Environ Resource Econ (2012) 51:1–21
DOI 10.1007/s10640-011-9516-4

Ethanol Production, Food and Forests

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Accepted: 16 April 2011 / Published online: 16 October 2011

Abstract This paper investigates the direct and indirect impacts of ethanol production on land use, deforestation and food production. A partial equilibrium model of a national economy with two sectors and two regions, one of which includes a forest, is developed. It analyses how an exogenous increase in the ethanol price affects input allocation (land and labor) between sectors (energy crop and food). The total effect of ethanol prices on food production and deforestation is decomposed into three partial effects. First, the well-documented effect of direct land competition between rival uses arises; it increases deforestation and decreases food production. Second, an indirect displacement of food production across regions, possibly provoked by the reaction of international food prices, increases deforestation and reduces the food sector's output. Finally, labor mobility between sectors and regions tends to decrease food production but also deforestation. The total impact of ethanol production on food production is negative while there is an ambiguous impact on deforestation.

Keywords Deforestation · Ethanol · Food · Indirect impacts · Land use · Migration

JEL Classification Q11 · Q24 · Q42

1 Introduction

After initially being hailed as a promising climate-change-mitigation strategy (Schneider and McCarl 2003; Pacala and Socolow 2004; Farrell et al. 2006), biofuels production has since been implicated in driving up food prices and causing deforestation (e.g. Righelato and Spracklen 2007; Fargione et al. 2008; Laurance 2007; Scharlemann and Laurance 2008;

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Tilman et al. 2009). Despite fears about these possible negative effects, expansion of biofuels production continues apace (Rajagopal and Zilberman 2007).

Biofuels production is currently dominated by ethanol, most of which is produced by the US (maize) and Brazil (sugarcane) (IEA 2007).[1] Global ethanol production is predicted to rise from around 60 billion liters in 2008 to 150 billion liters by 2018 (OECD and FAO 2009). Producers' efforts to increase supply are based on expectations of future 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), is clear that evidence linking ethanol production to deforestation would considerably decrease its attractiveness as a climate strategy. Current evidence, e.g. using life-cycle analysis, is not clear-cut and subject to ongoing research and analysis.

This paper aims to contribute to the debate on the possible social and environmental effects of ethanol production by investigating the impacts of production on land use, deforestation and food production, at the level of a national economy. A two-sector-two-input-two-region 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.[4] Three channels are isolated, two involving the land market and one involving the labor market. While Brazil, with its forest stock and prominent ethanol sector, is an obvious candidate for illustrating at least two of these channels and related policy implications, we show how our model may also be relevant for other countries.

Land is a limited resource allocated among different rival uses. 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 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). If production becomes more profitable then this increases incentives to clear forest for 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. For instance, Brazilian sugarcane producers in the state of São Paulo, far from the Amazon region, claim that expansion would have no effect on patterns of deforestation in the latter region (see Goldemberg and Guardabassi 2009). Yet evidence has begun to emerge suggesting that sugarcane production in the past may have displaced the production of other agricultural commodities from São Paulo to the Amazon (see Barona et al. 2010).

This is a type of "indirect" impact of ethanol production. It is more precisely defined as the conversion of forests and grassland to new cropland in order to replace the grain (or cropland) diverted to biofuels (e.g. Searchinger et al. 2008; Gallagher 2008; Keeney and Hertel 2009). We term this a displacement, which can occur either in the same country or in other countries. Intuitively, indirect land use changes can be understood as a kind of spillover

[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.

[4] Since we are mainly interested in the impacts of ethanol production on land use and deforestation, we abstract from the industrial process of ethanol production and focus on the rural economy, i.e. the feedstock sector.

effect. In this paper, we adopt a similar definition, although focusing on changes occurring within a given country. Thus, an expansion in the energy crop is *indirectly* affecting a given alternative land use (e.g. forests) so long as the former is grown in a region where the latter is completely absent. By contrast, an effect is *direct* if the energy crop and alternative land use are located in the same region.

Searchinger et al. (2008) utilize 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 gases savings compared to fossil fuels when emissions from indirect land-use changes are taken into account. While some drawbacks to the methodology used have been identified (see Gallagher 2008), this study is the first to take into account the possible indirect effects of ethanol production. Nevertheless, the market mechanisms underlying this effect remain unclear, although Feng and Babcock (2010) go some way towards clarifying these. Using a partial equilibrium framework, they investigate how US policies to promote corn ethanol production affect total cropland area and its allocation among different land uses. An increase in the ethanol price is shown to increase the total cropland area by increasing the returns on marginal land previously fallow. This gives incentives to producers to convert this land to agriculture including both corn and other crops. Feng and Babcock do not, however, include forests in their model and hence, do not explicitly model how ethanol demand might impact on forest conversion.

A second possible indirect effect of increasing ethanol production is that of changes in the demand for labor. Although expanding biofuels production has been promoted as a means of increasing rural employment possibilities (e.g. von Braun and Pachauri 2006; Ewing and Msangi 2009), its possible impacts on labor demand have yet to be properly investigated. Since off-farm employment opportunities have been shown to decrease incentives for poor rural agents to migrate to the forest frontier, (e.g. Bluffstone 1995; Shively and Pagiola 2004)[5] we argue that better agricultural employment opportunities in non-forest areas could potentially yield similar results. Accordingly, there is evidence of energy crop sectors increasing their demand for labor in recent years. For example, the Indian sugar industry employs up to 45 million farmers (Gonsalves 2007). Estimates of direct employment associated with sugarcane ethanol production in Brazil range from 500,000 to 1 million (FAO 2007), mostly of lower-skilled migrant workers in rural areas (Dufey 2008). Smaller producers such as Tanzania and Venezuela are planning to expand production at least partially in the hope of creating new rural jobs (see Pesket et al. 2007).

