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Scenario optimization modeling approach for design and management of biomass-to-biorefinery supply chain system

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HIGHLIGHTS

- A scenario optimization model addressing weather uncertainty in BSC is proposed.
- The modeling objective is to minimize the cost of biomass supply to biorefinery.
- Field harvest work hours influence major cost-related decisions in the BSC system.
- Yield of biomass is a crucial factor in determining the feasibility of BSC system.
- Biomass storage method selected is dependent on the cost and dry matter loss during storage.

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ABSTRACT

The aim of this study was to develop a scenario optimization model to address weather uncertainty in the Biomass Supply Chain (BSC). The modeling objective was to minimize the cost of biomass supply to biorefineries over a one-year planning period using monthly time intervals under different weather scenarios. The model is capable of making strategic, tactical and operational decisions related to BSC system. The performance of the model was demonstrated through a case study developed for Abengoa biorefinery in Kansas. Sensitivity analysis was done to demonstrate the effect of input uncertainty in yield, land rent and storage dry matter loss on the model outputs. The model results show that available harvest work hours influence major cost-related decisions in the BSC.

1. Introduction

Presently, biofuels account for around 3% of the transport fuel of the world and is estimated to increase by 30% or more by 2050 (BP, 2013). It has also been estimated that 30% of the petroleum-based energy consumption in the U.S. can be replaced with biomass, which will require roughly 1 billion tons of biomass (Perlack et al., 2005). But, producing and supplying large quantities of low density biomass to the biorefineries is challenging. Feasibility of alternative energy sources such as biodiesel and hydrogen is also investigated but still remains largely in research phase. Major barriers preventing commercialization of cellulosic biorefineries is its production technology, limited biomass availability, and complex Biomass Supply Chain (BSC) system (Sharma et al., 2013). It is estimated that biomass supply accounts for 20–30% of the ethanol production cost, of which 90% is associated with logistical processes (Eksioglu et al., 2009).

Recently, there has been extensive focus by researchers on developing mathematical models for BSC design and management. Majority of the research works have developed mixed-integer linear programming models with decision making capability ranging from strategic to operational-level (Sharma et al., 2013). Commonly used quantitative performance measure for BSC models are cost minimization or profit maximization (Gunnarsson et al., 2004; Huang et al., 2010; Tembo et al., 2003; Zamboni et al., 2009). New approaches for modeling BSC are also introduced such as state-task-network (Dunnett et al., 2007), spatially explicit (Zamboni et al., 2009), multi-stage (Huang et al., 2009), multi-echelon (Dal-Mas et al., 2011; Giarola et al., 2012), time-staged multi-commodity (An et al., 2011), multi-objective/multi-period (You et al., 2011; You and Wang, 2011), two-stage linear programming (Cundiff et al., 1997), techno-economic system model (Svanberg et al., 2013) and two-stage stochastic programming (Chen and Fan, 2012) models. These approaches have increased BSC decision

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making capabilities, and also address some of the critical issues and complexity associated with the BSC system. Studies by You and Wang (2011) and You et al. (2011) provide comprehensive assessment of the BSC with a focus on economic, environmental, and social impact of biofuel production. Majority of the models developed for BSC emphasize on considering sources of variability due to process and environment into the models for better management (An et al., 2011; Huang et al., 2010; You and Wang, 2011). Some of the models developed for BSC consider uncertainty in demand and price by formulating different scenarios (Akgul et al., 2010; Dal-Mas et al., 2011; Zamboni et al., 2009). The impact of weather uncertainty on BSC is crucial as it limits the amount of biomass supplied to a biorefinery and this variability is not considered by majority of the models.

Cundiff et al. (1997) developed a two-stage linear programming model for herbaceous biomass supply from 20 different farm locations to a centrally located biorefinery. The model determines monthly material flow and storage capacity expansion for each producer for four weather scenarios. However, the model does not capture complex BSC structure, and does not estimate number of equipment units required and storage treatments used. Therefore, to explicitly account for weather uncertainty and provide enhanced decision making capabilities for BSC, a scenario optimization model was developed in this present study. The component of weather uncertainty was incorporated into the model by estimating work hours available for harvesting biomass. The model provides decision about acres leased, material flow, number of harvesting units, in-field transportation units and transportation units purchased and rented, allocation of machinery units, and storage treatments used. The model also considers the technical and operational characteristics of the machinery units, and before-frost and after-frost harvesting of biomass. The specific objectives of the study were:

- To formulate a scenario optimization model for biomass supply to a biorefinery under weather uncertainty.
- To develop a case study for switchgrass supply chain to the Abengoa Biorefinery (AB) at Hugoton, Kansas.

