The Trade-off between Bioenergy and Emissions When Land Is Scarce

Nathan S. Kauffman and Dermot J. Hayes

Working Paper 11-WP 519
January 2011

Center for Agricultural and Rural Development
Iowa State University
Ames, Iowa 50011-1070
www.card.iastate.edu

Nathan Kauffman is a research assistant in the Department of Economics at Iowa State University and Dermot Hayes is a professor of economics and of finance at Iowa State University.

The authors acknowledge partial financial support from the Bioeconomy Institute at Iowa State University.

Questions or comments about the contents of this paper should be directed to Nathan Kauffman, 173 Heady Hall, Iowa State University, Ames, Iowa 50011-1070; Ph: (515) 294-2469; Fax: (515) 294-6336; E-mail: nathank@iastate.edu.

Abstract

Agricultural biofuels require the use of scarce land, and this land has opportunity cost. We explore the objective function of a social planner who includes a land constraint in the optimization decision to minimize environmental cost. The results show that emissions should be measured on a per acre basis. Conventional agricultural life cycle assessments for biofuels report carbon emissions on a per gallon basis, thereby ignoring the implications of land scarcity and implicitly assuming an infinite supply of the inputs needed for production. Switchgrass and corn are then modeled as competing alternatives to show how the inclusion of a land constraint can influence life cycle rankings and alter policy conclusions.

Keywords: biofuels, biomass, energy policy, land use, life cycle analysis.
JEL codes: Q16, Q48, Q58

The merits of biofuels relative to their fossil fuel counterparts often include independence from foreign oil supplies and lower greenhouse gas (GHG) emissions. That biofuels accomplish the first of these is not often disputed. The degree to which biofuels achieve the latter, however, has been vigorously debated. The controversies notwithstanding, the U.S. Congress first passed renewable fuel volume mandates in the Energy Policy Act of 2005. These mandates became known as the Renewable Fuel Standard (RFS). In 2007, the mandates were expanded through the enactment of the Energy Independence and Security Act (EISA), and the corresponding renewable fuel standards are now referred to as RFS2. In phases, EISA requires that 36 billion gallons of renewable fuel be blended into transportation fuel by 2022. In addition to the increased volume mandates, there are two key modifications to the original 2005 energy policy. The first is the disaggregation into four types of biofuels: renewable fuels, advanced biofuels, biomass-based diesel, and cellulosic biofuels. The second is the specification of GHG emission reduction thresholds for each category that must be met in order to qualify under RFS2.

In accordance with EISA, the Environmental Protection Agency (EPA) was delegated the responsibility of overseeing the implementation of RFS2. In this regard, the EPA conducted life cycle assessments (LCAs) for various biofuel pathways that would potentially be used in fulfillment of the RFS2 mandates. In their final rule, which became effective July 1, 2010, the EPA determined that corn grain ethanol produced at facilities coming online after 2007 would satisfy the 20% reduction in GHG emissions required to qualify as a renewable fuel (EPA 2010a). Likewise, cellulosic ethanol produced from both corn stover and switchgrass via enzymatic fermentation was determined to qualify as cellulosic biofuel as defined in EISA.

The purpose of the LCA is to measure all of the GHG emissions associated with the production and use of a particular biofuel in what is known as a "well-to-wheels" approach. The LCA conducted by the EPA, as well as other conventional agricultural LCAs, measures GHG emissions as the amount of carbon dioxide equivalent emitted per unit of energy provided by the pathway (i.e., gCO_2e/mmBTU). This measurement is then compared to a gasoline baseline so as to determine the percentage reduction in GHG emissions generated. This then determines whether the biofuel pathway qualifies within a specified category of biofuels. Well-known LCA models such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model and Biofuel Energy Systems Simulator (BESS) similarly measure emissions per gallon.[1] In their paper on indirect land use change, Searchinger et al. (2008) make use of GREET life cycle assessments whereby emissions are also measured per gallon. Farrell et al. (2006) determine emissions per gallon in an earlier work. However, there is a significant shortcoming of these per gallon LCAs in that they do not account for the critical role that land scarcity plays in ranking biofuel pathways according to their emissions reduction potential.

The environmental ranking of biofuel pathways that one obtains based on a measurement of emissions per gallon is not necessarily the same that one would obtain after accounting for differences in energy yields per acre. For example, according to the EPA analysis in the 2022 scenario (EPA 2010b), switchgrass used for production of cellulosic ethanol leads to a 110% reduction in GHG emissions. Corn grain ethanol leads to a 21% reduction. It would seem that switchgrass is certainly the more environmentally friendly of the two choices. However, if the quantity of gasoline displaced by production of ethanol from an acre of corn grain plus corn stover is sufficiently greater than that displaced from an acre of switchgrass, it is conceivable that corn could be the environmentally superior feedstock choice on a per acre basis. Although demonstrated here with corn and switchgrass, this same concept of potentially incorrect per acre emissions rankings is valid when comparing any single energy crop with a crop that generates multiple sources of energy from the same acre of land.

The case for a per acre measurement of emissions becomes even more compelling if there is an additional value to biofuel production beyond that associated with carbon. Assuming for the moment that corn yields more energy per acre than switchgrass, then more value derived from biofuel production results in a higher opportunity cost of choosing to grow switchgrass. Thus, even though switchgrass has a substantially better carbon profile per gallon than corn, there is a point at which it is not optimal from a social planner's perspective to choose switchgrass for production of biofuels if corn (both grain and stover) is available as an alternative feedstock. This could be due to either low carbon prices or high external values to biofuel production.

Deriving value from two sources on the same unit of land is not a new concept in agriculture, but it has not been adequately represented in a life cycle emissions setting. Farmers that choose to harvest corn for silage attribute value to both the grain and the stover on the same acreage. The same is true in ascribing value to the production of soybean oil and soybean meal from the same acre of soybeans. The value of both of these commodities is embedded in a farmer's decision to grow soybeans. Moreover, in deciding whether to grow soybeans or corn, a farmer also takes into account per acre yield differences across crops and would not choose to grow soybeans simply because the price per bushel is higher than that of corn. A per acre measure of social cost, emissions, is also consistent with this logic where commonality resides in the fact that there is a fixed amount of land available to grow crops. The requirement that emissions be measured per acre then is a result that falls out of any model that acknowledges a fixed amount of land.

