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Soil heterogeneity, agricultural supply and land-use change: an application to biofuels production

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Soil heterogeneity, agricultural supply and land-use change: an application to biofuels production*

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Abstract

Biofuels policies (blend mandate or tax credit) have impacts on food and energy prices, and on land-use. The magnitude of these effects depends on the market response to price, and thus on the agricultural supply curve, which, in turn, depends on the land availability (quantity and agronomic quality). To understand these relationship beyond marginal analysis, we develop a theoretical framework with an explicit representation of land heterogeneity. The elasticity of supply curve is shown to be non-constant. This influences the welfare economics of biofuel policies. This is due to the availability of new land of marginal quality. Biofuels policies have different impacts in different countries, depending on both their global land endowment and the position of the equilibrium on the non linear agricultural supply curve. Knowing this heterogeneity helps to refine welfare analysis.

Keywords: Land use, Soil heterogeneity, Agricultural economics, Supply functions, Equilibrium, Land-use changes, Biofuels.

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Contents

1 Introduction

Agriculture is challenged to tackle several sustainability issues, encompassing among others, food production to ensure food security, biomass and bio-energy production to mitigate climate change, and natural areas preservation to protect biodiversity. Among agricultural production factors, land plays a fundamental role. Most of the sustainability objectives previously cited are related to land use: each of those objectives require devoted land, in sufficiently large area. On going increasing demand for food world-wide, and the recent development of biofuels production, taken along with the willingness to protect wild areas (such as native forests which represent biodiversity hotspots and grassland which are a key component of agricultural landscapes from the biodiversity point of view) aggravate land use conflicts.

Biofuel production enhances these issues (Fargione et al., 2008; Groom et al., 2008; Tilman et al., 2009). The effect of biofuel production and trade on the environment is strongly dependent on indirect land-use change (both for green house gases emissions and biodiversity preservation). To assess these effects, Searchinger et al. (2008) consider response of market, and estimate new crop supply and demand using historical conversion patterns. However, land-use is not modeled directly, and agricultural land expansion is not endogenous.

Two main, complementary theoretical approaches are used in the literature to investigate the relationship between land use change and agricultural markets: Computable General Equilibrium (CGE) models and mathematical land-use share models.

GCE makes it possible to develop a general equilibrium analysis of land use impacts of biofuels. Keeney and Hertel (2009) consider land-use change using land supply curves. Baltzer and Kløverpris (2008) have shown that the way land use is described in the General Equilibrium models have to be improved to encompass land-use change properly. Valin et al. (2009) propose such an extension to examine the environmental impact of biofuel policies. The CGE approach provides powerful tools to simulate policy shocks, and assess their impact on trade equilibrium. However, these models are based on strong assumptions, in particular because they consider Constant Elasticities of Substitution and Constant Elasticities of Transformation. Moreover, the key drivers of computed phenomena are contained in the details of the model, and not always understandable.

Simpler mathematical analysis can facilitate the understanding of the key elements of biofuel policies and their impacts (Feng and Babcock, 2010). Even if this approach has a limited scope of analysis as the model has to be tractable, and is thus less representative of reality and observed data, it makes it possible to clearly describe the relationship between variable of interest. It is the case of land-use share models. The evidence from the empirical literature strongly supports the notion that private land-use decisions are determined by the financial net returns to different land uses (i.e., the Ricardian rent). As well, land quality is shown to consistently explain the aggregate distribution of land-use. For example, high quality land is typically allocated to intensive agricultural uses such as row cropping, while low quality land is often put into forestry. Land-use shares in a given area will depend on the distribution of land quality within this area. In most spatial econometrics applications, some variables are included to characterize this distribution (Wu and Segerson, 1995). Stavins and Jaffe (1990) treat land quality distribution as unobservable, but assume that it takes a particular log-normal parametric form, and estimate the parameters of the distribution as a part of the econometric analysis.

