INTRODUCTION

An extensive literature shows that inclusion of dedicated energy crops (hereafter, energy crops), such as switchgrass, in the mix of feedstocks to produce biofuels can greatly reduce the environmental footprint of these biofuels and, if energy crops are grown on marginal land (land not used for row crops in many years), ease the tradeoff between food and biofuel (e.g., Robertson et al., 2017; Schmer et al., 2008; Searchinger et al., 2008; Wang et al., 2015). A complementary strand of literature, however, shows that energy crops are costlier to produce than crop residues, casting doubt on the economic viability and carbon footprint of switchgrass for cellulosic biofuels: Insights from a spatial multi-feedstock procurement landscape analysis

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Abstract

We study a situation in which a multi-feedstock cellulosic biofuel plant can procure stover from productive cropland and switchgrass from marginal land, where growing corn for stover is typically not profitable. We calibrate our model to growing conditions in a promising area of Indiana, USA. We find that cost-minimizing biorefineries are likely to include switchgrass in the mix of feedstocks despite their high cost of production relative to corn stover. This is because the biorefinery can reduce cost by buying switchgrass grown on marginal land near the plant instead of paying to cover high transportation costs to procure stover from more distant suppliers. Moreover, the share of switchgrass will rise further if the procurement region is constrained by transaction costs or natural barriers. This is because procuring switchgrass can alleviate the cost of paying to induce land conversion to corn to procure additional stover from the intensive margin. Under the assumption that switchgrass is grown on marginal land, inclusion of switchgrass in the feedstock mix not only reduces the cost of producing biofuels but also their carbon footprint without displacing food crops. A key caveat is that high transaction costs of contracting for switchgrass and/or farmers’ reluctance to grow switchgrass on marginal land can severely undermine its inclusion in the feedstock mix. However, these forces may be countervailed by a differential subsidy for biofuels that include a higher share of switchgrass, which would be warranted because of their lower carbon footprint.

KEYWORDS

cellulosic biofuels, corn stover, marginal land, spatial landscape, switchgrass, transportation cost
likelihood that energy crops would be included in the feedstock mix (Brechbill et al., 2011; Duffy, 2007; Khanna et al., 2008; National Academy of Sciences, 2009; Perrin et al., 2008, 2017; Turhollow & Epplin, 2012).

Previous studies that quantify the cost of procuring feedstocks for biorefineries are based on the premise that the plant will exclusively rely on a single feedstock (e.g., Yang et al., 2015; Yoder et al., 2015). In this setting, corn stover dominates energy crops because it has a lower on-farm production cost. But in light of spatial limitations on corn planting density as well as economic and environmental constraints on stover removal, filling production capacity exclusively with corn stover may force the biorefinery to procure biomass from distant suppliers. This circumstance induces the plant to offer a higher price to cover large transportation costs (Sesmero & Gramig, 2013). Therefore, biorefineries could reduce procurement cost by including energy crops in the mix if they do not compete for land with corn, as it is likely the case when they are grown on marginal land. In this paper, we study the extent to which relying exclusively on crop residues may be too costly for biofuel plants due to large procurement distances and transportation cost, favoring inclusion of energy crops in the feedstock mix.

We develop an empirical framework capturing three key features of prospective biorefineries’ procurement markets: (1) high cost of transporting feedstocks (e.g., Brechbill et al., 2011); (2) the ability of modern technologies to combine multiple feedstocks to produce biofuels (e.g., Song et al., 2017); and (3) the availability of marginal land, where productivity of food crops is very low (e.g., Brechbill et al., 2011). As a result, our framework characterizes a spatial multi-feedstock procurement landscape. Developing such a framework is challenging for two reasons. First, we must extend the canonical Hotelling’s linear market model to accommodate multiple feedstocks (Hotelling, 1929). Second, given the lack of observational data, we combine historical data on land use from the National Agricultural Statistics Service, crop simulation models, and farm-level data to calibrate the model to growing conditions in two counties in Indiana. This area has high corn planting density and was also identified as promising in Sharma et al. (2020).

Our analysis reveals that, despite the high density of corn in our study area, transportation cost induces cost-minimizing biorefineries to include switchgrass (the energy crop we focus on) in the mix of feedstocks to fill capacity. This stands in sharp contrast with predictions from studies that either assume both feedstocks compete for land or ignore spatial aspects of procurement. The main reason for this is that the biorefinery can cut cost by buying switchgrass grown on marginal land near the plant instead of paying to cover high transportation costs to procure stover from more distant suppliers. We also find that spatial constraints to the procurement region resulting from transaction costs of negotiating with new and distant suppliers, natural barriers such as rivers or cities, or stover density that decreases with distance from the plant, which is likely because biorefineries will tend to locate where stover is abundant—increase the cost of stover relative to switchgrass, and can thereby push the biorefinery to raise the share of switchgrass in the mix even further. Moreover, we find that partially substituting stover for switchgrass reduces both feedstock cost and greenhouse gas (GHG) emissions per liter of biofuel produced relative to a counterfactual where these crops are excluded.

Our paper contributes to the literature that examines the economic viability of switchgrass, conditional on production of cellulosic biofuels (e.g., National Academy of Sciences, 2009; Perrin et al., 2017). It does not look at the economic viability of cellulosic biofuels per se, but rather builds on the observation that mandates for production of cellulosic biofuels are still in place, albeit not strictly enforced. Moreover, our analysis applies to other biomass-based outputs such as renewable natural gas which shows some promise of deployment in the future (Voegele, 2018). This study is also related to the literature looking at the environmental benefits of including energy crops in the mix to produce biofuels (e.g., Debnath et al., 2019; Robertson et al., 2017). We explicitly compute how a cost-minimizing feedstock mix fares relative to a stover-only counterfactual in terms of GHG emissions.

Our paper is related to Song et al. (2017) in that we consider a biorefinery that can process multiple feedstocks. Yet, our analysis differs from theirs in two crucial ways. First, we do not assume the biorefinery can perfectly price discriminate in a spatial landscape. Price discrimination is typically implemented through freight cost absorption (Sesmero, 2018) or reverse auctions (where potential sellers bid for selling prices and quantities); but these mechanisms are notorious for being hard to implement and prone to participation problems. Second, we do not assume that alternative feedstocks compete for land. We use historical planting data from USDA’s Cropland Data Layer in White and Jasper counties and previously reported estimates to carefully document two stylized facts of agricultural land: (1) row crops are seldom grown on marginal land (as we define it in this study), and (2) implausibly high prices (much higher than the ones we estimate in this study) are necessary to induce farmers to plant switchgrass on highly productive cropland (non-marginal land).

Our paper is perhaps most closely related to Brechbill et al. (2011) in that they also consider a biorefinery that can process multiple feedstocks and do not assume perfect price discrimination and land competition. In contrast to their approach, however, our study accounts for the fact that once the plant starts to use both biomass sources—stover and switchgrass—it will follow an input pricing strategy governed by the equi-marginal principle. Simply put, the equi-marginal principle states that if two inputs are perfectly substitutable in production and if one is more costly
than the other (adjusted for productivity), the buyer will reduce the price and procurement of the more costly input and raise the price and procurement of the other one until both are procured at the same marginal cost. This is unless the maximum available quantity of one input is reached, in which case the equi-marginal principle breaks down and the firm uses a hierarchical pricing strategy. Our results indicate that these economic considerations have important implications for the optimal feedstock mix, feedstock cost, and GHG emissions, underscoring the importance of our analysis.

