility was assumed to be 121 km.

The cost minimization was subject to constraints based on practical operation requirements and rules of mass balance:

$$\text{Available area for production}: \sum_{\text{m}} \text{AH}_{mip} \le Aa_{ip}, \forall i, \quad p\ \text{Nov} \le \text{m} \le \text{Feb}. \tag{7}$$

$$\text{Available harvest working hours}: NM_m^k \times Avehour_m - \sum_i \left(MTB_i^k \times \text{AH}_{mip}\right) \ge 0, \quad \forall k, m. \tag{8}$$

Harvest to shipment and storage balance:

$$\sum_p \text{AH}_{mip} \times Yield_i^{swg} = \text{XTN}_{mi}/\left(1 - DML^{trans}\right) + \text{NXE}_{mi}, \ \forall \text{m}, \text{i}. \tag{9}$$

Cumulative storage balance during harvest season:

$$XE_{(m+1)i} = \left(1 - DML_m^{stor}\right) \times \text{XE}_{mi} + \text{NXE}_{(m+1)i}, \quad \forall \text{m}, \text{i Nov} \le \text{m} \le \text{Feb}. \tag{10}$$

$$\mathrm{XE}_{(m+1)i} = \left(1 - DML_m^{stor}\right) \times \mathrm{XE}_{mi} - \mathrm{XTO}_{(m+1)ip} \Big/ \left(1 - DML^{trans}\right), \quad \forall \mathrm{m, i\ March} \le \mathrm{m} \le \mathrm{Oct}. \tag{11}$$

Cumulative storage balance during off-harvest season:

$$\text{Ethanol production requirement}: \lambda\left(\sum_i \mathrm{XTN}_{mip} + \sum_i \mathrm{X\Gamma O}_{mi}\right) - Q_m = 0, \forall m. \tag{12}$$

$$\mathrm{AH,\ NXE,\ XE,\ XTN,\ XTO,\ and\ NM} \ge 0. \tag{13}$$

Equation (7) restricts available land area based on switchgrass yields in each land resource unit. Machine hours month^{-1} are constrained in Equation (8) to available harvest days based on weather during harvest. Equation (9) requires switchgrass harvested to equal the summation of switchgrass delivered directly to the conversion facility (XTN) after adjusting for transportation dry matter losses and quantity of feedstock sent to storage (NXE). Equations (10) and (11) maintain the balance of the cumulative storage of switchgrass after accounting for storage dry matter losses. Feedstock deliveries to the conversion facility in each month need to meet the demand for biofuel production in Equation (12). All parameters and variables in the model are non-negative as required in Equation (13).

2.2.2. GHG emissions minimization

The framework presented by Yu et al. [32] was used to calculate GHG emissions generated in the switchgrass supply chain. Equations (14)–(18) model the minimization of total GHG emissions (TE, kg yr^{-1}) from supply chain activities:

$$\mathrm{Min}\ TE = E_{luc} + E_{energy} + E_{transportation} + E_{ind}. \tag{14}$$

$$E_{luc} = \sum_p \left(\sum_{mi} \mathrm{AH}_{mip} \times \left(\Delta LUCO_{2,P} + \Delta LUCH_{4,P} + \Delta LUN_2O_{,P}\right)\right), \tag{15}$$

$$E_{energy} = \sum_{mip} \mathrm{AH}_{mip} \times (ProE + HarE) + \sum_{mip} \mathrm{AH}_{mip} \times Yield_i^{swg} \times StorE, \tag{16}$$

$$E_{transportation} = \sum_{mi} TransE_{mip} \times (\mathrm{XTN}_{mi} + \mathrm{XTO}_{mi}) / \left(Loadwt \times \left(1 - DML^{trans}\right)\right), \text{and} \tag{17}$$

$$E_{ind} = \sum_{mip} (FertE + ChemE + SeedE) \times \mathrm{AH}_{mip} + \sum_{mb} \mathrm{NM}_{mb}^k \times machE^k. \tag{18}$$

The definitions for the emission parameters are listed in Table 1. The major sources of changes in emissions were from adjustments in land use (E_{luc}), energy consumption from switchgrass production, storage, and harvest (E_{energy}), transportation ($E_{transportation}$), and from the energy used to manufacture seed, fertilizer, chemicals, and machinery (E_{ind}) used in the supply chain. Emissions caused by changes in land use were calculated by multiplying the emission factors for CO_2, CH_4, and N_2O by the area of crop, hay, and pasture lands converted to switchgrass production [Equation (15)]. Energy consumption for switchgrass production and storage activities were calculated through the summation of land area times the farm operations' emission factors and storage weight times the storage emission factor [Equation (16)]. Transportation emissions were calculated through the multiplication of the emission factor per truck per route times the truck loads for all transported biomass [Equation (17)]. Indirect emissions are from the manufacture of fertilizer, chemicals, seed, and machinery used in the production of switchgrass [Equation (18)].

