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Ethanol production, food and forests

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by

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Ethanol Production, Food and Forests

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(Preliminary version. Comments are welcome)

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Abstract

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1 Introduction

After initially being hailed as a promising climate change mitigation strategy (Pacala and Socolow, 2004; Farrell et al., 2006), biofuels have since been implicated in driving up food prices and causing deforestation (e.g. Righelato and Spracklen, 2007; Fargione et al., 2008; Laurance, 2008; Scharlemann and Laurance, 2008; Tilman et al., 2009). Despite fears about these possible negative effects, expansion of biofuel production continues apace (Rajagopal and Zilberman, 2007).

Biofuel production is currently dominated by ethanol, most of which is produced by the US (corn or maize ethanol) and Brazil (sugarcane ethanol) (IEA, 2007).[1] Global ethanol production is predicted to rise from around 60 billion liters in 2008, to 150 billion liters by 2018 (OECD-FAO, 2009). Producers' efforts to increase their supply capacity are based on expectations of future increased demand, provoked by higher fossil fuel prices, growing mandates for blending biofuels in fossil fuels used for transportation,[2] and the recent commercialization of Flex-Fuel Vehicles.[3] Yet, with carbon dioxide emissions from deforestation and forest degradation accounting for up to one fifth of global emissions of carbon dioxide (van der Werf et al., 2009), it is clear that evidence for ethanol production in causing forest conversion would considerably decrease its attractiveness as a climate change mitigation strategy. But at the current time, the available evidence, e.g. using life-cycle analysis, is not clear-cut and subject to ongoing research and analysis.

The objective of this paper is to contribute to the current debate on the possible social and environmental effects of ethanol production by investigating the impacts of production on land use, deforestation and food production. A partial equilibrium model is developed to map out and hence, better understand the channels through which ethanol production influences the allocation of land and a mobile input, labor, for agricultural production.

One well-understood channel is the land market. Land is a limited resource allocated among different rival uses including forests. In competitive equilibrium, this allocation is such that the marginal net benefits of each use equate. If, for any reason, one of these uses becomes relatively more profitable, it will be allocated more land, at the expense of the other uses in the same region. At the forest frontier, this direct land competition may entail deforestation (e.g. Angelsen, 1999, 2007; Barbier, 2001).

Energy crops for ethanol production can directly compete with forests for land (Chakravorty et al., 2008). This would then increase incentives to clear land for

[1] First generation biofuels are divided into ethanol and biodiesel. Other producers of ethanol include Argentina, South Africa and India.

[2] Countries with such mandates include Brazil, Canada, India, China and the United States, among others.

[3] Flex-Fuel Vehicles are able to run with any blending of gasoline and ethanol.

energy crops. Although this argument applies when energy crops used for ethanol production are grown in forest frontier regions, it is far from obvious that it would still apply if energy crops are grown in regions where forest is not present. This argument is being used in Brazil, for instance, where ethanol producers claim that sugarcane expansion has no effect on deforestation in Amazonia since production occurs at large distance from the forest, e.g. in regions such as the state of Sao Paulo in the south (see Goldemberg and Guardabassi, 2009).

So-called "indirect" impacts of ethanol production have recently been discussed in the literature. The indirectness of these effects is based on the idea that they are manifested even when energy crops and forests grow in different regions. Searchinger et al. (2008) utilise a partial equilibrium computable model of agricultural markets to quantify the increased demand for land arising from US corn ethanol targets. This study shows the possibility of forests being converted to replace cropland diverted to corn production. It concludes that US corn ethanol has a negative net effect in terms of greenhouse gas savings compared to fossil fuels when emissions from indirect land-use changes are taken into account. Although some drawbacks to the methodology used have been identified (see Gallagher, 2008), this study is nevertheless the first to take into account the possible indirect effects of ethanol production. However, the market mechanisms underlying this effect remain unclear. In this paper, we formally investigate these indirect effects in order to clarify the conditions under which they might occur. A two-regions model is developed in which we explicitly consider the case where energy crops and forest grow in different regions.

Additional to deforestation, biofuel production has also been implicated in having a negative impact on food production, again through land competition (e.g. Hubert and Moreaux, 2007). The allocation of land away from food to the production of biofuels will, however, depend on various factors, some of which exhibit a substantial degree of uncertainty, e.g. newer generation biofuels may use land more efficiently than current biofuel technologies (see Chakravorty *et al.* (2009) for a complete review of the fuel-food debate). Although we focus primarily on how ethanol production might impact on land use and forest conversion, our framework for analysis also allows us to consider how it may affect output of the food sector.

In this paper, we develop a two-sector-two-input partial equilibrium model of a national economy, where two final goods – an energy crop[4] and a composite good representing all other agricultural commodities (termed "food") – are produced in two different regions. The two primary inputs considered are land and a mobile

[4] Some energy crops can also be used to produce food or other by-products than ethanol (e.g. sugarcane, which is also used to produce sugar, maize). For simplicity, we assume here that all energy crop produced is devoted to ethanol production. Also, by considering no processing costs, we assume the output price of the energy crop to be just equal to the ethanol price.

input (e.g. labor). Land type, i.e. land productivity, varies across the two regions, one of which includes a residual forest. Property rights over the forest are considered ill-defined. Ill-defined property rights are a common feature of developing and emerging economies (see Feder and Feeney, 1991) which are, with the exception of the US, the main current and likely future ethanol producers. Examples of such countries include Brazil, Colombia and India, among others.