2 | MATERIALS AND METHODS

We model a geographically localized market in which a biorefinery buys biomass from farmers. Our model is built on three key premises. First, inputs are costly to transport. Multiple studies have found that transportation cost can amount to 40% of the cost of procuring biomass, depending on the distance traveled (Thompson & Tyner, 2014). Second, the biorefinery can process multiple feedstocks. The ability of biorefineries to process different feedstocks has long been recognized in academic studies and, more importantly, it is routinely and explicitly stated by existing cellulosic biofuel producers. For instance, DuPont built the first cellulosic ethanol plant in the world in Nevada, IA (DuPont, 2017, “The DuPont”) and stated that their technology can work with a variety of feedstocks, from agricultural residues to energy crops. Since then, Verbio North America Corp. (VNA) purchased the plant and converted it to Renewable Natural Gas (RNG). VNA’s president, Greg Northup, released a statement on 11/20/2018 asserting the company “…will now finalize its plans to install facilities to produce RNG made from corn stover and other cellulosic crop residues at the site”, confirming the multi-feedstock nature of the facility (see http://biomassmagazine.com/articles/15770/verbio-completes-sale-of-du Pont-plant-wins-ieda-support, accessed 11/15/2020).

The third key premise of our model is that row crops are grown on productive cropland, switchgrass is grown on marginal land, and they do not compete with each other for land. Two stylized facts of agricultural land support our claim that the set of corn hectares is mutually exclusive from the set of switchgrass hectares. First, the share of what we consider marginal land in this study that was planted to row crops over the 2010–2017 period has been minimal, even during the commodity price boom. According to data from the USDA’s Cropland Data Layer in White and Jasper counties, the largest annual net changes in row crop hectares converted from fallow, grass, or pasture ranged from a reduction of 2000 ha to an increase in 1400 ha, representing land use changes of 0.001% or less based on 202000 total row crop hectares in Jasper and White counties over the years.

The second stylized fact reveals that switchgrass is very unlikely to be planted on productive cropland. Most studies looking at the economic viability of switchgrass have found that implausibly high prices (much higher than the ones we estimate in this study) are necessary for switchgrass to displace corn/soybeans systems in land regularly planted to these crops (e.g., Dumortier et al., 2017; Efroymson & Langholtz, 2017; Jain et al., 2010). These findings are only reinforced by studies including dynamic considerations in farmers’ decision to switch from row crops to switchgrass (Song et al., 2011), as well as studies considering transaction costs associated with contracting for energy crops (Alexander et al., 2012; McCarty & Sesmero, 2021). However, we must keep in mind that new precision technologies may be able to exploit sub-fields with lower crop productivity and plant switchgrass on those sub-fields (Brandes et al., 2017, 2018).

With the corresponding caveats, we now develop a framework that considers transportation cost in a spatial landscape, a multi-feedstock plant, and mutually exclusive land areas for corn and switchgrass.

2.1 | The demand side: Cost-minimizing plants

On the demand side of this market, we consider constrained and unconstrained procurement markets. In an unconstrained market, biorefineries can travel as far as they want to procure biomass, that is, they can continue to extract biomass from the extensive margin (include additional land in the procurement region). In a constrained market, plants cannot procure additional biomass from the extensive margin and, to fill capacity, are forced to offer higher prices to procure it from the intensive margin (i.e., higher prices to induce farmers to plant more corn and harvest stover).

We are primarily concerned with the case where the procurement region is not constrained, but also consider restrictions to the procurement region for three main reasons. First, biorefinery managers have stated that they plan to procure within a pre-defined distance from the plant (e.g., Thorp & Akhtar, 2015). This seemingly arbitrary decision is associated with strong non-convexities in transaction costs of contracting with new suppliers; that is, at some point it is cheaper to get substantial amounts of biomass from existing suppliers, rather than negotiating and contracting with a whole new group of suppliers located farther away from the plant. Second, because stover is likely to be the primary source of biomass (due to its low production cost and high abundance), plants will tend to locate in areas with high corn density. This means that density of corn is likely to decrease, sometimes drastically so, as one moves away from the plant potentially setting an upper bound to the maximum distance the plant can get stover from. Third, the procurement region
can be constrained by geographical barriers such as rivers, cities, or hills.

What complicates matters in our context is that there are no a priori reasons why spatial constraints on procurement markets have to be the same across feedstocks. While inputs are perfect substitutes in the production of biofuels, they come from different supply sources, which could result in disparate procurement patterns. Consider the following situation. Because of its lower on-farm cost and high density, plants will purchase corn stover first. At conventionally assumed plants’ sizes, filling capacity requires procuring stover from very distant farmers (e.g., owners of the VERBIO Iowa plant stated that the plant will procure 90,000 tons of corn stover yearly—a third of our assumed capacity in this study)—within a 80–120-km procurement distance https://www.verbio.us/project/verbio-nevada-biorefinery/), perhaps reaching geographical or cost barriers constraining the procurement region. In this case, instead of procuring more stover from the intensive margin, the biorefinery may prefer to procure switchgrass from nearby marginal land. Therefore, the market for stover may be constrained and the market for switchgrass may not.

With these considerations in mind there could conceivably be constellations of parameters (the size of the biorefinery, biomass supply responses, on-farm and transportation costs) that would result in procurement patterns involving just one feedstock or both, in spatially constrained or unconstrained procurement regions (a total of eight possible pairwise combinations). The specific procurement pattern will be determined endogenously in the model, and it will be a function of the model parameters. Prices and quantities of both feedstocks are also endogenously determined in the model.

We do not consider all eight possible procurement patterns. Because switchgrass has a much higher on-farm cost and marginal land is limited, procurement patterns that consist of procuring switchgrass only (in either a constrained or unconstrained setting) do not emerge in equilibrium under any parametric configuration. This is because of relatively high corn (and, hence, stover) yield relative to switchgrass in the US Corn Belt. Moreover, and perhaps more importantly, marginal land is limited precluding the plant from filling capacity on switchgrass only. One possibility would be for switchgrass to replace corn in highly productive land. However, as noted earlier, this is also highly unlikely. Based on our other parameters, we find that switchgrass yield would have to be three times higher than our estimate for switchgrass to replace corn in highly productive land, which is in line with findings by Mitchel et al. (2016) and Brandes et al. (2018). Similarly, procurement patterns that consist of procuring switchgrass in a constrained market and stover in an unconstrained market do not emerge in equilibrium. Therefore, we do not discuss these cases further.

Henceforth, we consider the five procurement patterns reported in Table 1. A situation in which the plant only purchases stover and it does so in a spatially unconstrained market. Second, a situation in which the plant only purchases stover, but it does so in a spatially constrained market. The third situation is one in which the biorefinery purchases both stover and switchgrass in spatially unconstrained markets. The fourth procurement pattern is one in which the biorefinery procures stover from a spatially constrained market and switchgrass from an unconstrained one. Finally, we also consider a situation in which the biorefinery procures both stover and switchgrass in spatially constrained markets. A graphical illustration and discussion of each procurement pattern is included in Supplementary Material A.

Studies of spatial feedstock procurement typically use a bidimensional draw area around the biorefinery (e.g., Perrin et al., 2012; Wang et al., 2020). In this study, we collapse a two-dimensional procurement region into a one-dimensional region like in the canonical Hotelling’s linear spatial market model. This results in much more parsimonious feedstock supply curves that are quadratic on price for stover and linear on price for switchgrass. This, in turn, allows us to obtain analytical solutions for pricing strategies and unambiguous comparative statics with respect to exogenous parameters as shown in our results below.

