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A mixed-integer optimization model for the economic and environmental analysis of biomass production

*Halil Ibrahim Cobuloglu, İ. Esra Büyüktahtakın**

Department of Industrial and Manufacturing Engineering, Wichita State University, 1845 Fairmount Street, Wichita, KS 67260, USA

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ABSTRACT

Biofuel production from second-generation feedstock has become critical due to environmental concerns and the need for sustainable energy supply. This paper provides a unique optimization approach of quantifying and formulating the economic and environmental benefits of switchgrass production at the farm level. In particular, we propose a multi-objective mixed-integer programming model, which maximizes the revenue from harvested switchgrass biomass and the economic value obtained from the positive environmental impacts of switchgrass yield during a ten-year planning horizon. Environmental impacts include soil erosion prevention, sustainability of bird populations, carbon sequestration, and carbon emissions, while economic impacts are analyzed under various budget, yield, and sustainability scenarios. The proposed model is then applied to a case study in the state of Kansas. Results show that given the current market prices, switchgrass cultivation on grassland and cropland is highly profitable. The model results also suggest that if utilized by the government, conservation reserve program (CRP) incentives could make marginal land more favorable over cropland. We perform sensitivity analysis to address the uncertainty in budget, yield, and utilization of cropland, and present insights into the economic and environmental impacts of switchgrass production. This model can also be extended to biomass production from any other types of energy crops to identify the most efficient production planning strategies under various management scenarios.

1. Introduction

Growing energy demand and related environmental concerns have motivated researchers to find alternative ways of energy production. The long-term inadequacy of fossil fuels and high greenhouse gas (GHG) emissions require the use of sustainable and environmentally friendly energy sources. Biofuel is promoted as one of the most important substitutes for fossil-fuel-based energy, among other renewable energy sources [1,2].

Biofuel is currently used in transportation and can be derived from various biomass resources, including food crops such as corn, wheat, soybeans, and sugarcane, as well

* *Corresponding author*. Tel.: +1 316 978 5915.
E-mail addresses: hicobuloglu@wichita.edu (H.I. Cobuloglu), esra.b@wichita.edu (İ.E. Büyüktahtakın).
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as lignocellulosic biomass feedstock, known as energy crops [3]. However, biofuel production from food crops generates debate about security of the food supply and soil acidification as a result of their high fertilization needs. These potential negative impacts motivate researchers to enhance biofuel production from non-food crops (second-generation energy crops) that have low carbon emissions and low-fertilization requirements. Consequently, the updated Renewable Fuel Standard (RFS2) in 2007 requires the annual use of 136 hm^3 of biofuels in 2022, while at least 60 hm^3 of this amount must be from second-generation energy crops [2]. Switchgrass (*Panicum virgatum*), a perennial warm-season grass native to North America, is one of the most favorable lignocellulosic biomass types because of its environmental benefits, such as soil erosion prevention, low-fertilization requirement, reduction in GHG emissions, tolerance to drought and variable soil conditions, and improvement of soil productivity via carbon sequestration, in addition to its high energy yield [4].

Biofuel production from switchgrass biomass includes a number of sequential activities, such as land selection and preparation, seeding and fertilization for establishment, harvesting, biomass transportation, and conversion to ethanol in a biofuel production facility, as shown in Fig. 1. Numerous decision alternatives with many trade-offs arise during this process. For example, the selection of land type for switchgrass cultivation impacts production cost and harvested biomass. Although cropland has a higher biomass yield, the rental cost of these lands is also high. Moreover, seeding time affects the seeding method to be used, thus resulting in various establishment cost scenarios. In addition, seeding, fertilization, and harvesting decisions are made based on a limited budget. Since biofuel production includes some conflicting trade-offs, as stated previously, and is a complex decision-making process by nature, compact decision support systems need to be established. In this paper, we propose an optimization model, which should provide maximum economic value from switchgrass-based biomass production while accounting for environmental as well as economic constraints.

In the literature, a significant number of studies focus on supply chain optimization for biofuel production, whereas very few studies explicitly include an analysis of switchgrass-based biomass production at the farm level in a mathematical model. Eksioglu et al. [5] develop a mixed-integer linear programming (MILP) model for the design and management of a biomass-to-biorefinery supply chain. Decision variables include the number, size, and location of biorefineries with a constraint on the availability of the lignocellulosic biomass. The model is then applied to a case study in the state of Mississippi. Parker et al. [6] consider the effects of policy and technology changes via an analysis of the MILP model for the biofuel supply. They maximize the total profit of the feedstock supplier and fuel producer while determining optimal locations, technology types, and sizes of biorefineries. They also combine a geographic information system (GIS) with the proposed model. Papapostolou et al. [7] develop an MILP model for a biofuel supply chain that exports important raw materials and biofuels while considering both technical and economic parameters. Similarly, An et al. [8] present a model to design a lignocellulosic biofuel supply chain system with a case study based on a region in central Texas. Their model also determines the technology type to be used for conversion in facilities and examines switchgrass as feedstock, assuming that there is always an available biomass supply. Čuček et al. [9] consider environmental and economic footprints while developing a multi-criteria optimization model of a regional biomass energy supply chain. Akgul et al. [10] propose an economic optimization model for an advanced biofuel supply chain in the UK. Their MILP model considers sustainability factors related to food supply and land use, while including strategic decisions such as locating biorefineries, biofuel production rate, and total supply chain cost. Zhang et al. [11] present an MILP model that minimizes the cost of a switchgrass-based ethanol supply chain. They consider switchgrass cultivation only on marginal land and different harvesting methods, in order to define biorefinery capacity and locations, biofuel production volume, and the amount transported to demand points.

Other than optimization models, simulation methodology has also been employed in some studies, such as that of Zhang et al. [12]. They propose a simulation model of a biomass supply chain for biofuel production by minimizing the cost of feedstock, energy consumption, and GHG emissions associated with harvesting and transportation activities. Ebadian et al. [13] integrate simulation with an optimization model to analyze an agricultural biomass supply chain for cellulosic ethanol production focusing on storage systems. They employ an MILP optimization model to find the number of storages, farms to contract, their locations, and the assignment of farms to storages. In addition, they present a simulation model in order to make more operational decisions such as storage capacity, daily working hours, required equipment, and logistic costs.

The biofuel supply chain has been extensively examined in the literature as stated above, and many of these efforts have identified and quantified all interrelated parameters. However, we have not found any study providing an optimization model and a detailed analysis of switchgrass production at the farm level. In addition, although environmental impacts of biomass production such as soil erosion, bird population, carbon sequestration, carbon emissions, and sustainability of the food supply have been investigated in various papers (see, e.g., Refs. [14,15]), these important features of biomass production have not been formulated simultaneously in an optimization model in order to be analyzed in a decision framework. Therefore, research is needed to incorporate these important environmental impacts into a mathematical decision model.

In this paper, we formulate a multi-objective MILP model that considers the positive environmental impacts of switchgrass biomass production and maximizes the economic value obtained from switchgrass-based biomass during its entire life cycle. The model incorporates the economic impacts of switchgrass-based biomass production such as the cost of establishment, production, harvesting, and transportation, and determines the optimal distribution of budget among operations and years, the allocation of land, seeding time, and harvesting amount and time of biomass to be used for ethanol production in a biorefinery.

Fig. 1 – Operation types included in biofuel production from switchgrass.

In addition, the proposed mathematical model contributes to the state of the art by considering the following aspects:

- To our knowledge, none of the reviewed literature considers the seeding scenario, including seeding season and seeding method. Each seeding scenario has a different cost and leads to various yield amounts. The proposed model determines the best seeding scenario including seeding season and seeding method in order to produce the maximum amount of yield given a limited budget.
- Again, to the best of our knowledge, none of the previous work considers the environmental contributions of switchgrass in a biomass production optimization model. As stated by Hartman et al. [16], switchgrass cultivation can be considered on degraded and marginal land that are in a conservation reserve program (CRP) since switchgrass can restore the soil quality through increasing its organic carbon content. In addition, having a very strong root system, switchgrass prevents soil erosion significantly, which in turn provides savings from reduced loss of fertile soil. The proposed model incorporates switchgrass production in productive as well as degraded land and analyzes its positive impacts on soil erosion prevention.
- This study also fills the gap of investigating and controlling the effect of harvesting patterns on grassland bird populations. It has been shown that rotational harvesting is required in order to provide a nesting area to birds during winter [16,17]. Our model handles sustainability of bird and wildlife populations by providing them available habitats through limiting the number of harvested regions.
- In the literature, land allocation is defined with respect to the amount of area needed for cultivation, and in most cases, cropland is used for the cultivation of biomass crops. The model proposed by An et al. [8] determines the biomass amount required, where biomass is assumed to be provided from cropland and lands in a CRP. On the other hand, Zhang et al. [11] limit the cultivation of switchgrass production to only marginal land. Our model is differentiated from others by leaving the choice of land type to decision-makers (landowners), since they can control cropland, grassland (pastureland), and marginal land in coordination. The model also enables decision-makers to quantify the availability of cropland to be used for switchgrass cultivation by incorporating a sustainability factor in the land-usage constraints.
- In this model, we have calculated the establishment cost for various seeding scenarios and production cost, which depend on the rental cost and the amount of fertilizers used. Furthermore, the savings from soil erosion prevention and CO_2 retained via soil carbon storage, which are not directly available in the literature, are calculated by incorporating a couple of sources. Therefore, this paper also provides compact data for researchers looking for various aspects of environmental and economic input and output of switchgrass biomass production.
- In the literature, many constraints are not directly available: growth function of the switchgrass population; cost of production including fertilizers; harvesting cost including cost of mowing, raking, baling, staging, and loading; as well as the limitation of harvested areas to ensure sustainability of bird populations. In order to incorporate these constraints into our optimization model, we have generated formulations by evaluating the research-based instructions and data available in the literature. Although we have established the model particularly for switchgrass, it can also be used as a basis for and applied to biomass production from any other types of energy crops.