Our results show that ethanol production can impact deforestation and food production in three distinct ways. Two of these, namely the indirect effects via the land and labour markets, are formalised for the first time. Taken together and in contrast to previous research in this area, our framework offers a more complete, integrated picture of how biofuel production might influence land use, deforestation and food production.

First, there is the standard, direct-land-competition effect by which forest conversion is increased while food production declines. Second, we characterize an indirect-displacement effect whereby an increase in ethanol prices reduces inputs available for food production thus entailing a lower output. This lower output may affect food prices and trigger a displacement of food production towards the forest frontier. Consequently, deforestation increases while total food production decreases. Finally, a third indirect effect emerges which relates to the sectors' competition for labor and to this factor's mobility. This labor mobility effect decreases food production but also deforestation by drawing potential migrants into the employ of the energy crop sector located in the non-forest region.

The remainder of the paper is organized as follows. Section 2 presents the model. The three effects are characterized in section 3. Finally, section 4 discusses the results and concludes.

2 The model

We consider a partial equilibrium setting with two inputs, land and labor, being used to produce two different agricultural goods – food and an energy crop. There are two regions in this model differentiated by their land quality. Region 1 has land of better quality, e.g. for agricultural production, than region 2. Forest is present in region 2 but not 1.[5] The objective is to investigate how private agents allocate inputs to the two sectors – depending on output prices – and how these decisions impact on land use, forest conversion and food production.

In the following sub-sections, we describe the assumptions regarding the technology and the institutions embodied in the model.

[5] Forest land is generally not very productive for agriculture (Chomitz and Thomas, 2003).

2.1 Technology

Let X_A and X_B be the quantities of food and energy crop produced, respectively.

2.1.1 The land factor

The amount of land available in region 1 $(\overline{R_1})$ is fixed and is used by both sectors, such that

$(A.1.1)$ $\overline{R_1} = R_{1A} + R_{1B}$, where $R_{1i}, i \in \{A, B\}$ corresponds to the amount of land in region 1 used to produce X_i.

In region 2, besides the initial stock of land $(\overline{R_2})$, agents can obtain additional land through forest conversion. Let R_2^D denote the total land cleared by the two sectors, and $R_{2i}, i \in \{A, B\}$ the amount of initial land in region 2 used to produce X_i. We denote by $R_{2i}^D, i \in \{A, B\}$, the quantity of deforested land used by each sector. Then the total amount of land used for agriculture in region 2 is[6]

$(A.1.2)$ $R_2 = \overline{R_2} + R_2^D$ with $\overline{R_2} = R_{2A} + R_{2B}$ and $R_2^D = R_{2A}^D + R_{2B}^D$.

Producers face a cost depending on the amount of forest land they decide to clear. This deforestation cost is given by $cR_{2i}^D, i \in \{A, B\}$, $c > 0$, where c denotes the unit "cost" of forest conversion, i.e., the cost of allocating time and resources to deforest one unit of land and prepare it for agriculture.

2.1.2 The labor factor

For simplification, we assume the total supply of labor to be inelastic. The economy's total labor endowment is denoted $\overline{L}$. We consider that labor can be either immobile $(A.2)$ or mobile $(\overline{A.2})$, such that if $L_{1i}, i \in \{A, B\}$ are the quantities of labor used by each sector in region 1 and $L_{2i}, i \in \{A, B\}$, the equivalent for region 2, then the constraint over this input can be written as

$(A.2)$: $\overline{L} = \overline{L_1} + \overline{L_2}$ with $\overline{L_1} = L_{1A} + L_{1B}$ and $\overline{L_2} = L_{2A} + L_{2B}$, where the upper bar designs fixed quantities;

or

$(\overline{A.2})$: $\overline{L} = L_1 + L_2 = L_{1A} + L_{1B} + L_{2A} + L_{2B}$, where only the total amount of labor available for the two sectors is fixed.

[6]Note that the maximum possible quantity of R_2 will be attained when all forest is converted into agricultural land. At that point, no more deforestation is possible and the stock of land of quality 2 becomes fixed. For simplicity, we abstract from such a corner solution.

2.1.3 The final good production

$X_i, i \in \{A, B\}$, can be produced in both regions or just in one of them. The latter case represents the possibility that some crops can only be produced using particular types or qualities of land. This can be seen, for example, in the case of Brazil where sugarcane is mostly produced in the centre-south part of the country where the soil and climate suit sugarcane better than that found in the north (Goldember, 2008). Similarly, sugarcane production is concentrated in certain regions of India such as the state of Kerala where conditions are subtropical and relatively wet compared with the north of the country. In order to take this possibility into account,[7] the production function of sector $i \in \{A, B\}$ is given by

$$(A.3)\text{: } X_i = (R_{1i})^{\alpha}(L_{1i})^{\beta} + \theta_i \left[R_{2i} + R_{2i}^{D}\right]^{\alpha} (L_{2i})^{\beta} \ ,$$

where $0 \leq \theta_i < 1$ is a parameter representing the factors' productivity difference between regions 1 and 2.

The special case where the energy crop cannot be produced in region 2, due to agro-ecological constraints, can be represented here by $\theta_B = 0$. In both cases $\alpha + \beta < 1$.