2.2.3. Soil erosion minimization

For the soil erosion minimization objective, changes in water-induced soil erosion from converting crop, hay, and pasture lands to switchgrass production were estimated using the RUSLE (Revised Universal Soil Loss Equation) [44–46]. Water-induced soil erosion is influenced by land use activity (crop, hay, and pasture production), tillage method, landscape, and precipitation factors in the RULSE model. Equation (19) models the annual soil loss ($TSoilE$, Mg ha^{-1} yr^{-1}) minimization objective:

$$\mathrm{Min}\ TSoilE = \sum_i \left\{ (R_i \times K_i \times LS_i \times P)_i \times \sum_p \left[(\Delta Cf) \times \sum_b AH_{ipb} \right] \right\}, \tag{19}$$

where R was rainfall and runoff factor, K was soil erodibility factor, LS was length and steepness of slope factor, P was support practice factor, and ΔCf was crop vegetation and management factor. The R, K, LS, and P factors in each land resource unit were obtained using the ArcGIS intersect geoprocessing method and pivot table in Excel to estimate weighted average values for each factor for each land resource unit.

To evaluate the impact on soil erosion of land conversion to switchgrass, the estimates of $TSoilE$ before and after the conversion of land to switchgrass production were compared with USDA NRCS (Natural Resources Conservation Service) estimates of soil loss tolerance (T, Mg ha^{-1} yr^{-1}) by land resource unit [47]. Soil loss tolerance, T, is defined in the RULSE2 database as "the maximum amount of soil loss [Mg ha^{-1} yr^{-1}], that can be tolerated and still permit a high level of crop productivity to be sustained economically and indefinitely." [48]. The frequency of land resources where $TSoilE > T$ before and after the conversion of crop, hay, and pasture lands into switchgrass production were evaluated to ascertain the effects of switchgrass production on soil erosion within the switchgrass supply chain area.

2.3. Multiple objective optimization

2.3.1. Improved augmented ε–constraint method in multi–objective program

The improved augmented ε–constraint method, AUGMECON2 [40], was applied to derive the tradeoff relationship among the three competing objectives for each potential conversion facility location. The tradeoff relationship among objectives indicates that the performance of one objective could not be improved without degrading the performance of the other objectives. The procedure was applied to all 150 potential industrial park locations for conversion facilities in the study area to generate the efficient frontier. The details of the AUGMECON2 method are available in Mavrotas and Florios [40].

The AUGMECON2 method for the three objectives takes the form:

$$\text{Min.}\left(TC - \varepsilon \times \left(s_2/r_2 + 10^{-1} \times s_3/r_3\right)\right), \tag{20}$$

Subject to:

$$TE + s_2 = e_2, \text{and} \tag{21}$$

$$TSoilE + s_3 = e_3, \tag{22}$$

where *TC*, *TE*, and *TSoilE* are the three competing objectives defined in Equations (1), (14) and (19), ε is a small number (in this study ε was set to be 10^{-3}), *s* is the non-negative slack variable, r_2 and r_3 are the ranges of the objective functions for *TE* and *TSoilE*, *e* is the constraint applied to the *TE* and *TSoilE* through interpolating four grid points to create five equal intervals in the value range (*r*). The slack variable *s* was added to the objective function in Equations (20)–(22) to produce only efficient solutions. Minimization of cost was the primary objective with the two environmental criteria as the secondary objectives in the optimization [40].

To determine the nadir values and generate the ranges of the *TE* and *TSoilE* objective functions, a 3 × 3 payoff table was generated by considering each of the objectives as a single objective problem. The diagonal of the payoff table provides the optima values for each of the three objectives. For the *TE* and *TSoilE* objectives, the optima were the lower bound values (l_2) and (l_3), respectively. The nadir value of *TE* and *TSoilE*, u_2 and u_3, respectively, were the maximum values of *TE* and *TSoilE*. The ranges of the objective value for *TE* and *TSoilE* were obtained from the differences between upper and lower bound values: $r_2 = u_2 - l_2$; $r_3 = u_3 - l_3$.

The AUGMECON2 method identifies weakly efficient points and bypasses the surplus grid points, reducing computation time [40]. The combination of two sets of grid points for other objectives started from looping through the inner most objective (*TE*) first from the nadir value grid to the optima value grid, followed by the exterior grid point (*TSoilE*) after each iteration of the inner objective loop. The feasible solution can be obtained with the first round of relaxed exterior constraints. The rolling computation for the exterior grid point could be saved to reduce computation time if no alternative optima were generated from the prior settings of lexicographic optimization objective in Equation (20). In this study, the algorithm was further improved by eliminating the iteration of the grid points for *TSoilE*, given that the solutions did not vary from those obtained from iterating the grid points of the *TE* objective. Thus, the iteration in constrained objectives for a conversion facility site was reduced from 36 (6 × 6) to 6 in the solving process, which consequently improved the computation efficiency and reduced computation time by more than 80%.

2.3.2. Compromise solution method

The set of conversion facilities on the efficient frontier for the study region was developed to evaluate the potential tradeoffs among the three competing objectives. The most preferred solution point on the frontier was identified using the compromise solution method [41]. The compromise solution optimal point was determined by the minimum distance (D(S)), measured by Tchebycheff norms [49], to the ideal point (z*) on the frontier:

$$\mathrm{D(S)} = \max_{j=1,\ldots,3}\left\{\lambda_j\left|z_j(S) - z_j^*\right|\right\}, \tag{23}$$

where *j* indexed the objective functions, λ_j was the normalized weight for each objective function, and *S* was the set of points on the frontier. The normalized weight, λ_j, was defined as:

$$\lambda_j = 1/r_j \times \left[\sum_{j=1}^{3}(1/r_j)\right]^{-1}, \tag{24}$$

where *r* was the previously defined objective value range. The ideal point (z*) was defined according to the individual minima of each objective ($z^* = [l_1, l_2, l_3]$) from the payoff tables. To further illustrate the relative relationship between each point on the frontier and the

Table 2
Data sources.