The purpose of this article is to explore the implications of conventional agricultural LCAs that do not consider the effects of land scarcity and the corresponding opportunity cost of feedstock choice. A two-stage optimization model is presented in which the social planner includes all internal and external costs. In the first stage, the social planner chooses the optimal amount of land to allocate to biofuel production given alternative potential uses of land. In the second stage, the social planner determines how to use the land that has been allocated to biofuel production. Our focus will be on the second stage. The second-stage optimization consists of a two-part objective function that the social planner maximizes by choosing among available biofuel pathways subject to a land constraint. The first part of the objective function is the cost associated with net GHG emissions given a price on carbon. This portion represents the environmental benefit associated with biofuel production. The second part of the objective function represents an external value associated with biofuel production that might be due to a desire to reduce dependence on imported oil. For the purposes of this study, we consider two competing feedstock choices: corn and switchgrass. In the case of corn, both grain and stover are used for production of ethanol.

The optimal solution to the social planner's problem will depend on three key factors: the relative energy yield per acre of corn and switchgrass, the price of carbon, and the external value to biofuel production. Even when there is no external value to production, the results will show that it is highly unlikely that switchgrass would be optimally chosen as a feedstock for biofuel production, particularly in the midwestern United States. In a more realistic setting where there is an additional external value to biofuel production, switchgrass becomes even more unlikely to be optimally chosen under most reasonable circumstances.

The article is organized as follows. In the next section, a model is introduced that is taken as the optimization problem that a social planner (i.e., U.S. society) would solve. Then, data and parameter assumptions required to solve the model are presented and described. The optimization problem is then solved numerically based on the defined parameter assumptions. Finally, the numerical solution to the model generates an "optimality frontier," which will be interpreted as an implied carbon price curve. The magnitudes of implied carbon prices will be used to illustrate the likelihood of switchgrass being optimal when compared to projected carbon prices. The model will be solved under two cases: first without, then with an external value to biofuel production. A discussion of the policy implications of the results is then presented, and the last section of the article provides concluding remarks.

The Model

The goal of society is separated into two maximization stages considered to be additively separable. In the first stage, the social planner has a fixed amount of land available and chooses to allocate land to either the production of biofuels or some other alternative. This alternative can be thought of as land allocated to food production. In this stage, the social planner faces a trade-off between bioenergy and food production.

First-Stage Optimization

This maximization problem is represented as follows:

$$\max_{\eta_b, \eta_f} \; b(\eta_b)\eta_b + f(\eta_b)\eta_f \tag{1}$$

subject to

$$\eta_b + \eta_f \leq T \tag{2}$$

$$\eta_b \geq 0, \eta_f \geq 0 \tag{3}$$

where η_b, (η_f) is the fraction of acreage devoted to biofuel (food and feed) production, $b(\eta_b)$ is the value associated with biofuel production, and $f(\eta_b)$ is the value associated with food and feed production. T is the (fixed) amount of land that the social planner has at his disposal. We do not attempt to solve this maximization problem. Arriving at functional forms for $b(\eta_b)$ and $f(\eta_b)$ are beyond the scope of this paper, although it is reasonable to assume that $\frac{\partial b(\eta_b)}{\partial \eta_b} < 0$ and $\frac{\partial f(\eta_b)}{\partial \eta_b} > 0$. For our purposes, we simply recognize that one of the solutions to the problem is the optimal acreage devoted to biofuel production, η_b^*.

Second-Stage Optimization

In the second stage, the social planner has already determined the amount of land available for biofuel production, η_b^*. From this available land, the social planner seeks to minimize the cost associated with emissions while maximizing the value attributable to biofuel production by choosing among potential biofuel pathways subject to a land constraint. For simplicity, we normalize η_b^* to be equal to 1, which amounts to a normalization of T given in the first stage. The model is expressed as

(4) $$\underset{\{\eta_i\}}{Max} \; -P\sum_i \gamma_i \eta_i + S\sum_i \delta_i \eta_i$$

subject to

(5) $$\sum_i \eta_i \leq 1 = \eta_b^*$$

(6) $$\eta_i \geq 0, \forall i$$

Here, η_i is the share of acreage devoted to biofuel pathway i, γ_i is the amount of GHG emissions corresponding to pathway i measured in metric tons of CO_2e per acre, δ_i is the energy yield corresponding to pathway i measured in gal/acre, P is the price of carbon in \$/Mt, and S is the positive externality associated with biofuel production measured in \$/gal. The term on the left-hand side of the maximand is the total cost associated with GHG emissions. (The negative sign makes it a benefit to be maximized.) The term on the right-hand side corresponds to the total "non-carbon" value attributable to biofuel production as previously motivated. The social planner thus maximizes the total value of biofuel production as shown in (4) subject to constraints (5) and (6).

Equations (2) and (5) represent a land constraint. While these are seemingly obvious constraints to include in the social planner's problem, their significance has been largely ignored in conventional agricultural LCAs and corresponding policy decisions. The land constraints simply state that the sum of acreage shares cannot be greater than one. The presence of this land constraint is what induces opportunity cost. Without this constraint, one would effectively be arguing that there is no opportunity cost associated with pathway choice and that land is costlessly available. Trivially, the optimal pathway in this case would be the one that reduces emissions the most in absolute terms, since land would be unconstrained, an indefensible supposition.

