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Effects of corn stover year-to-year supply variability and market structure on biomass utilization and cost

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ABSTRACT

The availability of corn stover can vary considerably from year to year in a region due to annual changes in yield and area planted with corn. Such variations interacting with biomass market structures can affect biomass cost and utilization rate. This study first characterizes year-to-year variations in corn stover supply for the US in general and for selected major US corn producing counties in particular. There have been 20–30% year-to-year variations in stover supply in the US since 1975. Game theoretic analysis is then applied to examining corn stover utilization rate and production cost in three market structures. The analysis reveals that a free market structure will take the form of oligopoly–oligopsony, where large stover supply variations will expose both biorefineries and farmers to significant price volatility. Price equilibrium will shift significantly from year to year. Of the three market structures analysed, the *"Derisked"* supply market structure will be most favorable to biorefineries and farmers. Under this structure, biorefineries will maintain a stover supply region that is based on *"Derisked"* (lower than average) yield density to buffer for the supply uncertainty associated with annual variations. This market structure results in significantly less volatility in biomass cost while on average only 63% of collectable stover will be used for biofuel production. Our findings suggest that year-to-year variation in corn stover availability will increase feedstock cost and reduce its potential for biofuel production.

Contents

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1. Introduction

Bioenergy has attracted increasing investments and support recently, as a result of growing emphasis on energy security [1] and reductions in greenhouse gas emissions [2]. More than 110 billion liters of biofuels was produced globally in 2012, of which around 50% was corn ethanol produced in the US [3]. Corn ethanol is referred to as a first-generation biofuel produced with mature technology [4]. Recently greater emphasis has been placed on advancement of second-generation biofuels produced from cellulosic feedstocks such as agricultural and forestry residues and perennial grasses [5]. Several commercial-scale cellulosic biofuel plants have been commissioned, and a few more are under development and expected to be operational soon [6]. Current US EPA (Environmental Protection Agency) target to produce 76 billion liters per year of second-generation biofuels by 2022 will require approximately 200 million metric tonne (dry basis) of biomass [7,8].

Corn and soybean are major crops in the US [9], and the largest sources of agricultural residues. Soybean residues are fragile, and the majority of them are required to be left on field to prevent soil erosion [10,11]. Therefore, corn stover is by far the largest source of agricultural residues available for use in cellulosic biofuel production in the US [11]. Feedstocks for corn ethanol and for cellulosic biofuels are fundamentally different. Two thirds of production cost of corn ethanol is the market value of corn grain [12], which is an internationally traded commodity and can be stored and transported over a long-distance economically [13]. On the other hand, long-distance transport of corn stover is not economically feasible, and storage is another issue, which can cause biomass loss, reduce feedstock quality, and increase biofuel production cost [14–21]. As a result, cellulosic biorefineries will have to source stover locally and endure regional supply constraints [11,12,14,15,16,22,23].

Several studies have examined supply and price variability of corn and the resultant implications for corn ethanol markets [24–29]. However, there is a literature gap on understanding year-to-year supply variability of corn stover, stover supply market structures, and their impacts on the decision making of cellulosic biofuel production. This study aims to narrow this gap and enable the advancement of supply chain strategies to address the uncertainties associated with biomass supply. The specific objectives of this paper are to characterize annual variations in corn stover supply and to device and evaluate stover supply market structures in response to its yearly supply variations. We will evaluate three stover market structures, including the oligopolistic–oligopsonistic market, contractual payment based on average stover yield, and contractual payment based on "*Derisked*" stover yield, and their associated equilibria.

Our work advances existing knowledge in several fronts. First, we quantify the yearly variations of corn stover availability using historical time series data and the autoregressive integrated moving average (ARIMA) approach [30]. Such an in-depth analysis of stover availability is lacking in the existing literature although temporal variations in stover supply have been recognized. ARIMA enables us to portray both the nonlinear trend line and the variability of stover availability. Besides offering insights into the variability of stover availability, this analysis lays a foundation to achieve our second objective.

Second, we explore the options through market arrangements to mitigate the adversary effect of temporal stover supply variations on biofuel production cost. Biomass pre-treatments (e.g., pelletizing) and storage (e.g., biomass depot) have been proposed to alleviate biomass transport costs and to meet biomass requirements for scaling up of biofuel production [31,32]. Meanwhile, storage itself can accommodate for some variations in stover supply. Pelletizing can reduce feedstock transport and storage cost, which will help increase feedstock supply stability. Stover pre-treatments and storage are engineering approaches to mitigate feedstock supply instability and will entail additional production costs. Here we examine market arrangement options for mitigating stover supply variations, which do not require additional infrastructure development and can be used together with the engineering options. Using game theoretic analysis, we are able to compare different market structures and associated strategies.

Third, our results have important implications for determining the supply of biomass under temporal yield variations and its potential for biofuel production. Starting with simply estimating the amount of biomass physically available on the ground and production costs using a deterministic approach [14,33–39], researchers have made a great deal of progress in assessing biomass supply and production cost, including (a) biomass cost estimation using an integrated biomass transportation modeling approach [8,40–49], (b) consideration of sustainability constraints, storability, and farmer supply response [18,32,50–56], and (c) optimization of the entire biofuel supply chain coupled with (a) and (b) [32,57–59]. This study adds a new dimension (uncertainty or variability, and impact of market structure) to analysing biomass supply and biofuel potential.

Overall, this study advances the understanding of stover supply variations and the *Equilibrium Pricing* of stover under different market structures. The approaches developed here, though applied to corn stover only, are generic and applicable to other feedstock types. The results from this study can aid in designing biofuel supply chains, devising biorefinery operation plans, and developing national strategies and policy to facilitate the development of a biofuel industry.

2. Methods and material

2.1. Characterizing year-to-year variations in stover availability

The total amount of stover produced by region in the US is estimated using the stover-to-grain ratio ω. Previous studies have found that stover yield is proportional to corn grain yield, and that the stover-to-grain ratio ω is around 1.0 [7,8,14,17,36,60]. Historical production data of corn grain by region is obtained from the US Department of Agriculture (USDA) [61]. Because corn grain production reported by the USDA is in units of bushels and acres, for conversion to dry metric tonne (t) of stover per hectare, it is assumed that a bushel of corn had dry grain mass of 21.5 kg (56 lb at a 15.5% moisture content) [36]. Using methods from a previous study [36], stover production is calculated as:

$$\begin{aligned}\text{Stover}\ (\text{dry t ha}^{-1}\ \text{yr}^{-1}) = &\ \text{yield}\ (\text{bushels corn acre}^{-1}\ \text{yr}^{-1})\\ &\times 21.5\left(\text{kg corn bushel}^{-1}\right)\\ &\times 1.0(\text{kg stover kg}^{-1}\ \text{corn})\\ &\times 0.001\ \text{t kg}^{-1} \times 2.47\ \text{acres ha}^{-1} \qquad (1)\end{aligned}$$

Besides equipment limitations in collecting more than 75% of stover physically available at the corn harvest site [36], a minimum amount of stover, η (t ha^{-1}) is required to be left on the field for soil and water conservation purposes. η varies by region and depends on several factors: soil moisture requirement [36]; stover needed to prevent soil erosion [36]; stover required for maintaining soil organic matter (SOM), carbon sequestration, and nutrient cycling [8,36,62]. SOM is essential for retaining and recycling nutrients, improving soil structure, and sustaining crop yields [63].