The remainder of this paper is organized as follows. The problem is defined in section 2, while the mathematical model is described in detail in section 3. The calculation of input parameters and the application of the model to a real case study in Kansas are presented in section 4. All computational results for the base-case scenario and sensitivity analyses are given in section 5. Finally, some concluding remarks with future directions are provided in section 6.

2. Problem statement

We focus on the following echelons for the switchgrass-based biofuel production shown in Fig. 1: land allocation, establishment, biomass production, biomass harvesting, and its transportation to a biorefinery. The land types to be allocated for switchgrass cultivation include cropland, grassland, and marginal land. Cropland defines the productive land where food crops are cultivated. Grassland is considered to have semi-productive soil covered by grasses. Marginal land refers to arid, degraded soil and lands that are in a CRP. After land type is determined, a seeding season (frost and spring) and a suitable seeding method (airflow, drill, and no-till drill) are decided. Harvesting, which includes mowing, raking, baling, staging, and loading, is performed by late September. Finally, the harvested switchgrass biomass is transported to the biorefinery to be converted into bioethanol.

The objective of the mathematical model is to maximize the total economic value obtained from switchgrass biomass production while determining the optimal decision strategies for the following:

- Land allocation (seeding zones) for switchgrass cultivation.
- Seeding time along with seeding scenario to be implemented.
- Biomass cultivated zones to be harvested and time for harvesting.
- Amount of harvested switchgrass in a related zone at the time of harvesting.
- Allocation of budget to various farm operations (seeding, production, harvesting, and transportation).

2.1. *Notation and assumptions*

Depending on the equipment used, the estimation of harvesting cost can vary considerably. The type of bale (large round or large square) also affects the cost. For the budget estimations in this paper, we consider harvesting in large square bales weighing 397 kg each, which are easy to transport and store [18,19].

Studies show that multiple harvesting in the same year decreases the total amount of biomass since the root system is weakened [19,20]. Therefore, single harvesting, which is suggested immediately after the first killing frost, is used in this model because it is stated to be the most economical and environmentally friendly harvesting method [11].

It has been shown that bioethanol producers prefer to obtain their biomass supply from within an 80-km radius of the biorefinery, due to the high cost of transporting bulky biomass [5]. Therefore, this study aims to maximize the economic value of switchgrass production, given that a predetermined facility is located in close proximity to the cultivation area.

Nomenclature

Indices

i	row of cultivation zone
j	column of cultivation zone
(i, j)	switchgrass cultivation zone
k	switchgrass seeding scenario
t	time period
l	transportation mode

Sets

I	set of rows of cultivation area
J	set of columns of cultivation area
K	set of seeding scenarios
T	set of time periods in planning horizon
L	set of transportation modes
M_t	set of time periods from the first period to period t ($M_t = \{1, \ldots, t\}$)
CR	set of cultivation zones on croplands in cultivation area

Binary decision variables

S^t_{ijk}	1 if zone (i, j) is seeded at time period t with seeding scenario k, and 0 otherwise
X^t_{ij}	1 if zone (i, j) is harvested at time period t, and 0 otherwise

Continuous decision variables

N^t_{ij}	switchgrass yield in zone (i, j) at time period t (t)
$\overline{N}^t_{ij}$	harvested switchgrass biomass in zone (i, j) at time period t (t)
E_b	establishment budget ($)
P_b	production budget ($)
H_b	harvesting budget ($)
T_b	transportation budget ($)

Parameters

P^t	sale price of switchgrass at time period t (\$ t^{-1})
SE_{ij}	soil erosion prevention economic value of switchgrass in zone (i, j) in each period ($)
CS_{ij}	carbon sequestration economic value of switchgrass in zone (i, j) in each period ($)
σ_k	carbon emissions penalty for seeding scenario k ($)
ρ	fixed carbon emissions penalty for production and harvesting ($)
ω	variable carbon emissions penalty specific for production and harvesting (\$ t^{-1})
τ	carbon emissions penalty for biomass transportation (\$ t^{-1} km^{-1})
α	weight of switchgrass sales
β	weight of soil erosion prevention value
μ	weight of savings from the reduction of GHG emissions via carbon sequestration
A_{ij}	potential switchgrass yield from zone (i, j) (t)
π^t	growth factor of switchgrass after t years of establishment
Δ	fraction of facility capacity assigned to biomass from switchgrass
Cap^t	biomass capacity of facility at time period t (t)
TEC_k	total expected establishment cost for seeding scenario k ($)
MC_k	machinery cost for seeding scenario k ($)
SC_k	seeding cost for seeding scenario k ($)
FC_k	fertilization cost for seeding scenario k ($)
PC_k	pesticide cost for seeding scenario k ($)
REC_k	re-establishment cost of seeding scenario k ($)
R_k	re-establishment probability of seeding scenario k
ψ	fixed cost of switchgrass production per cultivation zone ($)
γ	variable cost of switchgrass production (\$ t^{-1})
RC_{ij}	rental cost of cultivation zone (i, j) ($)
δ	fixed cost of harvesting per zone ($)
θ	variable cost of harvesting (\$ t^{-1})
D_{ij}	distance of zone (i, j) to facility (km)
F_l	fixed cost of transportation mode l ($)
V_l	variable cost of transportation mode l (\$ t^{-1} km^{-1})
A_b	total available budget in the planning horizon ($)
λ	sustainability factor defining the percentage of cropland, which is not allowed for biomass production

3. Mathematical modeling

An MILP model is formulated with the objective of maximizing economic values obtained from switchgrass-based biomass production as well as its beneficial environmental impacts. The optimal levels for various decisions regarding seeding and harvesting time periods and cultivation areas are determined by solving the MILP model. A detailed explanation of the objective function and the constraints of the proposed model are given in the following sections.

3.1. Objective function

The objective of the proposed model is the maximization of the weighted sum of the total economic value obtained from switchgrass production. The total economic value (TEV) includes revenue to be obtained from the sales of switchgrass biomass (TB), economic value of soil erosion prevention (TS), and savings from the reduction of GHG emissions via carbon sequestration (TC), as indicated below:

$$TEV = \alpha TB + \beta TS + \mu TC \tag{1}$$

All terms are multiplied by α, β, and μ, respectively, in order to assign the priorities of the decision-maker where the sum of α, β, and μ equals 1. The first term, direct revenue of the farmer from the sales of biomass production, is calculated as

$$TB = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\overline{N}_{ij}^{t}P^{t} \tag{2}$$

where $\overline{N}_{ij}^{t}$ is the amount of harvested switchgrass biomass in zone (i, j) at time t, and P^t is the sale price of switchgrass biomass at time t.

We also need to consider the cost of soil erosion to landowners and farmers. In most cases, farmers rent land from owners. Independent of whether the farmer is the owner or not, more fertilizer is needed to compensate for the impact of soil erosion, and eventually land value decreases due to loss of productivity. Studies show that growing switchgrass reduces soil erosion significantly [21,22]. Therefore, the second term represents savings from soil erosion via switchgrass cultivation as

$$TS = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\frac{N_{ij}^{t}}{A_{ij}}SE_{ij} \tag{3}$$

where the ratio of N_{ij}^{t} to A_{ij} is the percentage of switchgrass yield grown at time t with respect to the potential yield in zone (i, j), and SE_{ij} is the economic value of the soil erosion prevention in zone (i, j) in each period.

