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Food vs. biofuel: An optimization approach to the spatio-temporal analysis of land-use competition and environmental impacts

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HIGHLIGHTS

- Proposed optimization model presents trade-offs between biofuel and food production.
- Switchgrass (energy) production is more competitive than food production on cropland.
- Corn production and harvesting corn stover are not environment friendly.
- Order of total budget usage: production, harvesting, seeding, and transportation.
- Food security needs limitation of cropland use or CRP incentive on marginal land.

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ABSTRACT

Biofuel production from food crops leads to debates about the increase in food prices and security of the food supply. On the other hand, biofuels derived from cellulosic (energy) crops offer positive environmental impacts. In this study, we develop a multi-objective mixed-integer optimization model to investigate the trade-offs and competition between biofuel and food production using switchgrass and corn. This model maximizes total economic and environmental benefits and provides optimal decisions regarding land allocations to food and energy crops, seeding time, harvesting time and amount, and budget allocations to farm operations. A piecewise linear lower approximation is developed to linearize the nonlinear revenue curve of corn grain sales. Spatio-temporal environmental impacts such as soil erosion prevention, carbon sequestration and emissions, and nitrogen pollution are included in the model. The application of the model in Kansas indicates that switchgrass is more profitable than corn in cropland, while it requires Conservation Research Program (CRP) incentives for production on marginal land unless priority is given to the environment. In order to ensure food security, our study advises managers and policy makers to provide CRP incentives or to adjust the sustainability factor, which restricts cropland availability for biofuel production. Our spatio-temporal optimization model can also be adapted to different regions with alternative energy and food crops under various management scenarios.

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1. Introduction

The growing demand of energy, dependency on fossil fuels and environmental problems motivate researchers to seek sustainable ways of energy production. Biofuel, an environmentally friendly renewable energy source, is considered a substitute for fossil fuels. A number of sources, such as food crops, energy crops, and forest residues, can be used in biofuel production. In order to ensure the transition from fossil fuels to biofuel, the Renewable Fuel Standard (RFS2) was set by the US Congress in 2007 to provide a strategic plan for biofuel production [1].

Biofuels help to secure energy and fight against climate change by reducing CO_2 emissions. However, they also arouse some questions and debates. For example, biofuel production from corn (*Zea mays* L.) leads to concern about security of the food supply and increase in food prices [2,3]. Subsidies in corn production cause displacement of grasslands and other crops, thus impacting biodiversity. Some researchers claim that ethanol production from corn requires more energy input than its output [4,5]. Currently more than 25% of total corn yield is used in ethanol production in the US [6].

Abbreviations: CRP, conservation reserve program; GHG, greenhouse gas; MILP, mixed-integer linear programming; QP, quadratic programming; RFS2, renewable fuel standard; SOC, soil organic carbon; TB, total benefit; TCE, total carbon emissions; TCS, total carbon sequestration; TNP, total nitrogen pollution; TR, total revenue; TSE, total soil erosion prevention.

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Nomenclature

Indices

i	row of cultivation zone ($i = 1,\ldots,I$)
j	column of cultivation zone ($j = 1,\ldots,J$)
(i, j)	cultivation zone (cropland, grassland, marginal land)
k	crop type ($k = 1$: switchgrass, $k = 2$: corn)
s	segment of total supplied corn grain ($s = 1,\ldots,S$)
t	time period ($t = 1,\ldots,T$)
v	yield type ($v = 1$: switchgrass, $v = 2$: corn grain for food, $v = 3$: corn grain for biofuel, $v = 4$: corn stover)

Sets

CR	set of cropland zones in cultivation area
GR	set of grassland zones in cultivation area
MR	set of marginal land zones in cultivation area
M_t	set of time periods from first period to period t ($M_t = \{1,\ldots,t\}$)

Binary decision variables

R^t_s	1 if total corn grain for food at time period t is greater than lower bound of segment s, 0 otherwise
S^t_{ijk}	1 if zone (i,j) is seeded with crop type k at time period t, 0 otherwise
X^t_{ijv}	1 if zone (i,j) is harvested for yield type v at time period t, 0 otherwise