We develop a variation of the canonical Hotelling’s linear spatial market model to accommodate the existence of two feedstocks with possibly different procurement patterns (Hotelling, 1929). The canonical Hotelling model consists of buyers (sellers, in our case) uniformly distributed along a line at varying distances from a seller (buyer, in our case). This allows for a spatially explicit characterization of the price received and quantity sold by suppliers located at different distances from the plant, and the price paid by the buyer. Differences between the price paid by the buyer and received by suppliers, as well as differences in prices received by different suppliers, are explained by transportation costs and who absorbs them.

While there may be additional investments in equipments required to utilize multiple feedstocks (processing feedstocks with different lignin contents is still challenging, despite significant technological advances as discussed in Guragain

| Scenario No. | Feedstock procured | Spatial constraint |
|--------------|--------------------|--------------------|
| 1            | Corn stover only   | Unconstrained      |
| 2            | Corn stover only   | Constrained        |
| 3            | Corn stover        | Unconstrained      |
|              | Switchgrass        | Unconstrained      |
| 4            | Corn stover        | Constrained        |
|              | Switchgrass        | Unconstrained      |
| 5            | Corn stover        | Constrained        |
|              | Switchgrass        | Constrained        |
et al., 2015), we do not consider them here. This is because we are not examining the economic attractiveness of a multi-feedstock plant relative to a single-feedstock one. Instead we focus on whether multiple feedstocks would be used conditionally on the ability to use them, an assumption that is aligned with available technologies (Oke et al., 2016). But just as we do not consider every cost associated with a multi-feedstock technology, we are also not considering every benefit. For instance, using a mix of feedstocks may allow the plant to procure a steady flow of biomass and operate at capacity year-round. If using a single feedstock forces the plant to operate below capacity, inefficiencies could increase operating costs. However, previous studies have explored the possibility that a stover-only biorefinery could rely on a spot-market for corn stover, should one exist in equilibrium (Rosburg et al., 2017).

The biorefinery is located at the endpoint of a line segment of length $D$ (this captures any symmetric locational configuration with a plant located exactly in the middle) and engages in Free-On-Board (FOB) pricing. This means that the biorefinery offers a price at the plant gate, and farmers are responsible for the cost of transporting the biomass from the farm to the plant gate (Zhang & Sexton, 2001). Biomass suppliers (farmers) are uniformly distributed along the line segment. This is a reasonable assumption in our study area given the high and spatially uniform prevalence of agricultural and marginal land. The biorefinery is a cost-minimizing firm; thus, its objective is to fill capacity at minimum cost. This assumption is prompted by large capital costs and constant (or decreasing) marginal processing cost that characterize cellulosic biofuel production (Jung et al., 2020; Sesmero et al., 2016).

The formal characterization of the biorefinery’s cost-minimization problem is as follows. The biorefinery can (though will not necessarily) purchase corn stover and switchgrass. It offers a price at the plant gate for each feedstock, which we represent by $p_{kj}$; where superscript $i$ denotes the feedstock ($i = cs$ for corn stover and $i = sw$ for switchgrass), subscript $k$ denotes a constrained market for stover ($k = c$ if the market is constrained; $k = u$ if it is unconstrained), and subscript $j$ denotes a constrained market for switchgrass ($j = c$ if the market is constrained; $j = u$ if it is unconstrained). Prices must be such that the quantities procured of corn stover in dry megagrams ($Q_{kj}^{cs}$) and switchgrass in stover-equivalent dry megagrams ($Q_{kj}^{sw}$) must be equal to the total processing capacity of the plant, $Q$. Therefore, the biorefinery chooses prices in order to fill capacity at minimum total factor (input) cost TFC:

$$\min_{\{p_{kj}, p_{kj}^{sw}\}} TFC = p_{kj}^{cs} Q_{kj}^{cs} (p_{kj}^{cs}) + p_{kj}^{sw} Q_{kj}^{sw} (p_{kj}^{sw})$$

subject to: $Q = Q_{kj}^{cs} + Q_{kj}^{sw}$

Two important elements of this cost-minimization problem are the biomass supplies $Q_{kj}^{cs}$ ($p_{kj}^{cs}$) and $Q_{kj}^{sw}$ ($p_{kj}^{sw}$), which indicate quantities of biomass the biorefinery can purchase at each price. A key characteristic of these functions is that their cross-price elasticities are zero; that is, $Q_{kj}^{cs}$ is not a function of $p_{kj}^{sw}$, and $Q_{kj}^{sw}$ is not a function of $p_{kj}^{cs}$. This is because while feedstocks are perfect substitutes in cellulosic biofuel production, they have totally independent supplies because they do not compete for land. Therefore, corn growers decide how much stover to collect and deliver to the plant based on the stover price offered by the biorefinery, but without considering the price paid to switchgrass growers. Equivalently whether switchgrass is grown on a parcel of marginal land and subsequently delivered to the plant is a decision made entirely based on the price offered by the biorefinery for switchgrass and independent of the price offered for stover. We now turn our attention to biomass supply schedules.

### 2.2 The supply side: Modeling corn stover and switchgrass supplies

On the supply side, we will consider two biomass sources: corn stover and switchgrass. Much of the literature assumes that switchgrass and corn stover would compete for land. Instead, we assume the two feedstocks will not compete for land. The model can be readily extended to consider more sources of biomass as long as they do not compete with row crops for land, but in this study we focus on these two as they have been consistently identified as the most cost competitive (see National Academy of Sciences, 2009 as well as other studies cited therein).

In our framework, stover comes from traditional corn–soybean land. Land suitable for soybean is also suitable for corn and conversion from corn-soybean rotation to continuous corn increases the amount of harvestable stover. Hence, an increase in the price offered by the biorefinery for stover triggers an increase in stover supply from the intensive margin; that is, farmers located in the procurement region prior to the increase in stover price convert land to corn and sell the stover. It also triggers a supply response at the extensive margin; that is, distant farms that were not located within the procurement region prior to the increase in stover price are now included in that region as the increased price covers transportation cost to the facility (in addition to production cost).

The stover supply equation comes from Sesmero, Balagtas, et al. (2015). The stover supply at distance $r$ from the plant is a function of the linear participation rate $B\theta \left(\left(p_{kj}^{cs} - c^{cs}\right) - tr\right)$, where $B$ is the maximum corn stover potential at each spatial unit, $\theta$ is the participation rate, $p_{kj}^{cs}$ is the stover price offered by the firm at the plant gate, $c^{cs}$ is the on-farm cost of stover, and $t$ is the transportation cost. Assuming suppliers are uniformly distributed over space, the aggregate supply function
is the quantity (in dry megagrams) of stover when i is the maximum distance within which the bio-
refinery procures stover under procurement pattern k in the stover market (note there is no subscript for the switchgrass procurement pattern as it is consequential for this distance). The maximum procurement distance will differ according to whether the market is unconstrained (the bio-refinery serves only a part of the procurement region) or constrained (the bio-refinery procures from the entire procurement region). Equations (2) and (3) show the maximum procurement distances under these scenarios respectively:

\[ R_{cs}^{u} = r_{c} \int_{0}^{R_{u}} \left( \left( p_{cs}^{u} - c^{u} \right) - v \right) \, dv = \bar{B} \theta \left( \left( p_{cs}^{u} - c^{u} \right) R_{u}^{2} - \frac{R_{c}^{2}}{2} \right) \]  