2.2 Institutions

Sectors A and B are competitive and agents are price-takers regarding both output and input prices. We denote by P_A and P_B the world price of food and the energy crop, respectively.[8] While P_B is always exogenously given in the model, we investigate, in case 2 below, the implications of relaxing our assumption concerning P_A, i.e. having P_A affected by the quantity X_A produced in the national economy. Specifically, in this case we assume $P_A = (X_A)^{-\frac{1}{\eta_A}}$ $(\overline{A.4})$, where η_A represents the price elasticity of demand for good A in the world market. In the other cases , 1 and 3, P_A is assumed exogenous $(A.4)$.

Also, let P_1 and P_2 be the national land-rental prices. Wages are given by W_1 and W_2. In the case where labor is perfectly mobile $(\overline{A.2})$, the wage will be the same in both regions such that $W_1 = W_2 = W$. Note that wages vary across regions but not across sectors. This is due to the assumption that mobility within a given region is always possible. Input prices are always determined endogenously in the model.

[7] We note that other crops such as corn and switchgrass may be more adaptable to different conditions than sugarcane.

[8] Since we assume that all the energy crop is devoted to ethanol production, P_B also represents the ethanol price. In the following, we will use the terms "ethanol" and "energy crop" interchangeably.

3 The decentralized equilibrium

In this section we derive factor demands, quantities produced and the amount of deforestation in equilibrium.

The profit of sector $i \in \{A, B\}$ is given by
$\Pi_i = P_i X_i - W_1 L_{1i} - W_2 L_{2i} - P_1 R_{1i} - P_2 R_{2i} - c R_{2i}^D$.
Applying $(A.3)$, profits can be rewritten as

$$\Pi_i = P_i \left\{ (R_{1i})^\alpha (L_{1i})^\beta + \theta_i \left[R_{2i} + R_{2i}^D \right]^\alpha (L_{2i})^\beta \right\} - W_1 L_1 - W_2 L_2 - P_1 R_{1i} - P_2 R_{2i} - c R_{2i}^D.$$

After rearrangement, the first-order conditions for an interior solution write

$$R_{1i} = \left(\frac{P_1}{\alpha P_i} \right)^{\frac{1}{\alpha - 1}} (L_{1i})^{\frac{\beta}{1 - \alpha}}, \tag{1}$$

$$L_{1i} = \left(\frac{W_1}{\beta P_i} \right)^{\frac{1}{\beta - 1}} (R_{1i})^{\frac{\alpha}{1 - \beta}}, \tag{2}$$

$$R_{2i} + R_{2i}^D = \left[\frac{P_2}{\alpha P_i \theta_i} \right]^{\frac{1}{\alpha - 1}} (L_{2i})^{\frac{\beta}{1 - \alpha}}, \tag{3}$$

$$L_{2i} = \left(\frac{W_2}{\beta P_i \theta_i} \right)^{\frac{1}{\beta - 1}} \left(R_{2i} + R_{2i}^D \right)^{\frac{\alpha}{1 - \beta}}, \tag{4}$$

and

$$R_{2i} + R_{2i}^D = \left(\frac{c}{\alpha P_i \theta_i} \right)^{\frac{1}{\alpha - 1}} (L_{2i})^{\frac{\beta}{1 - \alpha}}. \tag{5}$$

Note that from (3) and (5) an interior solution requires $P_2 = c$ at equilibrium. This means that the cost of deforestation, given by c, must be equal to the market rental price of land in region 2. Otherwise, there are two possible corner solutions: either $P_2 < c$ and then no deforestation occurs or, on the contrary $P_2 > c$, and producers would not use the stock of land of type 2 already available $(\overline{R_2})$ and would prefer to clear forest. This paper will only consider interior solutions.[9]

In the subsections below, we present three different cases of equilibrium, in order to explore both direct and indirect effects of ethanol production. First, we

[9] This condition does not rule out the case where all land of type 2 initially available $(\overline{R_2})$ has already been put under production with new land only obtainable through forest conversion.

present the case where the energy crop is grown in the two regions. This implies that in region 2 there will be direct land competition between the three possible land uses. In the two following cases, we restrict the production of the energy crop to region 1, such that all effects of an exogenous increase in the ethanol price on activities in region 2 will be considered as being indirect. These indirect effects operate through the labor and land markets.

3.1 Case 1: The Direct Land Competition Effect

To illustrate the direct effect of ethanol production on deforestation, we assume a fixed stock of labor in each region (*A.2*). By excluding labor mobility we want to highlight the impact of using land to produce ethanol both on food production and deforestation. Moreover, we assume that both sectors A and B use land in the two regions (*A.3*). Finally, we consider the price of food P_A to be exogenously given (*A.4*).

3.1.1 The input demand functions

In this case, the input demand functions are obtained by using (1) and (2), substituting one into the other and rearranging to get

$$R_{1i} = \left(\frac{\alpha P_i}{P_1}\right)^{\frac{1-\beta}{\nu}} \left(\frac{\beta P_i}{W_1}\right)^{\frac{\beta}{\nu}} \tag{6}$$

and

$$L_{1i} = \left(\frac{\beta P_i}{W_1}\right)^{\frac{1-\alpha}{\nu}} \left(\frac{\alpha P_i}{P_1}\right)^{\frac{\alpha}{\nu}}. \tag{7}$$

where $\nu = 1 - \alpha - \beta > 0$.[10]

In the same way, using (3) and (4), we get

$$R_{2i} + R_{2i}^D = \left[\frac{\alpha P_i \theta_i}{P_2}\right]^{\frac{1-\beta}{\nu}} \left(\frac{\beta P_i \theta_i}{W_2}\right)^{\frac{\beta}{\nu}} \tag{8}$$

and

$$L_{2i} = \left(\frac{\beta P_i \theta_i}{W_2}\right)^{\frac{1-\alpha}{\nu}} \left[\frac{\alpha P_i \theta_i}{P_2}\right]^{\frac{\alpha}{\nu}}. \tag{9}$$

[10] $\nu > 0$ follows from our assumption of decreasing returns to scale.

