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Biofuel supply chain design under competitive agricultural land use and feedstock market equilibrium

Yun Bai [a], Yanfeng Ouyang [a,*], Jong-Shi Pang [b]

[a] Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States
[b] Department of Industrial & Enterprise Systems Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States

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ABSTRACT

The rapid expansion of the biofuel industry diverts a large amount of agricultural crops as energy feedstocks, and in turn affects farm land allocation, feedstock market equilibrium, and agricultural economic development in local areas. In this paper, we propose game-theoretic models that incorporate farmers' decisions on land use and market choice into the biofuel manufacturers' supply chain design problem. A noncooperative bi-level Stackelberg leader–follower game model and a cooperative game model are developed respectively to address possible business partnership scenarios between feedstock suppliers and biofuel manufacturers. The models determine the optimal number and locations of biorefineries, the required prices for these refineries to compete for feedstock resources, as well as farmers' land use choices between food and energy. Using corn as an example of feedstock crops, spatial market equilibrium is utilized to model the relationship between corn supply and demand, and the associated price variations in local grain markets. With linear corn demand functions, we develop a solution approach that transforms the original discrete mathematical program with equilibrium constraints (DC-MPEC) into to a solvable mixed integer quadratic programming (MIQP) problem based on Karush–Kuhn–Tucker (KKT) conditions. The proposed methodology is illustrated using an empirical case study of the Illinois State. The computation results reveal interesting insights into optimal land use strategies and supply chain design for the emerging "biofuel economy".

1. Introduction

The emerging biofuel production industry in the U.S. has continued to boom as the nation aims to reduce transportation related emissions and dependence on imported oils. A series of ambitious environmental policies provided remarkable government support and subsidies, such as the Energy Independence and Security Act of 2007 (EISA) and the Food, Conservation, Energy Act (FCEA) of 2008. Biofuel development is generally deemed as a promising way to enhance socio-economic and environmental sustainability, and such development has far-reaching yet complex impacts on critical issues such as climate change, energy security, and food security for a growing global population. The U.S. production of bio-ethanol (a popular type of biofuel) has grown from 0.2 billion gallons in 1983 to over 6.5 billion gallons in 2008, and the raw material is dominantly corn starch. The recent congressional mandate (EPA, 2007) further requires the annual production to reach 36 billion gallons by 2022, and over 80% of the mandated increase is required to be based on cellulosic feedstocks such as crop residues (e.g., corn stover) and dedicated energy crops (e.g., switchgrass and miscanthus).

Massive production of energy crops has significant impacts on the U.S. economy and imposes challenges to resource supply systems that are associated with different stages of the bio-fuel supply chain (e.g., biomass production, harvesting, storage, processing, and transportation) at regional, national or even global levels. In particular, the expected dramatic increase in U.S. biofuel consumption induces new demand for bio-energy crops including first and second generations of biomass. The new outlet for agricultural commodities results in competition between food and energy use and as a result increases food prices. According to O'Brien and Woolverton (2009), the U.S. average corn prices per bushel have increased dramatically since 2006, and climbed up from \$3.04 per bushel in the 2006/07 marketing year up to \$4.20 during the 2007/08 marketing years. Biofuel production has been criticized for reducing food supply and lifting up food prices to the record high in recent years (Rajagopal et al., 2009).

In view of the prospect of the biofuel industry, some researchers have raised concerns over biofuel's long-term socio-economic impacts including: e.g., the food-versus-fuel debate and the new link between energy and agriculture markets (Chen et al., 2010; Johansson

* Corresponding author.
E-mail address: yfouyang@illinois.edu (Y. Ouyang).

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and Azar, 2007; Rajagopal et al., 2009; Walsh et al., 2003) the strategic changes in agricultural land use (e.g., regular food crop production vs. Conservation Reserve Program (CRP) FSA USDA, 2011) and feedstock production (e.g., mix of feedstocks) required to support the biofuel production goals (Dicks et al., 2009; Khanna et al., 2008), the optimal size and locational distribution of biofuel refinery plants (Bai et al., 2011b; Kang et al., 2010), and the divergence between the privately profitable and the socially optimal designs (Ervola and Lankoski, 2011). The food versus fuel dilemma is essentially due to the limited resources (e.g., farmland). In other words, the impact of biomass feedstock production on the food market is ultimately due to the competition for farmland allocation between conventional food crops and energy crops.

The strategic design and planning of a biofuel supply chain system is critical for the commercial viability, cost-effectiveness, and sustainability of the industry. Many factors such as feedstock price, ethanol production location, and transportation cost are interrelated and interdependent. The regional economic structure (e.g., availability and price of feedstock, spatial distribution of supply and demand) not only plays an important role in biofuel supply chain design, but they are also influenced by the supply chain configuration. For example, in the advent of a new biofuel refinery, farmers who used to ship corn to nearby local markets may be attracted to sell corn as biofuel feedstock. As a result, the existence of biofuel refinery may boost local corn price, resulting in higher cost on feedstock procurement (McNew and Griffith, 2005). As such, having a large centralized refinery can decrease ethanol production costs through economy of scale but may result in higher cost on feedstock procurement and production distribution. On the other hand, different business partnership that could be formed between farmers and biofuel manufacturers also affect their investment decisions, individual profitability and the welfare of the entire supply chain. In reality, farmers face a wide variety of risks such as unforeseeable changes in market prices. Although farmers can make operational decisions each year, they also need to make long-term plans on whether to utilize their farmland to grow crops or enroll in the CRP, and what types of crops to grow in the next few years (Mapemba, 2005). Given the high cost of building refineries, transporting biomass feedstocks and inflexibility of changing farmland use, both farmers and biofuel manufacturers would be interested in long-term contracts that ensure incentives for farmers to grow sufficient feedstock supply and for manufacturers to invest on production facilities (Larson et al., 2008).