The first-order Kuhn-Tucker conditions corresponding to (4) are

$$-P\gamma_i + S\delta_i - \lambda \le 0; \quad \text{with C.S.C}: \eta_i\left(-P\gamma_i + S\delta_i - \lambda\right) = 0 \quad \forall i \tag{7}$$

where there is one FOC given by (7) for each biofuel pathway i in the choice set, and λ is the Lagrangian multiplier on the acreage constraint, representing the shadow value of an additional unit of land made available for biofuel production. From these FOCs, it can be seen that an interior solution only exists when $-P(\gamma_i - \gamma_j) = S(\delta_i - \delta_j)$ for $i \ne j$. In other words, the share of acreage devoted to two biofuel pathways will only be simultaneously positive if the difference between per acre emissions and per acre biofuel yield for pathways i and j, weighted by the respective prices for carbon, P, and per gallon biofuel value, S, coincidentally happen to be equal. For all practical purposes, this is a zero probability event. Thus, the solution to our problem will virtually always be a corner solution, where only one biofuel pathway is optimal.

For this study, we consider only two potential biofuel pathways, i.e., $i \in \{c, s\}$. Here, the subscript c denotes a pathway where land is allocated to corn; corn grain is used for production of ethanol and corn stover is used for production of cellulosic ethanol. The subscript s denotes a pathway where land is allocated to switchgrass, which is used for production of cellulosic ethanol. The problem explicitly considered in this article is thus represented as

$$\text{(8)} \qquad \underset{\eta_c, \eta_s}{Max} \; -P(\gamma_c \eta_c + \gamma_s \eta_s) + S(\delta_c \eta_c + \delta_s \eta_s)$$

subject to

$$\text{(9)} \qquad \eta_c + \eta_s \leq 1$$

$$\text{(10)} \qquad \eta_c \geq 0, \eta_s \geq 0$$

Alternative Social Planner Problem

Given that conventional agricultural LCAs measure emissions as gCO_2e/gal, it is worthwhile to consider an alternative social planner problem making use of these measurements and determine whether or not it would provide the same theoretical solution as that obtained with emissions measured per acre. Rather than choosing the share of acres devoted to each pathway, suppose a social planner chooses the share of gallons produced from each biofuel pathway, having an LCA measure of emissions in gCO_2e/gal. This analogous social planner problem would be specified as follows:

(11) $$\underset{g_c, g_s}{Max} \; -P(\phi_c g_c + \phi_s g_s) + S(g_c + g_s)$$

subject to

(12) $$g_c + g_s \leq 1$$

(13) $$g_c \in \{0,1\}, g_s \in \{0,1\}$$

where ϕ_i is emissions measured as gCO_2e/gal, g_i is the share of gallons produced from pathway i, and all other notation is as before. Here, the constraint given by (13) is explicitly making use of the reality that an interior solution where $0 < g_c^* < 1$ and $0 < g_s^* < 1$ is essentially a zero probability event. Then, the question can be asked under what conditions the solutions given by (8) will be the same as those of (11). In other words, if $\eta_c^* = 1$, under what conditions will we be guaranteed that $g_c^* = \eta_c^* = 1$?

Multiplying (8) by a scalar factor, $\frac{1}{\delta_c}$ does not change the optimal solution to the problem (although the value of the objective function is indeed altered). This results in

(14) $$\underset{\eta_c, \eta_s}{Max} \; -P\left(\phi_c \eta_c + \frac{\gamma_s}{\delta_s}\eta_s\right) + S\left(\eta_c + \frac{\delta_s}{\delta_c}\eta_s\right)$$

Equation (14) shows that in order for the solutions in (8) and (11) to be the same, (11) must be formulated as

(15) $$\underset{g_c, g_s}{Max} \; -P(\phi_c g_c + \beta\phi_s g_s) + S(g_c + \beta g_s)$$

where β is the relative energy yield ratio between pathways c and s and where $g_i = \eta_i$.

The implications of this result are best seen by rewriting (15) as

$$\text{(16)} \qquad \underset{g_c, g_s}{Max} \; -P_c \phi_c g_c - P_s \phi_s g_s + S_c g_c + S_s g_s$$

where $P_c = P$ and $S_c = S$ as before, but now it is apparent that we need a pathway-specific carbon price P_s as well as a pathway-specific biofuel production value S_s such that $P_s = \beta P$ and $S_s = \beta S$ to account for the fact that different biofuel pathways have differing energy yields per acre of land. For example, if corn has a higher energy yield per acre than switchgrass, the per gallon external production value as well as the carbon price on emissions for ethanol produced from switchgrass must be discounted by β. This is a very strong requirement and not likely to be implemented in practice. Nevertheless, it is a requirement that must be met in order to ensure that the opportunity costs arising from a land constraint be embedded in a social planner's problem in which life cycle emissions are measured on a per gallon basis.

Data and Parameters

The purpose of this section is to first present and describe the methodology and results of the LCAs conducted by the EPA in which emissions are measured on a per mmBTU basis. These measurements are then converted to a per acre basis to be used in the model described in the previous section. When parameters are used that deviate from those used in the EPA analysis, a justification is provided based on relevant literature.

The EPA has conducted LCAs for the production of ethanol from corn grain and cellulosic ethanol from corn stover and switchgrass. The LCAs utilizing corn grain and corn stover are combined into one pathway in order to obtain per acre emissions associated with corn. Likewise, the LCA for switchgrass is used to obtain per acre emissions associated with switchgrass as a feedstock for production of cellulosic ethanol. The EPA methodology is relevant to our work because we use all of the EPA assumptions including those related to indirect land use. The Appendix provides an overview of this methodology.

Table 1 displays the average annual emissions for the categories specified in the EPA analysis along with emissions from the 2005 gasoline baseline used for comparison and the corresponding percentage reduction in emissions that each pathway generates. As can be seen from the table, the production of cellulosic ethanol from corn stover (129% reduction in GHG emissions) meets the EISA requirements as a cellulosic (and advanced) biofuel whereas production of ethanol from corn grain (21% reduction) meets only the requirement for a renewable fuel.