These equations express the quantity of inputs the two sectors demand in order to produce a certain quantity X_i, given output price P_i. Also, using (8), $\overline{R_2} = R_{2A} + R_{2B}$ and $R_2^D = R_{2A}^D + R_{2B}^D$ total forest conversion can be written as

$$R_2^D = \left(\frac{\alpha}{P_2}\right)^{\frac{1-\beta}{\nu}} \left(\frac{\beta}{W_2}\right)^{\frac{\beta}{\nu}} \left[(P_A\theta_A)^{\frac{1}{\nu}} + (P_B\theta_B)^{\frac{1}{\nu}}\right] - \overline{R_2}. \qquad (10)$$

3.1.2 The equilibrium land and labor allocations

Replacing the demand functions derived above in the constraints $R_{1A}+R_{1B} = \overline{R_1}$, $L_{1A}+L_{1B} = \overline{L_1}$, and $L_{2A}+L_{2B} = \overline{L_2}$ one can compute the equilibrium factor prices $P_1^e = \alpha\left[(P_A)^{\frac{1}{\nu}} + (P_B)^{\frac{1}{\nu}}\right]^{\nu} \left(\frac{1}{\overline{R_1}}\right)^{1-\alpha} \left(\overline{L_1}\right)^{\beta}$, $W_1^e = \beta\left[(P_A)^{\frac{1}{\nu}} + (P_B)^{\frac{1}{\nu}}\right]^{\nu} \left(\frac{1}{\overline{L_1}}\right)^{1-\beta} \left(\overline{R_1}\right)^{\alpha}$

and $W_2^e = \beta\left(\frac{\alpha}{c}\right)^{\frac{\alpha}{1-\alpha}} \left[\frac{(P_A)^{\frac{1}{\nu}} + (P_B)^{\frac{1}{\nu}}}{\overline{L_2}}\right]^{\frac{\nu}{1-\alpha}}$, where e refers to equilibrium.

[11] Using these prices and replacing them into the factors' demand functions we obtain the equilibrium input allocations

$$(R_{1i})^e = \frac{\overline{R_1}}{1 + \left(\frac{P_j}{P_i}\right)^{\frac{1}{\nu}}}, \qquad (11)$$

$$(L_{1i})^e = \frac{\overline{L_1}}{1 + \left(\frac{P_j}{P_i}\right)^{\frac{1}{\nu}}}, \qquad (12)$$

$$\left(R_{2i} + R_{2i}^D\right)^e = \left(\frac{\alpha}{c}\right)^{\frac{1}{1-\alpha}} \left[\frac{\overline{L_2}}{(P_i\theta_i)^{\frac{1}{\nu}} + (P_j\theta_j)^{\frac{1}{\nu}}}\right]^{\frac{\beta}{1-\alpha}} (P_i\theta_i)^{\frac{1}{\nu}}, \qquad (13)$$

[11] Since we've assumed $P_2 = c$, we do not have to compute the equilibrium price for land of type 2.

and

$$(L_{2i})^e = \frac{\overline{L_2}}{1 + \left(\frac{P_j\theta_j}{P_i\theta_i}\right)^{\frac{1}{\nu}}}, \tag{14}$$

where $i, j \in \{A, B\}$, $i \neq j$.

These equations represent the equilibrium quantities exchanged in the input markets. From equations (11) and (13) we note that the equilibrium amounts of land used by one sector decrease in the output price of the other sector's final good. For instance, if the price P_B of ethanol increases, ceteris paribus, the amount of land used by sector A in both regions decreases. This is because the energy crop becomes more profitable to produce and sector B consequently demands more land. There will then be a shift of land in favor of the energy crop sector, up to the point where the marginal rents of the two sectors equalize again. This mechanism also holds for the labor factor.

The equilibrium amount of forest conversion is given by

$$\left(R_2^D\right)^e = \left(\frac{\alpha}{c}\right)^{\frac{1}{1-\alpha}} \left(\overline{L_2}\right)^{\frac{\beta}{1-\alpha}} \left[(P_A\theta_A)^{\frac{1}{\nu}} + (P_B\theta_B)^{\frac{1}{\nu}}\right]^{\frac{\nu}{1-\alpha}} - \overline{R_2}. \tag{15}$$

3.1.3 The Direct Land Competition Effect

Proposition 1 *Without labor mobility, and when the food price P_A is given, deforestation is increasing in world ethanol price P_B, as long as $\theta_B > 0$.*

Proof. *Taking the derivative of (15) with respect to P_B yields*

$$\frac{\partial(R_2^D)^e}{\partial P_B} = \left(\frac{1}{1-\alpha}\right)\left(\frac{\alpha}{c}\right)^{\frac{1}{1-\alpha}} (\theta_B)^{\frac{1}{\nu}} (P_B)^{\frac{\alpha+\beta}{\nu}} \left[\frac{\overline{L_2}}{(P_A)^{\frac{1}{\nu}} + (P_B)^{\frac{1}{\nu}}}\right]^{\frac{\beta}{1-\alpha}}$$

which is positive, as long as $\theta_B > 0$. ■

We term this the Direct Land Competition effect. Ethanol production implies setting land aside to grow energy crops. This additional land use increases land competition and pressure on forests. We consider this effect to be direct because the impact on forest conversion is only observable if the energy crop is grown at the forest frontier ($\theta_B > 0$). In the case where $\theta_B = 0$, the equilibrium amount of deforestation given by equation (15) would be independent of the ethanol price P_B.

