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

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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.

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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

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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.