Finally, since the storage of atmospheric CO_2 as soil organic carbon (SOC) increases the soil quality and since carbon sequestration can be potentially used as savings in carbon emission trading systems, the net CO_2 sequestration is also evaluated as a benefit of switchgrass cultivation [23,24]. The last term, TC, savings from net carbon emission reduction, is calculated by

$$TC = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(\frac{N_{ij}^{t}}{A_{ij}}CS_{ij} - \sum_{k\in K}S_{ijk}^{t}\sigma_k - X_{ij}^{t}\rho - \overline{N}_{ij}^{t}\left(\omega + D_{ij}\tau\right)\right) \tag{4}$$

where CS_{ij} is the economic value of carbon sequestered in zone (i, j) in each period, σ_k is the carbon emissions penalty for seeding scenario k, ρ is the carbon emissions penalty for production operations depending on harvesting, while ω is the carbon emissions penalty for production operations depending on yield. Finally, τ is the carbon emissions penalty for transporting harvested biomass.

3.2. Production constraints

Total switchgrass amount grown in zone (i, j) in year t, N_{ij}^{t}, is defined as

$$N_{ij}^{t} = \sum_{k\in K}\sum_{z\in M_t}A_{ij}\pi^{t-z+1}S_{ijk}^{z} \quad \forall\, i,j,t \tag{5}$$

where A_{ij} is the potential switchgrass yield in zone (i, j), S_{ijk}^{t} is the binary variable defining seeding scenario k in zone (i, j) at time t, and π^{t-z+1} is the switchgrass growth factor. It takes three years for switchgrass to reach its potential yield [19]. Therefore, π^{t-z+1} shows the portion of potential switchgrass yield reached by time period t, where z represents the time period of seeding.

The total number of seedings at each zone (i, j) is limited to one, and only one seeding scenario k can be used through period t:

$$\sum_{k\in K}\sum_{t\in T}S_{ijk}^{t} \le 1 \quad \forall\, i,j \tag{6}$$

Harvesting at each zone (i, j) at time t can only be made if that zone is already seeded through time period t by any seeding scenario k as

$$X_{ij}^{t} \le \sum_{k\in K}\sum_{z\in M_t}S_{ijk}^{z} \quad \forall\, i,j,t \tag{7}$$

Harvested switchgrass biomass in zone (i, j) at time period t, $\overline{N}_{ij}^{t}$, cannot exceed the amount of switchgrass grown, N_{ij}^{t}, in that zone:

$$\overline{N}_{ij}^{t} \le N_{ij}^{t} \quad \forall\, i,j,t \tag{8}$$

On the other hand, the harvested switchgrass biomass in zone (i, j) at time period t can be, at most, equal to the potential switchgrass yield of zone (i, j), if X_{ij}^{t} is set to 1. If there is no harvest at time t, i.e., if X_{ij}^{t} is set to zero, then $\overline{N}_{ij}^{t}$ is zero:

$$\overline{N}_{ij}^{t} \le A_{ij}X_{ij}^{t} \quad \forall\, i,j,t \tag{9}$$

The total amount of the harvested biomass in each period is limited by the capacity of the facility:

$$\sum_{i\in I}\sum_{j\in J}\overline{N}_{ij}^{t} \le \Delta Cap^{t} \quad \forall\, t \tag{10}$$

where Δ is the fraction of facility capacity assigned to biomass from switchgrass, and Cap^t is the biomass capacity of the facility at time period t.

3.3. Budget constraints

The budget assigned for establishment, E_b, is defined by the total establishment cost of seeding in all zones (i, j) for all seeding scenarios k in the planning horizon as

$$E_b = \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{t\in T} TEC_k S^t_{ijk} \tag{11}$$

where switchgrass establishment cost, TEC_k, is the sum of machinery, seeding, fertilization, and pesticide costs for seeding scenario k, as well as the expected re-establishment cost, REC_k, of a failed establishment trial. In order to find the expected establishment cost, REC_k is multiplied by R_k, the probability of establishment failure for seeding scenario k. TEC_k is used as an input and computed as

$$TEC_k = MC_k + SC_k + FC_k + PC_k + REC_k R_k \quad \forall\ k \tag{12}$$

The budget assigned for production, P_b, is defined by the total production cost of switchgrass cultivation as

$$P_b = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(\psi X^t_{ij} + \gamma \overline{N}^t_{ij} + \sum_{k\in K}\sum_{z\in M_t} S^z_{ijk} RC_{ij}\right) \tag{13}$$

where ψ is the fixed cost of nitrogen (N) application, and γ is the variable cost for phosphorus (P) and potassium (K) applications, since a fixed amount of N after harvesting and variable amounts of P and K for each tonne of harvested biomass are suggested for the best production practices of switchgrass [18,19]. The term RC_{ij}, the rental cost of zone (i, j), is multiplied by the seeding decision variable, which becomes 1 if switchgrass is seeded in that zone, and 0 otherwise.

Similarly, the budget assigned for harvesting, H_b, is defined by the overall cost of harvesting as

$$H_b = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(\delta X^t_{ij} + \theta \overline{N}^t_{ij}\right) \tag{14}$$

where the total harvesting cost consists of the fixed cost, δ, of harvesting, and variable cost, θ, which depends on the amount of harvested switchgrass biomass. Mowing and raking have a fixed cost per harvested zone, while the cost of baling, staging, and loading depends on the harvested switchgrass biomass [19].

Various available transportation modes can be used to transport biomass to the biorefinery facility. The budget assigned for transportation, T_b, is defined as the total expenses related to transportation as

$$T_b = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\sum_{l\in L}\left(F_l X^t_{ij} + V_l D_{ij} \overline{N}^t_{ij}\right) \tag{15}$$

where F_l is the fixed cost incurred for the chosen transportation mode l, if zone (i, j) is harvested, and V_l represents the variable cost of mode l, which depends on the distance to the biorefinery and the harvested biomass amount [19].

The total cost of farm operations—establishment, production, harvesting, and transportation—which are given in detail in equations (11)–(15), cannot exceed the total available budget, A_b, in the planning horizon, as given below:

$$E_b + P_b + H_b + T_b \le A_b \tag{16}$$

Equation (16) is formulized in the model in order to determine the value of optimal budget allocation to establishment, production, harvesting, and transportation operations.

3.4. *Environmental constraints*

We formulate environmental constraints, considering the ecological consequences of switchgrass production, with the purpose of maintaining biodiversity and providing food supply safety.

The following constraint is introduced to the model to sustain continuity and diversity of bird populations:

$$\sum_{m=i-1}^{i+1}\sum_{n=j-1}^{j+1}\left(1 - X^t_{mn}\right) \ge X^t_{ij} \quad \forall\ i, j, t \tag{17}$$

Constraint (17) ensures that if zone (i, j) is harvested, then one of its neighbor zones should remain unharvested in each time period t to ensure a nesting area for birds during winter. It has been also stated that diversity of bird species increases only when there is a mixture of harvested and unharvested fields in a region, since shortgrass bird populations grow on harvested fields, while tallgrass bird populations can survive better on unharvested fields [16,17].

For sustainability of the food supply, a particular percentage of cropland should be kept for food crop production. Zones to be converted to energy crop production cannot exceed the allowable share, $1-\lambda$, of cropland:

$$\sum_{(i,j)\in CR}\sum_{k\in K}\sum_{t\in T} S^t_{ijk} \le (1-\lambda)\,|CR| \tag{18}$$

where $|CR|$ refers to the cardinality of the set of croplands.

4. Case study

The MILP model explained in section 3 has been applied to the case of a biofuel production project in Hugoton, Kansas. The project was announced by the United States Department of Agriculture as one of the Biomass Crop Assistance Program projects in 2011. The proposed area to be used for biomass production from switchgrass is up to 8094 ha and is sponsored by Abengoa Bioenergy LLC. This planned biorefinery has 95 hm^3 of cellulosic ethanol capacity through the conversion of 330,000 t of crops [25,26]. We assumed an ample capacity for the biorefinery, which does not limit the biomass production, where full capacity is assigned to biomass obtained from switchgrass. The cultivation area surrounding the biorefinery in the center of Hugoton has three different soil types: cropland, grassland, and CRP land, which we consider as marginal land in this study. The total area is divided into 21 by 21 rectangular arrays, leading to 441 zones, each 2.59 km^2 (1 square mile) in size. A total of 11 seeding scenarios have been evaluated in this case study. Since the expected life of switchgrass is at least ten years, in order to obtain the maximum utilization of the investment on switchgrass production, the planning horizon is considered as ten years in this case study [29]. The other necessary input parameters used in the model are provided with detailed explanations in the next section.

4.1. *Input parameters*

In this section, we present the data collected from various resources in order to formulate our case study. Since we have different land types and seeding scenarios, for some parameters, we have consulted a combination of various publicly

Table 1 – Seeding scenarios and corresponding yield amounts.