Feng and Babcock (2010) include land quality heterogeneity distribution in a land-use share model with Ricardian rents. Their interesting analysis is based on the examination of the marginal effects of biofuel policies around equilibrium, and their impact on land-use change and intensification. However, biofuels policies are likely to modify agricultural production and consumption more than marginally, and the results of a broader analysis will depend on supply elasticities away from equilibrium (which are likely to be non-constant). This difference matters when one focuses on the welfare effect of biofuel policies. De Gorter and Just (2009b) conclude their article on that point, emphasizing that the shape of supply curve is influenced by available land for expansion, which modifies the supply elasticity, and then the deadweight costs of biofuels policies.

This paper proposes a formal framework to account for agricultural soil quality heterogeneity while addressing land-use change issues. Based on the Ricardo concept of a land rent margin, we develop a Land Use model that account for land quality heterogeneity (Hardie and Parks, 1997). The land quality distribution provides a formal means of aggregating individual land-use decisions. The rule is to allocate land to the use providing the highest profit. In general, output yields and optimal input levels vary with the quality of the land, and thus the profit varies with land quality as well. If the quality is defined in terms of agricultural productivity, profit from agricultural use would generally be assumed to be an increasing function of quality. In this case, profits from each use will exceed profits from all other uses over a compact range of land quality. By integrating the land quality distribution for the area over this range of land quality, one obtains an expression for the share of land that is optimally allocated to that use.

To represent soil quality heterogeneity, we adopt the theoretical framework developed by Lichtenberg (1989) (and often used since then, e.g., by Feng and Babcock (2010)), who use a scalar measure to represent land quality, and density and distribution functions of this parameter to represent land quality heterogeneity. According to Segerson et al. (2006), such a framework makes it possible to define a threshold quality between two land uses (all land of quality higher than the threshold would be devoted to one of the alternative uses, and the rest of land, of lower quality, to the other use).

In the spirit of Feng and Babcock (2010), we assess the impact of biofuel demand on agricultural product price and acreage considering both changes at the extensive margin (land-use change to cropland) and intensive changes (increasing input use to increase yield). However, we here consider global effects. This requires to specify the form of the soil quality distribution. In particular, we show that the form of the agricultural supply function depends on the soil quality heterogeneity, and is likely to be non-linear. Our result includes the increase of fertilizer use and yield in response to output price increase, and the extension of arable land. Area base models using heterogeneous land quality have not been used to determine agricultural supply functions and land supply curves (Arnade and Kelch, 2007). We build such functions, accounting for agricultural land expansion and intensification, as Feng and Babcock (2010). Application of our approach to France data illustrates our stylized facts.

This framework allows us to examine the effect of biofuel policies when equilibrium is modified more than marginally. We discuss how accounting for heterogeneous land distribution refines the analysis of welfare implication of tax credit (De Gorter and Just, 2009a; Feng and Babcock, 2010) and blend mandate (De Gorter and Just, 2009b; Feng and Babcock, 2010). The elasticity of supply curve is shown to be non-constant, and influence the deadweight costs of biofuel policies. This is due to the availability of new land of marginal quality. Biofuels policies have different impacts in different countries, depending on both their global land endowment and the position of the equilibrium on the non linear agricultural supply curve.

