# Staff Paper

## Can Dispersed Biomass Processing Protect the Environment and Cover the Bottom Line for Biofuel?

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# Abstract:

# Can Dispersed Biomass Processing Protect the Environment and Cover the Bottom Line for Biofuel?

This paper compares environmental and profitability outcomes for a centralized biorefinery for cellulosic ethanol that does all processing versus a biorefinery linked to a decentralized array of local depots that pretreat biomass into concentrated briquettes. The analysis uses a spatial bioeconomic model that maximizes predicted profit from crop and energy products, subject to the requirement that the biorefinery must be operated at full capacity. The model draws upon biophysical crop input-output coefficients simulated with the EPIC model, as well as input and output prices, spatial transportation costs, ethanol yields from biomass, and biorefinery capital and operational costs. The model was applied to 82 cropping systems simulated across 37 sub-watersheds in a 9-county region of southern Michigan in response to ethanol prices simulated to rise from $1.78 to $3.36 per gallon. Results show that the decentralized local biomass processing depots lead to lower profitability but better environmental performance, due to more reliance on perennial grasses than the centralized biorefinery. Simulated technological improvement that reduces the processing cost and increases the ethanol yield of switchgrass by 17% could cause a shift to more processing of switchgrass, with increased profitability and environmental benefits.

***Keywords***: biomass production, bioenergy supply, cellulosic ethanol, environmental trade-off analysis, bioeconomic modeling, EPIC, spatial configuration, local biomass processing.

**JEL Codes**: Q16, Q15, Q57, Q18

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## 1- Introduction

Sustainable production of biofuel will be facilitated by cropping systems with perenniality, no tillage, low inputs, and high diversity  (Robertson, et al., 2008, Tilman, et al., 2006). Diverse, perennial cropping systems not only reduce greenhouse gases emissions but also may be a breeding habitat for beneficial insects for arthropod-mediated ecosystem services such as pollination and pest suppression (Fletcher Jr, et al., 2011, Gardiner, et al., 2010).

Centralized biorefineries represent a threat to diversified cropping systems, because the most profitable means to meet their feedstock demand is from the cheapest, most abundant biomass crop.  Recent modeling has shown these to be crop residues from annual corn and wheat, supplemented at high biomass prices by monocropped perennial grasses (Egbendewe-Mondzozo, et al., 2011a).  Environmental policy offers one path to assure sustainable cropping systems by balancing bioenergy market price drivers with environmental incentives or constraints(Egbendewe-Mondzozo, et al., 2011b).  But biomass processing technology may offer another avenue to sustainable feedstock production.

Local biomass processing depots (LBPDs) have been proposed to address logistic problems of a centralized biorefinery (Eranki, et al., 2011). Yet LBPDs may also offer a means to disperse bioenergy crop production and potentially yield environmentally beneficial plant biodiversity.

The original motivation for LBPDs is to moderate the cost of delivering and storing biomass: Centralized biorefinery designs range in capacity from medium (730-1400 Gg/year (Aden, et al., 2002)) to large (4700-7800 Gg/year (Wright and Brown, 2007)). The bulky nature of the cellulosic biomass feedstock and its spatial uneven distribution across the landscape can result in high costs of storage and delivery of biomass feedstock to the biorefinery. A set of LBPDs (35-180 Gg/year) that pretreat and concentrate biomass before shipping it to a biorefinery plant for final processing into ethanol can potentially reduce logistics costs (Bals and Dale, 2011, Eranki, et al., 2011). At the same time, reduced logistics costs from shorter transport routes and concentrated biomass could make profitable more diversified cropping systems.

Sustainable biofuel production requires both profitability and environmental services. Some recent studies have shown that biomass supply from annual crop residues (e.g. corn stover and wheat straw) as feedstock for biofuel production can deteriorate environmental quality while biomass supply from perennial energy crops (e.g. switchgrass, miscanthus, native prairies and mixed grasses) tends to mitigate environmental impacts (Egbendewe-Mondzozo, et al., 2011a, Graham, et al., 2000, Love and Nejadhashemi, 2011, Robertson, et al., 2011). Increased greenhouse gas emissions such as carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$-N) as well as nutrient runoff ( phosphorus (P) and nitrate (N) runoffs into water streams) are associated with biomass supply from annual crop residues while biomass supply from perennial energy crops will generally reduce greenhouse gas emissions and improve water quality. The environmental sustainability and associated profitability of centralized versus decentralized biofuel production configuration have not been studied. This paper tests how profitability and environmental outcomes from cellulosic ethanol production are affected by processing at a centralized biorefinery as opposed to dispersed LBPDs that supply a central biorefinery.

The principal objective of this paper is to understand profitability and implied environmental impacts of two alternative biorefinery spatial configurations: the centralized biorefinery versus the local biomass preprocessing depot (LBPD) configuration. Specifically, for each biorefinery spatial configuration, the study will 1) evaluate biorefinery profitability based on biomass production, transport, pretreatment and final processing costs, 2) estimate implied environmental impacts in terms of soil nutrient runoff and greenhouse gas emissions, and 3) evaluate the impact of technological change on biorefinery profitability and environmental quality. To reach the objectives of this study, the following research questions will be addressed: a) What are the key parameters driving profitability of biorefinery spatial configuration? b) What are the land use changes and the environmental costs associated with each of the biorefinery spatial configurations (nutrients runoff, greenhouse gas emissions, land use change and soil erosion)? and c) How are biorefinery profitability and environmental impacts altered by technological change?

The remainder of the paper is organized as follows. First, a spatially explicit bioeconomic model developed and used to study biomass production and supply in southwest Michigan (Egbendewe-Mondzozo, et al., 2011a) is described and extended to include biorefinery processing as well as the possibility of biomass preprocessing in LBPDs. Second, the empirical data and the assumptions regarding the method of pretreatment as well as the final processing of biomass are given. Third, the results of the analysis related to the biorefinery spatial configuration and the corresponding environmental impacts and profitability are presented and discussed. The paper concludes with a discussion of the potential for environmental benefits from dispersed biomass processing if further technological changes can be achieved.

## 2 – Material and Methods

This study builds on a previously published spatially explicit bioeconomic model for biomass production and supply analysis based on a risk-neutral representative agent profit-maximization approach (Egbendewe-Mondzozo, et al., 2011a). We extended the existing model to incorporate biomass processing into ethanol via both preprocessing activities (via LBPDs) for biomass pretreatment and final biorefinery processing to convert biomass into ethanol and byproducts (Figure 1). The general model includes several component models. A biophysical model, the Environmental Policy Integrated Climate (EPIC) model, simulates and validates crop and environmental yield parameters. Crop prices are obtained and production costs are calculated using data from U.S. Department of Agriculture (USDA) statistics and Michigan State University Extension. To calculate transport costs, geographic information system (GIS) tools are used to calculate distance and time of travel for biomass from farm supply points to processing demand points (LBPDs and biorefinery). A techno-economic model of the LBPD and biorefinery settings provides fixed costs (capital and maintenance costs) and variable costs for biomass pretreatment and final conversion into ethanol and byproducts (based on ethanol yields assumptions). All these component models generate parameters that are fed into a constrained mathematical optimization model that calculates the most profitable way to produce ethanol at the capacity of the biorefinery. Ethanol prices are simulated to obtain outputs such as biomass supply and price, land use change, total environmental outputs, ethanol supply and total profits from biomass production and conversion activities.

### *2.1 The empirical model*

The empirical model is built to maximize profit for a multi-product firm that manages crop land and refines cellulosic ethanol; profits are maximized subject to the constraint that the ethanol biorefinery must operate at full capacity.  The model selects among a set of 82 cropping systems the biomass feedstock that will maximize biorefinery profit from the sale of cellulosic ethanol. The cropping systems simulated are defined in terms of four management practices: crop rotation, level of fertilization, tillage, and crop residue removal for energy biomass (see Table 1). The Environmental Policy Integrated Climate (EPIC) model (Williams, et al., 1989) is used to simulate and validate crop and environmental yields for each cropping system based on weather, topography and soil data. The geographic region modeled is situated in southwest Michigan (counties of Allegan, Barry, Eaton, Van Buren, Kalamazoo, Calhoun, Cass, St. Joseph and Branch) and divided into 37 watersheds, as defined by their 10-digit hydrologic unit codes (HUC) that overlap these counties. The watersheds, in turn, are subdivided into two levels of soil quality to yield a total of 70 land units (note that four of the watersheds lacked the lower quality soil quality). The two spatial biorefinery configurations are placed in the sub-region to reflect two alternative cases: a) a single centrally located biorefinery (in Kalamazoo city) that collects biomass and pretreats it before processing it into ethanol and byproducts (Figure 2, left panel), and b) multiple local biomass processing depots (LBPDs) that pretreat biomass before shipping it to a central biorefinery (in Kalamazoo) for conversion into ethanol and byproducts (Figure 2, right panel).