2. Methodology

2.1. Mathematical model

A scenario optimization model was developed to minimize cost of biomass supply to a biorefinery considering harvest, transportation, and storage costs. One year planning period with monthly time increments was considered. The model utilizes the yearly weather data to make the harvesting work-hour decision and each year was considered as a weather scenario. The daily weather data was obtained from the Oklahoma Mesonet for determining the work-hours available for harvesting (Mesonet, 2012). Each weather scenario was assigned equal probability of occurrence as the weather pattern was considered to be random and unpredictable. The soil moisture content, rain, snow, and daylight hours determine the number of harvest work-hours available in a time period. The network structure consists of biomass source sites, storage sites, and a biorefinery site. The harvest unit consists of a self-propelled windrower, a rake with a tractor and a large square baler with a tractor. The in-field transportation unit comprised of a bale

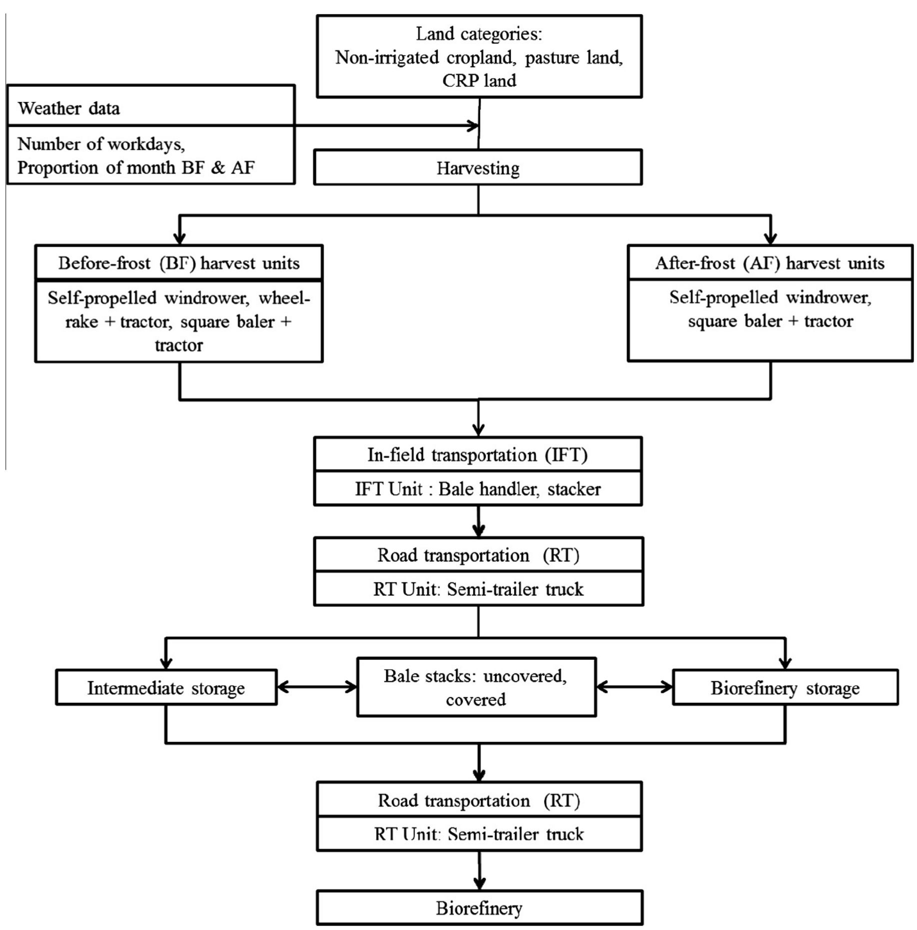

Fig. 1. Schematic of various components considered in the model.