	Economic cost	GHG emissions	Soil erosion
Land conversion from crop land to switchgrass	Opportunity cost: Crop yields: USDA SSURGO [56]; Crop price and hectares: USDA NASS [57,58]; Crop production cost: USDA ERS [58], POLYSIS [59] Switchgrass plantation: Yield: Jager et al. [36]; Production and harvest Cost: Larson et al. [60], University of Tennessee [61]	Land use change (Daycent [62]): Weather data: DayMET[1]; Soil texture: USDA SSURGO[3] [56] Management practice for crops: University of Tennessee [61] Hay/pasture management [63,64]: Switchgrass management [65]:	R factor: USDA RUSLE2[2] K factor: USDA SSURGO [56] C factor: USDA RUSLE2 [64,65], P factor: [64] LS factor: Drained area method [66,67].
Production	Establishment: American Agricultural Economics Association [68] Annual maintenance: American Society of Agricultural and Biological Engineers [69]	Fuel usage: GREET [53] Fertilizer, herbicide, seed: GREET [53] Machine production: GREET [53]	
Harvest	Fuels and labors: University of Tennessee [61]	Fuel: GREET [53] Machine production: GREET [53]	
Storage	Covers and pallets: University of Tennessee [61]		
Transportation	Trailer, fuel and labor: University of Tennessee [61]	MOVES modeling [54]; Indirect emission from truck production: GREET [53]	

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

compromise solution point, a D score was calculated as the relative value of the D(S) of each point to the D(S) of the compromise optimal solution (i.e. the min. D(S)):

$$\text{D score} = [\text{D(S)}/\text{min. D(S)}]. \tag{25}$$

The solution for the efficient frontier was used to impute the costs of mitigating GHG emissions and soil erosion in the supply chain [31]. Two measures of the tradeoffs among higher feedstock costs, lower GHG emissions, and lower soil erosion were calculated using the model solution for the feasible and efficient set of conversion facilities on the efficient frontier. The first approach was to calculate the MRS (marginal rate of substitution) between feedstock cost and GHG emissions. MRS was determined using the ratio of the normalized weights for feedstock costs and GHG emissions and the ratio of the range of cost to the range of GHG emissions on the efficient frontier [50]. The MRS between feedstock cost and soil erosion was also derived. The respective MRS of cost-GHG emissions and cost-soil erosion provide the average costs Mg^{-1} of reducing GHG emissions and soil erosion on the frontier. The second approach was to calculate the costs Mg^{-1} of reducing GHG emissions and soil erosion for the compromise solution conversion facility locations versus the cost minimization solution conversion facility locations. Cost comparisons were also made for the GHG emission and soil erosion minimization conversion facility locations versus the cost minimization solution conversion facility locations.

2.4. Data

The data sources and models used in the lexicographic model to estimate feedstock cost, GHG emissions, and soil erosion are summarized in Table 2. The data and derived parameters were all associated with geospatial characteristics of the land resource units. DAYCENT, a daily time-step biogeochemical plant-soil system model, was adopted to simulate soil carbon uptake and CH_4 and N_2O emission factors [51]. The change in soil carbon stock was calculated using IPCC (Intergovernmental Panel on Climate Change) guidelines [52]. Differences in geography and soils between east, middle and west Tennessee were considered in the estimation of soil carbon. Emission factors for energy combustion from farm equipment operations and the indirect emission factors for the manufacturer of agricultural machinery, fertilizer, chemicals, and seed were estimated using the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) Model [53]. Emissions from feedstock transportation were estimated using the MOVES (Motor Vehicle Emissions Simulator) version 2010b [54], considering travel distance, local weather, travel speed and slopes of roads.

3. Results and discussion

3.1. Efficient frontier

Fig. 3 presents the relationships among the three competing objectives for a single conversion facility site (Fig. 3-i), all 150 potential sites (Fig. 3-ii), and the efficient frontier (Fig. 3-iii). The following describes the key components in the frontier that are illustrated in each panel of the chart and the resulting economic implications. First, GHG emissions and soil losses were mitigated in the supply chain when switchgrass procurement costs increased; whereas, GHG emissions and soil erosion were positively correlated with each other (Fig. 3-i). The model converted more crop land to accommodate the tradeoffs in lower levels of GHG emissions and soil erosion for higher feedstock costs. Crop lands have higher