2 Soil heterogeneity and agricultural land use

2.1 Heterogeneous soil quality

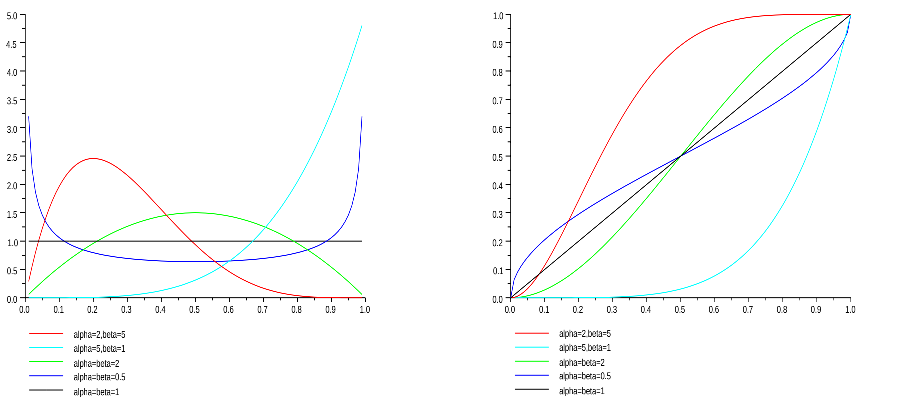
Let us consider an agricultural region, of total area L_0, where soil quality is heterogeneous and results in different agricultural productivities for the potential crops, or land uses. Following the tradition in land-use share models (from Lichtenberg (1989) to Feng and Babcock (2010)), we assume that soil quality is represented by an indicator normalized into the interval $[0, 1]$. It means that the soil with the worst agricultural quality will be represented by a nil value of the indicator, and the soil with the best quality will be valued 1. We consider that the acreage of land that is of quality $Q \in [0, 1]$ is given by a density function $f : [0, 1] \mapsto \mathbb{R}$, and that the proportion of acreage of the considered area that is of quality Q or less is given by $F(Q) = \frac{1}{L_0} \int_0^Q f(q)dq$. The function F is continuous and increasing. We also have the property $F(1) = 1$ which means that all the soils have a quality lower or equal to the highest quality. According to Hardie and Parks (1997), a convenient form cannot be chosen for the density function, since assumptions about its form amount to assumptions about the region distribution of land quality soils. From an empirical point of view, we agree with this limit. Nevertheless, it is possible to approximate an empirical distribution function using flexible density functions, with sufficient parameters. For this purpose, we consider theoretical distribution of soil quality, and use the Beta function: the density function of Q is:

$$f(q, \alpha, \beta) = \frac{q^{\alpha-1}(1-q)^{\beta-1}}{B(\alpha, \beta)} \tag{1}$$

where Beta function $B(\alpha, \beta) = \int_0^1 q^{\alpha-1}(1-q)^{\beta-1}dq$ appears as a normalization constant to ensure that the total distribution integrates to unity. By denoting $B_Q(\alpha, \beta) = \int_0^Q q^{\alpha-1}(1-q)^{\beta-1}dq$ the incomplete Beta function, the cumulative distribution of soil quality is

$$F(Q, \alpha, \beta) = \int_0^Q f(q, \alpha, \beta)dq = \frac{\mathrm{B}_Q(\alpha, \beta)}{\mathrm{B}(\alpha, \beta)} \tag{2}$$

The beta function has the great advantage to make it possible to represent a wide range of heterogeneity patterns with only two parameters, providing a powerful theoretical tool for application (Eugene et al., 2002; Hennessy, 2009). Fig. 1a) represents soil quality distributions for various values for parameters α and β, including uniform, U-shaped, asymmetric (concave or convex), unimodal, and linear distributions.[1] And Fig. 1b) represents the associated cumulative distribution.



(a) Soil quality distribution (b) Cumulative soil quality distribution

Figure 1: Beta function for various parameters (α, β)

Beta functions are particular cases of the Dirichlet distributions, for two parameters. To estimate the value of the parameters, an easy way is to compute

[1] Other distributions could be used, in particular multimodal functions to represent high density of some soils qualities.

mean $\bar{x}$ and variance v of a distribution, which leads to $\alpha = \bar{x}\left(\frac{\bar{x}(1-\bar{x})}{v}\right)$ and $\beta = (1-\bar{x})\left(\frac{\bar{x}(1-\bar{x})}{v}\right)$. This theoretical framework is thus simple to apply and quite flexible. As an illustration, Fig. 2 provides a beta function calibrated on the soil quality heterogeneity of France.