Biofuels production has also been implicated in having a negative impact on food production through land competition and the diversion of crops from food to feedstock (FAO 2008). 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 technologies.[6] Although we focus primarily on how ethanol production might impact forest conversion, our framework also allows us to consider how it may affect the output of food.

In this paper, we develop a model in which two final goods – an energy crop. [7] and a composite good representing all other agricultural commodities (termed “food”)—are produced

[5] Labor is typically included as an input to production when considering agricultural sectors and analyzing deforestation (Angelsen 1999).

[6] See Chakravorty et al. (2009) for a complete review of the fuel-food debate.

[7] Some energy crops can also be used to produce food or other by-products than ethanol (e.g. sugarcane to produce sugar). For simplicity, we assume that all the energy crop produced is devoted to ethanol production.

in two different regions. This set-up allows for the possibility of confining the production of one good to a particular region due to region-dependent agro-ecological conditions. Variations in soil and climate often restrict the production of maize and sugarcane to certain regions within a given country, for example, in Brazil, India and the US. We consider land and labor as primary inputs to agricultural production in order to represent a partition between immobile inputs and mobile ones. Moreover, we restrict attention to inputs supplied inelastically at the national level.[8] Land is immobile—or regionally inelastic—while labor is a relatively mobile input, which is inelastic at the national level. This division between mobile and immobile inputs allows us to define two market channels through which the direct and indirect effects materialize. Finally, land type, i.e. land productivity, varies across the two regions, one of which includes a forest. Property rights over the forest are considered ill-defined, resulting in *de facto* open access.[9]

We show that ethanol production can impact deforestation and food production in three distinct ways. First, there is the Direct Land Competition effect in 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 – as would be the case if world prices were sensitive to the country's food production – 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 has neither been explicitly considered nor modelled in previous studies, and 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 if the latter is located in the non-forest region.

The remainder of the paper is structured as follows. Section 2 presents the model while the three effects are isolated and characterized in Sect.n 3. Finally, Sect. 4 discusses the results and presents some policy implications before concluding.

2 The Model

We consider a partial equilibrium setting with two inputs, land and labor, which are used to produce two different agricultural goods— food and an energy crop. There are two regions 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.[10] The objective is to investigate how markets allocate inputs to the two sectors— depending on output prices—and how this allocation influences 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. These are used to establish and isolate three

Footnote 7 continued
Relaxing this assumption would not change the results obtained from the model (see Feng and Babcock 2010). Additionally, we do not consider processing costs. Thus, the output price of the energy crop is equivalent to the ethanol price.

8 Inputs with perfect supply elasticity, i.e. where national prices are given by world markets, are irrelevant when considering national allocations. Given that land and labor are inelastically supplied at the national level, adherence to the standard framework of Mas-Collel et al. (1995) enhances rather than it reduces the empirical relevance of our analysis.

9 Ill-defined property rights, especially over forested land, are a common feature of developing and emerging economies (see Feder and Feeney 1991).

10 Forest land is generally not very productive for agriculture (Chomitz and Thomas 2003).

partial effects, which operate through different channels and rely on a number of distinct assumptions. Isolating each effect clarifies these assumptions and therefore the contexts in which they manifest. Combining them gives the *total* effect of a change in the energy crop price on the allocation of inputs, and thus on deforestation. In the baseline framework the three partial effects occur jointly.

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

$$\overline{R_1} = R_{1A} + R_{1B}, \tag{1}$$

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

$$R_2 = \overline{R_2} + R_2^D, \tag{2}$$

with[11] $\overline{R_2} = R_{2A} + R_{2B}$ 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 forest conversion cost is linear, 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.[12] Note that one might consider the marginal cost of conversion to be increasing as deforestation and forest degradation moves beyond the initial frontier. We assume, however, that forest conversion occurs as a final step in the process of deforestation from forest to agriculture and thus always takes place at the frontier. Therefore, we do not consider the marginal cost of deforestation to be increasing. Also, since our aim is to investigate the direction of energy crop price effects on forest conversion we restrict attention to interior solutions where there is still some forest to be cleared. Hence, although deforestation prospects are finite, bounded by the initial size of the forest, we do not need to specify this amount.

Finally, following Mas-Collel et al. (1995),[13] the supplies of initial stocks of agricultural land in the two regions ($\overline{R_1}$) and ($\overline{R_2}$) are assumed perfectly inelastic. Therefore, these stocks are completely used by producers as long as their respective prices are non zero.

[11] Note that (2), by defining deforestation as land of type 2 used in excess of the initial stock available, makes clear that all the initially-available land will be used irrespective of the land price.

[12] We do not consider here any social values of forests such as those relating to biodiversity or carbon storage. Also, we assume that producers do not derive any private benefits from standing forests such that when deciding to convert forest they only compare the cost of doing so, c, and the cost of renting land of type 2.

[13] Mas-Collel et al. (1995) consider the case of a small, open economy, where inputs are traded solely within the country. By assuming that consumers have no direct use of their inputs' endowments, (land and labor in our particular case), the total supply of factors is equal to the total endowments so long as prices are strictly positive.

2.1.2 The Labor Factor

The economy's total labor endowment is denoted $\overline{L}$ and its supply is perfectly inelastic (ibid). In the following and for reasons given below, we alternatively assume labor to be perfectly mobile or perfectly immobile across regions 1 and 2. Let $L_{1i}, i \in \{A, B\}$, be the quantities of labor used by sector i in region 1 and $L_{2i}, i \in \{A, B\}$, the equivalent for region 2. Then, if labor is perfectly mobile the constraint over the use of this input can be written as

$$\overline{L} = L_1 + L_2 = L_{1A} + L_{1B} + L_{2A} + L_{2B}, \tag{A.1}$$

where only the total amount of labor available for the two sectors is fixed. However, if labor is perfectly immobile then the constraint writes

$$\overline{L} = \overline{L_1} + \overline{L_2} \text{ with } \overline{L_1} = L_{1A} + L_{1B} \text{ and } \overline{L_2} = L_{2A} + L_{2B}, \tag{$\overline{A.1}$}$$

where the upper bar denotes a fixed quantity. Note that under ($\overline{A.1}$) where labor mobility is constrained across regions, labor can still freely move from one sector to the other, within the same region.