Given the measure of emissions as shown in table 1, it is a simple exercise to convert to a measure of emissions per acre if we know the amount of energy provided by an acre of feedstock (i.e., mmBTU/acre). However, 2022 yield projections, particularly for switchgrass, are highly uncertain. Moreover, there is also uncertainty as to the external value of biofuel production. Making parameter assumptions for each of these, while resulting in an easily determinable solution to the model, provides little information given the extensive range of possible outcomes of these parameter values. For this reason, we have chosen to model various potential scenarios so as to generate an "optimality frontier," interpreted as an implied carbon price curve. On one side of the frontier, corn is optimal for biofuel production while switchgrass is optimal on the other side over a range of possible yields and external biofuel production values.

Corn Grain Ethanol

In converting GHG emissions from a per mmBTU basis to a per acre basis, some care is required in order to properly account for how emissions change with varying yields. This is particularly relevant for emissions associated with land use change, which is the largest contributor to emissions in the production of corn grain ethanol. With the exception of land use change, it is assumed that emissions as measured in g/mmBTU do not change as yields change. For example, the plant emissions associated with production of one gallon of ethanol are the same regardless of whether corn yields are 180 bu/acre or are 10% lower at 162 bu/acre. Emissions due to land use change must be treated differently. In this case, if corn yields are 162 bu/acre, 10% more acreage devoted to corn is necessary to produce a certain volume of ethanol. Thus, emissions associated with land use change must be 10% higher on a per gallon basis. On a per acre basis, however, emissions associated with land use change are constant.

In order to calculate emissions from land use change for varying yields, the values from the EPA analysis are used as a baseline. For simplicity, it is assumed that the marginal contribution to emissions from an additional gallon of ethanol (or acre of land) due to land use change is equal to the average contribution as determined by the EPA.

Cellulosic Ethanol from Corn Stover

With emissions measured per acre, corn grain ethanol constitutes only one part of the biofuel pathway utilizing corn as a feedstock. The corn stover can also be used for production of cellulosic ethanol. Combining this pathway together with the production of corn grain ethanol to obtain a net measure of emissions associated with corn is a bit more complicated and requires a few more assumptions.

There are two critical, often controversial, assumptions that must be made in any LCA that uses corn stover as a feedstock for production of cellulosic ethanol. These are the rate of corn stover removal and the conversion rate of corn stover to ethanol. It is recognized in the impact analysis that, while needed, specific guidelines for determining sustainable removal rates do not yet exist (EPA 2010b). It is generally accepted that some amount of residue must remain on the field for protection against erosion and to provide nutrients for the next crop. However, there is not widespread agreement as to what constitutes a sustainable removal rate, recognizing that a field's susceptibility to erosion is dependent on a number of factors, including tillage, timing of field operations, soil type, field specific characteristics (e.g., slope), and of course the amount of residue left on the field.

Sheehan et al. (2003) estimate corn stover removal rates of 40% for corn acreage under mulch till and 70% under no-till. Perlack et al. (2005) use removal rates of 33%, 54%, and 68% depending on whether the type of tillage is the current (2004) tillage mix, increased no-till, or all no-till in the commonly referenced "Billion Ton Study." There has been some criticism directed at the Billion Ton Study for not being conservative enough on removal rates, suggesting that these are too high because of their focus on soil erosion as the limiting factor whereas soil organic carbon (SOC) is an additional constraint (Wilhelm et al. 2007). The default removal rate assumed in GREET (version 1.8c) is 50%.

The EPA provides an in-depth discussion of the issues surrounding sustainable removal rates, ultimately using assumptions of 0%, 35%, and 50% based on whether the type of tillage is conventional tillage, conservational tillage, or no-till, respectively. In addition to the wide range of removal rates cited in the literature, it is reasonable to assume that in the near-term corn stover would be most advantageously removed from cropland managed under no-till first, given that there is very little stover currently being removed for production of cellulosic ethanol. For these reasons, a removal rate of 50% is assumed for this study.

There is also some disagreement surrounding the conversion rate of agricultural residue into ethanol as cited throughout the literature. According to Kadam and McMillan (2003), who cite unpublished National Renewable Energy Laboratory (NREL) data, the theoretical ethanol yield from corn stover is 115 gallons per dry ton. However, this technology is still in its infancy and significant commercial scale production has yet to be realized. For this reason, there is a great deal of speculation about what a reasonable conversion rate on a commercial scale might be. Sometimes a distinction is made between near-term and long-term technology, with a higher conversion rate assumed in a long-term scenario.

In the impact analysis produced by the EPA, different conversion rates are used depending on the year in which GHG emissions are modeled. For the 2012, 2017, and 2022 scenarios, the EPA uses conversion rates of 71.9, 89.8, and 92.3 gallons per dry ton, respectively. GREET assumes a conversion rate of 90 gallons per dry ton as a default value in both near-term (2010) and long-term (2020) scenarios. In their technical report for NREL, Aden et al. (2002) cite a conversion rate of 87.9 gallons per dry ton. However, in a subsequent analysis, this number is revised sharply downward to 71.9 gallons per dry ton (Aden 2008). In their study, Tokgoz et al. (2007) use a conversion rate of 70 gallons per dry ton. For our analysis, we seek to avoid controversial speculation regarding technology progression and assume a conversion rate of 70 gal/ton.

Based on the assumptions discussed thus far, a per acre measure of emissions associated with cellulosic ethanol production from corn stover can be calculated. It should be noted that there are no emissions associated with land use change in the case of ethanol production from corn stover. This is consistent with the EPA assumption that emissions from land use change are already accounted for in the use of corn grain (whether from food and feed or from biofuel production). Having obtained a measure of emissions per acre for ethanol produced from corn grain and corn stover, we need to simply combine these two measures to arrive at a per acre measure of emissions associated with corn, using both grain and stover as feedstocks for biofuel production.