(2)

where \( Q_{cs}^{u} \) is the quantity (in dry megagrams) of stover when the procurement region is unconstrained (i = u) or constrained (i = c), \( R_{cs}^{u} \) is the maximum distance within which the bio-refinery procures corn stover under procurement pattern k in the stover market (note there is no subscript for the switchgrass procurement pattern as it is consequential for this distance). The maximum procurement distance will differ according to whether the market is unconstrained (the bio-refinery serves only a part of the procurement region) or constrained (the bio-refinery procures from the entire procurement region). Equations (2) and (3) show the maximum procurement distances under these scenarios respectively:

\[ R_{cs}^{u} = r_{c} \int_{0}^{R_{u}} \left( \left( p_{cs}^{u} - c^{u} \right) - R_{cs}^{u}t \right) \, dv = 0 \rightarrow R_{cs}^{u} = \frac{p_{cs}^{u} - c^{u}}{t} \]  

(3)

When the market is unconstrained the boundary of the procurement region is determined by the distance at which the supplier is indifferent between selling to the plant or not, that is, where the price exactly covers on-farm and transportation cost. Moreover, the maximum procurement distance is increasing in price as more distant producers are brought into the plant’s procurement region as plant-gate price increases. Because the boundary of the procurement region decreases with transportation cost, all else constant, more distant producers are excluded from the procurement region. When the procurement region is constrained, the maximum distance is simply the distance between the bio-refinery and the boundary of the procurement region. Plugging Equations (3) and (4) back into the aggregate supply function (2) yields the aggregate stover supply function faced by the bio-refinery in constrained and unconstrained markets respectively:

\[ Q_{cs}^{u} = \bar{B} \theta \left( \left( p_{cs}^{u} - c^{u} \right) \right) \frac{2}{2t} \]  

(5)

\[ Q_{cs}^{c} = \bar{B} \theta \left( \left( p_{cs}^{c} - c^{c} \right) \right) D - \frac{D^{2}t}{2} \]  

(6)

On the other hand, in our framework, switchgrass will come from marginal land—land suitable for switchgrass but not corn/soybeans. What drives a supply response at the intensive margin for stover is heterogeneity in corn or soybean yields (or both), and costs across the landscape. We exploit these to estimate the supply response at the intensive margin. In contrast, information on the heterogeneity of switchgrass yield and cost across the landscape is not readily available and an intensive margin response cannot be estimated from observational data. This forces us to assume a corner solution in each land unit, whereby operators of marginal land decide to either plant switchgrass or not, but do not plant switchgrass on just a fraction of their land. As a result, additional switchgrass can only be procured from the extensive margin, and if the procurement region is not constrained.

We normalize the supply of switchgrass to express it in stover-equivalent megagrams (Mg). Switchgrass has more energy content than corn stover, which makes an Mg of switchgrass produce more biofuel than one Mg of stover. The normalizing coefficient is equal to the biofuel yield (L/Mg) of switchgrass divided by the biofuel yield (L/Mg) of stover. This coefficient, \( a_{eq} \), is displayed in the following aggregate switchgrass supply equation:

\[ Q_{j}^{sw} = \int_{0}^{R_{j}} a_{eq} q_{j}^{sw} \, dr = a_{eq} \left( q_{j}^{sw} R_{k}^{sw} \right) \]  

(7)

Equation (7) is the generalized aggregate switchgrass supply equation where, \( q_{j}^{sw} = \frac{\text{yield} \times \text{planting density} \times \text{area}}{D} \). The maximum procurement distances are identical to those for corn stover supply, except the price variable is for switchgrass instead of stover. The switchgrass supply equations for unconstrained and constrained markets are, respectively:

\[ Q_{u}^{sw} = a_{eq} \left( q_{u}^{sw} \left( p_{k,u}^{sw} - c_{u}^{sw} \right) \right) \]  

(8)

\[ Q_{c}^{sw} = a_{eq} q_{c}^{sw} D \]  

(9)

### 2.3 Market equilibrium

The equilibrium procurement pattern of the bio-refinery is determined endogenously by the confluence of two forces: feasibility and optimality. First, a procurement pattern is feasible if, under the optimal prices conditional on such procurement pattern, the bio-refinery can fill capacity. Second, among the feasible set of procurement patterns, the optimal one is that under which the plant fills capacity at minimum cost.

We derive feasibility and optimality conditions hierarchically. We start by characterizing feasibility conditions for each procurement pattern. The size of the procurement region (as measured by distance from the bio-refinery to the edge of the procurement region) \( D \), the plant’s capacity \( Q \), and the
planting density will determine what procurement patterns can provide sufficient biomass to fill capacity. For instance, some procurement regions may be small enough to rule out unconstrained markets. Formal conditions for feasibility of each possible procurement pattern are formally derived and characterized in Supplementary Material (B.1–B.5). When the size of the procurement region is consistent with several procurement patterns (e.g., stover only in a constrained market and stover in a constrained market plus switchgrass in an unconstrained one), the optimal one is that under which the plant fills capacity at minimum feedstock cost. The procedure to identify the cost-minimizing procurement pattern is described in Supplementary Material B.6. Finally, once the optimal procurement pattern is identified we use our expressions for optimal pricing, maximum procurement distances, and biomass supplies to compute farm surplus or profits (for stover farmers, switchgrass farmers, and total) as described in Supplementary Material B.7.

### 2.4 Optimal feedstock mix and greenhouse gas emissions

A key component of our analysis is the calculation of greenhouse gas (GHG) emissions associated with alternative feedstock mixes. The performance of switchgrass-based biofuels in terms of GHG emissions is important because policy support for specific types of biofuels is tied to their GHG footprint. For instance, if a biofuel reduces emissions by 60% relative to conventional gasoline, then it receives a renewable identification number (RIN) code of D3; which effectively means the biofuel is benefited by a larger subsidy in the market. Stover-based biofuels are generally considered to meet this mark, so if switchgrass-based biofuels reduce emissions even further, they too would benefit from this larger subsidy.

We compute GHG emissions under the counterfactual of an operating biorefinery and compare it to a baseline level of emissions without a biorefinery and with currently prevailing land use. Moreover, just as our analysis examines whether a mix of feedstocks can reduce cost compared to a single feedstock, we also look at the extent to which a mix of feedstocks (if one emerges in equilibrium) enhances or deteriorates the GHG footprint of cellulosic biofuels. To do so, we compute GHG emissions associated with the procurement pattern that arises in equilibrium and compare it to a situation in which the plant fills capacity solely with corn stover.

Emissions associated with procuring and processing biomass depend upon the land use types from which the plant sources biomass. There are five land use types or land covers in the area we study from which biomass can be sourced. First, stover can be sourced from continuous corn land, with or without cover crops. Second, stover can be sourced from corn/soybean rotation land with or without cover crops. We include the possibility of planting cover crops because it is usually considered as a management practice adopted in conjunction with stover removal to mitigate its effects on soil organic matter and nutrients; and it provides non-trivial carbon sequestration benefits. Finally, the firm can source switchgrass from marginal land.