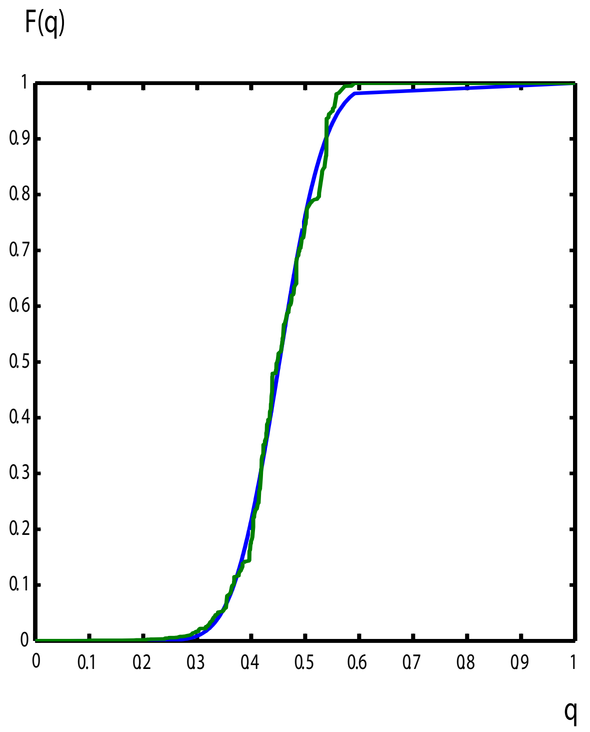


Figure 2: Soil quality heterogeneity and Calibrated Beta function from France yield data

2.2 Agricultural land use and production

Denoting $\mathcal{N} \equiv \{1, \ldots, N\} \subset \mathbb{N}$, assume that there are N potential land use on the considered area, and that the revenue of various land uses are defined by a vector of output prices $p \in \mathbb{R}^N_+$, in which element p_n is the price of output n (e.g., agricultural output price, of forest output price). For all $n \in \mathcal{N}$, $Y_n(q)$ is the potential yield of agricultural production n with respect to the soil of quality Q; it is a non-decreasing function of q, meaning that $q_1 > q_2 \Rightarrow Y_n(q_1) \geq Y_n(q_2)$.

For our theoretical analysis, yield functions are inspired by the Spillman-Mitscherlich form (Llewelyn and Featherstone, 1997; Frank et al., 1990; Kastens et al., 2003) as in Bond and Farzin (2008). If we consider two production factors: the soil quality q that is exogenously given for a field, and the quantity of added fertilizer f, the production Y_n of crop n is

$$Y_n(q,f) = (Y_{inf} + q(Y_{sup} - Y_{inf})) \left(1 - e^{-c_1(c_2+f)}\right) \tag{3}$$

where each c_i denotes a constant parameter. In that case, the soil quality parameter characterizes the soil with respect to all its endogenous characteristics, except nitrogen. c_2 is the natural contain of nitrogen in the soil, and c_1 is linked to the marginal productivity effect of nitrogen.

Each production is associated to an economic value. We define the profit (per area unit) of a production as a function of the yield (per surface unit), price p_n, a cost function $c_n(Y_n)$ which depends on the yield of this crop y_n.[2] In the present theoretical analysis, we consider linear cost of fertilizers ωf. The profit function per area unit reads

$$\pi_n(p_n,q,f) = p_n \left(Y_{inf} + q(Y_{sup} - Y_{inf})\right) \left(1 - e^{-c_1(c_2+f)}\right) - \omega f. \tag{4}$$

The optimality condition on the use of fertilizers is

$$\frac{\partial \pi_n(p_n,q,f)}{\partial f} = 0 \tag{5}$$

which implies after some basic computation

$$f^\star(p_n,q) = -c_2 - \frac{1}{c_1} ln \left(\frac{\omega}{p_n \left(Y_{inf} + q(Y_{sup} - Y_{inf})\right) c_1} \right) \tag{6}$$

There is thus a unique optimal fertilizer use for a crop n on a field, which depends on the soil quality of the field. Having characterized input choices, we will henceforth take them as given and fixed, focusing instead on the soil heterogeneity distribution and its impact on yields and land use.

