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Effect of outdoor storage losses on feedstock inventory management and plant-gate cost for a switchgrass conversion facility in East Tennessee

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ABSTRACT

Little is known about the potential impacts of storage losses on the optimal design of a switchgrass (*Panicum virgatum*) supply chain for an ethanol conversion facility. This study analyzed how storage losses impact plant-gate cost and feedstock inventory management for a 94,635 kL year^{-1} switchgrass-based ethanol conversion facility in East Tennessee. A spatially-oriented, mixed-integer mathematical programming model was used to analyze plant-gate cost and harvest, storage, and delivery schedule for switchgrass packaged in large round or rectangular bales. Results indicate that *last in, first out* inventory management of feedstock minimized plant-gate cost. The key factor influencing inventory management was dry matter loss increasing at a decreasing rate with time in storage and distance of switchgrass production from the conversion facility. Our findings imply that the conversion facility can optimize the feedstock inventory and delivery management through coordinating the timing and location of switchgrass harvest with storage and delivery.

1. Introduction

Development of a bio-based fuel, power, and product industrial sector in the United States has been a major policy focus at the federal and state levels. The Energy Independence and Security Act of 2007 mandates a minimum of 136 million kL year^{-1} of renewable fuels for vehicles in the United States by 2022 [1]. To meet the aforementioned mandate, lignocellulosic biomass (LCB) from dedicated energy crops, agricultural residues, forest resources, and other bi-products will need to be produced on a cost competitive basis with fossil fuel sources [2]. Estimates suggest that up to 10% of agricultural land in the United States could be converted to dedicated energy crop production [2,3]. The southeastern U.S. has high potential to be the largest producer of least-cost LCB from dedicated energy crops such as perennial switchgrass (*Panicum virgatum*) of any region of the United States [4].

In 2007, the state of Tennessee invested $70 million in the Tennessee Biofuels Initiative to encourage development of a renewable fuel sector in the state [5]. Genera Energy LLC, a for-profit company formed by The University of Tennessee, and DuPont Cellulosic Ethanol joined together to start operating a 0.32 kL year^{-1} ethanol pilot refinery in Vonore, TN using corncobs, corn stover, and switchgrass as feedstocks in January 2010. The Initiative also contracted with 61 farmers to establish about 2000 ha of switchgrass on-farm fields within an 80 km radius of the pilot refinery. In addition, the Biomass Innovation Park in Vonore, TN was established to evaluate alternative harvest, storage, pre-processing, and pretreatment methods for LCB feedstock in 2011 [6]. Switchgrass from the farm fields is being used by the pilot biorefinery and the Biomass Innovation Park for research. Depending on market conditions and the success of the pilot plant in Vonore, a commercial facility may be developed and switchgrass area in East Tennessee expanded to supply the facility [6].

Perennial switchgrass was chosen by the Initiative because it is well adapted to the humid subtropical climate of Tennessee and the southeastern U.S. Switchgrass is capable of producing high LCB

Abbreviations: DM, dry matter; LCB, lignocellulosic biomass; GIS, geographical information system.

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yields on soils not suited to row crop production, and can be harvested using standard hay equipment owned by many farmers [7,8]. These characteristics are believed to give switchgrass a competitive advantage over other potential feedstocks in the region [4]. One of the factors influencing whether switchgrass production for biofuels will be sustainable is how often feedstock is harvested. A production system that harvests mature switchgrass once after senescence has the potential to maximize the yield of sugars available for conversion to a biofuel [7,9]. The single harvest system may also minimize the removal of nutrients and the need for their replacement [7,9]. However, the need for storage increases with the single harvest system [10]. By comparison, harvesting feedstock twice a year (summer and fall) would nearly double nutrient requirements, provide equivalent LCB yields, and reduce total harvest and storage costs with a coordinated harvest system [11–14]. However, the quality characteristics of switchgrass are affected by the timing and frequency of harvest and thus the harvest plan will likely be related to the end use of the feedstock and the conversion technology [15].