We first run COMET-Farm (described below) for representative hectares in Jasper and White counties to calculate emissions per hectare of each one of these land types relative to a baseline (current land use). We then divide these figures by biomass yields, to calculate emissions per Mg of biomass. Finally, we combine estimated emissions per Mg with the equilibrium feedstock mix from our spatial model and biofuel yields of those feedstocks to estimate the net change in emissions per liter of biofuel produced. A detailed description of this procedure is included in Supplementary Material D.

In addition to calculating the net change in GHG emissions under the optimal procurement strategy, we also compare this net change with that resulting from a stover-only procurement strategy. We repeat the process by which we compute net change in emissions from the optimal procurement strategy, but we apply it to a situation in which a biorefinery fills capacity exclusively with stover. Finally, we subtract the net change in GHG emissions under a stover-only procurement strategy from the net change in GHG emissions under the optimal procurement strategy. This difference reveals the effect of using a mix of feedstocks on the GHG footprint of cellulosic biofuels.

### 2.5 Model parameterization

Data from Jasper and White Counties in Indiana are the basis for calculation of most of the exogenous parameters. These counties have the highest corn planting densities and yields in Indiana, and are, as such, a promising location for an ethanol plant (Sesmero, Balagtas, et al., 2015; Sharma et al., 2020). In addition to access to feedstocks, infrastructure (roads, rail, etc.) is an important determinant in plant location (Lambert et al., 2008). Indiana has eight Primary Interstate Highways, two national highways, and easy access to commercial freight rail, which makes it a good location for biofuel plants.

Data for cropland, marginal land, and land area for both counties come from the 2012 Agricultural Census available in USDA-NASS Quick Stats from (NASS USDA, 2012). Corn yield for both counties is the mean of annual values from 1990 to 2020 obtained from Agricultural Surveys in NASS Quick Stats. Table 2 shows the biomass production parameters for Jasper and White counties. The stover removal rate in both counties is 50% (e.g., Perrin et al., 2012), and the switchgrass yield is 11.87 Mg/ha (Song et al., 2017). Land suitable for corn production in both counties is determined as land that is used for corn–soybean rotation. Total land
suitable for corn is then divided by total land area to obtain the maximum potential corn planting density.

Land suitable for switchgrass production is calculated as the sum of marginal lands that include pastureland, idle land, failed cropland, and land under the Conservation Reserve Program or CRP (a program whereby the government pays the farmer a yearly rental rate and the farmer removes environmentally sensible land from production and plants species deemed to increase soil health). These land categories are consistent with federal biofuel policies. According to data from USDA NASS, there are a total of about 101 square kilometers of marginal land in Jasper and White counties, or around 5% of total (marginal and cropland) agricultural land. About 39% of marginal land comes from pastureland, 33% from idle land, 27% from CRP land, and the rest from failed cropland. Our sources of land suitable for switchgrass are consistent with those considered by previous studies. Perrin et al. (2012), for instance, included idle cropland, pastureland and hay land as land suitable for switchgrass. Brechbill et al. (2011), a study also conducted in Indiana, included the same categories we include. The sum of these land categories was also divided by the total area of the counties to compute supply density.

Jasper County has a total area of 1450 km² with approximately 73 ha/km² suitable for corn production and 3.97 ha/km² suitable for switchgrass production. The yield for corn stover under a 50% removal rate is 4.85 Mg/ha, calculated as half of mean corn yield which assumes (as it is typically the case) a 1:1 ratio between grain and aboveground biomass (stover). White County has a land area of 1308 km² with a maximum corn planting density of 78 ha/km² and switchgrass planting density of 3.29 ha/km². The stover yield for White County under a 50% removal rate is 4.56 Mg/ha, also calculated as half of mean corn yield.

Table 3 shows the values of all the exogenous parameters in the spatial model. The production capacity of the biorefinery is 94.6 million liters (25 million gallons) per year. We divide capacity in liters by the ethanol conversion coefficient for corn stover, which converts capacity from liters of biofuel into equivalent Mg of processed biomass. The capacity we assume in this study is smaller than capacity levels previously used in the literature (e.g., Field et al., 2020; Perrin et al., 2012). Assuming a rather small plant limits the distance that the plant must travel to procure enough stover, favoring stover in the mix to the detriment of switchgrass. This only reinforces our main finding that transportation costs may warrant the inclusion of switchgrass into the feedstock mix.

The stover to ethanol conversion coefficient is 303 L/Mg or 80 gallons/ton (Sesmero, Balagtas, et al., 2015). With firm capacity expressed in terms of stover Mg, switchgrass must be measured in stover-equivalent Mg because switchgrass has a higher ethanol conversion coefficient (366 L/Mg or 96.7 gallons/ton, Department of Energy, 2016). To do this, we divide the conversion coefficient of switchgrass by the conversion coefficient of stover. This yields a coefficient of 1.21 which we use to adjust switchgrass quantities to stover-equivalent Mg. The switchgrass and corn stover breakeven prices (on-farm cost) in Indiana come from Brechbill et al. (2011). We refer the reader to Supplementary Material C for a detailed discussion of key cost categories.

The distance between the two furthermost points of these adjacent counties is 81 km (50 miles). That distance is used

| Parameter (units) | Jasper county | White county |
|-------------------|---------------|-------------|
| County area (km²) | 1450          | 1308        |
| Suitable corn land (ha/km²) | 73          | 78          |
| 50% Stover yield (Mg/ha) | 4.85        | 4.56        |
| Switchgrass land (ha/km²) | 3.97        | 3.29        |
| Switchgrass yield (Mg/ha) | 11.87       | 11.87       |

| Symbol | Value (units) | Source |
|--------|---------------|--------|
| Q      | 312500 (Mg)   | Sesmero, Balagtas, et al. (2015) |
| q_sw   | 2361 (Mg)     | Author calculation |
| B      | 22980 (Mg)    | Author calculation |
| θ      | 0.0089        | Sesmero, Balagtas, et al. (2015); PCLP |
| t      | 0.89 ($/km)   | Brechbill et al. (2011) |
| D      | {D ∈ N/0} | Author calculation |
| a_eq   | 1.21          | U.S. DOE (2016) |
| Switchgrass breakeven price | $70/Mg | Brechbill et al. (2011) |
| Corn stover breakeven price | $53/Mg | Brechbill et al. (2011) |
to calculate the stover biomass potential and switchgrass biomass potential at each kilometer. The stover potential is calculated as the maximum stover potential divided by the 81 km. Switchgrass potential is calculated in the same fashion. In line with assumptions in previous studies that both stover and switchgrass are subjected to the same custom rate for transportation (a rate of $1.42 per loaded mile or $0.89 per loaded kilometer for both feedstocks), and combining this with the truck’s loading capacity in bales and weight of the bale, we calculate a transportation cost of $0.25 per Mg-kilometer. Finally, parameters of the farmer participation rate function came from Sesmero, Pratt, et al. (2015) and the Purdue Crop Linear Programming model (PCLP).

The environmental analysis is conducted using the COMET-Farm tool. COMET-Farm is a web-based, farm and ranch carbon and GHG accounting system published jointly by USDA-NRCS and Colorado State University. Results are based on the location of the parcels of land specified by the user, crop grown, and management practices employed to produce the crop. Results are shown in levels of carbon monoxide (CO), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), and carbon sequestered in soil (C). We calculate emissions under a baseline land use situation without biofuels, and under a counterfactual land use pattern with biofuel production. In the counterfactual, a given vector of exogenous variables would result in an equilibrium procurement pattern, with its corresponding set of prices and land use. Emissions associated with that particular land use pattern are calculated with COMET-Farm; and they are contrasted with the baseline land use pattern without biofuels.