This result is standard and in line with theory explaining land-use changes by variations in marginal rents of competing land uses (e.g. Angelsen, 1999). This effect has been observed in Brazil, for example, where ethanol producers have been found responsible for illegally clearing the country's rapidly-shrinking Atlantic forest.[12]

Proposition 2 *Without labor mobility, and when the food price P_A is given, food production is decreasing in ethanol price P_B.*

Proof. *Proof of this proposition is obtained by analyzing equations (11) and (13), where the amount of land allocated to one use is, ceteris paribus, decreasing in the other good's price.* ■

This second result establishes the rationale for fuel-food competition and is also in line with the previous literature on land competition among rival uses (ibid).

3.2 Case 2: The Displacement Effect

Similar to the Direct Land Competition effect, the displacement effect materializes through the land market. To isolate this effect we maintain the assumption regarding labor immobility (*A.2*). Also, we set $\theta_B = 0$ such that energy crop production is restricted to region 1, to abstract from the Direct Land Competition effect. Finally, although agents remain price takers, we now consider that the quantity X_A produced in the country affects the world price P_A ($\overline{A.4}$). This corresponds to cases where the country's production represents a significant part of the world total production or where the goods investigated are only traded within the national economy, so that P_A is a national price. The equilibrium amount of inputs used by the two sectors in region 1 are the same as presented in the section above, i.e. they are given by equations (11) and (12). Since sector B is restricted to region 1, it does not employ any labor in region 2. The equilibrium amount of labor for sector A in region 2 is given by $L_{2A} = \overline{L_2}$. Similar reasoning applies for land of type 2, such that $R_{2A} = \overline{R_2}$.

The equilibrium amount of good A produced is given by

$$(X_A)^e = \frac{\left(\overline{R_1}\right)^{\alpha}\left(\overline{L_1}\right)^{\beta}}{\left[1+\left(\frac{P_B}{P_A}\right)^{\frac{1}{\nu}}\right]^{\alpha+\beta}} + (\theta_A)^{\frac{1}{1-\alpha}}\left(\frac{\alpha P_A}{c}\right)^{\frac{\alpha}{1-\alpha}}\left(\overline{L_2}\right)^{\frac{\beta}{1-\alpha}}. \qquad (16)$$

[12] http://www.illegal-logging.info/item_single.php?it_id=2766&it=news

Finally, the total amount of land conversion in this case is given by the following expression:

$$R_2^D = R_{2A}^D = \left(\frac{\alpha P_A \theta_A}{c}\right)^{\frac{1}{1-\alpha}} \left(\overline{L_2}\right)^{\frac{\beta}{1-\alpha}} - \left(\overline{R_2}\right). \tag{17}$$

3.2.1 The Displacement Effect

Proposition 3 *Without labor mobility and if the output price of the food sector P_A is endogenous, then an increase in the world ethanol price increases deforestation, even if the energy crop and the forest grow in different regions.*

Proof. *When P_A is affected by quantity X_A produced in the country, then given $(\overline{A.4})$:*

$X_A = (P_A)^{-\eta_A} \Leftrightarrow X_A (P_A)^{\eta_A} = 1.$

From (16), we see that X_A is decreasing in P_B. Now, consider an increase in P_B. Then, to restore the equality $X_A (P_A)^{\eta_A} = 1$, P_A has to increase.

Finally, from equation (17), one can see that deforestation increases in P_A. Thus, an increase in P_B induces an increase in P_A, which increases forest conversion. ■

More precisely, the effect of P_B on P_A works through the land market in region 1. In fact, a higher P_B implies that the amount of land in region 1 used by sector B increases at the expense of sector A. Consequently, the total quantity of food produced is lower, which increases its final price.[13] This increases the profitability of deforestation in region 2. We term this the displacement effect, meaning that increased marginal profitability of ethanol may induce a displacement of other agricultural activities towards the forest frontier.

It is important to highlight that this result holds *if and only if* the quantity X_A produced in the national economy is sufficiently high to affect the world price P_A or if it is only traded within the national economy. The former case can be seen, for example, in Brazil, which was responsible for approximately 25 percent of global soya production, in 2008. Another example, India, the world's second-largest producer of sugarcane and with plans to rapidly expand ethanol production, produced 22 percent of global rice output, in 2008.[14] The latter is generally the case for locally-produced staple food crops in many developing economies.

Proposition 4 *Without labor mobility and if the output price of the food sector P_A is endogenous, then an increase in world ethanol price P_B decreases the total*

[13] The correlation between ethanol and food prices has been highlighted in the literature (see Charkravorty *et al.*, 2009).

[14] Crop data for both Brazil and India are available at www.faostat.fao.org

quantity X_A produced in the country.