Seeding scenario	Seeding scenario characteristics			Yield ($t\ ha^{-1}$)		
	Land type	Seeding season	Method	t = 1	t = 2	t = 3–10
1	Cropland	Frost	Airflow	3.75	10	15
2	Grassland	Frost	Airflow	2.63	7	10.5
3	Cropland	Spring	Airflow	3.75	10	15
4	Cropland	Spring	Drill	3.75	10	15
5	Cropland	Spring	No-till drill	3.75	10	15
6	Grassland	Spring	Drill	2.63	7	10.5
7	Grassland	Spring	No-till drill	2.63	7	10.5
8	Marginal land	Frost	Airflow	1.87	5	7.5
9	Marginal land	Spring	Airflow	1.87	5	7.5
10	Marginal land	Spring	Drill	1.87	5	7.5
11	Marginal land	Spring	No-till drill	1.87	5	7.5

available sources in order to gather and calculate the data. The next subsections include those references that we have used for the purpose of data collection. This section also provides a valuable asset to researchers looking for compact data in this field.

4.1.1. *Seeding scenarios and yields*

Seeding scenarios and corresponding yield amounts for each scenario in different years are given in Table 1. Seeding scenarios are defined by three characteristics: land type, seeding season, and seeding method. Land type includes cropland, grassland, and marginal land. There are two available seeding seasons: frost seeding and spring seeding. For seeding method, airflow and no-till drill are used as modern seeding methods because they lead to low soil erosion and less carbon emissions, in contrast to drill seeding, which is used as the conventional (traditional) seeding method. In this study, we add four seeding scenarios of marginal land to those seven scenarios provided for cropland and grassland by Duffy and Nanhou [18].

The amount of switchgrass yield is mostly affected by land type and time passed since the establishment. Various yield amounts, ranging from 10 to 20 $t\ ha^{-1}\ y^{-1}$, are estimated for cropland. In this case study, for cropland, we use an average value, 15 $t\ ha^{-1}\ y^{-1}$ as the potential yield, which is a practical amount in Kansas [27,28]. We also consider lower and upper bound values on the yield level in the computational experiments in order to investigate the impact of possible changes in yield level. The potential switchgrass yield is reached at the third year after establishment [19]. The first-year switchgrass yields may only be 25% of the potential yield. In the second year of establishment, biomass yields can reach 66% of the potential yield, based on the discussion by Garland et al. [29] and West and Kincer [30]. For instance, in order to obtain the yield amount in cropland in the first year, the potential yield (15 t) is multiplied by 25%, thus leading to 3.75 t, while it is multiplied by 66% to calculate the yield amount in the second year. On the other hand, the yield of grassland and marginal land drops to 70% and 50%, respectively, of that in cropland [31]. For instance, to compute the amount of switchgrass yield in marginal land in the first year, 3.75 t is multiplied by 50%.

4.1.2. *Establishment cost and selling price*

Data regarding the establishment and re-establishment costs for various scenarios are provided in Table 2 [18,19]. The selling price of switchgrass is taken as \$120 t^{-1} [32], while establishment cost depends on many variables such as machinery, seed, fertilizer, and pesticide costs. In machinery cost, grassland seeding scenarios (2, 6, and 7) include the cost of additional Roundup spraying to prepare the land for cultivation. Pure live seed (PLS) in the amounts of 6.7 $kg\ ha^{-1}$ and 5.6 $kg\ ha^{-1}$ is used for frost seeding and spring seeding, respectively, in both cropland and grassland. PLS in the amount of 11.2 $kg\ ha^{-1}$ and 8.9 $kg\ ha^{-1}$ are used for frost and spring seeding, respectively, in marginal land. Phosphorus (P)

Table 2 – Switchgrass establishment, re-establishment, and total expected establishment costs.

Seeding scenario	Establishment cost (\$ ha^{-1})	Re-establishment cost, REC_k (\$ ha^{-1})	Total expected establishment cost, TEC_k (\$ ha^{-1})
1	407.15	112	435.15
2	417.77	112	445.77
3	416.84	112	472.84
4	589.35	121.4	650.05
5	505.60	116	563.60
6	599.97	121.4	660.67
7	516.62	116	574.62
8	446.80	112	474.80
9	426.53	112	482.53
10	599.97	121.4	660.67
11	516.62	116	574.62

in the amount of 33.6 kg ha^{-1} and potassium (K) in the amount of 44.8 kg ha^{-1} are applied for establishment. Nitrogen (N) fertilizer is usually not applied during the seeding year because this tends to stimulate weed growth more than switchgrass growth. Atrazine and 2,4 D pesticides are used on all types of lands.

Re-establishment is required if there are not enough switchgrass stands a year later than seeding. Re-establishment cost consists of seeding, fertilizer, pesticide, and machinery costs. Since Roundup is already used for land preparation in establishment, it is not included in re-establishment cost. The probability of re-establishment is taken as 25% for frost seeding and 50% for spring seeding scenarios, as suggested in the literature [18]. Re-establishment cost is multiplied by the corresponding probability values and added to the establishment cost in order to compute the expected cost of establishment.

4.1.3. *Production cost*

Annual production cost includes rental, fertilizer, and pesticide costs. Average land rental costs for 1 ha of cropland, grassland, and marginal land in southwest of Kansas are \$234.6, \$23.7, and \$75.3 [33], respectively. Fertilizers P and K are applied in the amounts of 0.42 kg and 9.47 kg, respectively, for each tonne of switchgrass harvested. A moderate amount of N (112 kg ha^{-1}) is used in this case study. Nitrogen application costs \$137 ha^{-1}, while each kg of K and P costs \$12. The cost of pesticide is \$16.89 ha^{-1} [18].

4.1.4. *Harvesting cost*

The harvesting operation includes mowing, raking, baling, staging, and loading. For the budget estimations in this paper, it is assumed that harvesting is done in large square bales weighing 397 kg each. Mowing and raking has a fixed cost of \$31.61 ha^{-1}. The cost of baling is \$7, while the cost of staging and loading is \$2.8, leading to a total of \$9.8 for each bale [18]. Since 2.5 bales are obtained for each tonne, the variable cost of harvesting is taken as \$24.5 t^{-1} of switchgrass harvested.

4.1.5. *Transportation cost*

The cost of transporting the biomass by truck is calculated based on the following formula: \$5.70 + 0.1367X, where X is the distance of the cultivation zone to the facility in km, while 0.1367 is the variable cost in \$ km^{-1} t^{-1}. On the other hand, transporting the biomass by rail costs \$17.10 + 0.0277X [19]. In this study, distance to the facility is calculated based on a city-block distance, also known as the Manhattan distance. Among the transportation modes, only one mode of transportation, transportation by truck is considered for this specific case because of its availability in Kansas.

4.1.6. *Soil erosion*

Parameter values regarding the environmental benefits of switchgrass cultivation have also been computed. A recent study of the U.S. Department of Agriculture (USDA) considers farmer and societal costs of soil erosion by providing scientifically derived estimates. Summing the values of fertilizer saved (\$1.95) and water quality benefits (\$5.43), the USDA estimates that the yearly savings of the farmers and society from erosion is equal to \$7.38 for each tonne of soil [21]. The USDA estimates soil erosion in Kansas to be 8.29, 1.34, and 2.69 t ha^{-1} for cropland, grassland, and marginal land, respectively. Multiplying these amounts by \$7.38, value of one tonne of soil per year, we estimate soil-erosion savings via switchgrass cultivation to be \$61.18, \$9.89, and \$19.85 ha^{-1} y^{-1} for cropland, grassland, and marginal land, respectively.

4.1.7. *Carbon sequestration and CO_2 emissions*

The amount of soil organic carbon (SOC) sequestered, its CO_2 equivalence, and saving values due to carbon sequestration for each seeding scenario are given in Table 3. SOC sequestration depends on soil type. The value of SOC sequestration in cropland is taken as 4.42 t ha^{-1} y^{-1} [34]. On the other hand, sequestration rates of up to 2.4–4.0 t ha^{-1} y^{-1} are reported for switchgrass crop grown in the CRP in South Dakota [35]. Therefore, an average value of 3.2 t ha^{-1} y^{-1} is used for carbon sequestration on marginal land. Since grassland is expected to be already saturated with high concentration of SOC, carbon sequestration via switchgrass cultivation is less than 1 t ha^{-1} y^{-1} [36]. In this study, it is assumed to be 10% of that is on marginal land. To compute the equivalent CO_2 sequestered from the atmosphere, the SOC values in Table 3 are multiplied by 3.67 [37]. The average cost of CO_2 emissions is \$20 t^{-1}, according to the emissions trading system in the EU [38]. The savings column is computed by multiplying CO_2 equivalence with \$20 t^{-1}.

Carbon emissions that occur during seeding, production, harvesting, and transportation operations are given in Table 4 [39,40]. CO_2 emitted during in each sub-operation including pesticide or fertilizer application is given under the CO_2 emissions column. The number (amount) of these sub-operations (pesticides or fertilizers) in each operation is indicated in the usage column. Finally, the cost of CO_2 emissions is presented in the cost column and is equal to the multiplication of CO_2 emissions, usage, and \$20 t^{-1}. For instance, the cost of pesticide application in the seeding operation is obtained by 6.3(kg kg^{-1}) * 5.25(kg ha^{-1}) * \$20 t^{-1}, which equals \$0.66 ha^{-1}.