Costs associated with the harvest, storage, and transportation of LCB such as switchgrass to a conversion facility have been identified as a barrier to the development of a sustainable LCB supply chain in the southeastern U.S [16]. One important issue is the outdoor storage of switchgrass after harvest and before delivery to the conversion facility. Exposure of feedstock to weathering and losses of dry matter (DM) may adversely affect the quantity, quality, and cost of feedstock delivered to the conversion facility [10]. The potential tradeoffs among the costs of outdoor storage, DM losses, and the value of managing those losses through inventory management in a feedstock supply chain have only been examined on a limited basis [e.g., [17–23]]. While there is a substantial literature examining costs in a potential LCB feedstock supply chain, the potential interactions among harvest, storage, and transportation activities and their effects on feedstock inventory management to limit DM losses and minimize plant-gate costs have not been evaluated in the LCB feedstock supply chain literature (Table 1).

If the production of switchgrass for ethanol production is increased to meet the needs of commercially scaled ethanol production in East Tennessee, information will be needed about the least-cost methods of delivering switchgrass to a conversion facility considering the aforementioned supply chain management issues. Thus, our research objectives are: 1) to assess the impact of storage DM losses for alternative harvest methods on plant-gate feedstock costs for an ethanol conversion facility that uses switchgrass harvested once a year after senescence and 2) to evaluate the potential effects of storage losses on harvest and feedstock inventory management for a once a year harvest system.

2. Review of literature

Several important factors influence the economics of harvesting mature switchgrass. First, weather may limit field days to harvest feedstock and may be an especially important factor influencing plant-gate costs for switchgrass harvested in fall and winter [24]. Sunlight and temperature for field drying of feedstock is limited during this period giving fewer hours over which to harvest and spread fixed equipment costs [10]. Given the large amounts of LCB required for a conversion facility, most storage is projected to occur outdoors either on-farm or at a satellite location [25]. Harvested switchgrass stored outdoors is subject to rain, ultraviolet rays, and fluctuations in temperature and humidity that cause DM losses and is influenced by the methods used to harvest and store the feedstock and time in storage [26]. Switchgrass is currently harvested using standard hay equipment, and

Table 1
Selected lignocellulosic feedstock supply chain optimizations studies that explicitly considered feedstock harvest, storage, and transportation logistics.

Factor	Cundiff et al., 1997 [17]	Tembo et al., 2003 [18]	Mapmepa et al., 2008 [19]	An et al., 2011 [20]	Ebadian et al., 2011 [21]; Ebadian et al., 2013 [22]
Feedstock	Switchgrass	Native grasses, improved grasses, switchgrass, corn stover, wheat straw	Native grasses, improved grasses, switchgrass, corn stover, wheat straw	Switchgrass, wood residues	Wheat straw
Study Site	Virginia, USA	Oklahoma, USA	Oklahoma, USA	Texas, USA	Saskatchewan, CA
Spatial resolution	Not specified	County level	County level	County level, yields & costs not different across counties	Regional
Facility siting	Not considered	County level	Assumed Canadian County	County level	Assumed Prince Albert
Harvest					
Period	One & two cut yr^{-1}; based on available field harvest days	Crop dependent	Crop dependent; based on available harvest days	Switchgrass, summer & fall; wood waste, continuous	Summer & fall—Aug—Oct
Method	Large round bales	Not specified	Large rectangular bales	Not specified	Large rectangular bales
Storage					
Method	Indoor, outdoor uncovered	At conversion facility, method not specified	Outdoor at field edge, covered	Indoor, anaerobic: outdoor, uncovered	Indoor, outdoor uncovered at field edge and satellite location
Losses	Monthly; differentiate between indoor, outdoor uncovered;	Assumed % loss mo^{-1}; harvest & inventory management not evaluated	Assumed % loss mo^{-1}; harvest & inventory management not evaluated; effect on feedstock draw area	Assumed % loss mo^{-1}; harvest & inventory management not evaluated; effect on feedstock draw area	Assumed % loss yr^{-1}; harvest & inventory management evaluated; effect on feedstock draw area
Transportation	Based on assumed truck cycle time in hr	Straight-line, county centroid	Straight-line, county centroid	Straight-line, county centroid	Straight-line
Feedstock flows	Harvest into storage; amount required; storage drawdown	Considered in model structure but not evaluated	Monthly harvest into storage	County of production to county of conversion	Harvest into storage; amount required; evaluated storage drawdown, carryover
Feedstock costs	Not include land opportunity costs	Include land opportunity costs	Include land opportunity costs; harvest compliment/costs based on available harvest days	Not include land opportunity costs	Not include land opportunity costs