The parameterized and calibrated model chooses which of the 82 cropping systems to practice on each of the 70 land units in order to maximize net returns from sales of crop products, ethanol, and electricity, subject to the requirement that the biorefinery must operate at full capacity and subject to other resource constraints. The final model is written as a calibrated constrained quadratic optimization program that maximizes the joint profit of farm and ethanol production enterprises in a centralized biorefinery as follows:

$$\text{Max}_{x_{ij}} \sum_{i=1}^{70}\sum_{j=1}^{82}\left[-c_j x_{ij} - \sum_{l=1}^{3} r_l o_{lj} x_{ij} + \sum_{s=1}^{15} p_s (1-\emptyset_s)(\rho_s x_{ij} - \delta_s x_{ij}^2)\right] - \sum_{h=1}^{9} TC_h$$
$$-(PTVC + PTFC + RCVC + RCFC) + (RET + REL) \qquad (1)$$

Subject to:

$$\sum_{j}^{82} x_{ij} \leq \ b_i\,, \forall\, i = 1\ to\ 70, \qquad (2)$$

$$\sum_{i=1}^{70}\sum_{j=1}^{82} e_{nj} x_{ij} - E_n^o \leq M, \forall\, n = 1\ to\ 5, \qquad (3)$$

$$\sum_{i}^{70}\sum_{j}^{82} a_{ijh}\, x_{ij} * (\beta + \gamma y_i + \theta z_i) = TC_h, \qquad \forall\, h = 1\ to\ 9, \qquad (4)$$

$$\sum_{h}^{9}\sum_{i}^{70}\sum_{j}^{82} a_{ijh}(1-\emptyset_h)\, x_{ij} = \Psi \qquad (5)$$

$$\sum_{h=1}^{9}\sum_{i}^{70}\sum_{j}^{82} a_{ijh}\,(1-\emptyset_h) x_{ij} \varphi_h = PTVC \qquad (6)$$

$$\sum_{h=1}^{9}\sum_{i}^{70}\sum_{j}^{82} a_{ijh}\,(1-\emptyset_h) x_{ij} \omega_h = RCVC \qquad (7)$$

$$\sum_{h=1}^{9}\sum_{i}^{70}\sum_{j}^{82} a_{ijh}\,(1-\emptyset_h) x_{ij} \pi_h q = RET \qquad (8)$$

$$\sum_{h=1}^{9}\sum_{i}^{70}\sum_{j}^{82} a_{ijh}\,(1-\emptyset_h)x_{ij}\mu_h d = REL \tag{9}$$

The mathematical sets, variables and parameters used in the model are defined in Table 2. The objective function (1) contains six expressions. The first expression $\left(-\sum_i^{70}\sum_j^{82} c_j x_{ij}\right)$ represents the total variable production costs across all cropping systems and sub-watersheds. The second expression $\left(-\sum_i^{70}\sum_j^{82}\sum_{l=1}^{3} r_l o_{lj} x_{ij}\right)$ is the total cost of synthetic fertilizers across systems and sub-watersheds. The third expression $\left(\sum_i^{70}\sum_j^{82}\sum_{s=1}^{15} p_s(1-\emptyset_s)(\rho_s x_{ij}-\delta_s x_{ij}^2)\right)$ is the total crop sales revenue from all cropping systems and sub-watersheds adjusted for storage losses. The term $(\rho_s x_{ij}-\delta_s x_{ij}^2)$ defines the quadratic output levels obtained by multiplication of the linear calibrated marginal yield expression $(\rho_s-\delta_s x_{ij})$ by the quantity of land $x_{ij}$ allocated to the production of output $s$. The fourth expression $(\sum_{h=1}^{9} TC_h)$ represents the total transport cost of each biomass type to the refinery plant. These four expressions calculate the gross margin of the representative farmer from cereal and biomass sales. The fifth expression corresponds to the pretreatment variable costs (*PTVC*), biomass pretreatment fixed costs (*PTFC*), refinery conversion variable costs (*RCVC*) and refinery conversion fixed costs (*RCFC*). The last expression represents the revenues from ethanol sales (*RET*) and net electricity sales (REL). The final two expressions calculate the refinery's profits and can be adapted to calculate profits for LBPDs as well.

Equation (2) expresses the 70 land resource constraints. Equation (3) is a set of constraints enabling the creation of limits on permitted environmental output levels. Equation (4) calculates transport costs to the biorefinery. $(\beta+\gamma y_i+\theta z_i)$ is the transport cost of a metric ton (Mg) of biomass to the refinery site; with $\beta$ being the cost of loading and unloading, $\gamma$ is the cost per Mg per kilometer of hauling distance and $\theta$ the cost per hour of hauling time. The variables $y_i$ and $z_i$ are respectively the hauling distance and time from a parcel $i$ to the refinery plant site. Equation (5) calculates the total biomass produced and helps impose capacity constraint on the model. Equations (6) to (8) calculate the pretreatment variable costs, ethanol variable conversion costs, and the total ethanol and net electricity sales.

In presence of LBPDs, the transport cost become $\sum_{k=1}^{8}\sum_{h=1}^{9} TC_{kh}$ which calculates the biomass transport from the farm points to the 8 LBPD locations plus the transport costs from each LBPD to the biorefinery. The pretreatment variable costs expression in equation (6) has to add costs for each of the 8 LBPDs. Finally, the pretreatment fixed costs in the objective function will be a summation of fixed costs from each LBPD.

## 3- Data

Three data types are used to parameterize the model: a) simulated crop yield and environmental outcomes, b) crop production costs, market prices, and biomass transport costs, and c) biomass pretreatment and conversion yields and costs.

### *3.1. Biophysical crop and environmental yields data*

The biophysical EPIC model (Izaurralde, et al., 2006, Izaurralde, et al., 2007, Jones, et al., 1991, Williams, 1995, Williams, et al., 1989, Zhang, et al., 2010) is used to simulate average crop yield and environmental outcome parameters (soil erosion, phosphorus loss, nitrate loss, nitrous oxide emissions and soil carbon loss) in southwest Michigan for a 24 year period (1986-

2009). The nitrous oxide emissions and the soil carbon loss are used to calculate the total greenhouse gas emission in carbon equivalent, based on the fact that most of the soil carbon lost is transformed into carbon dioxide. The model includes grain and forage yields from six field crops plus biomass yields from seven cellulosic bioenergy crops and biomass residue yields from two field crops (a total of 9 biomass types). Field crops include corn grain, soybean, wheat, alfalfa, canola and corn silage. Cellulosic energy crops simulated are switchgrass, miscanthus, native prairie cool season mix, native prairie warm season mix, grass mixes of five types and six types, and hybrid poplar. Crop residues include corn stover and wheat straw. Key parameters of the average simulated biomass yields are reported in Table 3.

### *3.2. Crops production costs, market price and biomass transport cost data*

The economic crop production costs are obtained respectively from Stein for 2009 (Stein, 2009, Stein, 2010). Market prices for 2007-09 come from the USDA National Agricultural Statistics Service (NASS) (USDA, 2010). GIS is used to calculate transport costs based on travel time and distance from supply points to demand points with hauling distance and per-hour hauling time cost drawn from Graham, English and Noon (Graham, et al., 2000). The model also accounts for storage loss for all biomass types except poplar trees , using an 8.8% loss coefficient, which corresponds to dry matter losses for wrapped round bales stored at field edge for 6 months as reported in recent literature (Brechbill, et al., 2011). Key parameters on input costs, output price and transport costs are given in Table 3. Fuller details on the crop production part of the model appear in Egbendewe-Mondzozo et al. (2011a). The model does not include livestock production or the possibility of feeding byproducts of ethanol distillation to livestock.

### *3.3. Biomass pretreatment, conversion yields and costs*

We compare two spatial configurations of biorefining. The first is a LBPD configuration that collects heterogeneous biomass types and pretreats them before they are shipped to a biorefinery. The second is a centralized biorefinery that pretreats and processes biomass on site. The LBPD and the centralized biorefinery configuration are designed for a near medium capacity of 700Gg per year.