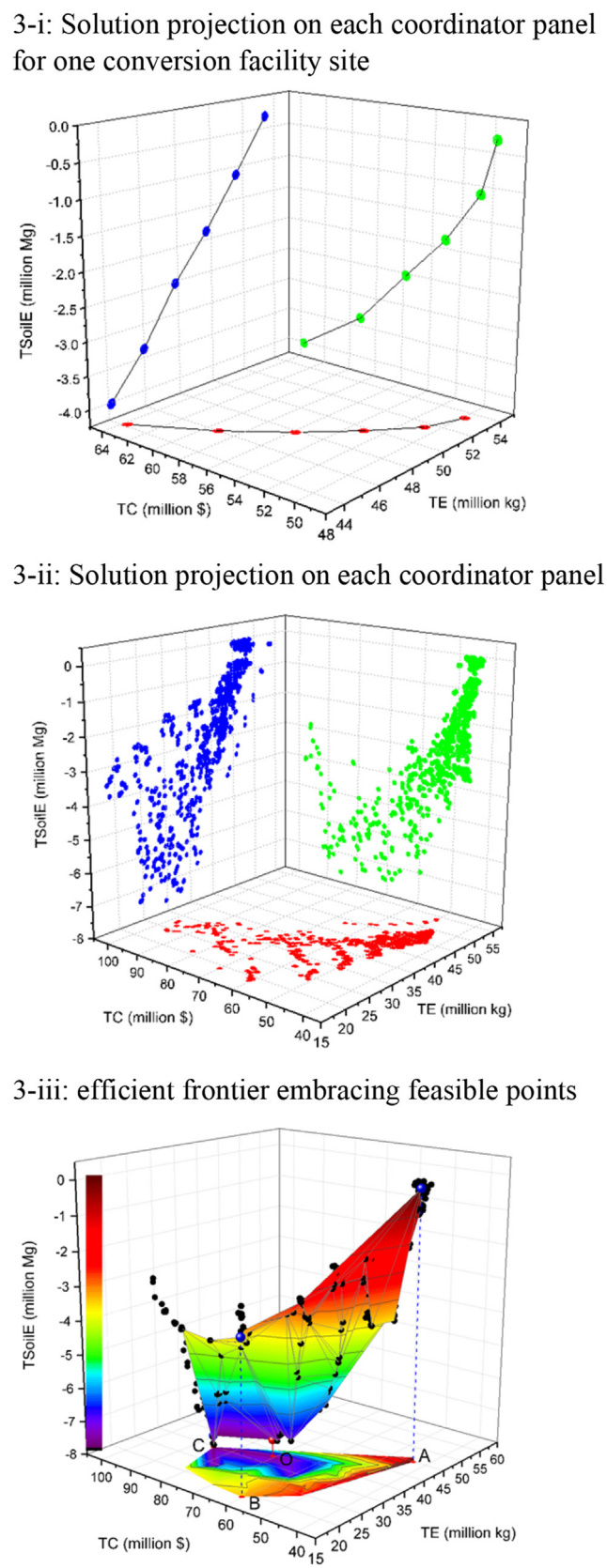

Fig. 3. Regional feasible solutions (A: total cost minimization, B: GHG emission minimization, C: soil erosion minimization, O: compromise solution).