2.1.3 The Final Good Production

The output of each sector, $X_i, i \in \{A, B\}$, is produced according to

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

Two parameters are important in this equation. First there is $0 \leq \theta_i < 1$, which represents the factors' productivity difference between regions 1 and 2. Furthermore, we also include a sector-specific total productivity index $\lambda_i > 0,\ i = A, B$. This parameter captures differences in the production process of the two goods.[14] Moreover, the production function of both sectors exhibits decreasing returns to scale: $\alpha + \beta < 1$.

Finally, in (3) we assume that the energy crop is either produced in both regions or is restricted to region 1. The former case is formalized by

$$\theta_B > 0, \tag{A.2}$$

while the latter implies

$$\theta_B = 0. \tag{$\overline{A.2}$}$$

($\overline{A.2}$) is an interesting case for two reasons. First, restricting energy crop production to the non-forested area allows us to investigate the potential indirect impacts of its expansion on deforestation. Second, it could reflect cases where some energy crops can only be produced using particular types or qualities of land, as described in the introduction.

2.2 Institutions

Sectors A and B are composed of price-taking agents. We denote by P_A and P_B the world prices of food and the energy crop, respectively. [15]

[14] Therefore, production functions across sectors differ in two respects: total factors' productivity and factors productivity in region 2. In order to obtain tractable results, we only assume the production function to differ in these respects.

[15] Since we assume that all the energy crop is devoted to ethanol production, P_B also represents the ethanol price.

Table 1 The three effects and the supporting assumptions

Effects	Labor mobility	θ_B	Food price
General baseline case	Perfect mobility (*A.1*)	$\theta_B > 0$ (*A.2*)	Sensitive to X_A (*A.3*)
Direct land competition	No labor mobility ($\overline{A.1}$)	$\theta_B > 0$ (*A.2*)	Given ($\overline{A.3}$)
Displacement	No labor mobility ($\overline{A.1}$)	$\theta_B = 0$ ($\overline{A.2}$)	Sensitive to X_A (*A.3*)
Labor mobility	Perfect mobility (*A.1*)	$\theta_B = 0$ ($\overline{A.2}$)	Given ($\overline{A.3}$)

The objective of Sect. 3 is to undertake comparative statics on P_B and to decompose the effect of this price change. Hence, we assume the ethanol price to be exogenously given. However, we might be interested in potential reactions of the world price P_A to changes in national production as would be the case for a major food-producing country. Let us consider the assumption that P_A is sensitive to X_A. In this case, it is given by

$$P_A = (X_A)^{-(1/\eta_A)}, \tag{A.3}$$

where $\dfrac{1}{\eta_A}$ is the elasticity of the world price P_A to national production X_A.[16] Alternatively, we might consider that P_A is insensitive to changes in X_A, as might occur if our economy were a minor food producer, entailing

$$P_A = \overline{P_A}. \tag{$\overline{A.3}$}$$

Also, there is a land market for each region with P_1 and P_2 denoting the regional land-rental prices. Regarding the labor market, we consider a national labor market where labor is assumed mobile with wage denoted W. If labor is immobile, then there are two regional markets with wages denoted by W_1 and W_2, respectively. In equilibrium, note that wages may vary across regions but not across sectors within the same region.

2.3 Road-Map

As outlined, an increase in the energy crop price, P_B, will trigger three different effects. In the baseline case, defined by (*A.1*), (*A.2*) and (*A.3*), these effects operate simultaneously thus giving the net effect of a change in P_B on food production and deforestation. Our objective is to decompose this total effect in order to understand the mechanisms behind each of the partial effects. We do so by assuming successively but in an isolated manner (*A.1*), (*A.2*) and (*A.3*). To clarify this, we briefly summarize our approach in Table 1.

First, we consider the Direct Land Competition effect, which implies direct competition for land between the possible land uses. We therefore set $\theta_B > 0$ (*A.2*) such that the energy crop is grown in the forest region. In order to isolate it from the two other effects, we fix the channels through which they operate, i.e. the mobility of the labor factor and the food price. This implies a need to assume ($\overline{A.1}$) and ($\overline{A.3}$). Hence, the Direct Land Competition effect should be understood as the effect of an increase in the energy crop price *if* energy crop and forests compete for land *for a given* food price and supply of labor available at the forest frontier. We investigate the two other partial effects in a similar fashion.

We discuss the implications of the assumptions that have been made so as to isolate each effect in the following section.

[16] Accordingly, η_A is the price elasticity of the country's world's *residual* demand.

3 The Decentralized Equilibrium

In this section we first derive factor demands, quantities produced and the amount of deforestation in equilibrium. We then proceed to analyze the three partial effects of an increase in the ethanol price P_B on food production and deforestation.