Cellulosic Ethanol from Switchgrass

As with the LCA for production of cellulosic ethanol from corn stover, there are two particular components of the LCA utilizing switchgrass that have a great deal of uncertainty. The first, as with corn stover, is the conversion rate. The EPA assumes that the conversion rate of switchgrass to ethanol is the same as that of corn stover to ethanol. In reality, these rates should be slightly different because of differing cellulose, hemicellulose, and lignin contents of the respective biomass as shown by Spatari, Zhang, and MacLean (2005) who used a conversion rate of 87.2 gal/ton for switchgrass versus 89.8 for corn stover. Thus, using a conversion rate that is constant across feedstocks results in a minor penalty against corn.

The second source of uncertainty is in regard to switchgrass yields, which vary widely throughout the literature. As stated in the EPA impact analysis, commonly reported yields based on field trials range from 1 to 12 tons per acre depending on, among other things, geographical location, switchgrass variety, and soil attributes (EPA 2010b). Khanna, Dhungana, and Clifton-Brown (2008) reported an average yield in Illinois of 3.9 tons/acre. Lemus et al. (2002) came to a similar conclusion for Iowa switchgrass yields of the “Cave-In-Rock” variety at 3.8 tons/acre. Higher switchgrass yields are typically observed in the south where growing conditions are considered to be more favorable. Cassida et al. (2005) reported a range of switchgrass yields in the south central U.S. of 4.8 to 8.8 tons per acre.

In the proposed ruling issued by the EPA in 2009, switchgrass yields for 2022 were projected at 6.3 (wet) tons per acre. This projection was revised substantially upward in the final rule to 7.8 tons per acre. The modification from the proposed rule to the final rule is based on a study conducted by the Pacific Northwest National Laboratory (Thomson et al. 2009). However, it is unclear how this particular study, which reports simulation-based 30-year regional average yields as ranging from 0.6 to 3.3 tons/acre, justifies the increase in the EPA assumption. When the maximum simulated yields for the regions modeled by Thomson et al. are used, the second highest, after excluding the

South Atlantic-Gulf region, is 7.8 tons/acre. Thus, it is our belief that the EPA switchgrass yields, particularly relative to corn, are excessively optimistic. This highly variable data and widespread disagreement on switchgrass yields underscores the need for our model to be applied over a range of yields.

Table 2 summarizes the per acre emission calculations for each pathway discussed here maintaining the yield assumptions made by the EPA. Corn grain ethanol and cellulosic ethanol are presented separately. The row labeled “Total” represents total emissions not including a gasoline displacement credit based on the amount of energy provided by the pathway on a per acre basis. In order to arrive at a measure of emissions for corn, the totals from corn grain ethanol and cellulosic ethanol from corn stover are combined. For the numerical analysis, the measure of emissions including the gasoline displacement credit is used so as to keep separate the carbon and non-carbon portion of each pathway.

Results

In our model, we want to keep separate the value attributable to carbon (through P and γ_i) and all other value associated with production of ethanol (through S and δ_i). Thus, accounting for the energy content of ethanol and emissions associated with gasoline production, each gallon of ethanol produced by a given pathway generates an additional carbon credit. This adjusted measure of GHG emissions associated with each feedstock is shown in table 2 in the last row labeled “Total Including Gasoline Displacement.”

Having established a methodology for determining a per acre measure of emissions, we now have everything that is required for our optimization model to proceed. For the empirical portion of this study, the optimization model and methodology for converting emissions from a per gallon basis to a per acre basis were programmed in Matlab and the "fmincon" routine was used to obtain solutions to equations (8) through (10). The model is solved over a range of switchgrass yields and external production values to arrive at an optimality frontier representing a switching point between corn and switchgrass as optimally chosen feedstocks. Corn yields are normalized to 165 bu/acre. The ranges considered for this analysis are 3-12 tons/acre for switchgrass yields and $0 to $1.00 per gallon for the external value. The next subsection describes the results when there is no external value to biofuel production. Only the cost associated with GHG emissions is considered. Thereafter, a more realistic scenario is presented in which there is an additional external value to biofuel production beyond that associated with carbon.

Results With No External Biofuel Value

The results of this section show that when emissions are measured per acre, there is a range of yield assumptions whereby the social planner optimally allocates cropland to corn even if there is no external biofuel production value. Figure 1 illustrates these results. Switchgrass yields are presented on the horizontal axis and GHG emissions are shown on the vertical axis.

From figure 1, it can be seen that emissions associated with switchgrass increase as switchgrass yields decrease, moving leftward along the horizontal axis. Emissions associated with corn are constant as yields are held fixed at 165 bu/acre. As a result of measuring emissions per acre, there is a threshold level of switchgrass yields representing an optimality frontier. This threshold, 4.8 tons/acre, is determined as the intersection of the two lines depicted in figure 1. For any switchgrass yields less than 4.8 t/acre, corn is optimal since emissions associated with corn are lower than those of switchgrass.

The results shown here are particularly significant given the current debate in the U.S. Midwest as to whether corn or switchgrass is better for emissions reduction. These results show that the answer to this question depends on whether emissions are considered per acre or per gallon. As we argue, a realistic social planner problem requires that emissions be measured per acre. If this is the case, it is unlikely that switchgrass would be an optimal feedstock choice for production of biofuels in the Midwest based on reasonable yields for that region.

Results With External Biofuel Value

Whereas the previous section illustrated results when there is no external value to biofuel production, this section provides a more realistic setting in which there is an additional per gallon value to producing biofuels, possibly resulting from the desire to reduce dependence on imported oil. For this case, we model equations (8) through (10) as in the previous section, but we add an additional dimension to allow for variability in the external value to biofuel production. The numerical results are illustrated in figure 2.

Consistent with figure 1, corn is always optimal whenever switchgrass yields are below 4.8 t/acre, as seen in figure 2 by the cutoff of the surface plot at this point. For yields lower than this, there is no carbon price that would cause switchgrass to become optimal since emissions reduction favors corn. Conversely, whenever switchgrass yields are greater than 10.2 t/acre, switchgrass is always optimal, since switchgrass reduces emissions more than does corn and has a higher energy yield per acre.