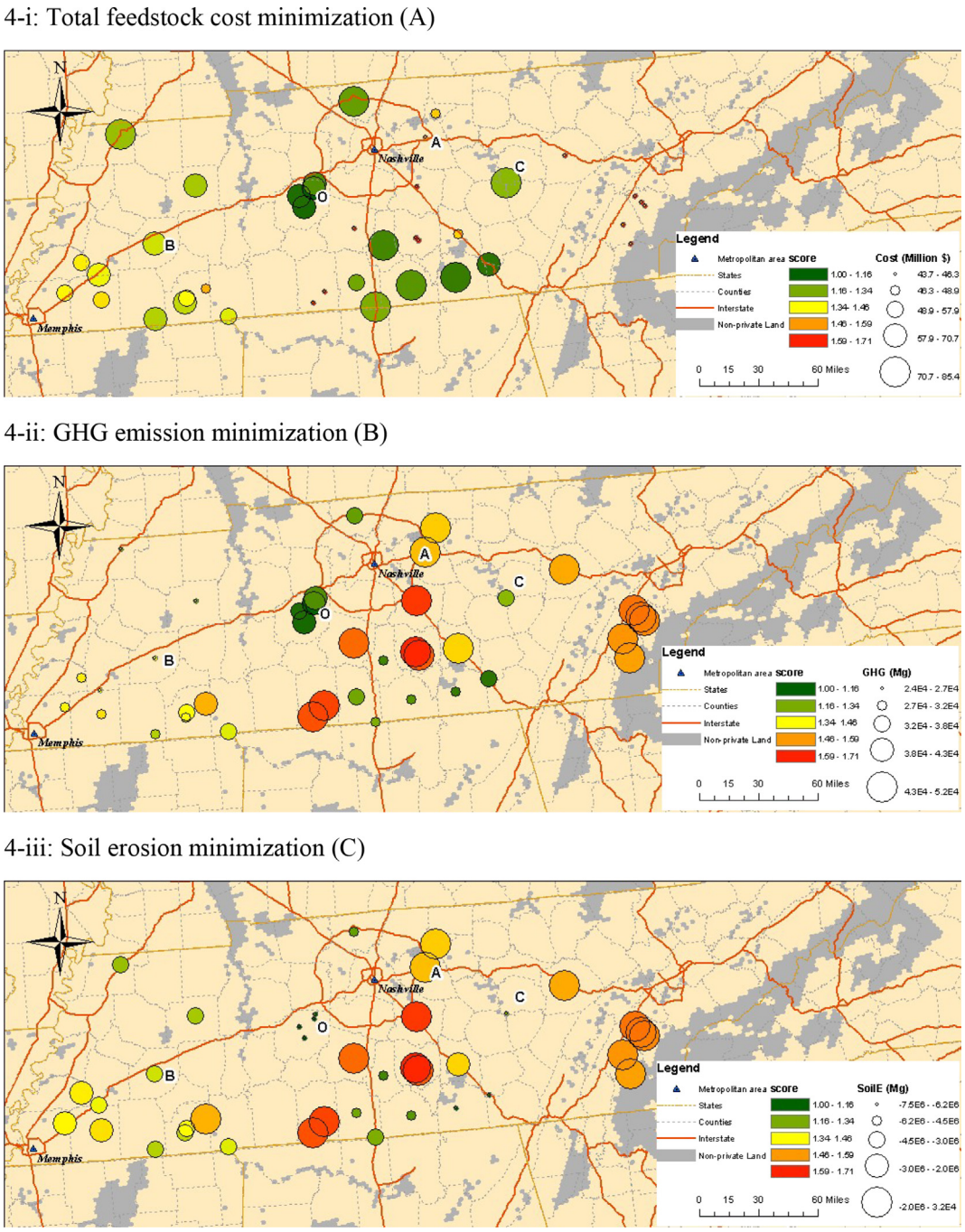

Fig. 4. Distance scores and objective values for the 40 conversion facility sites on the efficient frontier.

opportunity costs, larger fertilizer and chemical expenditures, greater soil erosion, and were more geographically dispersed relative to hay and pasture lands.

Second, GHG emissions and soil erosion in the supply chain were less dispersed with low feedstock costs (Fig. 3-ii). The ranges of GHG emissions and soil erosion expanded as feedstock costs increased in the model to facilitate tradeoffs in the cost and environmental objectives. Low feedstock costs were associated with the conversion of hay and pasture lands. Abatement of GHG emissions and soil erosion were achieved through the conversion of crop land, leading to a wider dispersion in feedstock costs.

Third, a total of 881 feasible solution points were found in the optimization (Fig. 3-iii) for the 150 potential conversion facility sites. Black dots on the efficient frontier are the final conversion facility site solution points given that the value of one objective could not be improved without degrading the values of the other two objectives. Among those 881 feasible solution points from 150 sites, there were a total of 40 *efficient* potential conversion facility sites on the frontier. The individual-optimum solution points for feedstock costs (A), GHG emissions (B), and soil erosion (C) are identified as blue dots on the efficient frontier. The compromise solution point (O) is identified as a red dot.