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 (3), profits can be rewritten as

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

After rearrangement, the first-order conditions for the choice of profit-maximizing input quantities $R_{1i},\ L_{1i},\ R_{2i},\ L_{2i}$ and R_{2i}^D, in an interior solution write

$$R_{1i} = \left(\frac{P_1}{\alpha \lambda_i P_i} \right)^{1/(\alpha-1)} (L_{1i})^{\beta/(1-\alpha)}, \tag{4}$$

$$L_{1i} = \left(\frac{W_1}{\beta \lambda_i P_i} \right)^{1/(\beta-1)} (R_{1i})^{\alpha/(1-\beta)}, \tag{5}$$

$$R_{2i} + R_{2i}^D = \left(\frac{P_2}{\alpha \lambda_i P_i \theta_i} \right)^{1/(\alpha-1)} (L_{2i})^{\beta/(1-\alpha)}, \tag{6}$$

$$L_{2i} = \left(\frac{W_2}{\beta \lambda_i P_i \theta_i} \right)^{1/(\beta-1)} \left(R_{2i} + R_{2i}^D \right)^{\alpha/(1-\beta)}, \tag{7}$$

and

$$R_{2i} + R_{2i}^D = \left(\frac{c}{\alpha \lambda_i P_i \theta_i} \right)^{1/(\alpha-1)} (L_{2i})^{\beta/(1-\alpha)}. \tag{8}$$

Note that from (6) and (8) an interior solution requires $P_2 = c$ at equilibrium. This means that the marginal cost of deforestation, given by c, must be equal to the market rental price of land in region 2. By focusing on interior solutions, we are ruling out the two cases $c = 0$ and $c \to +\infty$.[17] This is due to our objective of better understanding how producing energy crops might influence deforestation. Thus, restricting attention to interior solutions were deforestation is positive although not extreme (i.e. where the forest is completely cleared) allows us to avoid uninteresting cases where deforestation is insensitive to changes in energy crop production.

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.1*). By excluding labor mobility we want to highlight the impact

[17] $c = 0$ would imply a corner solution where producers only use deforested land. One argument to abstract from this case is that although forest conversion may actually be a cheap way of obtaining land for agriculture, it still requires some effort (labor) and time to convert land. It is then reasonable to assume that $c > 0$.

$c \to +\infty$ would imply that there is no forest conversion at all. This case can arise in contexts where property rights over the forest are fully defined and enforced. It nonetheless contradicts our assumption of vulnerable forests. Similarly, if all the forest stock has been converted to agricultural land no more deforestation is possible, which is equivalent to having $c \to +\infty$. The total amount of land of type 2 available for agriculture then becomes totally fixed.

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.2). Finally, we consider the price of food P_A to be fixed (A.3).

3.1.1 The Equilibrium Land and Labor Allocations

From the first order conditions (4) to (8), one can compute the input demand functions (see Appendix A). Together with inelastic supplies of land and labor, these demand functions give the equilibrium input prices (see Appendix B) and the equilibrium input quantities below:

$$(R_{1i})^e = \frac{\overline{R_1}}{1 + \left(\frac{\lambda_j P_j}{\lambda_i P_i}\right)^{1/\nu}}, \tag{9}$$

$$(L_{1i})^e = \frac{\overline{L_1}}{1 + \left(\frac{\lambda_j P_j}{\lambda_i P_i}\right)^{1/\nu}}, \tag{10}$$

$$\left(R_{2i} + R_{2i}^D\right)^e = \left(\frac{\alpha}{c}\right)^{1/(1-\alpha)} \left[\frac{\overline{L_2}}{(\lambda_i P_i \theta_i)^{1/\nu} + (\lambda_j P_j \theta_j)^{1/\nu}}\right]^{\beta/(1-\alpha)} (\lambda_i P_i \theta_i)^{1/\nu} \tag{11}$$

and

$$(L_{2i})^e = \frac{\overline{L_2}}{1 + \left(\frac{\lambda_j P_j \theta_j}{\lambda_i P_i \theta_i}\right)^{1/\nu}}, \tag{12}$$

where $i, j \in \{A, B\}$, $i \neq j$ and $\nu = 1 - \alpha - \beta > 0$.

From (11) and $R_2^D = \left(R_{2A} + R_{2A}^D\right) + \left(R_{2B} + R_{2B}^D\right) - \overline{R_2}$, the equilibrium amount of converted forest is given by

$$\left(R_2^D\right)^e = \left(\frac{\alpha}{c}\right)^{1/(1-\alpha)} \left(\overline{L_2}\right)^{\beta/(1-\alpha)} \left[(\lambda_A P_A \theta_A)^{1/\nu} + (\lambda_B P_B \theta_B)^{1/\nu}\right]^{\nu/(1-\alpha)} - \overline{R_2}. \tag{13}$$

3.1.2 The Direct Land Competition Effect

The following proposition states the effect of an increase in the ethanol price on deforestation for case 1.

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

Proof See Appendix C □.

The Direct Land Competition effect stems from land reallocation between rival uses in region 2. In equilibrium, an increase in P_B entails a reallocation of land in favor of the energy crop sector at the expense of both forest and sector A. This effect on forest conversion clearly relies on the fact that the energy crop is grown at the forest frontier ($\theta_B > 0$). It is therefore a *direct* effect following the definition given in the introduction. Otherwise, i.e. if $\theta_B = 0$, the equilibrium amount of deforestation given by equation (13) 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). While not illustrative of ethanol production in Brazil say, this effect has been most clearly observed in Indonesia, for example, where forest has been directly converted to palm oil (Fargione et al. 2008).

The reallocation of inputs in region 2 also occurs at the expense of the food sector. This results in the following proposition.

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

Proof See Appendix D □.

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.

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 ($\overline{A.1}$). Also, we set $\theta_B = 0$ such that energy crop production is restricted to region 1 ($\overline{A.2}$), and use this to control for the Direct Land Competition effect. Finally, although competitive agents remain price takers, we now consider that the total quantity X_A produced in the country affects the world price P_A (*A.3*): $P_A = (X_A)^{-(1/\eta_A)}$.

The equilibrium amount of inputs used by the two sectors in region 1 are the same as presented in Sect. 3.1, i.e. they are given by equations (9) and (10). 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 thus given by $L_{2A} = \overline{L_2}$. Similar reasoning applies for land of type 2 such that $R_{2A} = \overline{R_2}$.