Proof. *Taking the derivative of $(X_A)^e$ in equation (16) with respect to P_B gives*

$$\frac{\partial (X_A)^e}{\partial (P_B)} = -\frac{\left(\frac{\alpha+\beta}{\nu}\right)\left(\overline{R_1}\right)^{\alpha}\left(\overline{L_1}\right)^{\beta}}{(P_A)^{\frac{1}{\nu}}\left[1+\left(\frac{P_B}{P_A}\right)^{\frac{1}{\nu}}\right]^{1+\alpha+\beta}}(P_B)^{\frac{\alpha+\beta}{\nu}}$$

which is negative. ■

Note that the decrease in the equilibrium quantity of food X_A depends on the variation of P_A subsequent to an increase in P_B, which depends on several parameters including the price elasticity of food, η_A.[15]

In this setting, the decrease in the amount of food produced due to the induced increase in food price is dampened by the possibility of creating new agricultural land through deforestation. As compared to the case where P_A is exogenous, consumers of food are therefore less affected from the increase in ethanol demand, although new food production will occur at the cost of the environment.

3.3 Case 3: The Labor Mobility Effect

Here we aim to better understand how ethanol production may affect deforestation and the food sector, but this time through the labor market. By introducing labor mobility, we show that the quantity of labor used in activities in region 1 has an influence on the amount of labor available for activities in region 2 and hence, on the amount of forest clearing. From (15), deforestation is positively correlated with the amount of labor in region 2. In order to isolate this effect, we again set

[15] This variation can be computed by solving for $\frac{dP_A}{dP_B}$, which can be accompolished by totally differentiating $X_A = (P_A)^{-\eta_A}$ with respect to P_A and P_B and using equation (16) to replace for the equilibrium value of X_A. The sign of this expression is nevertheless ambiguous:

$$\frac{dP_A}{dP_B} = \left\{ \frac{\frac{\eta_A}{(P_A)^{1+\eta_A}} + \left(\frac{\alpha}{1-\alpha}\right)(\theta_A)^{\frac{1}{1-\alpha}}\left(\frac{\alpha}{c}\right)^{\frac{\alpha}{1-\alpha}}\left(\overline{L_{2A}}\right)^{\frac{\beta}{1-\alpha}}(P_A)^{\frac{2\alpha-1}{1-\alpha}}}{\frac{\left(\overline{R_1}\right)^{\alpha}\left(\overline{L_1}\right)^{\beta}\left(\frac{\alpha+\beta}{\nu}\right)(P_B)^{\frac{\alpha+\beta}{\nu}}}{(P_A)^{\frac{1}{\nu}}\left[1+\left(\frac{P_B}{P_A}\right)^{\frac{1}{\nu}}\right]^{1+\alpha+\beta}}} - \frac{P_A}{P_B} \right\}^{-1}.$$

$\theta_B = 0$ – such that sector B is only present in region 1[16] – and consider P_A to be exogenous ($A.4$). Contrary to cases 1 and 2, we assume perfect labor mobility ($\overline{A.2}$). The wage in both regions will then be the same and is hence denoted W.

3.3.1 The ethanol sector maximization problem

Sector B now maximizes $\Pi_B = P_B X_B - W L_{1B} - P_1 R_{1B}$, subject to $X_B = (R_{1B})^\alpha (L_{1B})^\beta$. From the first-order conditions of the problem, one can derive the demand functions of land and labor for sector B, which are given by

$$R_{1B} = \left(\frac{\alpha P_B}{P_1}\right)^{\frac{1-\beta}{\nu}} \left(\frac{\beta P_B}{W}\right)^{\frac{\beta}{\nu}} \tag{18}$$

and

$$L_{1B} = \left(\frac{\beta P_B}{W}\right)^{\frac{1-\alpha}{\nu}} \left(\frac{\alpha P_B}{P_1}\right)^{\frac{\alpha}{\nu}} \tag{19}$$

3.3.2 The agriculture sector maximization problem

Sector A uses land of both regions for its production. It then solves for

$$\begin{aligned} \max_{(R_{1A}, L_{1A}, R_{2A}, R_{2A}^D, L_{2A})} \Pi_A &= P_A X_A - W(L_{1A} + L_{2A}) - P_1 R_{1A} - P_2 R_{2A} - (c+\gamma) R_{2A}^D \\ s.t.\ X_A &= (R_{1A})^\alpha (L_{1A})^\beta + \theta_A \left[R_{2A} + R_{2A}^D\right]^\alpha (L_{2A})^\beta. \end{aligned}$$

Using the first-order conditions, the input demand functions of the sector are given by

$$R_{1A} = \left(\frac{\alpha P_A}{P_1}\right)^{\frac{1-\beta}{\nu}} \left(\frac{\beta P_A}{W}\right)^{\frac{\beta}{\nu}}, \tag{20}$$

$$L_{1A} = \left(\frac{\beta P_A}{W}\right)^{\frac{1-\alpha}{\nu}} \left(\frac{\alpha P_A}{P_1}\right)^{\frac{\alpha}{\nu}}, \tag{21}$$

$$\overline{R_2} + R_2^D = \left[\frac{\alpha P_A \theta_A}{P_2}\right]^{\frac{1-\beta}{\nu}} \left(\frac{\beta P_A \theta_A}{W}\right)^{\frac{\beta}{\nu}}, \tag{22}$$

and

$$\overline{L_2} = \left(\frac{\beta P_A \theta_A}{W}\right)^{\frac{1-\alpha}{\nu}} \left[\frac{\alpha P_A \theta_A}{P_2}\right]^{\frac{\alpha}{\nu}}. \tag{23}$$

[16] This implies, as in case 2 above, that $R_{2A} = \overline{R_2}$, $R_{2A}^D = R_2^D$ and $L_{2A} = \overline{L_2}$.