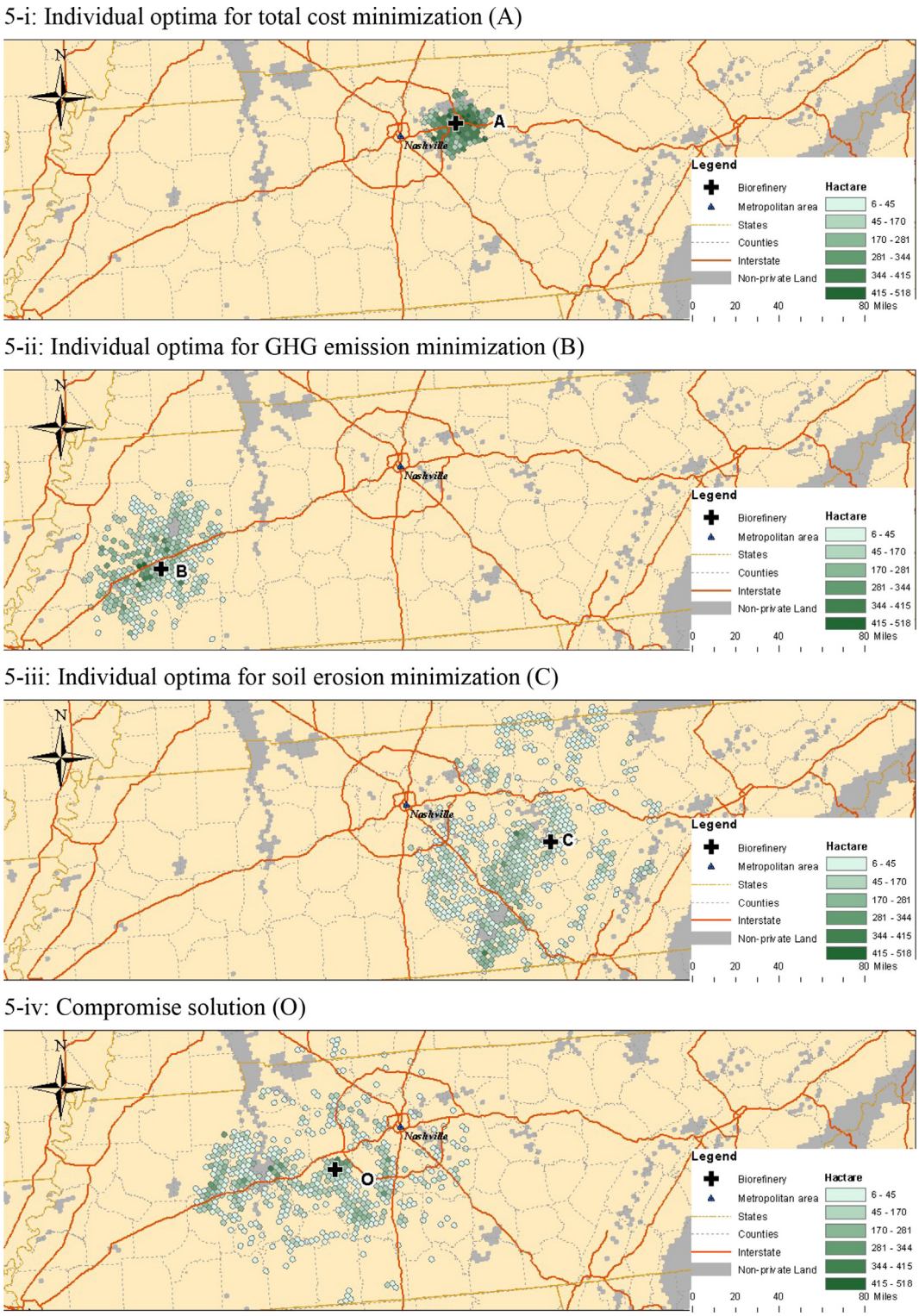

Fig. 5. Placement of the conversion facility and switchgrass draw area under individual-optima and compromise solution cases.

Finally, the tradeoffs between higher feedstock costs and lower GHG emissions or lower soil erosion on the efficient frontier (Fig. 3-iii) were imputed using the MRS. For the 40 conversion facilities on the frontier, the average cost of abating one Mg of GHG emissions was $2378. The average abatement cost for GHG emission was considerably higher than the $10 average cost to reduce soil erosion by one Mg. Results indicated that soil erosion may be a more cost effective environmental criterion than GHG emissions in the design of a sustainable switchgrass supply chain in Tennessee.

Fig. 4 further illustrates the tradeoffs among the three competing objectives. D scores for the 40 conversion facilities on the efficient frontier and the geographic locations of the efficient facilities are shown in the figure. The color of each circle is related to the D score and the size of the circle represents the level of

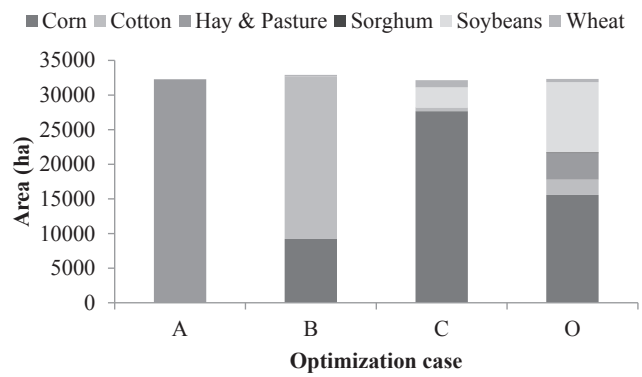

Fig. 6. Land area converted to switchgrass for each optimization case (A: total cost minimization, B: GHG emission minimization, C: soil erosion minimization, O: compromise solution).

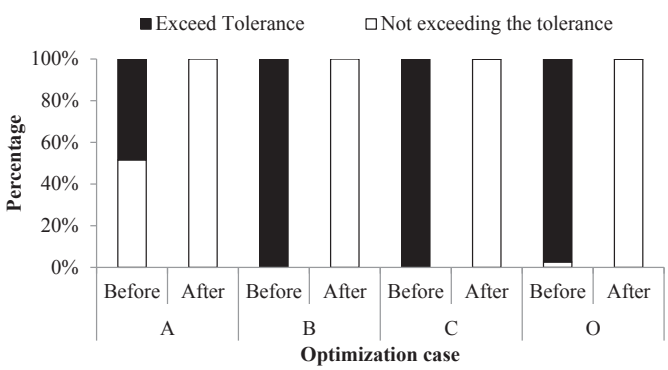

Fig. 7. Changes in soil erosion within the feedstock draw area before and after the land was converted to switchgrass (A: total cost minimization, B: GHG emission minimization, C: soil erosion minimization, O: compromise solution).

feedstock cost (panel i), GHG emissions (panel ii), and soil erosion (panel iii). For example, the compromise solution point (O) had larger feedstock costs and GHG emissions but lower soil erosion relative to many of the other sites on the efficient frontier.

3.2. Individual-optima and compromise solution

The feedstock draw areas for each individual-optimum conversion facility site and for the compromise solution conversion facility site are displayed in Fig. 5. The feedstock draw area for the cost minimization solution (A) was the most geographically compact, while the draw areas for the GHG emission, soil erosion, and compromise solutions (B, C, and O) were more geographically dispersed. Feedstock cost is related to the density of switchgrass production in the conversion facility draw area, which impacts feedstock transportation costs [42]. Crop production is more concentrated in West Tennessee while hay and pasture production is more prevalent in Middle and East Tennessee. With the two environmental objectives, the model traded off feedstock costs to convert highly erodible crop land to switchgrass in Middle and East Tennessee for the compromise solution (O). Thus, the choice of conversion facility location and feedstock draw area was primarily related to the availability of land resources and existing agricultural production.

Fig. 6 shows the land coverage change for switchgrass production. Hay and pasture lands were primarily selected in the cost minimization solution (A), whereas crop lands were mostly utilized for switchgrass production in the GHG minimization (B) and soil erosion minimization (C) solutions. Converting crop lands to switchgrass resulted in higher opportunity cost from land use selection, increased soil carbon storage, and reduced soil erosion. The opportunity costs for converting hay and pasture lands to switchgrass were lower but resulted in higher soil carbon and soil erosion losses [19,55]. Thus, a combination of crop, hay, and pasture lands were utilized in the compromise solution (O) to achieve the integrated multi-objective goal embodied in the compromise solution.