In particular, using eq.(6), one can compute the optimal production level of a given crop on soil quality Q:

$$Y_n^\star(p_n,q,f^\star(p_n,q)) = (Y_{inf} + q(Y_{sup} - Y_{inf})) - \frac{\omega}{p_n c_1} \tag{7}$$

The optimal production of a crop is linearly increasing with respect to the soil quality.

One can now define the profit of that crop with respect to the soil quality:

$$\begin{aligned} \pi_n^\star(p_n,q,f^\star(p_n,q)) &= p_n Y_n^\star(p_n,q,f^\star(p_n,Q)) - \omega f^\star(p_n,q) \\ &= p_n \left[(Y_{inf} + q(Y_{sup} - Y_{inf})) - \frac{\omega}{p_n c_1} \right] \\ &\quad -\omega \left[-c_2 - \frac{1}{c_1} ln \left(\frac{\omega}{p_n \left(Y_{inf} + q(Y_{sup} - Y_{inf})\right) c_1} \right) \right]. \end{aligned} \tag{8}$$

[2]Fixed costs and subsidies could also be included, without modifying the results.

Eq.(8) defines the per area unit profit of land use n on a soil of quality Q with respect to a given economic price of output p_n. It is of interest to show that this relationship is increasing with respect to q, i.e., the higher the soil quality, the higher the profit of the land-use.

Monotonicity: Taking the derivative of that profit with respect to Q leads to

$$\frac{d\pi_n^\star(p_n, q, f^\star(p_n, q))}{dQ} = p_n(Y_{sup} - Y_{inf}) - \frac{\omega}{c_1}\left(\frac{Y_{sup} - Y_{inf}}{Y_{inf} + q(Y_{sup} - Y_{inf})}\right) \tag{9}$$

We thus have the following positivity condition: $\frac{d\pi_n^\star(p_n,q,f^\star(p_n,q))}{dq} \geq 0 \Leftrightarrow q(Y_{sup} - Y_{inf}) + Y_{inf} \geq \frac{\omega}{p_n c_1}$. This condition will be respected if the optimal yield (eq.7) is positive, which will be true on $[0,1]$ if $Y_{inf} \geq \frac{\omega}{p_n c_1}$, which is always true if the profit is positive. If such a condition holds, profit functions (with optimal fertilizer use) are increasing w.r.t. soil quality.

Moreover, the minimum and maximum profit for a given agricultural production n will appear to be useful indicators. We have $\pi_n^\star(p_n, 0, f^\star(p_n, 0)) = p_n\left[Y_{sup}(1-c_1) - \frac{\omega}{p_n c_2}\right] - \omega\left[-c_3 - \frac{1}{c_2} ln\left(\frac{\omega}{p_n Y_{sup} c_2 (1-c_1)}\right)\right]$ and $\pi_n^\star(p_n, 1, f^\star(p_n, 1)) = p_n\left[Y_{sup} - \frac{\omega}{p_n c_2}\right] - \omega\left[-c_3 - \frac{1}{c_2} ln\left(\frac{\omega}{p_n Y_{sup} c_2}\right)\right]$.

As a remark, note that monotonicity is assumed in several theoretical area base models, in which land rent is a monotonically increasing function of the land quality parameters (see references in Hardie and Parks (1997)).

Convexity: Taking the second derivative of the profit with respect to q leads to

$$\frac{d^2\pi_n^\star(p_n, q, f^\star(p_n, q))}{dq^2} = \frac{\omega}{c_1}(Y_{sup} - Y_{inf})\left(\frac{Y_{sup} - Y_{inf}}{(Y_{inf} + q(Y_{sup} - Y_{inf}))^2}\right),$$

which is positive. The profit function is thus increasing and convex.