Between these two bounds, switchgrass is better from an emissions reduction perspective, but corn is better from an energy perspective. Thus, assigning a higher weight to the carbon portion of equation (8) through increasing carbon prices causes switchgrass to be favored more relative to corn. The surface of figure 2 can then be interpreted as an implied carbon price curve. Between switchgrass yields of 4.8 t/acre and 10.2 t/acre, there is a carbon price that is implied if switchgrass is indeed considered the optimal feedstock for any given external biofuel production value.

Using the existing $0.45 biofuel tax credit as a frame of reference for the external per gallon value to biofuel production, figure 2 shows that the implied carbon price based on EPA relative yield assumptions is $72/Mt. This is illustrated as point A in figure 2. The implied carbon price at these yield assumptions steadily increases from $8/Mt with a $0.05 external production value to over $100/Mt once the external value rises above $0.65 per gallon. Most near- to long-term projections of carbon prices are within a range around $30/Mt. As shown in figure 2, with a $0.45 per gallon external value to biofuel production, switchgrass yields would need to be at least 8.1 t/acre for switchgrass to be optimal relative to corn. This is represented by point B in figure 2.

In recent years, switchgrass has received steadily increasing attention as a potential feedstock that could be the most suitable for meeting both environmental goals and satisfying the RFS2 mandate for cellulosic biofuel production. This has been especially true in the past two years following a study prepared by Schmer et al. (2008) for the Proceedings of the National Academy of Sciences. In their study, Schmer et al. estimated that switchgrass, used for production of cellulosic ethanol, produces 540%

more energy than it requires in inputs. Their study is based on field-trials of switchgrass grown in the mid-continental United States (Nebraska, South Dakota, and North Dakota) with average yields ranging from 2.3 to 5.0 tons/acre. Schmer et al. strongly imply that, consistent with their results, switchgrass should play a prominent role in the production of U.S. biofuels. The results from our study come to a rather different conclusion.

Average corn yields in Nebraska for 2010 are reported as 166 bu/acre (USDA 2010). From Schmer et al., the highest switchgrass yield observed in Nebraska was 3.9 t/acre. At these yields, corn is always optimal in our model. For North Dakota and South Dakota, the circumstances are only slightly different. Corn yields for 2010 reported for South Dakota are 140 bu/acre and the maximum observed switchgrass yield in South Dakota, according to Schmer et al., was 4.7 t/acre. With a $0.45 external value to biofuel production, the price of carbon must be $280/Mt if switchgrass is to be optimal. It is important to recognize that conventional agricultural LCAs would support the implication made by Schmer et al. that it would be environmentally preferable to grow switchgrass in these regions. As shown by the EPA, switchgrass generates a 110% reduction in GHG emissions whereas corn grain ethanol generates only a 21% reduction. However, when emissions are measured per acre, the gap between these reductions narrows because of differing per acre energy yields. With an added external value to biofuel production, the rankings are actually reversed at any reasonable carbon price such that corn becomes optimal. Thus, expanding on the previous section, it is even more unlikely that midwestern crop yields would be such as to favor switchgrass for production of biofuels in the presence of an external value to biofuel production.

Conclusion

In this article, we describe a model constructed to be representative of the interests of U.S. society to minimize environmental damage associated with the use and production of advanced biofuels while maximizing the value associated with the production of these fuels subject to a land constraint. The structure of this model was designed to encompass opportunity costs associated with selection among competing alternative biofuel pathways and stemming from land scarcity. The structure of the model then requires that GHG emissions be measured on a per acre basis, rather than on a per gallon basis as is done in most agricultural LCAs.

Drawing upon the data and parameter assumptions used by the EPA in conducting LCAs for corn grain ethanol and cellulosic ethanol produced from corn stover and switchgrass, a per acre measurement of GHG emissions was calculated for corn, using both grain and stover, as well as for switchgrass. The optimal pathway was then determined numerically over a range of corn yields, switchgrass yields, and an external per gallon biofuel production value in accordance with the optimization model that was presented. The solutions to this model resulted in an implied carbon price curve, which represents the minimum carbon price required for switchgrass to be an optimal feedstock choice relative to corn in the production of biofuels.

The results of our empirical analysis show that at reasonable Midwest U.S. corn yields (165 bu/acre) and switchgrass yields (4 t/acre), there is no carbon price at which switchgrass is optimal since corn yields more energy per acre as well as having a better carbon profile per acre. Conventional agricultural LCAs would predict that switchgrass would have a better carbon profile than would corn, as they do not take into account differing energy yields per acre once a land constraint is imposed. Under the relative yield assumptions made by the EPA and an external value to biofuel production of $0.45 per gallon, the implied carbon price at which switchgrass is optimally chosen is $72/Mt.

Given that most reasonable near- to mid-term projections of carbon prices lie in a range around $30/Mt, the results of this study indicate that one should be cautious when suggesting that switchgrass is an environmentally superior choice relative to corn. There is a trade-off between GHG emissions (or emissions reduction) and energy production that must be considered. The presence of a land constraint makes this trade-off less obvious than what is often implied by conventional LCAs. Policymakers would be wise to consider the implications of a land constraint when drawing upon the conclusions of agricultural LCAs so as to design policies that are environmentally focused while acknowledging the need for production of alternative transportation fuels.

Appendix

EPA Life Cycle Methodology

To obtain GHG emissions on a life cycle basis, the EPA analyzed two separate scenarios for each biofuel pathway considered in a consequential LCA approach. The first scenario was constructed as a baseline or business-as-usual case in which the volume of biofuels produced in 2022, the final year by which the RFS2 mandates must be phased in, is simply the forecast taken from the 2007 Annual Energy Outlook. Then, in order to determine the average GHG impact of a marginal gallon of biofuel from a specific pathway, a control case is modeled in which the volume of biofuel corresponding to that pathway is set equal to the volume observed in the RFS2 mandates. All of the other biofuel volumes are held constant at the baseline value. For example, in the reference case for renewable biofuel (i.e., ethanol produced from corn grain), the volume modeled is 12.3 billion gallons. The allowable volume under RFS2 for non-advanced renewable biofuel is 15 billion gallons. Each of these scenarios is modeled, and GHG emissions for each are calculated. The difference in emissions between the two scenarios represents the additional emissions associated with 2.7 billion gallons of renewable biofuel.