The percentage of land area with soil erosion exceeding USDA NRCS tolerance levels *ex ante* and *ex post* land converted to switchgrass for the individual-optima and compromise solutions are shown in Fig. 7. Prior to converting land to switchgrass production, nearly 50% of the switchgrass feedstock draw area for the cost minimization solution (A) exceeded tolerance levels. Whereas, all of the land area for the GHG emission (B) and soil erosion (C) minimization solutions had soil erosion exceeding the tolerance level. For the compromise solution (O), almost all (97%) of the switchgrass draw area prior to land conversion had soil erosion exceeding the tolerance rate. In contrast, less than 1% of all land area *ex post* switchgrass production exceeded the soil erosion tolerance levels for all four solutions. The reduction in soil losses mostly resulted from the year-round ground cover and deep root system provided by perennial switchgrass.

Itemized costs for each of the individual-optima and compromise solutions are summarized in Table 3. The cost minimization solution (A) had a total plant gate feedstock cost of $43.4 million. Harvest cost accounted for 51.6% of total feedstock cost, followed by production cost at 19.8% of total costs. Opportunity cost of $1.3 million for the cost minimization solution was the lowest among the three objectives because low-cost hay and pasture lands were

Table 3
Output summary for the single objective solutions and the compromise solution.

	Feedstock cost minimization (A)	GHG emissions minimization (B)	Soil erosion minimization (C)	Compromise solution (O)
Cost item	$ (millions)			
Opportunity cost	1.334	15.697	35.628	22.056
Production cost	8.606	8.773	8.572	8.617
Harvest cost	22.395	22.613	22.351	22.409
Storage cost	2.775	2.775	2.775	2.775
Transportation cost	8.307	10.607	16.081	14.881
Total cost	43.417	60.466	85.408	70.738
Mg (thousand)				
Total GHG emissions	44.887	18.587	29.689	32.844
Mg (million)				
Total soil erosion	−0.106	−3.545	−7.646	−7.495

primarily converted to switchgrass production. For the environmental objectives, the two primary factors influencing cost differences were increased opportunity costs, caused by conversion of crop lands that had higher GHG emissions and soil erosion, and increased feedstock transportation costs caused by a more widely dispersed switchgrass production area. Total feedstock cost increased to $60.5 million for the GHG minimization solution (B). Opportunity cost for the GHG solution was 11.8 times greater and transportation cost was 27.7% larger than for the cost minimization solution (A). Soil erosion minimization (C) had the highest total cost among all individual-optima cases of $85.4 million with considerably higher opportunity ($35.6 million) and feedstock transportation ($16.1 million) costs. Total feedstock cost for the compromise solution (O) was $70.7 million, 62.9% higher than the cost minimization solution, but 20.7% lower than the soil erosion minimization solution (C).

The cost effectiveness of switchgrass production in reducing GHG emissions and soil erosion was further evaluated through an examination of differences in cost and abatement amounts among the four solutions (Table 3). The GHG emission minimization (B) solution reduced total net GHG emissions by 59%, from 44.9 thousand Mg to 18.6 thousand Mg, but at an increased feedstock cost of $17 million when compared to feedstock cost minimization (A) solution (Table 3). The imputed cost of abating GHG emissions was $648 Mg^{-1} ($17 million/26.3 thousand Mg) between the two solutions. Reduction in total emissions resulted from converting crop lands to switchgrass that sequestered more soil carbon and used fewer inputs than the crops it replaced [19,55]. For the feedstock cost minimization (A) and soil erosion minimization (C) comparisons, the imputed cost of GHG emission sequestration was $2765 Mg^{-1} given that feedstock cost nearly doubled and GHG emissions declined by only 33%. Similarly, the imputed cost of GHG emissions abatement was $2270 Mg^{-1} when comparing the feedstock cost minimization solution (A) to the compromise solution (O).

With respect to the soil erosion minimization (C) solution, 7.5 million Mg of soil erosion was averted at an additional feedstock cost of $15.2 million when compared with the feedstock cost minimization (A) solution. The imputed cost of reduced soil erosion was $5.60 Mg^{-1} for the soil erosion minimization (C) solution. Contrasting the GHG emission minimization (B) solution with the cost minimization (A) solution resulted in 3.4 million Mg less soil erosion with an imputed cost of abatement of $5.00 Mg^{-1}. Finally, about 7.4 million Mg soil erosion was averted with an increase in total feedstock cost of $12 million with the compromise solution (O). The imputed cost for conserving soil in the feedstock draw area was the lowest among the four optimal solutions at $3.70 Mg^{-1}. The efficient frontier and compromise solution results indicate that targeting soil erosion as an objective in the development of a sustainable switchgrass supply chain in Tennessee may be more cost effective than targeting GHG emissions.