After harvest, biomass is assumed to be processed year-round at local biomass processing depots (LBPDs), which range from processing 100-250 Mg/day of material (Eranki, et al., 2011). At the LBPDs, the bales of biomass are ground and then pretreated using ammonia fiber expansion (AFEX$^{TM}$) pretreatment[4]. This pretreatment is performed in packed bed batch reactors (Chundawat, et al., 2011). Steam is used to heat the bed as well as strip ammonia from one bed of biomass to the next. A compressor is used to repressurize the ammonia prior to transfer to the next reactor.  After pretreatment, the biomass is partially dried in a drum dryer if a high severity pretreatment was used, and then all biomass is briquetted prior to shipping to a centralized biorefinery. These LBPDs purchase electricity and natural gas to produce steam for the AFEX process. At the biorefinery, the briquettes are saccharified, and the C5 and C6 sugars are fermented into ethanol. The ethanol is distilled off, while the remaining wastewater is digested to produce biogas. This biogas is combined with the unhydrolyzed solids and combusted to produce steam and electricity to provide heat and power to the biorefinery, with excess electricity exported to the power grid. The second spatial configuration scenario eliminates the LBPDs and moves the grinding and AFEX treatment to the centralized refinery (no briquetting or drying is performed in this operation), with all steam and power required for pretreatment is provided via

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[4] AFEX is a trademark of MBI International

combustion of lignin and natural gas. In the LBPD scenario, biomass collected near the centralized biorefinery is sent directly to the biorefinery, where it is ground and AFEX treated in a manner similar to the scenario in which no LBPDs were present.

Feedstocks react differently to pretreatment and saccharification based on their cell wall structure and composition. To capture this variation, each feedstock in the model was assigned to a low severity (0.8:0.5:1.0 weight ratio of ammonia, water, and biomass) or high severity (1.5:0.8:1.0 ratio of ammonia, water, and biomass) pretreatment. The low severity pretreatment is for highly digestible material such as corn stover (Teymouri, et al., 2005) , wheat straw, and mixed grasses, and requires much less energy input than the high severity pretreatment. The high severity is for highly recalcitrant biomass such as switchgrass (Garlock, et al., 2011), miscanthus (Murnen, et al., 2007), or native prairie, in which a high concentration of sugars is not attainable under low severity conditions. The total sugar production from each type of biomass was obtained from previous studies of biomass composition and sugar yield (as a percentage of total C5 or C6 sugars). In addition to affecting sugar production, the composition of the biomass and the amount of sugars produced affects the amount of electricity that can be produced. The pretreatment severity, biomass composition, sugar yield, and gross electricity production of each type of biomass is shown in Table 4. Net electricity revenue was estimated by calculating the gross electricity production and subtracting off steam use and electricity required in the biorefinery as determined via the National Renewable Energy Laboratory (NREL) model (Humbird, et al., 2011). Purchase price of electricity from the grid was assumed to be \$0.068/kWh (Bals and Dale, 2011)while the selling price to the grid was set at \$0.0572/kWh (Humbird et al., 2011)

To estimate the costs associated with ethanol production, process models of both the LBPDs (Bals and Dale, 2011) and the biorefinery were developed. The LBPD model sizes the major pieces of equipment based on expected incoming biomass to estimate the fixed costs associated with production. Variable costs include labor, maintenance, ammonia use (fixed at 22 g/kg biomass treated), and purchased natural gas and electricity. The biorefinery model is based on one developed by the NREL and adapted for use in this process. In this model, the costs associated with pretreatment were eliminated (for the centralized biorefinery, the costs for AFEX were determined by the same method as in the LBPDs). In addition, the fixed costs for downstream processes (saccharification, fermentation, distillation, wastewater treatment, and combustion) were all sized appropriately for the process conditions used in this study. The capital cost was estimated annually as the total capital investment annuitized over the total lifetime (20 years for the pretreatment and LBPD, 30 years for the refinery) assuming an annual interest rate of 5%. For this study, the processing assumptions were 20% solid loading during saccharification (Bals, et al., 2011), a total of 72 hours residence time between saccharification and fermentation, 100% C6 sugar consumption, 80% xylose consumption (Jin, et al., 2010), 60% arabinose consumption, and an enzyme loading of 10 mg/g biomass (Gao, et al., 2010). Enzymes were assumed to be purchased at $3.60/kg for this study(Humbird, et al., 2011). The variable operating costs of labor, maintenance, fly ash removal and nutrients for fermentation were drawn from the NREL model. Total steam and electricity consumption were also determined from the biorefinery and subtracted from the gross electricity production. Total fixed and variable costs for the LBPDs, centralized biorefinery in the LBPDs approach, and centralized biorefinery in the no-LBPD scenario are shown in Table 5.

## 4- Model Simulation Results and Discussion

After calibration to 2007-09 average crop market prices and land use, the entire model was run without ethanol production to generate predicted baseline environmental outcome levels corresponding to farming conditions in 2007-09 (Egbendewe-Mondzozo et al., 2011a). Then, holding all other parameters constant, ethanol price was progressively raised from \$1.78/gal to \$3.36/gal (or \$2.66/gal to \$5.05/gal gasoline-gallon-equivalent, using the fact that 1.5 gallons of ethanol are need to produce the energy equivalent of one gallon of gasoline). The range of ethanol prices was chosen to start at \$1.78/gal, the minimum 2010 price (Agricultural Marketing Resource Center, 2011) and end at \$3.36, a forward looking price that corresponds to gasoline just over \$5.00/gal. The biorefinery capacity is set to 700Gg/year for a near medium size biorefinery of 2000Mg/day. Given that energy biomass is not currently commercially produced in Michigan, the average biomass price at the biorefinery gate is calculated as the shadow price of the capacity constraints expressed in Equation (5). This value expresses the implied total cost (direct cost plus opportunity cost) of producing biomass to meet the required biorefinery operating capacity. The initial results are presented in terms of the types of biomass supplied by farmers, the total profits earned from biomass production and conversion activities, the land use change, and the changes in environmental output levels compared to the baseline without biomass production. Ethanol yield parameters are subsequently modified to analyze the sensitivity of the initial results to technological change in biomass plant growth and conversion techniques.

### *4.1. Initial results*

For the centralized biorefinery configuration, only low cost biomass types from annual crop residues (corn stover and wheat straw) are supplied as feedstock (Figure 3a). By contrast, in the LBPD configuration, diverse sources of feedstock are supplied, including not only annual crop residues (corn stover and wheat straw) but also perennial energy biomass such as grass mixes. The supply of perennial energy crops as feedstock under the LBPD configuration is explained by the fact that the LBPDs operate with minimum capacity levels and additional feedstock from expensive biomass sources are needed to reach the minimum capacity in certain local depots. As a consequence of using more expensive sources of biomass plus the fixed costs needed for building these LBPDs, the joint enterprise of biomass and ethanol production will be profitable under the LBPD configuration only if the ethanol price reaches or exceeds $2.30/gal (corresponding to a minimum biomass price level of $74/Mg). By contrast, with centralized ethanol production, the joint enterprise becomes profitable at ethanol price of $2.00/gal (for a minimum biomass price level of $44/Mg).

As for land use, in the LBPD configuration about 2% of cropland (roughly 9,000 acres) is diverted to perennial energy biomass production (Figure 3b). As a result of using more perennial crops, the dispersed LBPD configuration yields less environmental damage (nutrient runoff, greenhouse gas emissions, spatial diversity of land use, and soil erosion) than the centralized biorefinery configuration. Clearly, there is a trade-off between total farm and biorefinery enterprise profitability and environmental quality. High biorefinery profitability implies use of the least cost biomass feedstock from crop residues of annual crops that cause more environmental damage than perennial crops. By contrast, moving to the LBPD configuration encourages the use of more perennial crops that cause less environmental damage but lack revenue from a grain product and so require a higher biomass price to cover costs. The LBPD results suggest that variants of the LBPD configuration (like shifting capacity to areas with more corn and wheat residue availability) could increase profitability, but those same changes would result in more environmental damage.

### *4.2. Sensitivity to a medium increase of switchgrass ethanol yield*

The initial model results in little production of perennial biomass crops in part because they require a more severe pretreatment to achieve similar ethanol yields than the crop residues. In the face of active research globally to increase the yield of biofuel from perennial crops, we wish to examine technological change scenarios for lower cost processing via improvements in the ethanol yield from resistant forms of biomass. We specifically consider two scenarios for enhanced ethanol yield from switchgrass. The medium increase scenario increases the ethanol yield parameter for switchgrass from 277.1 liters/Mg to 298.6 (an 8% increase) while also shifting its pretreatment requirements to low severity from high severity. The results in Figure 4 show that the only major changes that would result from this medium improvement in ethanol yield consist of switchgrass replacing the grass mixes under the LBPD configuration. The small amount of switchgrass produced under the centralized biorefinery configuration is insufficient to induce much change in profitability (Figure 4a) and environmental outputs (Figure 4b) compared to the baseline scenario.