Hence, regional agricultural activities and feedstock market fluctuation should be integrated as part of the biofuel supply chain design. To address this complex problem, this paper develops an integrated optimal biofuel supply chain design approach based on game theory and spatial network equilibrium to incorporate major economic forces that affect feedstock prices, demand and supply allocation, and farmers' land use choices. Specifically, the following decisions of different stakeholders in the supply chain are addressed simultaneously: i) the number, location and size of biofuel refineries; ii) site-specific feedstock procurement prices under spatial market equilibrium; iii) farmer's land use choices between food and fuel, and local market (transportation) choices.

The exposition of the remainder of this paper is as follows. Section 2 reviews related literature on biofuel economy and the state-of-the-art analysis methods. Section 3 presents the assumptions, notations and formulation of a noncooperative Stackelberg leader–follower game model. A solution approach that transforms the original bi-level discretely constrained mathematical program with equilibrium constraints (DC-MPEC) for the Stackelberg game into a solvable single-level MIQP is developed. We also propose a cooperative game model formulated as an MIQP problem in comparison with the noncooperative model. Section 4 illustrates the proposed methodologies using a numerical example in the context of Illinois State biofuel industry. Section 5 concludes the paper and discusses possible future research.

2. Literature review

In recent years, economic theories (e.g., partial and general equilibrium models) and simulation methods have been used to estimate global and national impacts of the expanding biofuel industry on macro-economic performance. For example, Rajagopal et al. (2009) and Chen et al. (2010) examined the food-versus-biofuel trade-off in terms of losses and gains in consumer surplus in different socio-economic sectors. Benjamin and Houee-Bigot (2007) focused on the world arable crop markets and simulated the impact of alternative national and international agriculture policies under land availability constraints using a partial equilibrium model. Tyner and Taheripour (2008) conducted a firm-level ethanol refinery analysis and compared break-even corn and ethanol prices under zero profit conditions. Rajagopal et al. (2009) built a partial equilibrium multi-market framework to model the interactions between supply and demand in food and fuel markets. In comparison, general equilibrium models capture the economic implications at the global level rather than that at regional, industry or commodity levels (e.g., Berkes et al., 2003; Feng and Babcock, 2008; Gehlhar et al., 2010; Keeney and Hertel, 2009; Tyner and Taheripour, 2008). Simulation models were frequently utilized to predict the growth of the ethanol industry with the gasoline/additives demand (Gallagher et al., 2003), and bioenergy crop production and land use patterns under various agricultural policies and bioenergy prices scenarios (Dicks et al., 2009; Walsh et al., 2003). The Biofuel and Environment Policy Analysis Model (Chen et al., 2010) incorporated greenhouse gas emission and social welfare implications to simulate market equilibrium for fuel, biofuel, food/feed crops and livestock during 2007–2022.

Another school of literature focuses on optimal biofuel supply chain and logistics design. Earlier research on biofuel supply chain systems mainly relies on simulations and Geographic Information System (GIS) based models to optimize the collection, storage, and transport of agricultural biomass to a biorefinery (Sokhansanj et al., 2006). These models consider a variety of factors such as spatially-explicit resource inventory, feedstock availability, biofuel production technologies, transportation costs, local biofuel demand (Eathington and Swenson, 2007; Parker et al., 2008), and biomass prices variability (Panichelli and Gnansounou, 2008). Recent studies focus on developing mathematical programming models to optimize biorefinery locations and the shipment of biomass feedstock and ethanol products (Huang et al., 2010; Kang et al., 2010; Mapemba, 2005; Tursun et al., 2008). Bai et al. (2011b) further addressed the interdependencies among shipment routing decisions, traffic congestion, and biofuel refinery location decisions. In these supply chain planning models, biomass supply is normally assumed to be exogenous.

These studies are very relevant but the biomass production models have not captured the economic behavior of buyers and sellers in local crop markets. While farmers and biofuel companies seek to maximize their own profits, factors such as site-specific feedstock availability, price and transportation cost directly interrelate the farmers' decisions on farmland use to the industry's decision on supply chain design. McNew and Griffith (2005) developed a spatial econometric model to quantify the local impact of introducing an ethanol plant on regional corn prices. Biofuel production was found to push up crop prices, and therefore investing in refineries or contracting with biofuel companies could also be beneficial to farmers. These existing economic models, unfortunately, rely heavily on aggregated historical data, but did not explicitly capture the mechanism behind the competition between the new biofuel industry and existing food markets or the competitive behaviors of farmers, so they can hardly provide useful insights in this regard (Tyner and Taheripour, 2008). While making decisions on farm land allocation, refinery industry distribution, and ethanol production and consumption (Berkes and Seixas, 2005; Berkes et al., 2003) state-of-the-art research on biofuel supply chains generally adopts a sequential optimization