Continuous decision variables

E_b	establishment budget used ($)
E^t_s	yield amount of corn grain for food obtained in segment s (tonne)
H_b	harvesting budget used ($)
N^t_{ij}	switchgrass yield in zone (i,j) at time period t (tonne)
$\overline{N}^t_{ij}$	harvested switchgrass biomass in zone (i,j) at time period t (tonne)
P_b	production budget used ($)
$R^t(\widetilde{Y}^t)$	revenue obtained from total corn grain for food at time period t ($)
$\widetilde{R}^t(\widetilde{Y}^t)$	approximated revenue obtained from total corn grain for food at time period t ($)
T_b	transportation budget used ($)
$\widetilde{Y}^t_{ij}$	corn grain used for food production in zone (i,j) at time period t (tonne)
$\widetilde{Y}^t$	total corn grain used for food production at time period t (tonne)
$\bar{Y}^t_{ij}$	corn grain used for biofuel production in zone (i,j) at time period t (tonne)
Y^t_{ij}	harvested corn stover in zone (i,j) at time period t (tonne)

Parameters

A_{ijv}	potential yield of yield type v in zone (i,j) (tonne)
B	total available budget in planning horizon ($)
C_t	biofuel production capacity of facility at time period t (l)
CS_{ijk}	economic value of carbon sequestration in zone (i,j) via crop type k ($)
D_{ij}	distance of zone (i,j) to facility (km)
e_v	biofuel conversion factor for yield type v (l/tonne)
F_v	fixed cost of transporting yield type v ($)
fe_k	nitrogen fertilization applied for crop type k (kg)
p^t_v	sale price of yield type v at time period t ($/tonne)
$\tilde{p}^t_{2s}$	sub-price of corn grain for food in segment s ($)
RC_{ij}	rental cost of cultivation zone (i,j) ($)
SE_{ijk}	economic value of soil erosion prevention in zone (i,j) via crop type k ($)
TEC_{ijk}	total expected establishment cost for crop type k in zone (i,j) ($)
U^t_1	first non-negative price constant of corn grain in food market
U^t_2	second non-negative price constant for corn grain in food market
V_v	variable cost of transporting yield type v ($/tonne * km)
Z_s	upper bound value for segment s (tonne)
α	weight of profit
β	weight of environmental effects
ϕ	soil erosion prevention reduction constant for harvested yield
ξ	carbon sequestration reduction constant for harvested yield
σ_k	carbon emissions penalty of seeding crop type k ($)
ρ_v	carbon emissions penalty of harvesting yield type v ($)
ω_v	carbon emissions penalty of production operations for yield type v ($/tonne)
τ	carbon emissions penalty of transporting yield ($/tonne * km)
η	economic damage caused by nitrogen pollution ($/kg)
μ_k	percent nitrogen uptake by crop type k
ψ	percent nitrogen contamination (leaching) in drinking water
π_t	growth factor of switchgrass after t years of establishment
$\varDelta$	fraction of facility capacity assigned to biofuel production from switchgrass and corn biomass
ϵ_k	fixed cost of producing crop type k per cultivation zone ($)
γ_v	variable cost of producing yield type v ($/tonne)
δ_v	fixed cost of harvesting yield type v per zone ($)
θ_v	variable cost of harvesting yield type v ($/tonne)
λ	sustainability factor defining percentage of cropland not allowed for energy crop production

According to RFS2, ethanol made from grain can comprise up to 15 billion gallons of a 36-billion-gallon annual ethanol goal [1].

Another source of biofuel is cellulosic plants (energy crops), such as switchgrass (*Panicum virgatum*), which is native to North America and has many environmental benefits including soil erosion prevention and carbon sequestration [7]. Ethanol production from both food and energy crops is also known to reduce GHG emissions [8]. RFS2 requires the annual use of at least 16 billion gallons of biofuel from energy crops by 2022 [1].

Ethanol is mostly produced from first-generation crops, which are mainly food crops in the form of sugars and vegetable oils. In addition to first-generation crops, the availability of ethanol production from second-generation crops, which are cellulosic biomass, woody crops and agricultural residues, have motivated researchers to find more efficient and economical ways of designing biofuel production and the supply chain. Xie et al. [9] propose a Mixed-Integer Linear Programming (MILP) model to minimize overall cost of transporting cellulosic feedstock by providing optimal locations for biorefineries, hubs, and terminals. Cobuloglu and Büyüktahtakın [10] develop an MILP model that integrates economic and environmental impacts of switchgrass biomass production. Their model defines the best seeding method, harvesting time and amount for different land types, and budget allocation to farm operations under various scenarios. Kim et al. [11] develop