In equilibrium, the amount of good A produced is determined according to

$$X_A = \frac{\left(\overline{R_1}\right)^{\alpha} \left(\overline{L_1}\right)^{\beta}}{\left[1 + \left(\frac{\lambda_B P_B}{\lambda_A P_A}\right)^{1/\nu}\right]^{\alpha+\beta}} + (\theta_A)^{1/(1-\alpha)} \left(\frac{\alpha \lambda_A P_A}{c}\right)^{\alpha/(1-\alpha)} \left(\overline{L_2}\right)^{\beta/(1-\alpha)}, \quad (14)$$

where, unlike in Case 1 and according to (*A.3*), $P_A = (X_A)^{-(1/\eta_A)}$.

(14) and (*A.3*) give the effect of an increase in the ethanol price P_B on the food price P_A and on food quantity X_A. As we shall see in Proposition 4, P_B negatively affects X_A. It thus positively affects P_A. Using (13) and $\theta_B = 0$ ($\overline{A.2}$), the total amount of land conversion in this case is given by

$$R_2^D = R_{2A}^D = \left(\frac{\alpha \lambda_A P_A \theta_A}{c}\right)^{1/(1-\alpha)} \left(\overline{L_2}\right)^{\beta/(1-\alpha)} - \left(\overline{R_2}\right) \quad (15)$$

which only depends on P_A. Therefore we have the following proposition.

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

Proof See Appendix E □.

In this second case, sectors B and A only compete for inputs in region 1 where an increase in the energy crop price expands the former at the expense of the latter. Even after taking into account sector A's production in region 2, this decreases total national production X_A, thus leading to a higher P_A, from (*A.3*). However, in region 2, this effect increases the food sector demand for inputs and as a consequence, deforestation. We term this the Displacement effect, which means that increasing marginal profitability of the energy crop may induce a displacement of other agricultural activities towards the forest frontier.

This result holds *if and only if* the quantity X_A produced in the national economy affects the world food price P_A. This can be the case either if the national economy under study is a major food producer or if X_A is only traded within the national economy. The former case can be seen, for example, in India which is currently the world's second-largest producer of sugarcane—and with plans to rapidly expand ethanol production—as well as an important rice producer.[18] Similarly, Brazil was responsible for approximately 25 percent of global soya production, in 2008. The latter case is generally the case for locally-produced staple food crops in many developing economies.

The influence of X_A on P_A also depends on how elastic (or inelastic) food demand is, i.e. on the category of food products the national economy is producing. This effect is magnified in the case of staple foods, for which demand—either residual world demand or national demand—tends to be inelastic (Fafchamps 1992).

The following proposition summarizes the effect of an energy crop price increase on national food production.

Proposition 4 *Without labor mobility and if the output price of the food sector P_A is sensitive to quantity X_A, then an increase in world ethanol price P_B decreases the total quantity X_A produced in the country.*

Proof See Appendix F □.

Although X_A decreases, by proposition 3 the decrease in the amount of food produced—is dampened by the possibility of creating new agricultural land through forest conversion. As compared to the case where P_A is fixed, consumers of food are therefore less affected by the increase in ethanol demand, although new food production will occur at the cost of the environment. This particular point can have implications in terms of policy choice. Indeed, it suggests a trade-off between poor households' food security and environmental protection. More precisely, in our setting, if policy makers opt for higher forest protection,[19] this will increase the cost of forest conversion. In turn, this diminishes the forest's ability to act as a buffer for the food price increase subsequent to an increase in the ethanol price. Higher food prices will consequently increase poor households' vulnerability. On the other hand, leaving the forests unprotected—so that they can be converted to cropland and thus mitigate the food price increase—implies potential environmental damages such as diminished carbon storage capacity and biodiversity losses.

3.3 Case 3: The Labor Mobility Effect

In this case, we aim at better understanding how ethanol production may affect deforestation and the food sector through the labor market. By introducing labor mobility (*A.1*), we show

[18] In 2008, India produced 22 percent of global rice output. See: http://www.faostat.fao.org.

[19] For example, by providing positive incentives such as Payments for Environmental Services (PES) to agents such that they keep land in forest rather than convert forest to agriculture (see Engel et al. 2008).

that the quantity of labor used by 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. In order to isolate this effect, we again set $\theta_B = 0$ ($\overline{A.2}$)—such that sector B is only present in region 1.[20]—and consider P_A to be insensitive to quantity X_A ($\overline{A.3}$). Finally, by ($A.1$), there is a single wage in both regions denoted by W.

Using (4) to (8), $\theta_B = 0$, $P_2 = c$ and $W_1 = W_2 = W$ we derive the demand functions of land and labor for both sectors A and B (see Appendix G). In particular, the demand for deforested land by sector A in region 2 is given by

$$R_2^D = \left(\frac{\alpha}{c}\right)^{(1-\beta)/\nu} \left(\frac{\beta}{W}\right)^{\beta/\nu} (\lambda_A P_A \theta_A)^{1/\nu} - \overline{R_2}$$

which negatively depends on the wage level. Moreover, using the input demand functions of both sectors and inelastic supplies of land and labor.[21] we can establish an implicit positive relation between P_B and W, given by

$$\begin{aligned}\overline{L} &= \left(\frac{\beta}{W}\right)^{1/(1-\beta)} \left[(\lambda_A P_A)^{1/\nu} + (\lambda_B P_B)^{1/\nu}\right]^{\nu/(1-\beta)} \left(\overline{R_1}\right)^{\alpha/(1-\beta)} \\ &\quad + \left(\frac{\beta}{W}\right)^{(1-\alpha)/\nu} \left(\frac{\alpha}{c}\right)^{\alpha/\nu} (\lambda_A \theta_A P_A)^{1/\nu}.\end{aligned}$$

The effect of an increase in the energy crop price P_B on forest conversion is addressed in the following proposition.