### *4.3. Sensitivity to a high increase in switchgrass ethanol yield*

A more optimistic technological change scenario would cause a high increase in the switchgrass ethanol yield from 277.1liters/Mg to 323.1 liters/Mg (a 17% increase), while continuing to require only low severity pretreatment. If the ethanol yield from switchgrass increases by 17%, the centralized biorefinery would demand more switchgrass as feedstock and progressively replace the low cost crop residues biomass with switchgrass as the ethanol price increases (Figure 5a). In the LBPD configuration, the minimum capacity requirement at each LBPD produces a slower decline in the use of annual crop residues as biomass. The centralized biorefinery configuration would still be profitable at $2.00/gal ethanol price (as in the initial scenario) but at a higher minimum biomass price of $60/Mg (since switchgrass remains an expensive source of biomass relative to annual crop residues). Even with the high increase in ethanol yield from switchgrass, for the LBPD configuration to become profitable would require an ethanol price of $2.20/gal with biomass minimum biomass price of $74/Mg, as in the initial scenario.

The high increase in switchgrass ethanol yield causes a decline in land use for wheat cropping systems in favor of more perennial cropping systems (Figure 5b). As ethanol price increases, land for perennials increases from 0% to 8% of total crop land (0 to 52,000 ha). As a consequence of perennial cropping systems adoption, the levels of environmental damage are reduced relative to the initial scenario results. As ethanol price increases, the environmental results improved gradually as more switchgrass is used as feedstock in the biorefinery. Contrary to the initial scenario results, a large increase in ethanol yield from switchgrass causes environmental outputs to improve more under the centralized biorefinery configuration than under the LBPD configuration. At high ethanol prices (greater than $3/Gal), the environmental outputs improve to a point similar to the baseline level of no biomass production.

## 5. Conclusion

This paper develops an optimization model to analyze the impact of two biorefinery spatial configurations on the total profitability of biomass production and conversion to ethanol along with associated implications for land use and environment in southern Michigan. Our initial results show that the centralized biorefinery configuration is more profitable than the local biomass processing depot (LBPD) configuration because the minimum capacity constraint required for LBPDs to operate causes the use of more expensive perennial biomass sources as feedstock. Nevertheless, the LDPD configuration produces less environmental harm than the centralized biorefinery configuration. Specifically, the use of more perennial crops in the biomass feedstock mix causes less greenhouse gas emissions, and less nutrient runoff in the spatially dispersed LBPD configuration compared to the centralized biorefinery.

To evaluate how our initial results might respond to technological change in the efficiency of biomass conversion, we simulated two additional scenarios under which ethanol yield from switchgrass is increased by 8% and 17% respectively. We find that with an 8% increase in ethanol yield from switchgrass, the perennial grass mixes that were initially produced in the LBPD configuration will be replaced by switchgrass, leaving profitability and environmental results without significant change. However, with a 17% increase in the ethanol yield from switchgrass, we find that increasing quantities of switchgrass will displace the biomass from annual crop residues as the ethanol price increases. In particular, wheat-based crop rotations decline in favor of perennial cropping systems. As a consequence of introducing more perennials, the greenhouse gas and nutrient runoff levels gradually improve as ethanol price increases. The changes are most pronounced in the centralized biorefinery, rather than the dispersed LBPD scenario.

This research establishes the potential for spatially dispersed biomass processing to generate better environmental outcomes than centralized biorefining for cellulosic ethanol. However, with current technology, costs of ethanol production remain high. Especially for the spatially dispersed local biomass processing depots, costs of ethanol production exceed revenues at lower ethanol prices. Improvements in the ethanol conversion efficiency of more resistant forms of ligno-cellulosic biomass, could trigger substantial shifts toward perennial feedstocks such as switchgrass, with attendant benefits in water quality and greenhouse gas emissions. Interestingly, however, such technological change leads to greater environmental gains (and profits) for the centralized biorefinery than for the decentralized local biomass processing depots. Clearly, both spatial configuration and technological gains in processing efficiency can have important repercussions for the environmental performance of biofuel production systems.

Further research will be needed to explore related means to enhance profitability and mitigate the environmental consequences of increased production of cellulosic ethanol. The sale of ethanol production byproducts for animal feed has been found to reduce the threshold for biorefinery profitability(Sendich and Dale, 2009). Two spatial configuration approaches deserve further attention to reduce environmental consequences of biofuel production. First, this paper shows evidence that the location and capacity constraints of individual LBPDs can affect spatial distribution of perennial crop production, thereby driving selected environmental consequences. Second, more spatially explicit models of environmental fate, such as the Soil and Water Assessment Tool (SWAT) have shown that placement of specific crops *within* a watershed can affect water quality(Gassman, et al., 2007). Hence, future research should explore the potential to achieve better environmental outcomes from biofuel production with the same set of resources by manipulating the location both of perennial crops within watersheds and of individual local biomass processing depots that service a centralized biorefinery.

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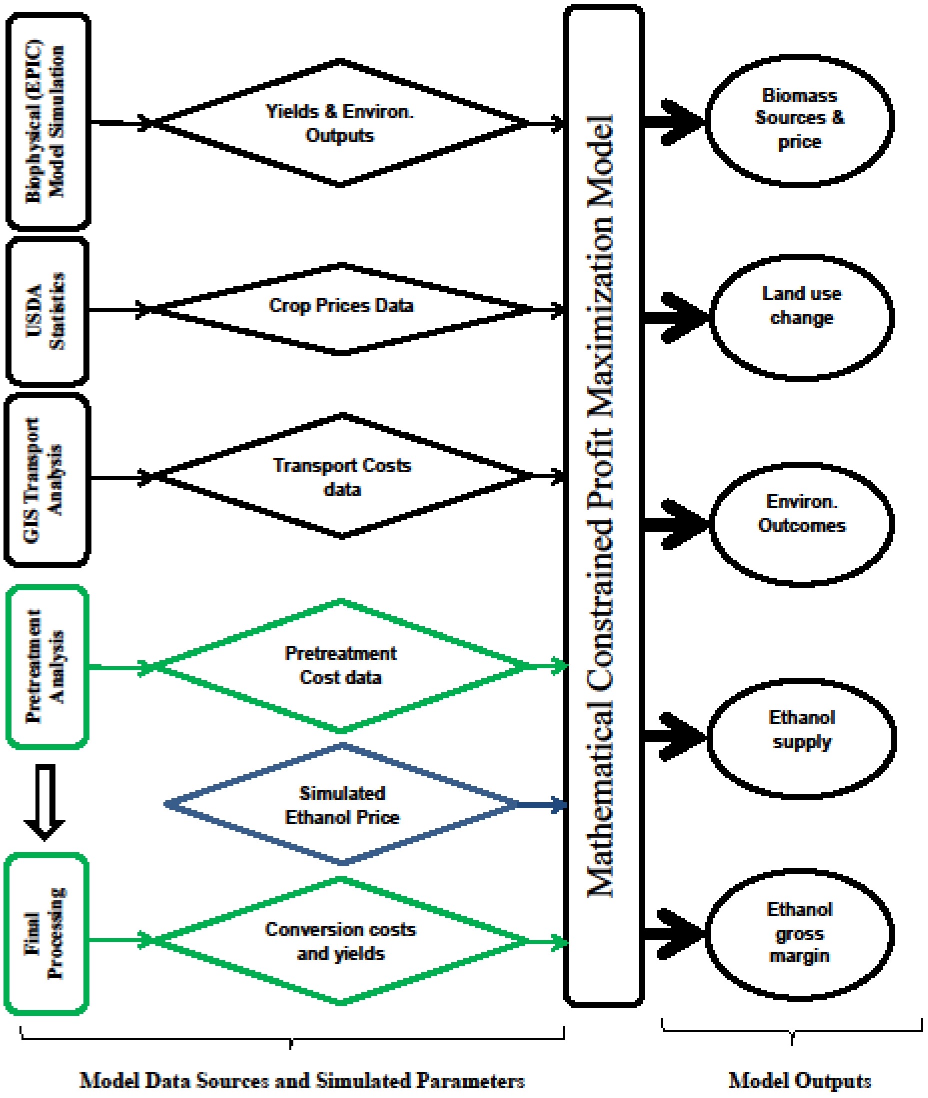