EPA Biofuel Modeling Approach

The EPA draws on various models and data sources in order to obtain GHG emission measurements. Measures of GHG emissions in domestic categories are obtained using the Forest and Agricultural Sector Optimization Model (FASOM) together with emission factors taken from GREET, DAYCENT (a daily version of the CENTURY ecosystem model) and the Intergovernmental Panel on Climate Change (IPCC) as appropriate. For GHG emissions originating from international sources, Food and Agricultural Policy Research Institute (FAPRI) models are combined with Winrock satellite data. Tailpipe emissions are obtained from Motor Vehicle Emissions Simulator (MOVES) results.

In its impact analysis, the EPA reports a measurement of GHG emissions on a gCO_2e/mmBTU basis for each emission category. The EPA considered various time frames for the amortization of emissions in the proposed rule but decided on 30 years for the final rule with no discounting. Average annual emissions for each category are then easily obtained by dividing the cumulative emissions observed throughout the time frame considered by 30.

Endnote

[1] Throughout this article, the measure of emissions per gallon is treated as being a scaled equivalent to emissions per mmBTU once a BTU/gallon assumption is made. It is also equivalent to emissions per mile driven once a mile/gallon assumption is made.

References

Aden, A. 2008. *Biochemical production of ethanol from corn stover: 2007 state of technology model*. NREL: Golden, CO. NREL/TP-510-43205.

Aden, A., M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B.Wallace, L. Montague, A. Slayton, J. Lukas, et al. 2002. *Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover*. NREL: Golden, CO. NREL/TP-510-32438.

Cassida, K., J. Muir, M. Hussey, J. Read, B. Venuto, and W. Ocumpaugh. 2005. Biomass yield and stand characteristics of switchgrass in south central US environments. *Crop Science* 45 (2):673-681.

Environmental Protection Agency. 2010a. Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule. *Federal Register* 75:58.

———. 2010b. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. EPA-420-R-10-006.

Farrell, A., R. Plevin, B. Turner, A. Jones, M. O'Hare, and D. Kammen. 2006. Ethanol Can Contribute to Energy and Environmental Goals. *Science* 311:506-508.

Kadam, K., and J. McMillan. 2003. Availability of corn stover as a sustainable feedstock for bioethanol production. *Bioresource Technology* 88 (1):17–25.

Khanna, M., B. Dhungana, and J. Clifton-Brown. 2008. Costs of producing miscanthus and switchgrass for bioenergy in Illinois. *Biomass and Bioenergy* 32 (6):482–493.

Lemus, R., E. Brummer, K. Moore, N. Molstad, C. Burras, and M. Barker. 2002.

Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. *Biomass and Bioenergy* 23 (6):433–442.

Perlack, R., L. Wright, A. Turhollow, R. Graham, B. Stokes, and D. Erbach. 2005. *Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply*. Washington DC: U.S. Department of Agriculture, U.S. Department of Energy.

Schmer, M., K. Vogel, R. Mitchell, and R. Perrin. 2008. Net energy of cellulosic ethanol from switchgrass. *Proceedings of the National Academy of Sciences* 105 (2):464-469.

Searchinger, T., R. Heimlich, R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu. 2008. Use of Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change. *Science* 319:1238-1240.

Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelson. 2003. Energy and environmental aspects of using corn stover for fuel ethanol. *Journal of Industrial Ecology* 7 (3-4):117–146.

Spatari, S., Y. Zhang, and H. MacLean. 2005. Life cycle assessment of switchgrass-and corn stover-derived ethanol-fueled automobiles. *Environ. Sci. Technol* 39:9750–9758.

Thomson, A., R. Izarrualde, T. West, D. Parrish, D. Tyler, and J. Williams. 2009. *Simulating potential switchgrass production in the United States*. Pacific Northwest National Laboratory. PNNL-19072.

Tokgoz, S., A. Elobeid, J. Fabiosa, D. Hayes, B. Babcock, T. Yu, F. Dong, C. Hart, and J.

Beghin. 2007. *Emerging biofuels: Outlook of effects on US grain, oilseed, and livestock markets*. CARD Staff Report 07-SR 101. Center for Agricultural and Rural Development, Iowa State University, Ames, IA.

U.S. Department of Agriculture. 2010. Quick Stats. National Agricultural Statistics Service (NASS), Washington D.C. Accessed November, 2010.

Wilhelm, W., J. Johnson, D. Karlen, and D. Lightle. 2007. Corn Stover to Sustain Soil Organic Carbon Further Constrains Biomass Supply. Agronomy Journal 99 (6):1665-1667.