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

Proof See Appendix G □

Proposition 5 states that a higher ethanol price increases demand for labor in the ethanol sector in region 1 thus increasing the wage. In region 2, since P_A remains fixed, a higher equilibrium wage lowers the potential for deforestation. Intuitively, increased labor demand in region 1 provokes a shift in the labor force from sector A to sector B, which only operates in region 1. We term this the Labor Mobility effect.

The idea that the reallocation of labor might indirectly drive forest conversion could, in principle, represent an argument for developing or expanding ethanol production in regions far from the forest frontier. Our framework indicates, furthermore, that increasing biofuels production may have the potential to lower the incentives for migration towards forest regions hence reducing pressure on forests. Qualitative case studies suggest that this effect is a possibility. For instance, Moraes and Alves (2008) investigate working conditions in São Paulo sugarcane plantations, in the Center and South of Brazil. They describe the flows of temporary migrants from Maranhão and Piauí states in the Northeast. These migrants are mainly landless people and small farmers who have been identified as key deforestation actors in the Brazilian Amazon (Fearnside 2008). Thus, there is evidence for the existence of migration flows originating in the Northeast, and gravitating either towards the forest frontier or the sugarcane plantations around São Paulo. Although these movements would need to be investigated and tested empirically, the two migration destinations could be seen as substitutes

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

[21] See Appendix G for details.

since they meet the same need, i.e. a desire to improve livelihoods. In this case, an increase in the intensity of the flow towards the South—say due to higher labor demand in sugarcane plantations—could in theory decrease migration towards the forest frontier.

The effect stated in proposition 5 is mainly driven by the assumption of perfect inelasticity in total labor supply. Had we assumed perfect elasticity of supply in the factors' markets then the factors' prices would have been given exogenously in the model. This would have implied that an increase in the energy crop price, even if increasing this sector's labor demand, would not affect wages. Therefore, the labor supply available for the food sector would not decline,[22] implying no effect on deforestation. In reality, labor supply to agriculture is likely to be somewhere in between these two polar cases, i.e. is finitely-elastic. Nevertheless, we believe that labor effects in rural areas of developing countries should not be underestimated given evidence of the continuing importance of agriculture for employment and livelihoods. For instance, in India, 52 percent of the country's total labor force in 2006 was employed in agriculture.[23] Also, according to the World Bank,[24] agriculture accounted for almost 20 percent of total employment both in Brazil and Colombia in 2006. While these figures do not completely justify the perfect inelasticity assumption, they corroborate the fact that demand for labor in agriculture may be sufficiently important to affect wages, at least regionally. Additionally, the magnitude of the effect naturally depends on the degree of mobility between the ethanol-producing region and the forested region.

Finally, note that if the food price were affected by quantity X_A, then the Labor Mobility effect would be coupled with a Displacement effect. In this case, although the Displacement effect would tend to increase forest conversion, the Labor Mobility effect would go in the opposite direction. The magnitude of this "compensation" will depend mainly on the influence of X_A on P_A, the influence of labor demand in the energy crop sector on agricultural wages and the degree of mobility in the rural labor force. The stronger the impact of X_A on P_A the more wages would have to increase and the more labor would have to be mobile in order that the Labor Mobility effect can compensate the Displacement effect.

Turning to the effect of an increase in the energy crop price on national food production, we have the following proposition.

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

Proof See Appendix H □.

Again, the energy crop sector expands at the expense of the food sector. Therefore, P_B decreases national food production X_A. 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 this region. In (9) one can see that the equilibrium amount of land allocated to sector A in region 1 is given by $(R_{1A})^e = \frac{\overline{R_1}}{1+\left(\frac{\lambda_B P_B}{\lambda_A P_A}\right)^{1/\nu}}$, 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 food production. Within region 1,the reallocation

[22] This is because perfect elasticity of *total* labor supply implies that the total stock of labor available for the two sectors is not fixed. This supposes that the sectors' labor demand is too small to influence national wages.

[23] See: https://www.cia.gov/library/publications/the-world-factbook/geos/in.html#Econ.

[24] See: http://data.worldbank.org/indicator/SL.AGR.EMPL.ZS.

of inputs in favor of the energy crop sector is of a kind that is reminiscent of the Direct Land Competition effect.

Finally, when both the Displacement and the Labor Mobility effects combine, national food output is further affected by an increase in the energy crop price since deforestation will play a smaller buffer role compared to the role played when considering the Displacement effect without labor mobility.

4 Discussion and Conclusions

This paper investigates the direct and indirect impacts of energy crop production on land use, deforestation and food production with 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 partial effects are highlighted and analyzed separately. In this section, we discuss the conditions under which each of the three effects materialize. In doing so, we present some policy implications for the Displacement and Labor Mobility effects before discussing how policy relates to the overall model approach. Policy implemented in the Brazilian ethanol industry is used to illustrate our points. Table 2 below summarizes these effects.

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 in the literature through the notion of indirect land-use changes (e.g. Gallagher 2008; Searchinger et al. 2008). There is also some empirical evidence for the displacement of other agricultural activities from the South of Brazil towards the Amazon as a result of the expansion of sugarcane production (Barona et al. 2010). Thus, the increased profitability of one agricultural sector has the potential to displace other agricultural activities towards marginal lands such

Table 2 Summary of conditions under which each effect occurs

Effects	Assumptions	Deforestation	Food production
Direct land competition	No labor mobility (A.1) $\theta_B > 0$ (A.2) P_A given (A.3)	–	–
Displacement	No labor mobility (A.1) $\theta_B = 0$ (A.2) P_A reactive to X_A (A.3)	–	–
Labor mobility	Labor mobility (A.1) $\theta_B = 0$ (A.2) P_A given (A.3)	+	–

note:"+" denotes potentially increasing; "−" denotes potentially reducing as those under forest. Our results are in line with those of Feng and Babcock (2010), as they relate to the impacts of an increase in the ethanol price on the food sector. Regarding impacts on deforestation, we show 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,[25] 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 would observe a simple direct reallocation of land between the two activities.