**Figure 1:** Model structure

**Table 1:** Simulated cropping systems

| Rotation | Tillage | Fertilizer level | Residue removal | Rotation length (years) | Number of cropping systems |
|---|---|---|---|---|---|
| Alfalfa-alfalfa-alfalfa-corn-corn | Till or No-till | Medium or High | Yes (50%) or No (0%) | 5 | 8 |
| Continuous corn | Till or No-till | Medium or High | Yes (50%) or No (0%) | 1 | 8 |
| Corn-soybean-canola | Till or No-till | Medium or High | Yes (50%) or No(0%) | 3 | 8 |
| Corn-soybean | Till or No-till | Medium or High | Yes (50%) or No (0%) | 2 | 8 |
| Corn-soybean-wheat | Till or No-till | Medium or High | Yes (50%) or No (0%) | 3 | 8 |
| Corn-corn-soybean | Till or No-till | Medium or High | Yes (50%) or No (0%) | 3 | 8 |
| Grass mixes of 5 types | No-till | Medium or High | - | 12 | 2 |
| Grass mixes of 6 types | No-till | Medium or High | - | 12 | 2 |
| Miscanthus | No-till | Medium or High | - | 12 | 2 |
| Native prairie cool season | No-till | Medium or High | - | 12 | 2 |
| Native prairie warm season | No-till | Medium or High | - | 12 | 2 |
| Hybrid poplar | No-till | Medium or High | - | 12 | 2 |
| Switchgrass | No-till | Medium or High | - | 12 | 2 |
| Alfalfa-alfalfa-alfalfa-corn(for silage)-corn (for silage) | Till or No-till | Medium or High | - | 5 | 4 |
| Continuous corn (for silage) | Till or No-till | Medium or High | - | 1 | 4 |
| Corn (for silage)-soybean-canola | Till or No-till | Medium or High | - | 3 | 4 |
| Corn (for silage)-soybean | Till or No-till | Medium or High | - | 2 | 4 |
| Corn (for silage)-soybean-wheat | Till or No-till | Medium or High | - | 3 | 4 |
| **All systems** | | | | | **82** |

Source: Egbendewe-Mondzozo et al. (2011)

**Table 2**: Model parameters and variables definitions

| Parameters, sets and variables | Definition |
|---|---|
| Sets | |
| $h$ | Set of 9 biomass outputs studied in the model |
| $i$ | Set of 70 sub-watersheds with good or poor land quality |
| $j$ | Set of 82 cropping systems simulated on each sub-watershed |
| $k$ | Set of 8 local biomass preprocessing depots (LBPDs) |
| $l$ | Set of three fertilizer nutrients used in the cropping systems |
| $n$ | Set of five environmental outputs of cropping systems |
| $s$ | Set of 15 traditional and biomass crop products combined |
| Parameters | |
| $a_{ijs}$ | Yield of crop $s$ from land parcel $i$ and cropping system $j$ |
| $b_i$ | Maximum quantity of cropland available in sub-watershed $i$ |
| $c_j$ | Average cost of production for cropping system $j$ |
| $e_{nj}$ | Value of environmental output $n$ in cropping system $j$ |
| $o_{lj}$ | Quantity per ha of fertilizer nutrient $l$ used in cropping system $j$ |
| $p_s$ | Market price of crop $s$ |
| $r_l$ | Unit cost of fertilizer nutrient $l$ |
| $\emptyset_s$ | Storage loss coefficient for biomass products |
| $\rho_s$ | Average base yield in the calibration of the output product $s$ |
| $\delta_s$ | Average linear yield decline with increasing land allocated to output product $s$ |
| $E_n^o$ | Quantity limit of environmental outputs allowed |
| $q, d$ | Assumed ethanol prices ($q$) and electricity price ($d$) |
| $M$ | Environmental constraints control parameter |
| $\varphi_h$ | Unit pretreatment variable cost for biomass type $h$ |
| $\omega_h$ | Unit ethanol conversion variable costs for biomass type $h$ |
| $\pi_h, \mu_h$ | Ethanol yield ($\pi_h$) and electricity yield ($\mu_h$) from biomass type $h$ |
| Variables | |
| $TC_h$ | Cost of transporting biomass product $h$ to the demand point |
| $\Psi$ | Total quantity of all biomass produced in the region |
| $x_{ij}$ | Quantity of land in sub-watershed $i$ allocated to cropping system $j$ |
| $PTFC$ | Pretreatment fixed costs |
| $PTVC$ | Pretreatment variable costs |
| $RCFC$ | Refinery conversion fixed costs |
| $RCVC$ | Refinery conversion variable costs |
| $RET$ | Revenues from ethanol sales |
| $REL$ | Revenues from net electricity sales |

**Table 3:** Parameters used in the empirical model

| Parameters | Values | Units | Source |
|---|---|---|---|
| *Field crop prices(as-stored basis)* | | | |
| Corn grain | 162.60 | $/Mg | 2007-2009 average from USDA-NASS |
| Soybean | 364.87 | $/Mg | |
| Wheat | 241.07 | $/Mg | |
| Alfalfa | 147.11 | $/Mg | |
| Canola | 400.95 | $/Mg | |
| Corn silage | 49.82 | $/Mg | Estimated by authors |
| *Fertilizer nutrient prices* | | | |
| Nitrogen | 0.95 | $/kg | 2007-2009 average from Stein (2010) |
| Phosphorus | 0.94 | $/kg | |
| Potassium | 1.00 | $/kg | |
| *Transport cost parameters* | | | |
| Loading and unloading | 3.37 | $/Mg | Updated from Graham et al. (2000) |
| Hauling distance cost | 0.09 | $/Mg-km | |
| Hauling time cost | 4.26 | $/Mg-h | |
| *Simulated EPIC mean yields* | | | |
| Corn grain | 6.37 | Mg/ha | 1986-2009 average simulated from EPIC |
| Soybean | 2.14 | Mg/ha | |
| Wheat | 3.03 | Mg/ha | |
| Alfalfa | 7.19 | Mg/ha | |
| Canola | 2.09 | Mg/ha | |
| Corn silage | 12.60 | Mg/ha | |
| Corn stover | 2.91 | Mg/ha | |
| Wheat straw | 2.41 | Mg/ha | |
| Switchgrass | 11.58 | Mg/ha | |
| Poplar | 8.06 | Mg/ha | |
| Miscanthus | 16.75 | Mg/ha | |
| Native prairie–- cool season | 8.17 | Mg/ha | |
| Native prairie–- warm season | 7.73 | Mg/ha | |
| Grass mixes of 5 types | 10.42 | Mg/ha | |
| Grass mixes of 6 types | 10.81 | Mg/ha | |
| *Storage loss coefficient* | 88 | kg/Mg | Obtained from Brechbill et al. (2011) |

Note: Biomass yields are given as dry matter but crops grain yields are on as-stored basis

**Table 4**: List of properties for the types of biomass considered in the study

| Biomass | Glucan content (g/kg) | Xylan content (g/kg) | Pretreatment severity | Ethanol yields (L/Mg) | Electricity produced[a] (kWh/Mg) | Variable costs[b] ($/Mg) |
|---|---|---|---|---|---|---|
| Corn stover | 350 | 220 | Low | 275.80 | 368.98 | 55.33 |
| Switchgrass | 335 | 240 | High | 277.10 | 367.67 | 55.32 |
| Miscanthus | 440 | 190 | High | 267.20 | 455.28 | 55.75 |
| Native prairies | 290 | 170 | Low | 208.30 | 428.74 | 55.63 |
| Wheat straw | 380 | 230 | Low | 295.50 | 360.42 | 55.28 |
| Grass mixes | 320 | 200 | Low | 274.10 | 323.63 | 55.11 |
| Poplar | 440 | 150 | High | 189.50 | 608.18 | 56.39 |

[a] Electricity produced after combusting the non-fermented biomass and supplying all heat and power to all operations except pretreatment in the biorefinery.

[b] Variable costs at the biorefinery, excluding pretreatment costs.

**Table 5**: Variable and capital costs associated with the facilities modeled

| Types[a] | Size (Mg/day) | Low severity variable costs ($/Mg) | High severity variable costs ($/Mg) | Capital costs (Million $/year) |
|---|---|---|---|---|
| LBPD | 100 | 42.73 | 49.60 | 0.79 |
| LBPD | 250 | 30.09 | 36.96 | 1.77 |
| Pretreatment | 550 | 30.40 | 37.94 | 1.50 |
| Pretreatment | 2000 | 31.70 | 39.24 | 5.25 |
| Biorefinery[b] | 2000 | | | 10.09 |

[a] The three types of facilities are 1) LBPDs, 2) Pretreatment centers at a centralized biorefinery, 3) the centralized biorefinery excluding pretreatment operations.

[b] The biorefinery variable costs are determined by the biomass type and listed in Table 4.