Running COMET-Farm requires information on historical management practices on a given parcel. This includes information on whether the land specified was enrolled in CRP before 2000, tillage system (intensive, reduced, no till), crop rotation (both switchgrass and corn with stover removal are included in the model), lime usage, irrigation, burn down, fertilizer, and yields. COMET-Farm includes default values for all of these inputs for specific locations within the Corn Belt. Default values are very homogeneous across locations in Jasper and White counties. Therefore, we randomly choose a location along the line between plants’ hypothetical location and define a representative hectare. We define a baseline land use for the representative hectare, which corresponds to a situation without biofuels plants. We then calculate GHG emissions under the baseline land use as the net flux of GHGs from the land to the air.

Next, we must compute GHG emissions under the counterfactual with a biofuel refinery. We start by computing the economic counterfactual land use with biofuel plants, which is then simulated in the COMET-farm model to calculate GHG emissions. To compute the counterfactual land use, we first calculate equilibrium prices and maximum procurement distances for both feedstocks (as indicated in Section 2.3). We use these values to predict land use at each point within the firm’s procurement region, and then use COMET-Farm to calculate GHG emissions from the predicted land use. We follow the same procedure to compute GHG emission under the counterfactual where a biofuel refinery fills capacity with stover only. The equations used to predict land use in land suitable for corn are calculated using information from Sesmero, Pratt, et al. (2015) and are as follows:

\[ s_{ce}^{75} = -0.26 + 0.0078 \left( p_{k,j}^{cs} \right) \]  
\[ s_{ch}^{75} = -0.55 + 0.02 \left( p_{k,j}^{cs} \right) - 0.0012 \left( p_{k,j}^{cs} \right)^2 \]

The prices from the relevant counterfactuals (optimal mix or stover-only procurement) are inserted in Equations (10) and (11) to compute the predicted share of land under continuous corn with 75% stover removal and under corn/soybean rotation with 75% stover removal, respectively. Furthermore, the stover analysis will be conducted with and without cover crop use to determine if there is a significant difference in emissions.

In terms of predicted land under switchgrass, we simply compute the counterfactual price of switchgrass and then subtract on-farm and transportation cost from that price to compute the hectares of marginal land that will find it optimal to plant switchgrass at the given price.

The discussion of parameters used to compute emissions from predicted land uses within the procurement region are described in Supplementary Material D.

3 RESULTS AND DISCUSSION

We start by reporting results on the procurement pattern that emerges in equilibrium and the resulting prices of feedstocks. Figure 1 depicts these under a range of sizes of the procurement region. When the procurement region is sufficiently large (126–160 km), the biorefinery purchases both feedstocks from unconstrained markets, that is, maximum procurement distances are smaller than the procurement region. In this situation, the equi-marginal principle dictates that the biorefinery fills capacity paying the same price for both feedstocks as shown in Figure 2 and formally characterized in Supplementary Material B. The intuition is straightforward; if one input is more costly than the other at capacity, the plant can reduce total cost by decreasing the price and procurement of the costly feedstock while raising the price and procurement of the less costly input. Because in this situation the biorefinery pays the same price for stover and switchgrass, the feedstock mix remains constant and includes, approximately, 33% switchgrass and 67% stover (Figure 3).
**Figure 1** Distance to edge of procurement area and distance to furthest supplier

**Figure 2** Distance to edge of procurement area and prices paid for feedstocks

**Figure 3** Distance to edge of procurement area and share of switchgrass in feedstock mix
When feedstocks are still available between 70 and 126 km away from the plant location, the biorefinery purchases both feedstocks. However, within this range, the boundary of the procurement region becomes binding for stover, which is why the distance to the furthest supplier is the same as the distance to the edge of the procurement region (Figure 1). In this range, the marginal cost schedules for both feedstocks are increasing in quantity procured; thus, the equi-marginal principle still applies, and prices are equal (Figure 2). Therefore, as the procurement region shrinks, the supply of stover decreases (supply from the extensive margin shrinks), while the supply of switchgrass remains unaffected. Governed by the equi-marginal principle, both prices rise by the exact same amount as a result of the reduction in the supply of stover (Figure 2). The equi-proportional increase in prices in combination with a reduction in the supply of stover relative to switchgrass cause the share of switchgrass in the feedstock mix to rise. At the lower bound of the 70–126-km range, the share of switchgrass climbs to a maximum of around 40% (Figure 3).

Finally, as indicated in Figure 1, when the farthest the biorefinery can go to procure feedstocks is between 23 and 70 km, the procurement region becomes binding for both feedstocks (if the procurement region is shorter than 23 km, there is not enough biomass for the biorefinery to fill capacity). The first implication of this is that the equi-marginal principle of pricing breaks down, and the price of stover becomes higher than the price of switchgrass. This is because, conditional on the size of the procurement region, the biorefinery offers a price for switchgrass that is just high enough to induce the marginal supplier (the supplier located at the boundary) to sell to the plant. Offering a higher price is not convenient, as no additional switchgrass would be procured. Offering a lower price would reduce procurement of switchgrass and force the plant to substitute that for a more costly stover. Therefore, the price of switchgrass is, under this procurement pattern, independent of that of stover.

Therefore, in this procurement pattern, the cost-minimizing strategy is a two-part pricing scheme formalized in Supplementary Material B.5. First, the biorefinery offers a price for switchgrass that allows it to procure all the switchgrass available within the procurement region at minimum cost (i.e., this is the price that is just high enough to induce the marginal supplier to sell to the plant). Conditional on the amount of switchgrass purchased at that price, the plant faces an upward sloping supply of stover (additional stover procured at higher prices come from the intensive margin) and so it offers a price for stover that is high enough to fill capacity.

The corollary of this pricing strategy is that, in the 23–70-km range, as the procurement region shrinks the biorefinery offers a lower price for switchgrass (Figure 2). This is because the price necessary to induce the most distant supplier to sell to the plant is lower. As a result, as the procurement region shrinks, the total amount of switchgrass purchased falls, reducing the share of switchgrass in the feedstock mix. This share drops from about 40% when the procurement region is 70 km long to about 14% when it shrinks to 23 km long (Figure 3). The reduction in switchgrass purchased forces the biorefinery to substitute switchgrass for stover to fill capacity. In order to procure enough stover the biorefinery is forced to offer an increasingly higher price for stover as the procurement region shrinks (Figure 2).

Some parameters in our analysis are stochastic. Therefore, our predicted share of switchgrass in the mix (Figure 3) is best described as the mean of a probability distribution. The most prominent stochastic parameters are stover and switchgrass yields (transportation cost is also stochastic but its incidence on the feedstock mix is much smaller than the incidence of yields). We build a confidence interval around our predicted share in Figure 3 based on the variability of stover yield. We do not have the necessary information to build probability distributions for switchgrass yield, so we assume random variations in stover yield translate into variations in relative yields. Finally, we would like to note that variability of other parameters in the literature typically stem from differences in assumptions and methodologies to compute them as well as regional differences, not from stochasticity. We do not want to build a confidence interval based on this type of variability but would rather build one that reflects the stochastic nature of parameters. We address non-stochastic variability in our section on sensitivity analysis.