3.3.3 The Labor Mobility Effect

In order to demonstrate the Labor Mobility effect, we proceed in two steps. First, we show that the wage level increases with the ethanol price. Then, we show how deforestation varies with the wage level. This represents an indirect effect of ethanol price on deforestation. This effect is expressed in the following proposition.

Proposition 5 *With labor mobility, when the food price P_A is given, and when ethanol is produced in a region different from the forest frontier, deforestation in the forest region is decreasing in the ethanol price.*

Proof. *Using equations (18), (20) and the constraint $\overline{R_1} = R_{1A} + R_{1B}$, we obtain an equation giving the price of land in region 1, P_1, as a function of the wage W*

$$P_1 = \alpha \left(\frac{\beta}{W}\right)^{\frac{\beta}{1-\beta}} \left[\frac{(P_A)^{\frac{1}{\nu}} + (P_B)^{\frac{1}{\nu}}}{\overline{R_1}}\right]^{\frac{\nu}{1-\beta}}. \tag{24}$$

Using the constraint $\overline{L} = L_{1A} + L_{1B} + L_{2A}$ and equations (19), (21), (23) and (24) we obtain the following expression:

$$\overline{L} = \left(\frac{\beta}{W}\right)^{\frac{1}{1-\beta}} \left[(P_A)^{\frac{1}{\nu}} + (P_B)^{\frac{1}{\nu}}\right]^{\frac{\nu}{1-\beta}} \left(\overline{R_1}\right)^{\frac{\alpha}{1-\beta}} + \left(\frac{\beta}{W}\right)^{\frac{1-\alpha}{\nu}} \left(\frac{\alpha}{P_2}\right)^{\frac{\alpha}{\nu}} (\theta_A P_A)^{\frac{1}{\nu}}. \tag{25}$$

From equation (25) we can see that, ceteris paribus, if P_B increases, then W must increase as well since P_1 and P_2 are given. Now, looking at equation (22) note that the amount of cleared land decreases with wage. Thus, an increase in ethanol price provokes an increase in wage because the sector demands more labor. This in turn decreases deforestation. ■

Our results show that a higher demand for labor in the ethanol sector attracts workers to region 1. This reduces labor supply in region 2 thus lowering the potential for deforestation in the region. We term this the Labor Mobility effect.

The idea that the reallocation of labour might indirectly drive forest conversion has not previously been considered in the literature. In principle, it could represent an argument for developing or expanding ethanol production in regions far from the forest frontier. Indeed, the energy crop sector has often been promoted as a potential source of employment for the rural poor (von Braun and Pachauri, 2006; Ewing and Msangi, 2009). Our framework indicates, furthermore, that increasing biofuel production may have the potential to lower the incentives for migration towards forest regions hence reducing pressure on forests.

Proposition 6 *With labor mobility, when the food price P_A is given, the quantity X_A of good A produced in the country is decreasing in the ethanol price P_B.*

Proof. *Using equations (18) to (24) and replacing these in the production function yields:*

$$X_A = \frac{\left(\overline{R_1}\right)^{\frac{\alpha}{1-\beta}} (P_A)^{\frac{\beta}{\nu}} \left(\frac{\beta}{W}\right)^{\frac{\beta}{1-\beta}}}{\left[1+\left(\frac{P_B}{P_A}\right)^{\frac{1}{\nu}}\right]^{\alpha} \left[(P_A)^{\frac{1}{\nu}}+(P_B)^{\frac{1}{\nu}}\right]^{\frac{\alpha+\beta}{1-\beta}}} + \left(\frac{\beta}{W}\right)^{\frac{\beta}{\nu}} \left(\frac{\alpha}{P_2}\right)^{\frac{\alpha}{\nu}} (P_A)^{\frac{\alpha+\beta}{\nu}}.$$

From the expression above, the quantity X_A of good A produced is, ceteris paribus, decreasing in the wage W. We have already seen that the wage is increasing in the ethanol price P_B (see Proof of Proposition 5 above). Thus, X_A is decreasing in P_B. ■

It is important to highlight that in this case, one can also observe the Direct Land Competition effect. In fact, additional to the increase in wage, a higher ethanol price P_B further decreases X_A by reducing the equilibrium amount of land allocated to sector A in region 1. Using equations (20) and (24) one can see that the equilibrium amount of land allocated to sector A in region 1 is given by $(R_{1A})^e = \frac{\overline{R_1}}{1+\left(\frac{P_B}{P_A}\right)^{\frac{1}{\nu}}}$, which is decreasing in P_B. As a consequence, an increase in ethanol price has a combined effect through both the land and the labor markets, provoking a decrease in the production of food.

4 Discussion and Conclusions

This paper investigates the direct and indirect impacts of energy crop production on land use, deforestation, and food production, through a partial equilibrium model of input allocation between the energy crop and food sectors. The model incorporates two regions of which only one contains forest. New land can be allocated to crop production via forest conversion. Three distinct effects are highlighted and analyzed separately. In this section, we discuss the conditions under which each of the three effects materializes. Table 1 summarizes the results.