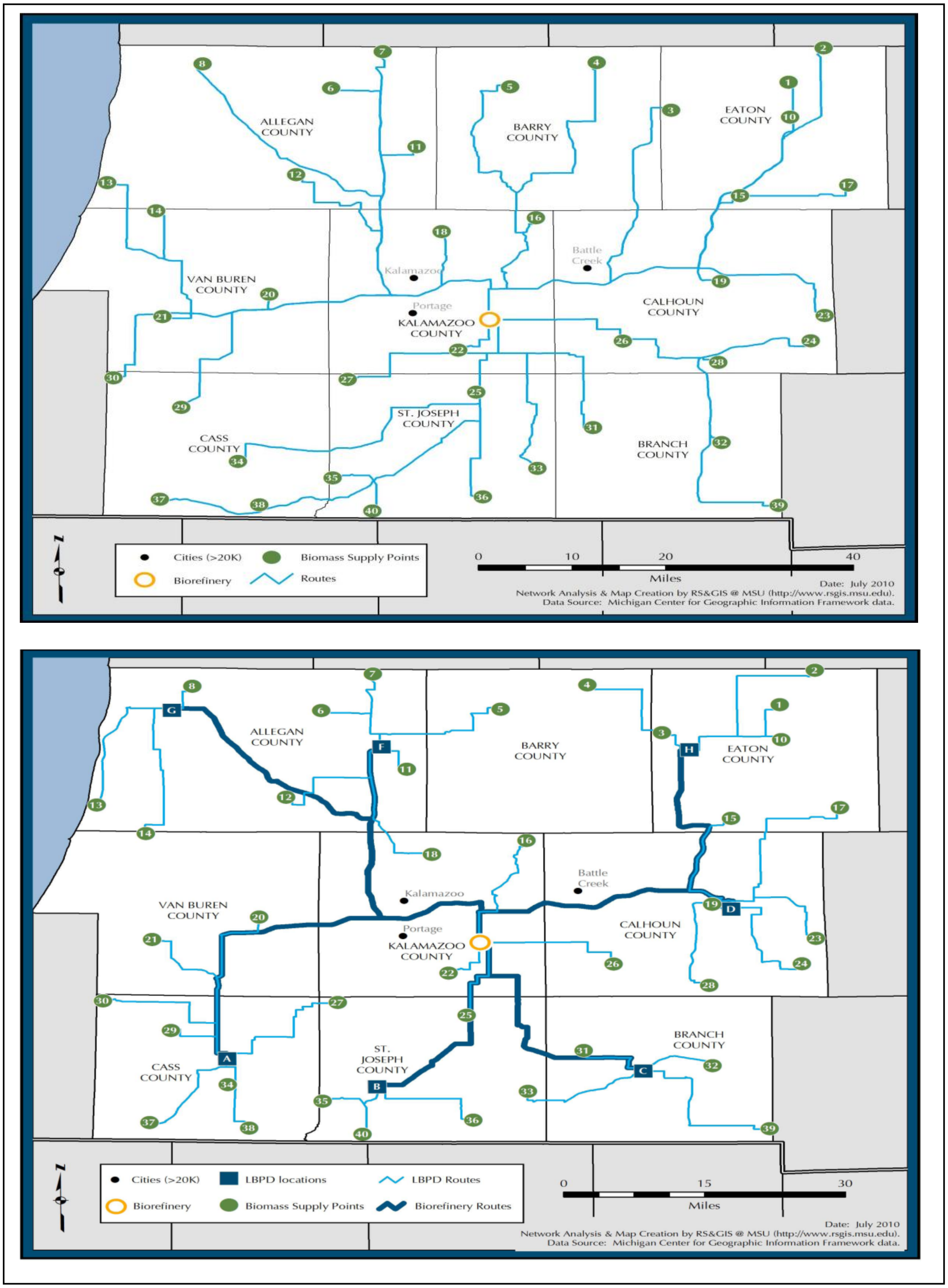

**Figure 2**: Southwest Michigan sub-region with the centralized biorefinery spatial configuration (upper map) and LBPD spatial configuration (bottom map).

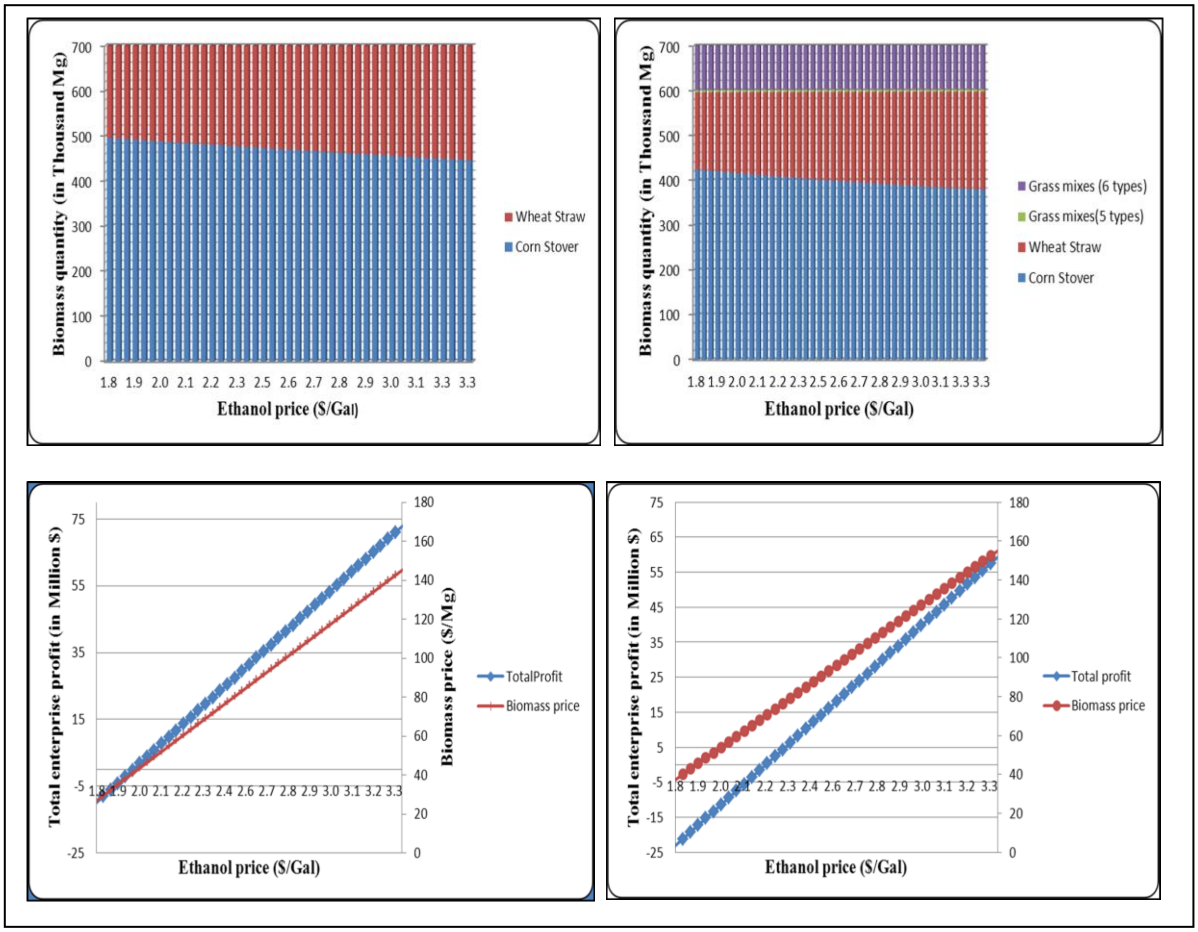

**Figure 3a**: Biomass sources (upper panels) and profitability (lower panels) comparison under centralized biorefinery (left panels) versus local biomass processing depots (right panels).