As given in equation (4), the net savings from CO_2 sequestration are obtained by subtracting the cost of carbon emissions in Table 4 from the savings via CO_2 sequestration in Table 3.

4.2. *Experimental design*

In this section, we evaluate the impact of key parameters on results. These parameters include the objective function weights, yield levels, sustainability factor, and the available budget amount for biomass production.

We investigate three different cases of weight selection for (α, β, and μ) in the objective function given in equation (1) in

Table 3 – Soil organic carbon (SOC), CO_2 equivalence, and savings.

Seeding scenario	SOC ($t\ ha^{-1}\ y^{-1}$)	CO_2 equivalence ($t\ ha^{-1}\ y^{-1}$)	Savings (\$ $ha^{-1}\ y^{-1}$)
1, 3, 4, 5	4.42	16.22	324.4
2, 6, 7	0.32	1.17	23.5
8, 9, 10, 11	3.2	11.74	234.8

Table 4 – CO_2 emissions and their equivalent costs from various operations.

Operation	Sub-operation	CO_2 emissions	Usage [16]	Cost
Seeding	Drill	35.3 kg ha^{-1}	1	0.706 \$ ha^{-1}
Seeding	No-till drill	5.8 kg ha^{-1}	1	0.116 \$ ha^{-1}
Seeding	Airflow	7.9 kg ha^{-1}	1	0.158 \$ ha^{-1}
Seeding	Pesticide	6.3 kg kg^{-1}	5.25 kg ha^{-1}	0.66 \$ ha^{-1}
Seeding	Fertilizer (P)	0.2 kg kg^{-1}	33.6 kg ha^{-1}	0.672 \$ ha^{-1}
Seeding	Fertilizer (K)	0.15 kg kg^{-1}	44.8 kg ha^{-1}	0.896 \$ ha^{-1}
Production	Pesticide	6.3 kg kg^{-1}	5.25 kg ha^{-1}	0.66 \$ ha^{-1}
Production	Fertilizer (N)	1.3 kg kg^{-1}	112 kg ha^{-1}	2.91 \$ ha^{-1}
Production	Fertilizer (P)	0.2 kg kg^{-1}	0.42 kg t^{-1}	0.00168 \$ t^{-1}
Production	Fertilizer (K)	0.15 kg kg^{-1}	9.47 kg t^{-1}	0.02841 \$ t^{-1}
Harvesting	Rake	1.7 kg ha^{-1}	1	0.034 \$ ha^{-1}
Harvesting	Bale	3.30 kg ha^{-1}	1	0.066 \$ ha^{-1}
Transportation	Truck	0.203 kg t^{-1} km^{-1}	1	0.00406 \$ t^{-1} km^{-1}
Transportation	Train	0.017 kg t^{-1} km^{-1}	1	0.0003 \$ t^{-1} km^{-1}

order to understand the relation between environmental factors (soil erosion prevention, carbon sequestration and GHG emissions) and the sales of switchgrass biomass. Another reason for analyzing these weights cases, which are (1 0 0), (0.33 0.33 0.33), and (0 0.5 0.5), is to reflect the perspectives and preferences of various stakeholders (farmers, co-ops, or government) on the problem.

We also investigate the impact of high, moderate, and low levels of switchgrass yield and present an analysis of their effects on the results. A high level of switchgrass yield indicates an upper limit of the yield that can be obtained from any type of land. On the other hand, low level yield is studied as a worst-case scenario, where productivity of switchgrass is very low because of unexpected incidents such as extreme drought.

The sustainability factor is another parameter that is expected to affect results and gives the percentage of cropland that is not allowed for biomass production. The first value of the sustainability factor is set to 0%, which refers to the full availability of cropland for cultivation of switchgrass. The second case, where the sustainability factor is set to 25%, is stricter since it forces switchgrass cultivation on marginal land and grassland by limiting the available area of cropland for switchgrass cultivation to 75%. Finally, the sustainability factor is set to 50% in order to ensure safety of the food supply from cropland.

Finally, we also investigate the effect of three budget cases: limited, moderate, and ample. The budget level that is enough for switchgrass cultivation in all studied regions is taken as the ample budget. A moderate budget is equal to 75% of the ample budget, while 50% of the ample budget is considered to be a limited budget in this analysis.

5. Computational results

The MILP model given in section 3 is solved using CPLEX 12.2 on a personal computer with a 3.40 GHz, 16.0 GB memory. The model has 696 continuous variables and 17,078 integer variables. Model solution statistics are summarized for all cases in Table 5. The global optimum was achieved for all cases in less than 310 CPU second. We observe that as the available budget and sustainability factor decrease, difficulty of the problem and thus computational time increases. If we emphasize the sales of switchgrass in the objective function, the solution time also increases due to additional decisions regarding the harvesting time and amount.

In the base-case scenario, the objective function weights (α β μ) in equation (1) are set to (1 0 0), which gives full priority to the revenue obtained from sales of switchgrass. The sustainability factor and budget in the base-case scenario are 25% and moderate (525 M\$), respectively. We also use a moderate level

Table 5 – Summary of computational statistics for different scenarios.

Objective function weights (α β μ)	Yield levels	Sustainability factor (%)	Budget level (M\$)	Objective function value (M\$)	CPU time (s)
(1 0 0)	Base	Base	Base	931.5	303.1
(0.33 0.33 0.33)				364.6	30.5
(0 0.5 0.5)				112.6	0.9
Base	Low	Base	Base	747.9	297.2
	Moderate			931.5	303.1
	High			942.0	296.8
Base	Base	0	Base	931.5	302.5
		25		931.5	303.1
		50		911.6	67.2
Base	Base	Base	350	631.3	296.8
			525	931.5	303.1
			700	1202.8	49.6

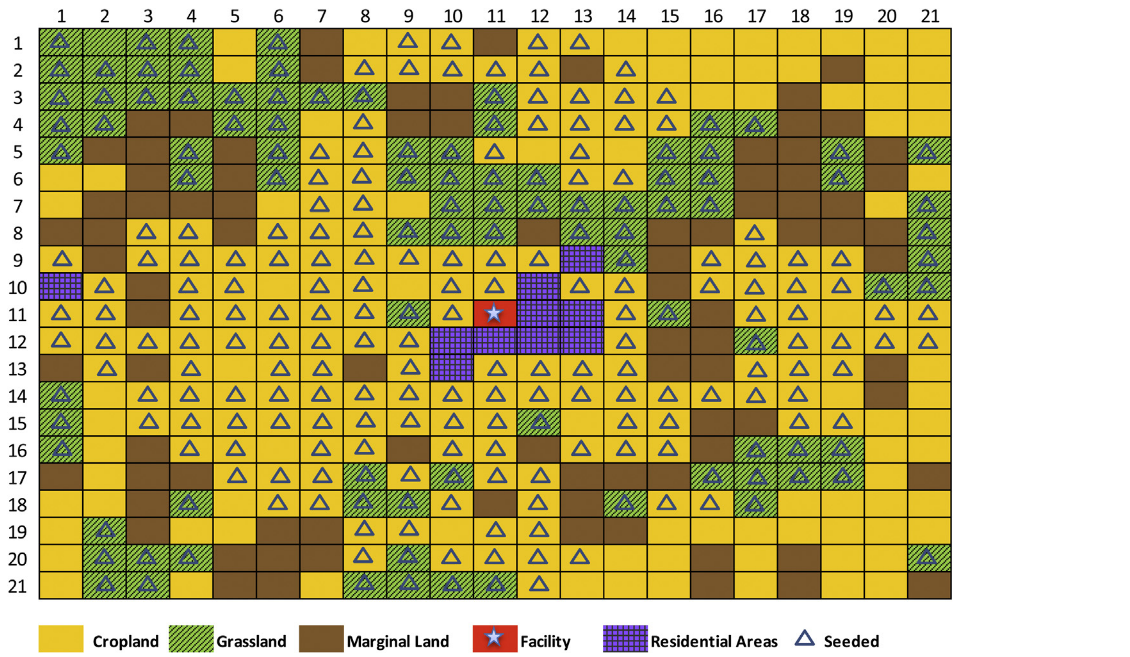

Fig. 2 – Hugoton area divided into 21 by 21 zones including land types, facility, residential areas, and optimal switchgrass seeding locations.

of switchgrass yield, which is given in Table 1, in the base-case scenario. The first four columns of Table 5 correspond to four different parameters that are investigated. In Table 5, four different sets of experiments are presented in each row-block of the table. In each set of experiments, each parameter is set to three different values, as explained in section 4.2, in order to analyze its impact on the results, while the remaining parameters are fixed to the base case values.