4. Conclusions

This study identified an efficient set of switchgrass conversion facilities and draw areas to minimize feedstock costs, GHG emissions, and water-induced soil erosion for a switchgrass supply chain in Tennessee. Results show that the type of agricultural land converted to switchgrass production is crucial in determining feedstock costs and environmental impacts of the supply chain. For instance, converting only crop lands to switchgrass in the GHG emissions minimization case incurred 10 times higher opportunity cost from land use change but stored 13 times more soil carbon and decreased soil erosion by almost 70 folds when compared with the cost minimization case that only converted hay and pasture lands. A mix of crop, hay, and pasture lands (48% corn, 31% soybean, 12% of hay/pasture, 7% cotton, and 1% wheat) achieved the goal of integrating the three objectives into the switchgrass supply chain in Tennessee.

Given the tradeoffs among minimization of feedstock costs, GHG emissions and soil erosion on the efficient frontier, the imputed cost of abating GHG emissions and soil erosion were evaluated by comparing marginal rates of substitution between feedstock cost and GHG emissions and feedstock cost and soil erosion. The average imputed cost of abating GHG emissions and soil erosion on the frontier was $2378 $Mg^{-1}$and $10 Mg^{-1}, respectively. This finding suggests that soil erosion could be a more cost effective environmental criterion than GHG emissions in the design of a sustainable switchgrass supply chain in Tennessee. However, the compromise solution conversion facility site generated 63% higher feedstock cost compared to the cost minimization location, but reduced soil erosion 70 fold and GHG emissions by 27%. The imputed costs of abating GHG emissions and soil erosion in the efficient set of supply chain sites in Tennessee could provide policy makers important information for the development of a sustainable switchgrass biofuels industry.

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Appendix

Table A1
Important economic cost parameters used in the model.

Range (Mean)							
Crop	Units	Corn	Hay/pasture	Sorghum	Soybeans	Wheat	Cotton
yield	Mg ha^{-1}	1.6–13.7 (7.4)	1.3–19.8 (4.6)	0.1–7.4 (2.9)	0.5–3.6 (2.4)	0.5–5.4 (2.9)	0.2–1.5 (1.0)
price	$ Mg^{-1}	243.3	96.6	242.9	485.3	254.8	164.1
area	ha	0.1–842 (60)	0.1–1083 (246)	0.1–571.4 (9.3)	3.2–21.4 (12.9)	0.1–324 (6.6)	0.1–1049 (53.8)
production cost	$ ha^{-1}	482–536 (514)	803–869 (840)	417–425 (422)	460–551 (496)	328–358 (345)	902–1158 (1010)
Switchgrass Range (Mean)							
yield	Mg ha^{-1}	18.3–23.2 (21.7)					
establishment	$ ha^{-1}	151					
annual maintenance	$ ha^{-1}	116					
harvest	$ ha^{-1}	630–704 (682)					
storage	$ ha^{-1}	8.2–13.6					
transportation	$ ha^{-1}	24.7–586 (561)					

Note: number in parenthesis refers to the mean for the range of parameters.

Table A2
Important GHG emissions parameters used in the model.

		Range (Mean)					
Land use change	CO_2 Mg ha^{-1}	Corn −0.62–−0.52 (−0.56)	Hay/pasture 0.06–0.08 (0.07)	Sorghum −0.48–−0.42 (−0.44)	Soybeans −0.32–−0.21 (−0.25)	Wheat −0.92–0.80 (−0.85)	Cotton −0.81–−0.70 (−0.74)
	(CH_4) CO_2 Mg ha^{-1}	−0.002–−0.0018 (−0.0019)	−0.0016–−0.0009 (−0.0013)	−0.0073–−0.0038 (−0.006)	−0.0014–−0.0024 (−0.0021)	−0.0014–−0.0021 (−0.0019)	−0.0023–−0.0014 (−0.002)
	(N_2O) CO_2 Mg ha^{-1}	−0.102–−0.098 (−0.099)	−0.0063–−0.0043 (−0.0052)	−0.028–−0.026 (−0.027)	−0.078–−0.057 (−0.069)	−0.027–−0.023 (−0.025)	−0.036–−0.033 (−0.034)
Crop management	MgN ha^{-1}	Corn: 0.104	Hay/pasture: 0.037	Sorghum: 0.043	Soybean: 0	Wheat: 0.035	Cotton: 0.037
Switchgrass management	MgN ha^{-1}	0.025					
Switchgrass production	L diesel ha^{-1}	28.6					
Input production	CO_2e Mg ha^{-1}	Fertilizer: 0.08	Herbicide: 0.003	Seed: 0.045			
Machine production	CO_2e Mg $unit^{-1}$	0.468–2.11 (1.25)					
Harvesting	L diesel Mg^{-1}	9.8					
Harvest equipment	CO2e Mg $unit^{-1}$	0.47–2.11 (1.25)					
Transportation	CO_2e Mg $load^{-1}$	0.01–0.57 (0.25)					

Note: number in parenthesis refers to the mean for the range of parameters.

Table A3
Important soil erosion parameters used in the model.

R Factor	Unitless, by county	140–420 (295)					
K Factor	Unitless, by the unit from USDA	0–0.59 (0.30)					
C factor	unitless	Corn 0.335–0.625 (0.528)	Hay 0.1	Soybeans 0.37–0.49 (0.452)	Wheat 0.16–0.22 (0.18)	Cotton 0.436–0.507 (0.483)	Sorghum 0.228–0.288 (0.248)
P factor	unitless, by land resource	0.5–1.0 (0.737)					
LS factor	unitless, by land resource	7.8–32.2 (5.88)					

Note: number in parenthesis refers to the mean for the range of parameters.

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