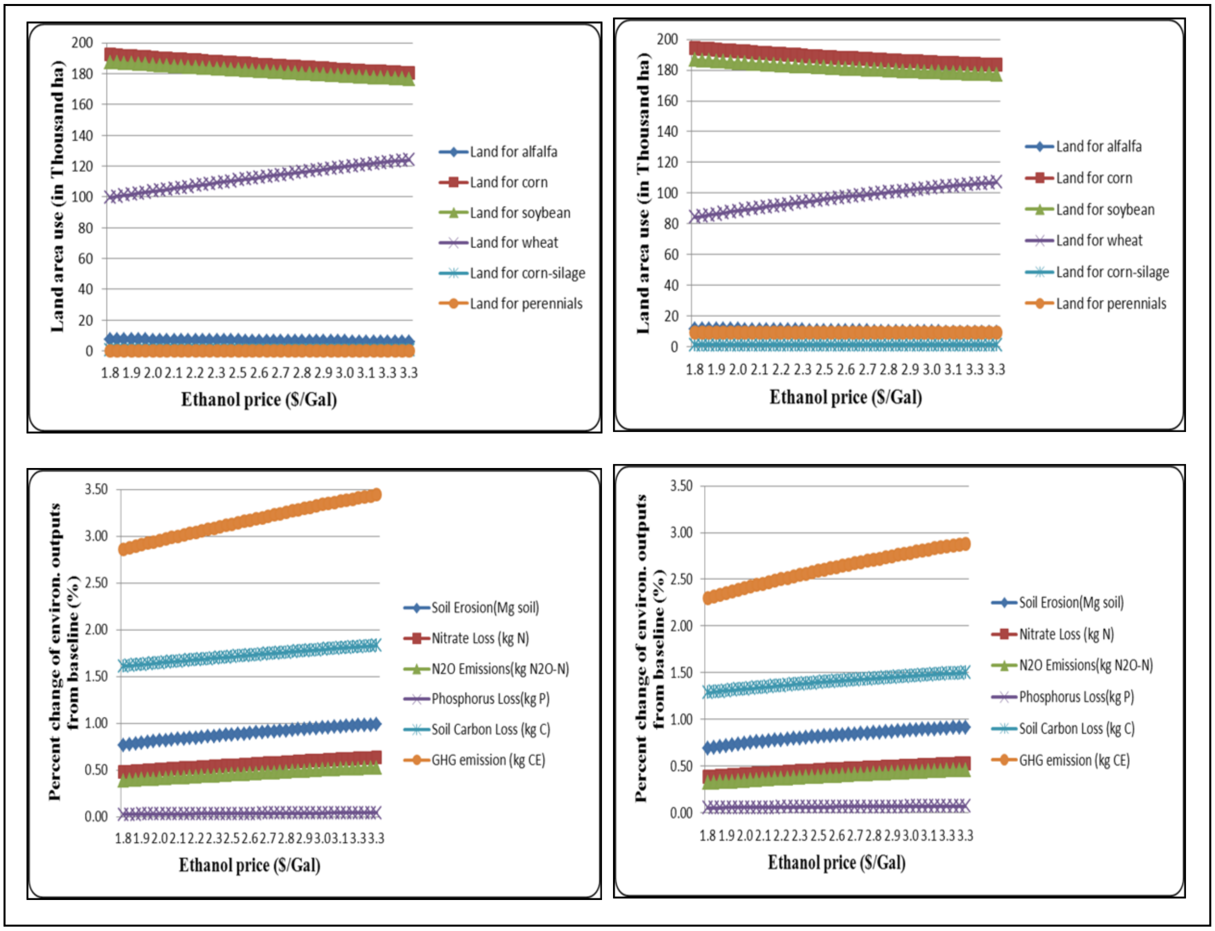

**Figure 3b**: Land use change (upper panels) and environmental outputs change (lower panels) comparison under centralized biorefinery (left panels) versus local biomass processing depots (right panels).

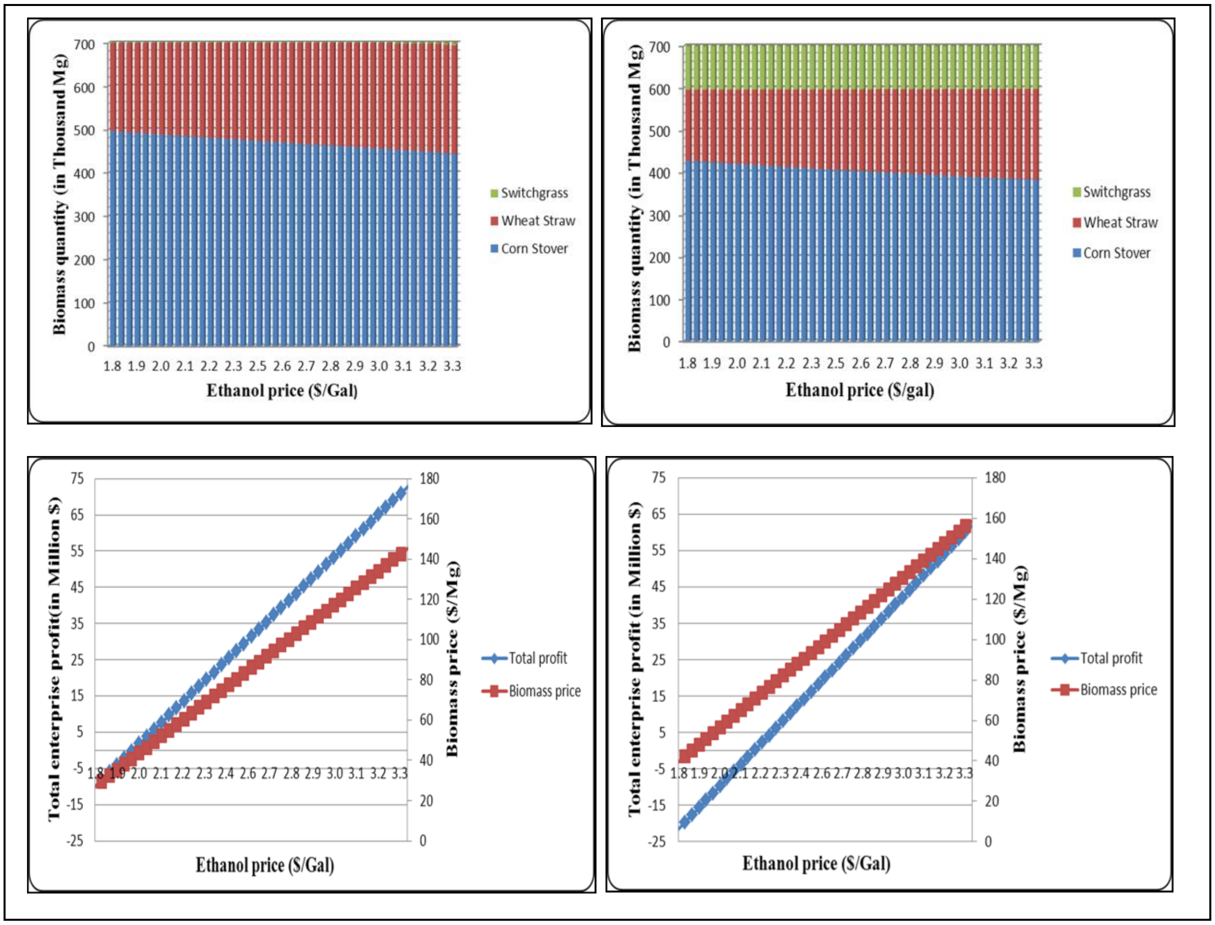

**Figure 4a:** Biomass sources (upper panels) and profitability (lower panels) comparison under centralized biorefinery (left panels) versus local biomass processing depots (right panels) *with medium (8%) increase in switchgrass ethanol yields*.

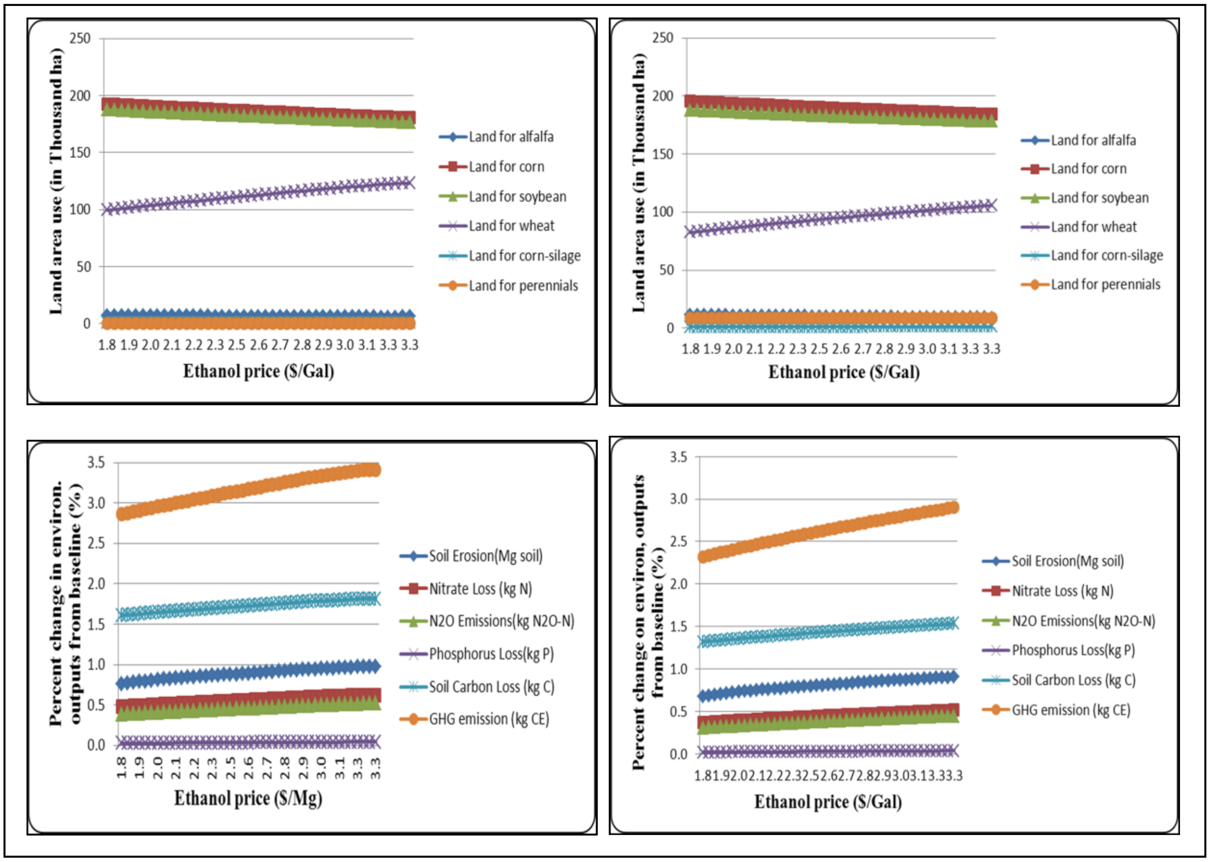

**Figure 4b:** Land use change (upper panels) and environmental outputs change (lower panels) comparison under centralized biorefinery (left panels) versus local biomass processing depots (right panels) *with medium (8%) increase in switchgrass ethanol yields*.