When we analyze the tightness of the constraints given the optimal solution in the base case, we observe that total switchgrass yield is equal to the potential switchgrass yield (constraint (5)), while harvested switchgrass biomass is equal to switchgrass yield (constraint (8)). Constraints (6), (7) and (9) are also binding. Inequality (10) is not a limiting constraint since we have considered an ample capacity in this case study. All constraints (11)–(16) regarding the budget allocation are binding. Inequality (17) limits harvested zones to ensure sustainability of bird populations, while constraint (18) is not binding in the base case since cropland utilization is already less than 75%.

As mentioned in section 4, the model is applied to a case study in Hugoton. Fig. 2 displays a map of the studied region in Hugoton, which is divided into 21 by 21 rectangular arrays of cultivation zones with the row and column numbers referring to zone (i, j) in the model. For example, zone (11, 11) shows the location of the facility, which is in the center of the Hugoton map, while cultivation zone (6, 9) shows one section of grassland in the considered region. This map displays the considered area with the distribution of land types, the location of the facility, and residential areas while indicating optimal seeding zones in the first year of the planning horizon when the MILP model is solved for the base-case scenario. It can be seen that the closest zones to the facility are selected for switchgrass cultivation. In addition, grassland is selected for cultivation since it has a lower rental cost while cropland becomes favorable due to its higher switchgrass yield. As the best seeding scenario, scenario 1 is selected for cropland, while scenario 2 is chosen for grassland. Both of these scenarios involve airflow planting in frost seeding. Seeding time is always chosen as the first year of the planning horizon in order to increase the overall production amount. Out of 248 zones of cropland, 163 are utilized for switchgrass production, while 93 out of 94 zones of grassland are converted into switchgrass cultivation. In other words, 87.6% of available cropland is used, while this value increases to 99% for grassland. For this case, none of the 88 zones of marginal land is chosen for switchgrass cultivation. The total area converted to switchgrass cultivation is as follows: 42,380 ha for cropland and 24,180 ha for grassland. The overall amount of biomass yield reaches 7.99 Mt, while 7.76 Mt of that amount is harvested in the ten-year planning horizon. The cost of switchgrass biomass harvested is calculated as \$67.63 t^{-1} for the

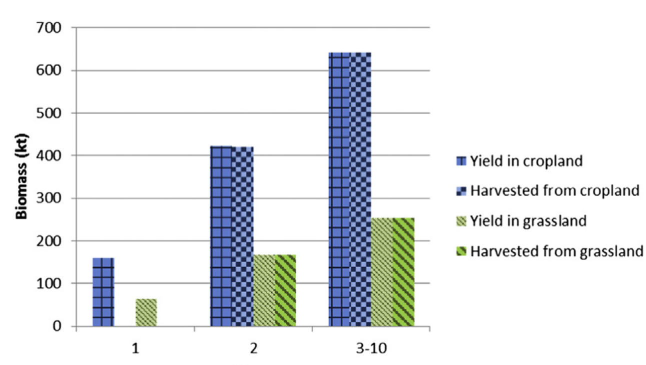

Fig. 3 – Biomass yield and harvested amount in the planning horizon.

base-case scenario, which is similar to current values in the market [41].

Fig. 3 shows the amount of biomass yield and harvested biomass in different types of lands. It is seen that harvesting decision is deferred to the second year due to the limited budget and the low yield in the establishment year. All switchgrass yield is harvested from year two to ten. This can be explained by the selection of the objective function weights in the base-case scenario in which the priority is given to the sales of switchgrass biomass.

We have also determined the optimal budget amounts to be allocated for operations involved in the biomass production. Fig. 4 shows the share of 525 M$ for seeding, land rent, fertilization, harvesting, and transportation throughout the planning horizon for the base-case scenario. As depicted in Fig. 4, harvesting, fertilization and rental costs require 210, 178.5, and 94.5 M$, respectively, and forms up 92% of overall budget.

Fig. 5 displays the optimum budget level for different farm operations at each time period in the base-case scenario. The rental cost is about 10 M$ in the first year and remains the same during the planning horizon. The budget amount allotted to seeding is about 33 M$, and is used only the first year of the planning horizon since all seeding decisions are made in the first year. The allocation of harvesting and fertilization budget starts in the second year, and increases in the third year. As the harvesting increases, budget allocated for fertilization and transportation also increases since their values depend on the harvested switchgrass biomass. The budget remaining after the first and second year is divided equally into eight years by the model.

Fig. 6 displays profitability ratios in the base case for various economical values obtained from switchgrass production. The profitability ratio is obtained by dividing net economical values (profits) of corresponding outputs by the budget value in the base case. Total economic benefits represent the summation of nominal values of switchgrass sales, savings via carbon sequestration, and soil erosion prevention. On the other hand, the objective function value is the amount of economical values after the terms in the objective function are multiplied with their corresponding weights. The highest profitability ratio for total economic benefits is obtained when equal consideration is given to both economic and environmental factors.

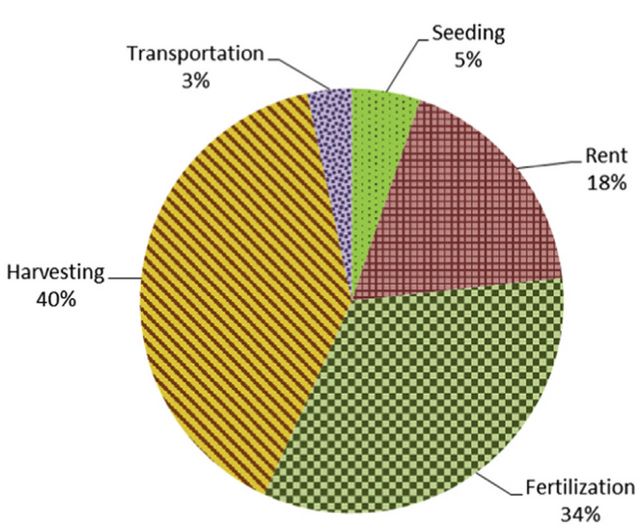

Fig. 4 – Optimal cost breakdown for the base-case scenario.

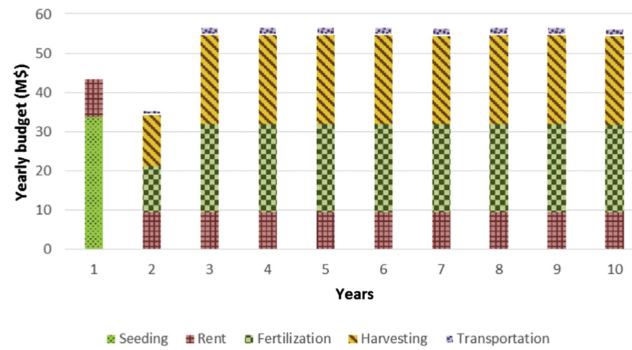

Fig. 5 – Optimal yearly budget allocation for farm operations of switchgrass biomass production in the base-case scenario.

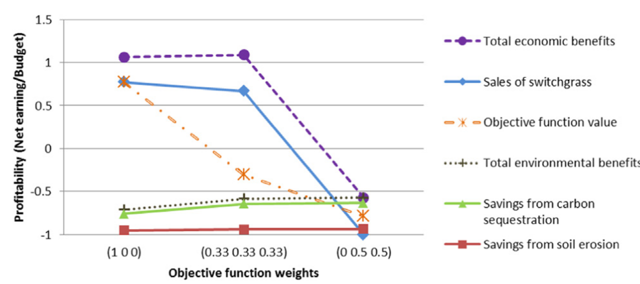

Fig. 6 – Profitability of various economical parameters based on changing weights.

In the following sections, we provide some scenario analyses by changing different parameter values in order to gain better insight into the nature of the problem. First, we investigate the impact of different objective function weights on the results. The second analysis addresses the effect of changing switchgrass yield levels on the model outputs. Third, we perform another analysis in order to determine the impact of sustainability factor on the solution, and finally, we investigate

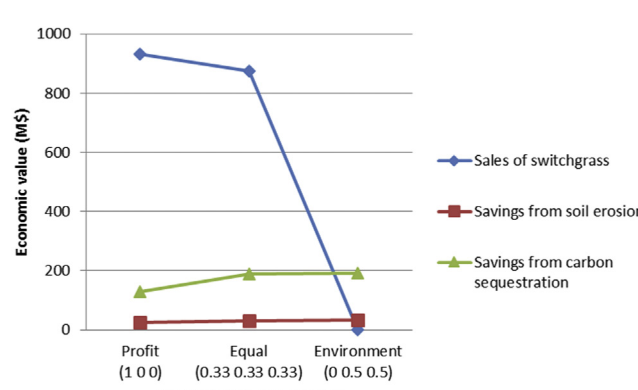

Fig. 7 – Economic value obtained from three objectives based on changing weights.

the impact of different budget levels. The values used in these analyses are summarized in Table 5. Furthermore, we also conduct a separate sensitivity analysis that examines the effect of CRP incentives on the selection of marginal land.