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. 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 providing technical assistance or building infrastructure such as roads to reduce costs to market, this could potentially mitigate food price increases while preventing deforestation. But, if little idle land is available to mitigate the food price increase, our results suggest a trade-off between increased food prices and forest protection, both having implications for social welfare. For countries with little idle land, ethanol production should neither be considered a desirable GHG-mitigation strategy nor a sustainable energy-producing strategy (see also, Ewing and Msangi 2009).

The Labor Mobility effect (case 3) is the other novelty of the paper, and one which is supported by evidence for increases in the flow of migrant labor towards sugarcane-growing regions of Brazil from the Amazon (Moraes and Alves 2008). 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 probably in between these two extremes and will not depend solely on wages. Other factors include the availability and quality of infrastructure, family ties and household composition, among others (Mincer 1978). Also, we have assumed total labor supply to be perfectly inelastic. This is, of course, unlikely to be the case in reality with the assumptions made in order to illustrate the effect in a tractable manner. Nevertheless, our results imply that in a context where the forest frontier is a suitable destination for poor rural households, an energy crop sector 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 in the energy crop sector could become an additional factor incentivizing agents to migrate towards the forest frontier. This could occur, for example, due to mechanization. For instance, the State of São Paulo, recently instituted a law forbidding the burning of sugarcane fields before the harvest. Without intending to,

[25] If the whole energy crop output is produced in the forest region then there is a Direct Land Competition effect, i.e. the energy crop directly competes for land with forests but with no displacement of other agricultural activities towards the forest frontier.

this law implicitly increases incentives for mechanization, since manual harvesting without previous burning is much less effective. Consequently, the sector's demand for unskilled rural labor, mainly employed in harvesting, is expected to decrease. 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 sensitive to changes in national food production, 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 it via the labor market (where there is free movement of labor). 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 on the impacts of ethanol production undertaken in a specific context.

Throughout the paper, we have considered the impacts of an exogenous increase of the energy crop price without considering the reasons for such an increase. In reality, this price shift may be driven by several factors including national and international pro-biofuels policies. These may include subsidies to production, the introduction of blending mandates or even higher oil taxes. The main implications of such policies in relation to both welfare impacts and land-use changes have already been discussed in previous studies (see, for example, Feng and Babcock 2010; de Gorter and Just 2009). In our setting, what matters ultimately is the output price faced by energy crop producers. Hence, all policies that favor the production of energy crops can be decomposed into the three partial effects discussed above, if the conditions supporting each of the effects are also met. As discussed, such policies were applied, for instance, in Brazil during the PróAlcool program, launched after the 1970s oil shocks to reduce the country's energy dependency. By acting both on the supply side (through low interest rates for loans to construct mills, and subsidized and regulated prices) and on the demand side (by imposing blending mandates), the federal authorities created a national market for ethanol. By the end of the program in the late-1990s, the conditions had been established for it to operate without further public intervention.

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 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 clearly more applicable to the former and not to the latter. Nevertheless, it also captures the cross-border indirect effect of increasing demand for US corn ethanol 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 minimizing negative impacts on deforestation and food production.

Appendices

A The Input Demand Functions

We derive the sectors' input demand functions in competitive equilibrium. They are obtained by using (4) and (5), substituting one into the other and rearranging to get

$$R_{1i} = \left(\frac{\alpha\lambda_i P_i}{P_1}\right)^{(1-\beta)/\nu} \left(\frac{\beta\lambda_i P_i}{W_1}\right)^{\beta/\nu} \tag{16}$$

and

$$L_{1i} = \left(\frac{\beta\lambda_i P_i}{W_1}\right)^{(1-\alpha)/\nu} \left(\frac{\alpha\lambda_i P_i}{P_1}\right)^{\alpha/\nu}. \tag{17}$$

where $\nu = 1 - \alpha - \beta > 0$.[26]

In the same way, using (6) and (7), we obtain

$$R_{2i} + R_{2i}^D = \left[\frac{\alpha\lambda_i P_i\theta_i}{P_2}\right]^{(1-\beta)/\nu} \left(\frac{\beta\lambda_i P_i\theta_i}{W_2}\right)^{\beta/\nu} \tag{18}$$

and

$$L_{2i} = \left(\frac{\beta\lambda_i P_i\theta_i}{W_2}\right)^{(1-\alpha)/\nu} \left[\frac{\alpha\lambda_i P_i\theta_i}{P_2}\right]^{\alpha/\nu}. \tag{19}$$

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 (18), $\overline{R_2} = R_{2A} + R_{2B}$ and $R_2^D = R_{2A}^D + R_{2B}^D$ total forest conversion can be written as

$$R_2^D = \left(\frac{\alpha}{P_2}\right)^{(1-\beta)/\nu} \left(\frac{\beta}{W_2}\right)^{\beta/\nu} \left[(\lambda_A P_A\theta_A)^{1/\nu} + (\lambda_B P_B\theta_B)^{1/\nu}\right] - \overline{R_2}. \tag{20}$$

B The Equilibrium Prices

Replacing the demand functions derived above in the constraints $R_{1A} + R_{1B} = \overline{R_1}$, $L_{1A} + L_{1B} = \overline{L_1}$, and $L_{2A} + L_{2B} = \overline{L_2}$ we obtain the input equilibrium prices

$$P_1^e = \alpha\left[(\lambda_A P_A)^{1/\nu} + (\lambda_B P_B)^{1/\nu}\right]^\nu \left(\frac{1}{\overline{R_1}}\right)^{1-\alpha} \left(\overline{L_1}\right)^\beta,$$

$$W_1^e = \beta\left[(\lambda_A P_A)^{1/\nu} + (\lambda_B P_B)^{1/\nu}\right]^\nu \left(\frac{1}{\overline{L_1}}\right)^{1-\beta} \left(\overline{R_1}\right)^\alpha$$

and

$$W_2^e = \beta\left(\frac{\alpha}{c}\right)^{\alpha/(1-\alpha)} \left[\frac{(\lambda_A P_A)^{1/\nu} + (\lambda_B P_B)^{1/\nu}}{\overline{L_2}}\right]^{\nu/(1-\alpha)},$$

where e refers to equilibrium. Note that since we've assumed $P_2 = c$, we do not need to compute the equilibrium price for type 2 land.