When stover yield is low (high), the supply of stover shifts upwards (downwards) increasing (lowering) the cost of stover relative to switchgrass. Moreover, because on-farm cost of harvesting stover includes fixed costs, a reduction (increase) in stover yield implies a slight increase (reduction) in on-farm cost of harvesting stover. As a result, the biorefinery includes more (less) switchgrass in the mix. We use historical yields from NASS in White and Jasper countries from 1990 to 2020 and estimate a probability distribution of stover yields. We then take random draws from that distribution and compute the cost-minimizing share of switchgrass for that draw. We compute a 95% confidence interval and report upper and lower bounds in Figure 3. The 95% confidence interval in Figure 3 shows relatively tight bounds around the mean, lending credence to our main result. Moreover, we should keep in mind that variations in stover yield in a given year are likely to be positively correlated with variations in switchgrass yield, a correlation we do not consider here due to lack of data on switchgrass yields. But such correlation would likely narrow the confidence interval even further.

A primary concern in our study is to assess the cost savings generated by the use of a feedstock mix as opposed to filling capacity exclusively with stover, the cheaper on-farm source. The cost comparison between a mix and stover-only
reveals the magnitude of the bias in cost estimates introduced by studies that assumed switchgrass away due to its higher on-farm cost. The expressions to compute total feedstock cost under the optimal mix and stover-only are formally derived in Supplementary Material B.6 and results are presented in Figure 4.

Our results indicate that while the procurement region is large and the biorefinery can freely procure from the extensive margin, savings from a feedstock mix are very small (about 0.5 cents per liter or 2 cents per gallon). This is because in a large procurement region, the biorefinery can procure stover at a relatively low cost as it procures from both the intensive and extensive margin. Cost savings are still positive because the biorefinery can reduce cost by purchasing some switchgrass near the plant, instead of buying stover from very distant suppliers. But they are small because those savings in transportation cost are partly offset by higher on-farm cost of producing switchgrass. As the procurement region shrinks, savings from using a feedstock mix grow considerably. Cost savings from using a feedstock mix peak at 10 cents per liter (38 cents per gallon) when the extensive margin is very limited, that is, when the farthest the plant can travel to obtain feedstocks is 23 km.

Another important aspect of our analysis is how rents from a market of cellulosic biofuels would distribute along the vertical supply chain. A key indicator of this is how much surplus accrue to farmers conditional on the capacity that the plant must fill, a metric formally characterized in Supplementary Material B.7. We present our results in Figure 5.

Figure 5 depicts surplus (profits) of farmers growing and selling switchgrass, harvesting and selling stover, and the total (sum of both). Notice that calculated surpluses are net of all costs, including opportunity cost of land for switchgrass. Our results show that farm surplus from stover collection ranges from $2 million to $14.5 million. Higher stover surpluses are associated with constrained procurement regions because the biorefinery must pay higher prices to procure enough stover to fill capacity from the intensive margin. To put this in context, since 2013 average (over farm sizes and rotations) net return for highly productive land in Indiana (which is the most prevalent land in White and Jasper counties) has been very stable around $716/ha or $290/acre (Purdue Crop Cost & Return Guide). Because land planted to corn and soybeans in these two counties is around 105,218 ha (the value we use for our analysis), producer surplus is typically around $76 million. Therefore, stover seems to increase short run surplus by 2.6% (when surplus is $2 million) to 20% (when surplus is $14.5 million).

The increase in surplus of marginal land associated with planting and trading switchgrass ranges between $2.5 million and $3.5 million. Constrains to the procurement region benefit switchgrass growers but only up to a point; if the procurement region is too small, they are pushed out of the feedstock mix because there is no intensive margin that the biorefinery can tap to its benefit. Since 2013, average (over farm sizes and rotations) net return for low productivity land in Indiana (similar to what we consider marginal land in White and Jasper counties in our analysis) has also been stable and close to our assumed land opportunity cost of $173/ha or $70/acre (Purdue Crop Cost & Return Guide). Because marginal land in these two counties is around 11,735 ha (the value we use for our analysis), producer surplus is typically around $2 million (29,000*$70). Therefore, switchgrass seems to increase short run surplus by 125% (when surplus is $2.5 million in excess of opportunity cost) to 150% (when surplus is $3.2 million in excess of opportunity cost).

We now turn our attention to the climate mitigation implications of cellulosic biofuels under a feedstock mix. To calculate emissions from stover at varying sizes of the procurement region, we insert the stover equilibrium prices into the land share Equations (10) and (11). The land shares are then summed to calculate total land share producing stover and then the respective share is divided...
by the total to calculate the share of continuous-corn and corn/soybean land producing stover. Those land share values are then multiplied by the amount of stover sourced, summed, and then divided by the ethanol conversion rate of 303 L/Mg to generate a GHG emission per liter of ethanol produced from stover. We complete this process for both cover crop and no cover crop scenarios. To calculate the emissions from switchgrass at varying sizes of the procurement region, GHG emissions per Mg of switchgrass was multiplied by the amount of switchgrass sourced and then divided by 366 L/Mg to express it in ethanol-equivalent units. The numbers for switchgrass and stover were added together to generate total emissions from biofuel production in GHG emissions/liter.

Figure 6 shows net GHG emissions (increase relative to a baseline with no biofuel plant) under four scenarios: optimal (cost-minimizing) mix with cover crops, optimal mix without cover crops, stover-only with cover crops, and stover-only without cover crops. The first two scenarios allow us to quantify the net effect of a cellulosic biofuel plant on GHG emissions. The last two, allow for a comparison of GHG emissions between the cost-minimizing mix and a counterfactual where the plant procures stover only.

Figure 6 reveals that GHG emissions from cellulosic biofuels are closely linked to two key factors: (1) the share of switchgrass in the feedstock mix, and (2) the extent to which stover is procured from the extensive or the intensive margin. Emissions associated with production of feedstock for cellulosic biofuels fall as the share of switchgrass in the feedstock mix rises and as the biorefinery procures larger amounts of stover from the extensive margin. A higher prevalence of switchgrass in the mix reduces emissions because planting switchgrass on marginal land provides substantial carbon sequestration benefits relative to the baseline land use (e.g., Follett et al., 2012; Liebig et al., 2008; Monti et al., 2012).

Moreover, when the biorefinery procures stover from the extensive margin (expanding the procurement region), it does so by purchasing mostly from farmers rotating corn and soybeans. On the other hand, when it procures larger amounts from the intensive margin, it does so by raising the price offered for stover which triggers conversion to continuous corn, a land use that results in higher emissions than corn/soybean.
rotation (as indicated by parameter $\theta$ in Table 3, a $1$ increase in stover price raises the share of land on continuous corn by $1\%$). Emissions decrease as the procurement region shrinks from $160$ km to $70$ because, as indicated in Figure 3, the share of switchgrass in the feedstock mix rises. In contrast, emissions rise as the procurement region shrinks beyond $70$ km because the share of switchgrass in the mix decreases and, additionally, the farmer is forced to procure more from the intensive margin by inducing conversion of more land to continuous corn.

Figure 6 also shows the difference in incremental GHG emissions (relative to a baseline of no cellulosic biofuels) between a situation in which the plant uses a cost-minimizing feedstock mix and a situation in which the biorefinery fills capacity solely with stover, both with and without cover crops on corn land. The inclusion of switchgrass in the mix is not only economically optimal, but also results in a reduction in the carbon footprint of cellulosic biofuels. Reductions in the carbon footprint are largest under parametric configurations that result in the largest prevalence of switchgrass in the feedstock mix.