5.1. Analysis of objective function weights

Three different weight cases are investigated to understand the impact of objective functions on the results. For the first set of weights (1 0 0), priority is given to revenue from biomass sales, which emphasize the problem only from the farm owner point of view. On the other hand, the second set of weights (0.33 0.33 0.33) gives equal consideration to revenue and environmental consequences of biomass production, which may reflect the government's goals. The last set of weight (0 0.5 0.5) gives full consideration to the environment.

The total economic value obtained from the sales of switchgrass, and savings from soil erosion and carbon sequestration for three different objective function weights is given in Fig. 7. The amount of switchgrass grown and harvested on different land types is also given for three different objective function weights in Fig. 8. As shown in Figs. 7 and 8, giving full consideration to the environment decreases the amount of switchgrass harvested to zero, which results in no sales. The equal-weight case (0.33 0.33 0.33) gives higher total economic value than that in the profit priority case (1 0 0), although the harvested amount decreases from 7.76 Mt to 7.30 Mt. This is because in the equal-weight case, savings from soil erosion and carbon sequestration increase faster than the decrease in sales of switchgrass on marginal land. In this case cropland, grassland, and marginal land account for 50%, 13%, and 37%, respectively, of the overall biomass production. Giving equal consideration to the environment and sales of switchgrass, some production is shifted from grassland to marginal land since marginal land has ten and two times better savings for carbon sequestration and soil erosion, respectively, than the savings from grassland. However, by further emphasizing environmental benefits, the model uses the entire harvesting budget to have almost 100% utilization of all land types including grassland. However, in this case, the change in soil erosion is minimal since switchgrass soil erosion prevention is not high for grassland, and further utilization of grassland does not provide much more additional benefit.

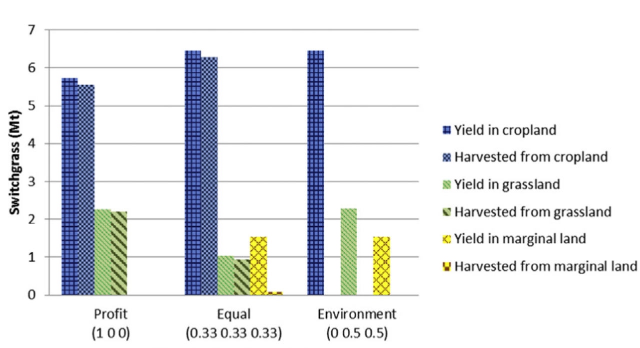

Fig. 8 – Switchgrass yield and harvested amount based on changing weights.

5.2. Analysis of switchgrass yield levels

In this study, potential switchgrass yield is assumed to be mostly dependent on land types and establishment year. However, lower and upper bounds are set on the potential switchgrass yield in order to reflect the impact of various factors such as changing weather conditions on potential yield. Potential yield in low level is set to 33% less than that in a moderate yield level, as shown in Table 1. Similarly, the potential yield in high level is taken as 33% more than that in a moderate yield level.

Figs. 9 and 10 show the effect of different yield levels on the economic value and harvested switchgrass from different land types, respectively. In the low-yield level case, all land types are utilized for biomass harvesting since there is not enough biomass grown on cropland and grassland. On the other hand, increasing the potential yield level to a moderate level removes marginal land from the solution. In other words, a moderate biomass amount in cropland and grassland leads to savings from the transportation cost, which can be used for more harvesting. Removing less-productive marginal lands from the solution leads to a higher economic value because the total biomass amount increases from 6.23 Mt to 7.76 Mt. However, further increasing the potential switchgrass yield provides only a slight improvement in the sales of switchgrass because, in this case, budget becomes a limiting factor. We still obtain a slight increase in sales because the same amount of biomass can be obtained from a closer region

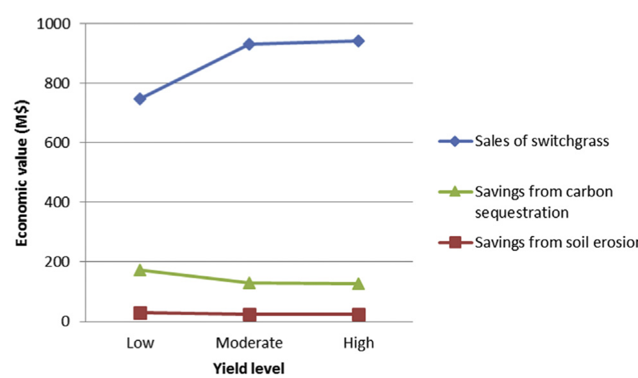

Fig. 9 – Economic value obtained from different objectives based on changing yield levels.

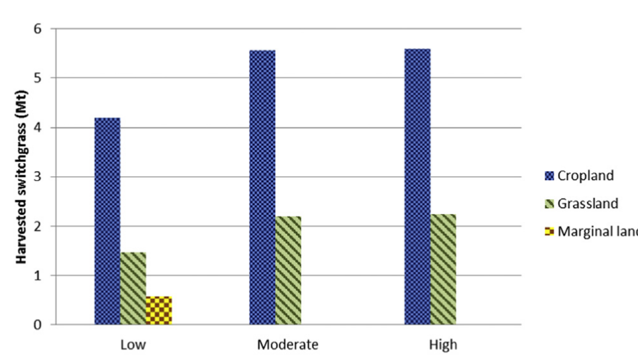

Fig. 10 – Harvested yield from different land types based on changing yield levels.

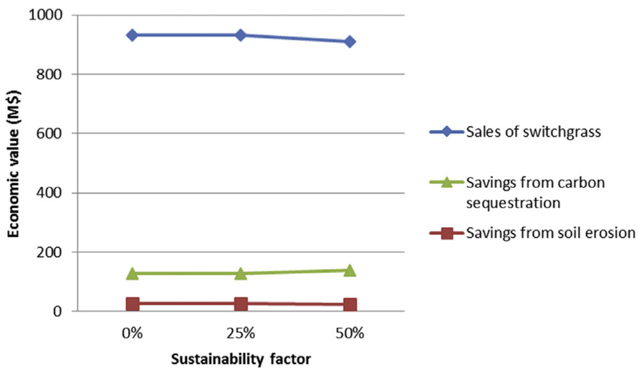

Fig. 11 – Economic value from three objective functions based on sustainability factor.

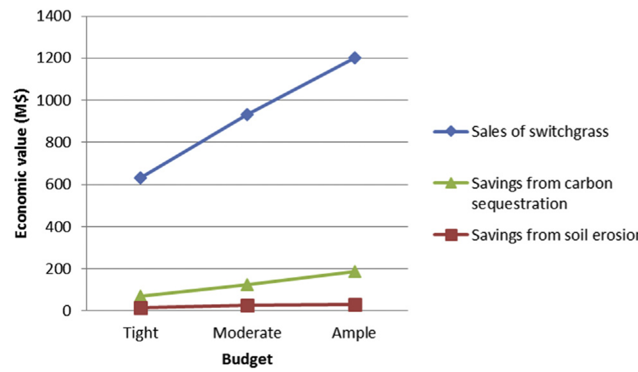

Fig. 13 – Economic value obtained from different objectives based on changing budget.

to the facility, which results in some savings from the transportation cost and leads to more harvesting. Another interesting result is obtained regarding savings from carbon sequestration. A higher potential yield level decreases the savings from carbon sequestration since the model does not select marginal land, which leads to ten times more carbon sequestration than that of grassland.

5.3. *Analysis of sustainability factor*

Figs. 11 and 12 provide the effect of the sustainability factor on economic value obtained for different objective functions and the amount of harvested switchgrass from different land types, respectively. First, full availability of cropland for biomass production is defined by setting the sustainability factor to 0%. Then it has been increased to 25%. Finally, for full security of the food supply, the sustainability factor has been increased to 50%. Based on Figs. 11 and 12, there is no difference in results for sustainability factors of 0% and 25%, while we observe a slight decrease in economic value from the sales of switchgrass when the sustainability factor is set to 50%. Since utilization of cropland is already less than 75% in the base case, i.e., the sustainability constraint is not binding, changing the sustainability factor from 0% to 25% (i.e., limiting the usage of cropland for biomass production to 75%) does not affect the results. The binding constraint on cropland utilization is the budget constraint. On the other hand, when we further increase the sustainability factor to 50% (i.e., limiting the usage of cropland to 50%), the model cannot use the same amount of cropland as in the base case. Therefore, in this case, the budget usage is shifted to marginal lands, which are not so productive, leading to a decrease in the harvested switchgrass biomass from 7.76 Mt to 7.50 Mt. By changing the allocation of land types between the cases of 0% and 50% sustainability factors, one can conclude that food supply safety can be provided without losing too much economic value.