Effects	*Assumptions*	*Deforestation*	*Food Production*
Direct Land Competition	P_A Exogenous ($\overline{A.4}$) $\theta_B > 0$ ($A.3$) No labor mobility ($A.2$)	–	–
Displacement	P_A Endogenous ($A.4$) $\theta_B = 0$ ($\overline{A.3}$) No labor mobility ($A.2$)	–	–
Labor Mobility	P_A Exogenous ($\overline{A.4}$) $\theta_B = 0$ ($\overline{A.3}$) Labor mobility ($\overline{A.2}$)	+	–

Table 1: Summary of conditions under which each effect occurs
Note: "–" denotes potentially increasing deforestation; "+" denotes potentially reducing deforestation

The Direct Land Competition effect (Case 1) is the one that has been most investigated in the literature (e.g. Angelsen, 1999). Given a finite stock of land, the allocation of land to one particular use can only be undertaken at the expense of other uses. If the relative marginal profitability of the energy crop sector increases, e.g. due to an increase in the ethanol price, a reallocation of land previously under rival land uses (food production and forest) in favor of the energy crop sector occurs.

The possible existence of a Displacement effect (Case 2) has also been discussed – but not formally derived – in the literature, through the notion of indirect land use changes (e.g. Gallagher, 2008; Searchinger *et al.*, 2008). It expresses the fact that the increased profitability of one agricultural sector can displace other agricultural activities towards marginal lands such as those under forest. We show, however, that there are two necessary conditions for this effect to be observed. First, the energy crop has to be produced, at least partially, in the non-forested region, i.e. away from the forest frontier. Second, the displaced activity has to be such that national production affects the output price. If this condition is not satisfied, then the price of the potentially displaced good will not vary, leaving its profitability unchanged. Instead of a displacement of production one instead observes a simple direct reallocation of land between the two activities. It then becomes a Direct Land Competition effect with no effect on deforestation.

Regarding the size of the displacement, it depends, among other factors, on how sensitive the food price is to a decrease in quantities produced, expressed by the elasticity η_A. Note, however, that the negative impact on the quantity of food produced is dampened by the possibility of new agricultural land emerging through deforestation. Indeed, the increase in the food price makes deforestation more profitable thus giving incentives to food producers to clear more land, a trend commonly observed in forest frontier regions (Angelsen and Kaimowitz, 1999; Barbier, 2001). Newly available land is converted to food production, which lowers the food shortage induced by land conversion to energy crop production in the non-forest region, subsequent to the increase in ethanol prices. This effect implies that governments and decision makers keen to promote ethanol production should focus on developing policy instruments to ensure that the displacement of food production is guided towards idle land. If such land can be converted to food production at relatively low cost, e.g. by proving technical assistance or building infrastructure such as roads to reduce costs to market, then this could potentially mitigate food price increases while preventing deforestation.

The Labor Mobility effect (Case 3) is the other novelty of the paper. Of course, our model assumptions regarding labor – perfect mobility or total immobility – are extreme cases used to illustrate this effect. In reality, agents' mobility is always imperfect and does not depend solely on wages. Other factors of mobility include the availability and quality of infrastructure, family ties and household composition, among others (Mincer, 1978). Nevertheless, our results imply that in a context where the forest frontier is a suitable destination for poor rural households, the energy crop sector, when located in a non-forest region may represent an alternative migration choice. This will particularly be the case when the energy crop sector is labor intensive and offers higher wages compared to other agricultural sectors. Conversely, a decrease in demand for labor for the energy crop sector, for example due to mechanization, could become an additional factor incentivizing agents to migrate towards the forest frontier. Finally, an increase in labor demand in the energy crop sector diverts labor away from the food sector thus decreasing food production. Moreover, if the food price is endogenous, we would expect to see additional upward pressure on the food price.

Our results show that the overall impact of ethanol production on food production is unambiguously negative: whether considering direct or indirect effects, increasing ethanol demand drives down food output. The overall impact of ethanol production on forest conversion, on the other hand, is ambiguous. In particular, when considering the indirect effects, increasing ethanol demand can both increase deforestation through the land market and reduce deforestation via the labour market (where there is free movement of labour). Which effect dominates is essentially an empirical question. Further ambiguities result from remaining uncertainties regarding a number of parameters including the price elasticity of the food sector, the size of the displacement effect, and the total land available for food and energy crops. Thus, the relative importance of these parameters in determining overall impact implies a need for empirical research, perhaps undertaken in a specific context.

Finally, we acknowledge that our model is only relevant for contexts where forest might be vulnerable to deforestation, with weak property rights to forest land, and where energy crops can only be grown under certain conditions. Thus, of the two current major producers of ethanol, Brazil and the United States, our model is only directly applicable to the former and not the latter. Nevertheless, our model also captures the cross-border indirect effect of increasing demand for US corn ethanol on deforestation in Brazil, as demonstrated by Searchinger et al. (2008). More pertinently, there are a number of countries and regions of the world where the ethanol sector is in the process of being developed on a large scale. These include India and Colombia (see Lapola et al., 2009; Quintero et al., 2008), which have stocks of natural forest vulnerable to deforestation and, along with Brazil, would form interesting case studies for further research. Such studies could then be used to derive more concrete policy implications to show under what conditions ethanol production could be expanded while minimising negative impacts on deforestation and food production.

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