To summarize, the main insight we draw from our analysis is that, under our model parameters, transportation cost can induce cost-minimizing biorefineries to include a significant share of switchgrass in the feedstock mix. Spatial constraints on the procurement region reinforce our insight as long as they are not so extreme that they greatly limit the amount of switchgrass available around the biorefinery. Using a combination of feedstocks not only improves the biorefinery’s bottom line but also reduces its environmental footprint.

4 SENSITIVITY ANALYSES

An important feature of our analysis is the uncertainty and spatial heterogeneity surrounding our model parameters (Rosburg et al., 2016, 2017). As a result, it is very important to examine the robustness of our main insight to variations in key model parameters. We conduct sensitivity analyses with respect to several parameters in our model and present results in Figure 7. All sensitivity analyses vary one parameter keeping everything else constant, and all analyses are conducted for the case of unconstrained procurement regions, our primary or baseline scenario. Overall, the results suggest an upper bound of $50\%$ switchgrass in the feedstock mix and a lower bound of $0\%$.

Higher density of land suitable for switchgrass and lower density of land suitable for corn result in higher inclusion of switchgrass in the mix. Because our analysis is conducted in an area with very high corn density, our baseline is, in a sense, identifying a lower bound to inclusion of switchgrass. For instance, in southern Indiana where corn density is much lower and the density of land suitable for switchgrass is much higher, a biorefinery is likely to include much more switchgrass into the mix. Much more switchgrass is also likely to be included if the rate of stover removal is limited due to environmental or soil productivity constraints. A similar effect may be observed if the farmer participation rate in corn planting and stover collection is lower than estimated in our study. This is quite possible as the participation rates we use are estimated based on data from two counties where corn/soybean farms are larger than average and corn yields are very high, which favors stover due to fixed costs of collection.

Our baseline scenario assumes no incremental marginal processing cost of including switchgrass in the mix. As Oke et al. (2016) points out, processing multiple feedstocks may need an array of commercial enzymes that can contribute to higher processing cost as the share of switchgrass in the mix rises. This is because different feedstocks have different optimal conditions for pretreatment, hydrolysis, and fermentation, and they also have varying moisture, ash, and cellulose content. To examine the robustness of our insights to these types of incremental processing costs, we simulate a $20\%$ increase in the marginal cost of switchgrass. Such an increase

![FIGURE 7](image)
would result in a significantly lower inclusion of switchgrass in the mix, that is, switchgrass would amount to 10% of the mix as opposed to 33% in the baseline scenario.

Another force that can hamper inclusion of switchgrass in the feedstock mix is a higher opportunity cost of land suitable for switchgrass. This may be due, for instance, to an increase in CRP payments or owners of marginal land valuing alternative uses very highly (Swinton et al., 2017). A reduction in transportation cost also reduces the share of switchgrass in the mix. This is because the plant finds it optimal to travel longer distances to procure stover instead of purchasing switchgrass (which has higher on-farm cost) nearby the plant. Our results also reveal the importance of stover removal rates on switchgrass inclusion. Our baseline assumes a 50% removal rate. An increase to a removal rate of 75% would persuade the biorefinery to not include switchgrass in the mix. Conversely, a reduction to a removal rate of 25% would induce the biorefinery to fill half of its biomass needs with switchgrass. This is because an increase (decrease) in stover removal rate shifts stover supply upwards (downwards) raising (lowering) the marginal cost of stover relative to switchgrass.

We find that variations in plant capacity (motivated by estimates used in Kazi et al., 2010) and biofuel yields per metric ton of biomass do not substantially affect the optimal feedstock mix. This is because changes in capacity do not affect the “relative” cost of inputs in a spatially unconstrained market (which is the situation we consider in the sensitivity analysis section). The same logic applies to a change in ethanol yield that is symmetric for both feedstocks (changes in relative yields do change the mix as also shown in this section).

It is worth noting that some, rather plausible changes could persuade a biorefinery not to include switchgrass in the mix at all. An increase in cost of processing switchgrass of 30% would eliminate switchgrass from the mix, in the absence of limits to the extensive margin for stover. Moreover, an increase in the opportunity cost of marginal land from $173/ha ($70/acre) to $395/ha ($160/acre) would also eliminate switchgrass from the mix, in the absence of limits to the extensive margin for stover. Finally, as previously pointed out, an increase in stover removal rate from 50% to 75% would eliminate switchgrass from the mix, in the absence of limits to the extensive margin for stover.

We have focused our sensitivity analysis on the case where the biorefinery operates without spatial constraints to the market for stover. Notice, however, that operating in a spatially constrained market for stover may counteract some of the forces that lessen the share of switchgrass in the mix. We should also notice that a differential subsidy for biofuels that include a higher share of switchgrass (which would be consistent with our finding that a higher share of switchgrass reduces the carbon footprint of the biofuel) would also counteract the forces that undermine the inclusion of switchgrass in the mix.

5 | CONCLUSIONS

Our analysis predicts that, if a cellulosic biorefinery can procure stover from productive cropland and switchgrass from marginal land, then it is likely to include switchgrass in the mix; especially if the biorefinery operates under a spatially constrained procurement region. This stands in contrast with previous studies that either assume both feedstocks compete for land or only consider on-farm production cost when making predictions regarding the cost-competitiveness of switchgrass. Finally, our results also show that increased inclusion of switchgrass in the mix leads to a reduction in the carbon footprint of cellulosic biofuels. Our analysis underscores that overlooking spatial aspects of biomass procurement and transportation cost can lead to (1) overestimation of feedstock cost, (2) underestimation of inclusion of switchgrass in the mix, and (3) overestimation of carbon footprint of biofuels. Our study is not without limitations. Perhaps one of the most important limitations is our inability to quantify transaction costs associated with contracting with farmers for switchgrass. Our sensitivity analysis suggests that if such transaction costs raise the cost of switchgrass by 30%, then switchgrass would be unlikely to be part of the feedstock mix. An important extension of this work could address this by better quantifying transaction costs including moral hazard, contract renegotiation, and real option of planting switchgrass. On the other hand, stover has other uses (e.g., livestock feed) that could increase its cost for the biorefinery and not considered here. Another important limitation of our study is the assumption that switchgrass and corn do not compete for the same land. Including an explicit model of farmers’ decision to plant corn or switchgrass may better qualify our quantitative results. Moreover, the framework developed here can be applied to examine the cost-effectiveness of other energy dedicated crops that have a higher cost of production than switchgrass but also higher yields, which can generate greater savings in transportation cost.

Our analysis suggests that the current classification of RIN codes that would lump stover and switchgrass into the same category are perhaps too coarse. A clear differentiation between these sources (which seems justified based on our calculations of their carbon footprints) may induce higher adoption of switchgrass. Our analysis also suggests that policies that subsidize establishment costs for energy crops can greatly increase the inclusion of switchgrass in the mix. This is because switchgrass has a higher cost of production (as it is a dedicated crop and not a byproduct of another crop like stover) so establishment payments would reduce the cost of switchgrass more than that of stover, favoring the former. In the United States, such payments are included in the Biomass Crop Assistance Program. This program includes establishment, annual per hectare, and per-ton payments. Our analysis indicates that an increase in establishment payments to the
detriment of per-ton payments (keeping the budget of the program constant) will increase switchgrass in the mix, a finding that is consistent with McCarty and Sesmero (2021) in the context of Miscanthus.

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DATA AVAILABILITY STATEMENT
The data used for this study are available from the authors upon request.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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