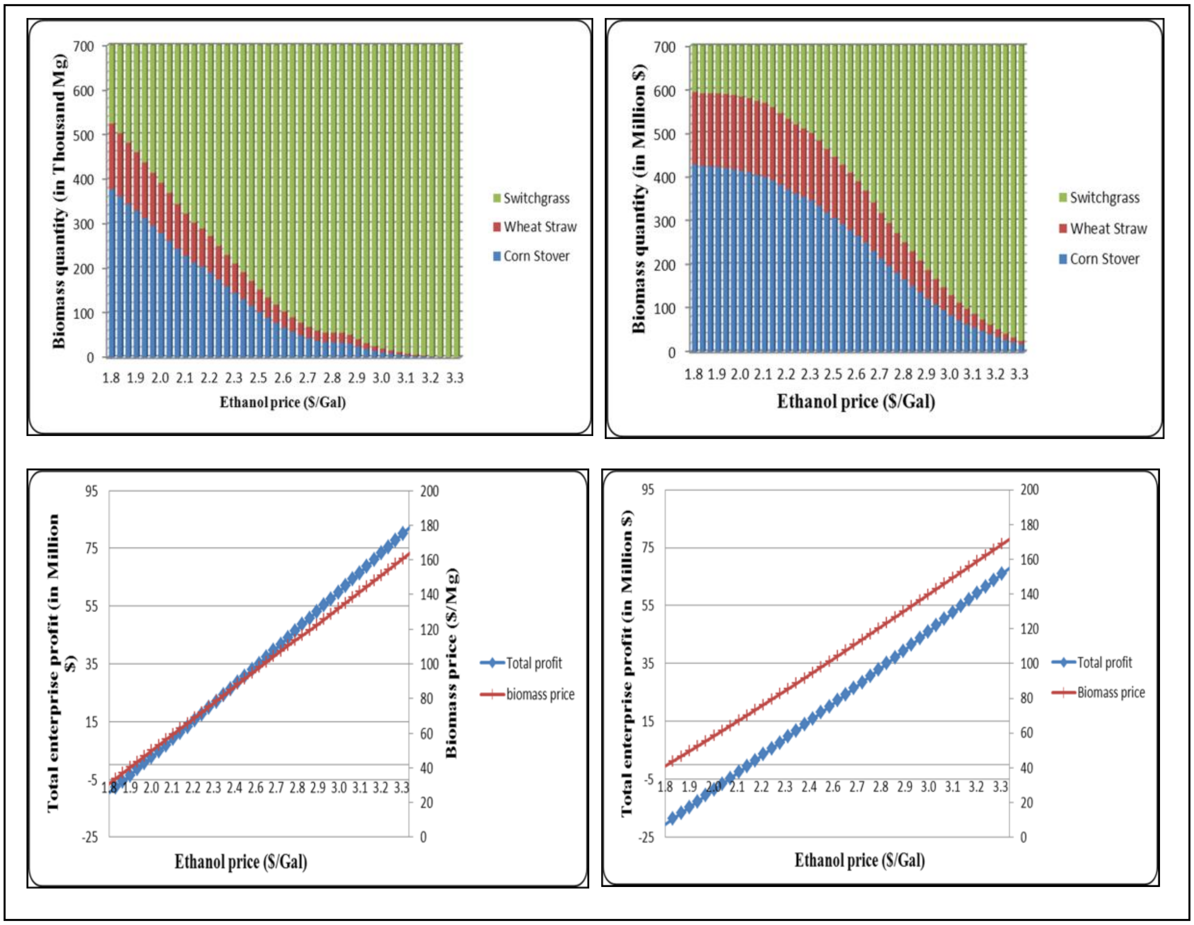

**Figure 5a:** Biomass sources (upper panels) and profitability (lower panels) comparison under centralized biorefinery (left panels) versus local biomass processing depots (right panels) *with high (17%) increase in switchgrass ethanol yields*.

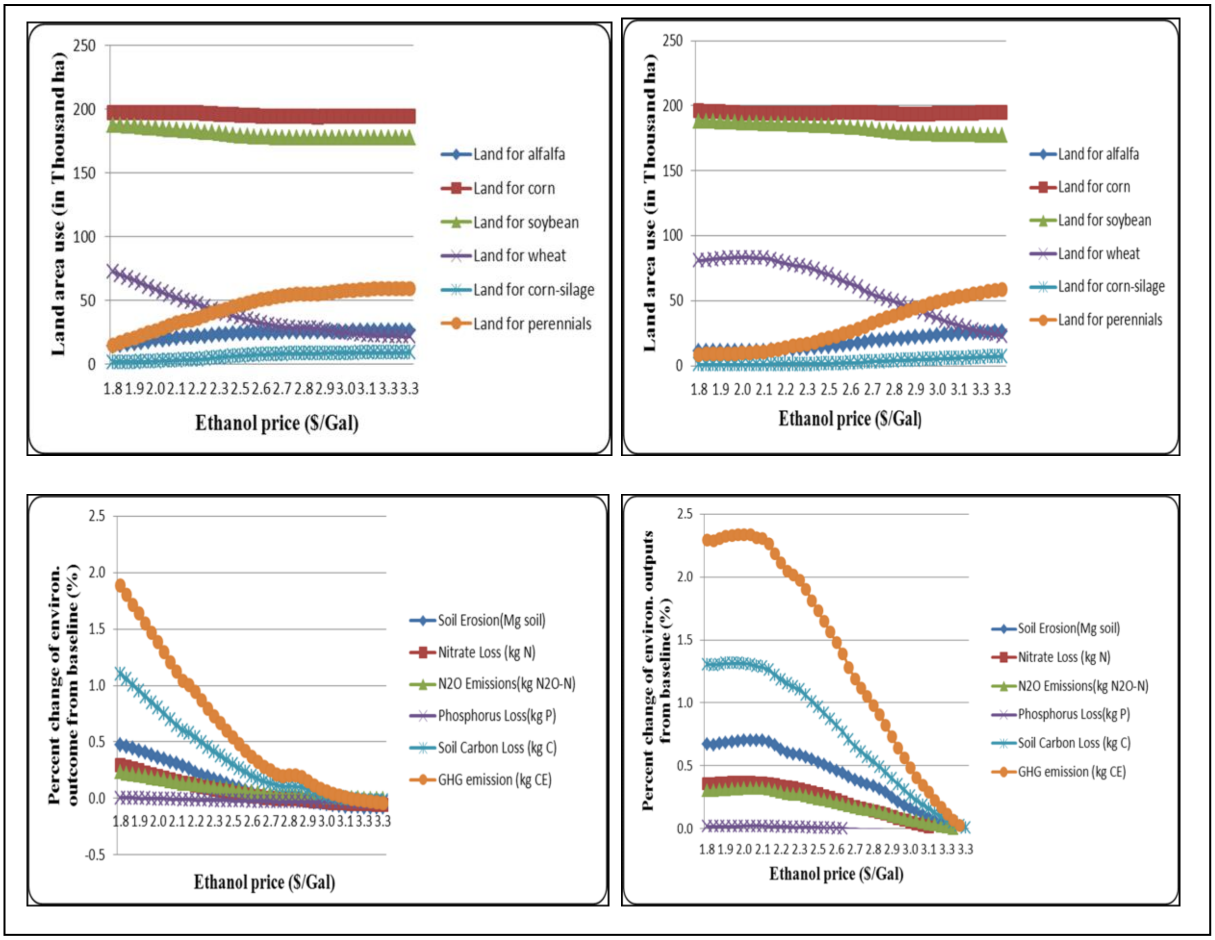

**Figure 5b:** Land use change (upper panels) and environmental outputs change (lower panels) comparison under centralized biorefinery (left panels) versus local biomass processing depots (right panels) *with high (17%) increase in switchgrass ethanol yields*.