Figures

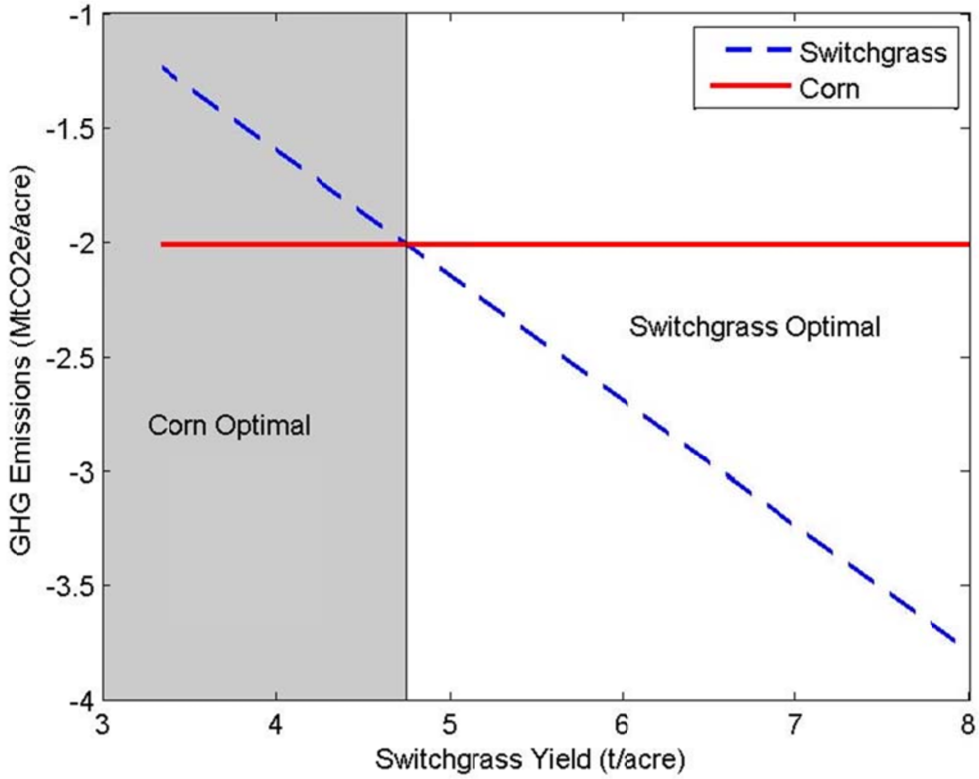

Figure 1. GHG Emissions With No External Value To Biofuel Production

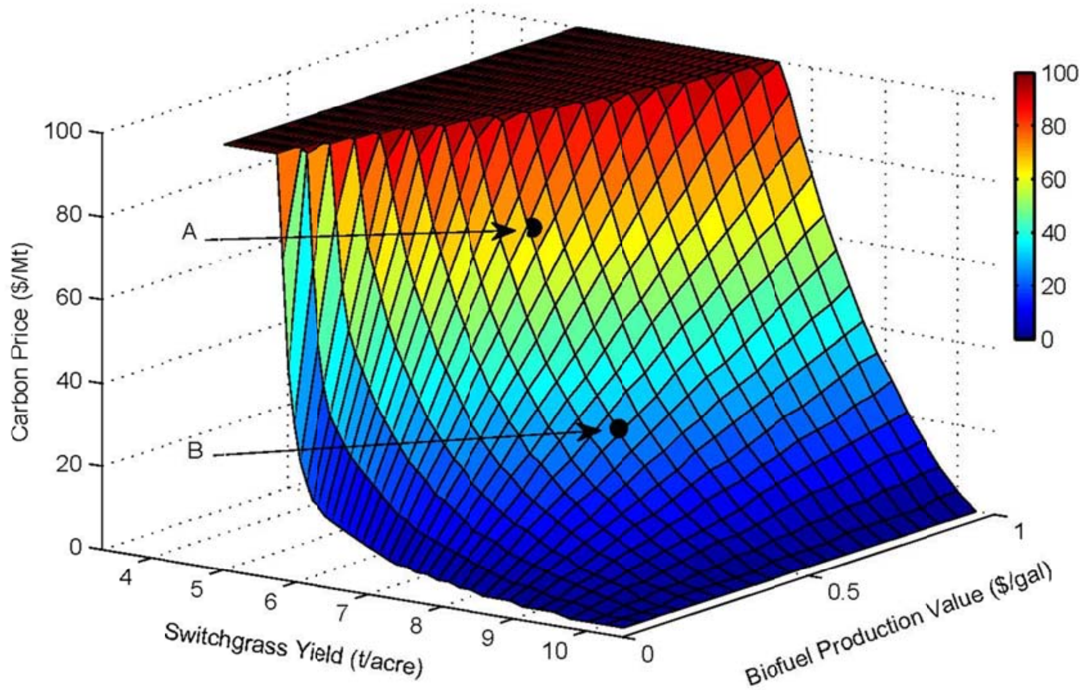

Figure 2. Optimality Frontier: Implied Carbon Price by Switchgrass Optimality

Tables

Table 1. EPA Annualized GHG Emissions by Biofuel Pathway (gCO_2e/mmBTU)

Emissions Category	Corn Grain Ethanol	Cellulosic Ethanol Corn Stover	Cellulosic Ethanol Switchgrass
Int'l Land Use Change	31,797	0	15,073
Fuel and Feedstock Transport	4,265	2,418	2,808
Domestic Farm Inputs and Fertilizer N_2O	8,281	1,660	4,217
Domestic Soil Carbon	-4,033	-10,820	-2,487
Domestic Livestock	-3,746	9,086	3,462
Domestic Rice Methane	-209	434	-1,555
Int'l Farm Inputs and Fertilizer N_2O	6,601	0	1,310
International Livestock	3,458	0	-245
International Rice Methane	2,089	0	-920
Tailpipe	880	880	880
Fuel Production Emissions	27,851	-32,628	-32,628
Total	77,233	-28,969	-10,087
2005 Gasoline Baseline	98,204	98,204	98,204
Percent Change from Gasoline Baseline	-21.4%	-129.5%	-110.3%

Table 2. EPA Annualized GHG Emissions by Biofuel Pathway (gCO_2e/mmBTU)

Emissions Category	Corn Grain	Corn Stover	Switchgrass
International Land Use Change	1.27	0	0.70
Fuel and Feedstock Transport	0.17	0.03	0.10
Domestic Farm Inputs and Fertilizer N_2O	0.33	0.02	0.15
Domestic Soil Carbon	-0.16	-0.17	-0.12
Domestic Livestock	-0.15	0.11	0.12
Domestic Rice Methane	-0.01	0.01	-0.05
International Farm Inputs and Fertilizer N_2O	0.26	0	0.05
International Livestock	0.14	0	-0.01
International Rice Methane	0.08	0	-0.03
Tailpipe	0.04	0.01	0.03
Fuel Production Emissions	1.12	-0.38	-1.15
Total	3.09	-0.38	-0.21
Total Including Gasoline Displacement	-0.84	-1.53	-3.68