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

C Proof of Proposition 1

Taking the derivative of (13) with respect to P_B yields

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

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

D Proof of Proposition 2

This proof is obtained by analyzing equations (9) and (11), where the amount of land allocated to one use is, *ceteris paribus*, decreasing in the other good's price.

E Proof of Proposition 3

Taking into account the fact that P_A is sensitive to quantity X_A produced in the national economy, we can replace it in (14) by $X_A^{-\eta_A}$. Rearranging we obtain

$$\begin{aligned} 0 = {} & \frac{\left(\overline{R_1}\right)^{\alpha}\left(\overline{L_1}\right)^{\beta}}{\left[1+\left(\lambda_B P_B.\lambda_A X_A^{\eta_A}\right)^{1/\nu}\right]^{\alpha+\beta}} \\ & + (\theta_A)^{1/(1-\alpha)}\left(\frac{\alpha\lambda_A}{c}\right)^{\alpha/(1-\alpha)}\left(\overline{L_2}\right)^{\beta/(1-\alpha)}\left(\frac{1}{X_A}\right)^{\eta_A\alpha/(1-\alpha)} - X_A. \end{aligned}$$

This relation implicitly defines X_A as a function of P_B. An increase in P_B decreases the RHS of the expression. Since all the terms on the RHS are also decreasing in X_A, in order to reestablish the equality, X_A has to decrease. Thus, X_A decreases in the energy crop price, which by (A.4) implies that P_A increases in the energy crop price.

From (15) it is straightforward to see that the equilibrium amount of deforestation is increasing in the price of food. Thus, an increase in P_B induces an increase in P_A, which in turn increases forest conversion.

F Proof of Proposition 4

This has been shown when proving proposition 3.

G Proof of Proposition 5

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 before showing how deforestation varies with the wage level. This represents an indirect effect of ethanol price on deforestation.

Using (4) to (8), $\theta_B = 0,\ P_2 = c$ and $W_1 = W_2 = W$ one can derive the demand functions of land and labor for both sectors B and A which are given by

$$R_{1B} = \left(\frac{\alpha\lambda_B P_B}{P_1}\right)^{(1-\beta)/\nu} \left(\frac{\beta\lambda_B P_B}{W}\right)^{\beta/\nu}, \tag{21}$$

$$L_{1B} = \left(\frac{\beta\lambda_B P_B}{W}\right)^{(1-\alpha)/\nu} \left(\frac{\alpha\lambda_B P_B}{P_1}\right)^{\alpha/\nu}, \tag{22}$$

$$R_{1A} = \left(\frac{\alpha\lambda_A P_A}{P_1}\right)^{(1-\beta)/\nu} \left(\frac{\beta\lambda_A P_A}{W}\right)^{\beta/\nu}, \tag{23}$$

$$L_{1A} = \left(\frac{\beta\lambda_A P_A}{W}\right)^{(1-\alpha)/\nu} \left(\frac{\alpha\lambda_A P_A}{P_1}\right)^{\alpha/\nu}, \tag{24}$$

$$\overline{R_2} + R_2^D = \left(\frac{\alpha\lambda_A P_A\theta_A}{P_2}\right)^{(1-\beta)/\nu} \left(\frac{\beta\lambda_A P_A\theta_A}{W}\right)^{\beta/\nu} \tag{25}$$

and

$$\overline{L_2} = \left(\frac{\beta\lambda_A P_A\theta_A}{W}\right)^{(1-\alpha)/\nu} \left(\frac{\alpha\lambda_A P_A\theta_A}{P_2}\right)^{\alpha/\nu}. \tag{26}$$

Using equations (21), (23) 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

$$P_1 = \alpha\left(\frac{\beta}{W}\right)^{\beta/(1-\beta)} \left[\frac{(\lambda_A P_A)^{1/\nu} + (\lambda_B P_B)^{1/\nu}}{\overline{R_1}}\right]^{\nu/(1-\beta)}. \tag{27}$$

Using the constraint $\overline{L} = L_{1A} + L_{1B} + L_{2A}$ and equations (22), (24), (26) and (27) we obtain the following expression

$$\overline{L} = \left(\frac{\beta}{W}\right)^{1/(1-\beta)} \left[(\lambda_A P_A)^{1/\nu} + (\lambda_B P_B)^{1/\nu}\right]^{\nu/(1-\beta)} \left(\overline{R_1}\right)^{\alpha/(1-\beta)} + \left(\frac{\beta}{W}\right)^{(1-\alpha)/\nu} \left(\frac{\alpha}{P_2}\right)^{\alpha/\nu} (\lambda_A\theta_A P_A)^{1/\nu}. \tag{28}$$

From equation (28) we can see that, *ceteris paribus*, if P_B increases then W must increase as well since P_1 and P_2 are given. Looking at equation (25) 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.

H Proof of Proposition 6

Using equations (21) to (27) and replacing these in the production function yields:

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

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.

Acknowledgments The authors thank, without implicating, participants at various conferences: the North-South Center Colloquium 2009 in Zurich; the SURED conference 2010 in Ascona; the World Congress of Environmental and Resource Economists 2010 in Montreal; the RESEC Winter School 2010 in Ascona; the AEL conference 2010 in Hannover. Special thanks go to Julien Daubanes, Astrid Zabel and to two anonymous referees. Financial support from the North-South Center is gratefully acknowledged.

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