5.4. *Analysis of changing budget levels*

We also investigate the effect of a changing budget on the results. The economic value and harvested switchgrass biomass are given in Figs. 13 and 14, respectively. Here, an ample budget represents a sufficient budget amount for seeding and harvesting on all types of land. A moderate budget is set to 75% of the ample budget, while a tight budget is considered to be 50% of the ample budget. Fig. 13 shows that an increase in the budget results in an increase in all objective functions in terms of economic value. However, the increment in sales in switchgrass biomass and savings from soil erosion is slower than the increment in the budget. This is

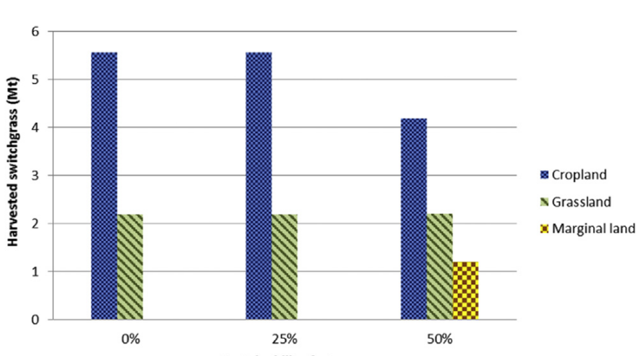

Fig. 12 – Harvested switchgrass based on sustainability factor.

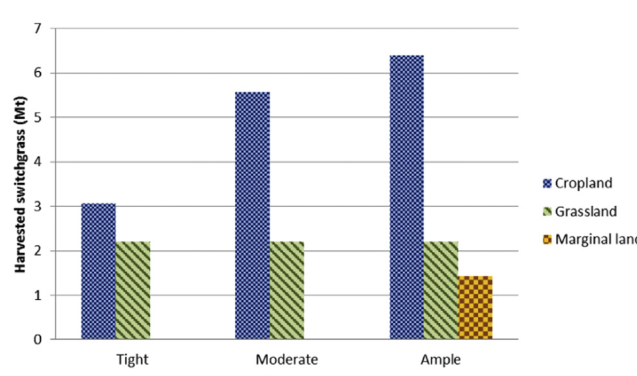

Fig. 14 – Harvested yield from different land types based on changing budget.

because budget is used more for transportation from marginal land to biorefinery, and marginal land is not very productive. On the other hand, the increase in savings from carbon sequestration is higher than the increment in the budget because marginal lands have more potential for carbon sequestration than all other land types. On the other hand, as shown in Fig. 14, a change in the budget does not affect the switchgrass biomass harvested from grassland since it is already fully utilized even under the medium-budget case, while expanding the available budget affects cropland and marginal land. Changing the budget from tight (350 M$) to ample (700 M$) leads to an increase in harvested switchgrass biomass from 5.3 Mt to 10 Mt.

The increase in sales of switchgrass biomass with respect to budget is not linear since as the budget increases, a higher share of the budget is allocated for long-distance transportation, and the model also starts using less-productive land. For example, increasing the budget from low to medium only increases the utilization of cropland, which is more productive than grassland. However the rental cost of cropland is also high. When we increase the budget from medium to ample, cropland utilization reaches 75%, while marginal land becomes fully utilized. However, the rate of increase in sales of switchgrass decreases when the budget is changed from medium to ample since, in this case, although the rental cost of marginal land is lower than that of cropland, those lands are less productive. On the other hand, the rate of increase in savings from environmental benefits increases when the budget level is increased. That is because a higher budget level leads to utilization of more cropland and marginal land where switchgrass shows higher environmental benefits compared to grassland.

5.5. *Sensitivity analysis of CRP incentives on land selection*

We also study the effect of CRP incentives on the utilization of marginal land. Since some studies suggest that switchgrass cultivation could substitute the CRP [16,35], we analyze how much incentive is needed to make switchgrass cultivation favorable on marginal land over its production on cropland and grassland. Fig. 15 shows how the amount of switchgrass harvested from different land types is influenced by the level of CRP incentives. If the government utilizes an incentive of $15 for each tonne of switchgrass produced on marginal land,

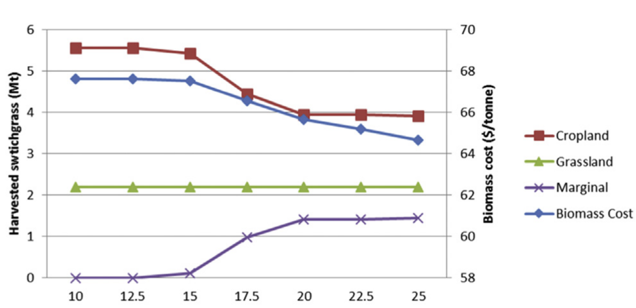

Fig. 15 – Impact of CRP incentives on switchgrass production and biomass cost.

then the total cost of biomass starts to decrease and marginal land starts to be utilized. On the other hand, an incentive of $20 for each tonne of biomass is sufficient for the maximum utilization of marginal land, while an incentive beyond $20 is overpayment to farmers for marginal land utilization. We observe another interesting result for the cost of biomass production when CRP incentives are considered. Without CRP incentives, the cost of harvested switchgrass biomass is $67.63 t^{-1} for the base-case scenario. If a $20 incentive is provided for marginal land, that value decreases to about $65.5 t^{-1}. Using CRP contracts as an incentive on switchgrass cultivation on marginal land may also decrease the switchgrass sales price, due to the decline in biomass production cost.

6. Concluding remarks and future directions

In this paper, we introduce a mixed-integer linear programming model that defines an optimal design for switchgrass cultivation on different land types in order to maximize the total revenue of biomass production as well as its beneficial environmental impacts. We apply the proposed model on a real case study of biofuel production site in Hugoton, Kansas. The case study shows that given the current market prices, switchgrass cultivation on grassland and cropland is highly profitable. Given the limited budget, marginal land is not utilized for biomass production, unless the government utilizes CRP contracts as an incentive on marginal land for switchgrass cultivation.

In the proposed model with a ten-year time horizon, results indicate that for all types of land, planting switchgrass with the airflow method in the frost season of the first year maximizes the total economic value. It can be seen that harvesting starts in the second year of seeding for optimum allocation of a limited budget, since switchgrass yield is low in the first year and reaches its maximum potential in the third year. In this paper, the effect of a sustainable food supply is also considered. Limiting biomass cultivation on cropland slightly decreases the overall biomass production since less-productive marginal land starts to be utilized. On the other hand, while giving full priority to revenue in the objective function maximizes the sales of switchgrass, it does not maximize the total economic value. Maximum benefit is achieved when equal consideration is given to revenue obtained from sales of switchgrass and economic value of its environmental impacts. We also observe that the increase of switchgrass yield level from low to moderate increases the biomass amount and thus the total economic value, while the increase of yield level from moderate to high provides very slight improvement on the total economic value, due to limited budget and high harvesting cost.

This paper provides a unique approach in terms of quantifying and modeling the environmental effects of switchgrass production as well as its economic impacts at the farm level. The model and methodology presented in this paper could be extended in a number of possible ways. In this paper, uncertainty regarding the yield, budget, and multi-objective function weights is handled by conducting sensitive analyses. In a future study, the uncertainty in yield levels, budget, and price of switchgrass biomass can be explicitly considered in a stochastic programming model where stochastic elements are modeled as random variables. Furthermore, the change of price can also be considered as a nonlinear function of yield.

We also represent the change of cost and environmental impacts of switchgrass production across space by considering different land types in our model. In particular, we model carbon sequestration and soil erosion prevention on a heterogeneous landscape as a linear function of yield. Although these environmental factors may be potentially time-varying, due to the unavailability of the data, we only consider the impact of yield, which is time-varying until it reaches its maximum value, on environmental factors. An extended version of this model could consider a potential decrease in savings from environmental benefits, particularly from carbon sequestration, in time due to saturation of the soil with soil organic carbon. We collect and synthesize various types of data regarding the establishment cost, carbon sequestration, and CO_2 emissions in order to build a model that accounts for important economic and environmental factors that affect switchgrass production. However, the environmental impacts could be further extended by considering the effects of switchgrass cultivation on water quality and the populations of other species in addition to bird species if adequate data is acquired.

In the future, in order to deal with a larger-size landscape and more complex problems, cutting planes and decomposition algorithms can be utilized to decrease the model solution times. This model can also be extended to biomass production from any other types of energy crops to identify the most efficient management and planning strategies for biomass production. In addition, economic and environmental analysis can be investigated for other energy crops along with currently cultivated food crops, and optimum allocation of lands could be determined for biomass and food supply.

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