2.3 Resulting agricultural supply

Land-use Given the previous results, one can draw the N profit functions with respect to the soil quality. We assume that the land-use will be such to maximize the profit on a soil, satisfying the maximization problem

$$LU(q) = \arg\max_{n \in \mathcal{N}} \pi_n(q) \ . \tag{10}$$

The purpose of the study is to derivate land-use characteristics from economic indicators (prices, costs, subsidies...) knowing agricultural potentials and soil quality distribution. Once the profit functions are defined for all possible agricultural production, it is possible to determine the optimal land-use allocation. In a given area, with a soil heterogeneity described by a Beta function depending on the quality parameter Q, one can define the yield of each soil quality, and determine the spin quality for any price system.[3]

For example, if there are only two possible land-uses: forest with constant profit π_f per hectare *vs.* crop with profit $\pi_c(q)$, one should define $\tilde{Q}_{f\rightarrow c}$ such that for all $q \geq \tilde{Q}_{f\rightarrow c}$, $\pi_c(q) \geq \pi_f$. Using our agricultural production function leads to the following condition

$$X - \frac{\omega}{pc_1} ln(X) \geq \frac{1}{p}\left(\pi_f - \omega c_2 + \frac{\omega}{c_1}\left(1 - ln\left(\frac{\omega}{pc_1}\right)\right)\right)$$

where X is the linear expression of q: $X = Y_{inf} + q(Y_{sup} - Y_{inf})$. The solution is unique but cannot be derived analytically.[4] Given monotonicity and convexity properties of the profit functions, a necessary and sufficient condition for the threshold quantity between two crops alternative (n and m) to be within $[0, 1]$ is $\pi^\star_n(0) > \pi^\star_m(0)$ and $\pi^\star_n(1) < \pi^\star_m(1)$ (or the reverse).

The solution of the profit-maximization problem (10) will divide the regional acreage into several compact sets, representing contiguous intervals of soil quality Q (Lichtenberg, 1989). The optimal problem (10) defines both optimal land use and optimal input use (fertilizers), maximizing the quasi-rents of the economic model. This provides a usual theoretical foundation for the area base model, accounting for Ricardian land rent margins. We can illustrate the reason behind the analysis with Fig. 3.

On Fig. 3, within the soil quality interval $[0, \tilde{Q}_1]$, the production 3 generates the highest profit. On $[\tilde{Q}_1, \tilde{Q}_2]$, this is production 2, and for $Q > \tilde{Q}_2$, this is production 1. In this example, production 3 corresponds to a production with little productivity variability with respect to the soil quality, and small costs (or high subsidies) such as forest or grassland. On the contrary, production 1 is associated with high fixed costs, but an increasing marginal profit, such as arable cropland.

The spin soil qualities $\tilde{Q}$ are defined such that $\pi_i(\tilde{Q}) = \pi_j(\tilde{Q})$.[5] For a stable potential agricultural production (i.e., if the yield functions $Y_n(Q)$ don't change

[3] We consider that all soils with the same quality have the same use. We do not include a "share factor" describing the share of land of a given quality devoted to a given crop, as Feng and Babcock (2010). Hence, our approach is more suited to examine the share of quite different types of land-use (e.g., forest, agriculture, pasture) than to examine the acreage of various crops.

[4] It could be in a model without fertilizer.

[5] It is possible to have analytical expression of these levels only if the yield functions are affine transformations one of the others, and if the cost functions are linear. They can be computed numerically in other cases. However, as our theoretical exercice aims at understanding the effect of soil heterogeneity on land-use change, we don't need analytical expressions for the values of $\tilde{Q}$ for the following discussion, but just that they exist. If we assume that land-use pattern follows the optimization problem (10), there are as much "spin qualities" as trade-offs between observed productions.

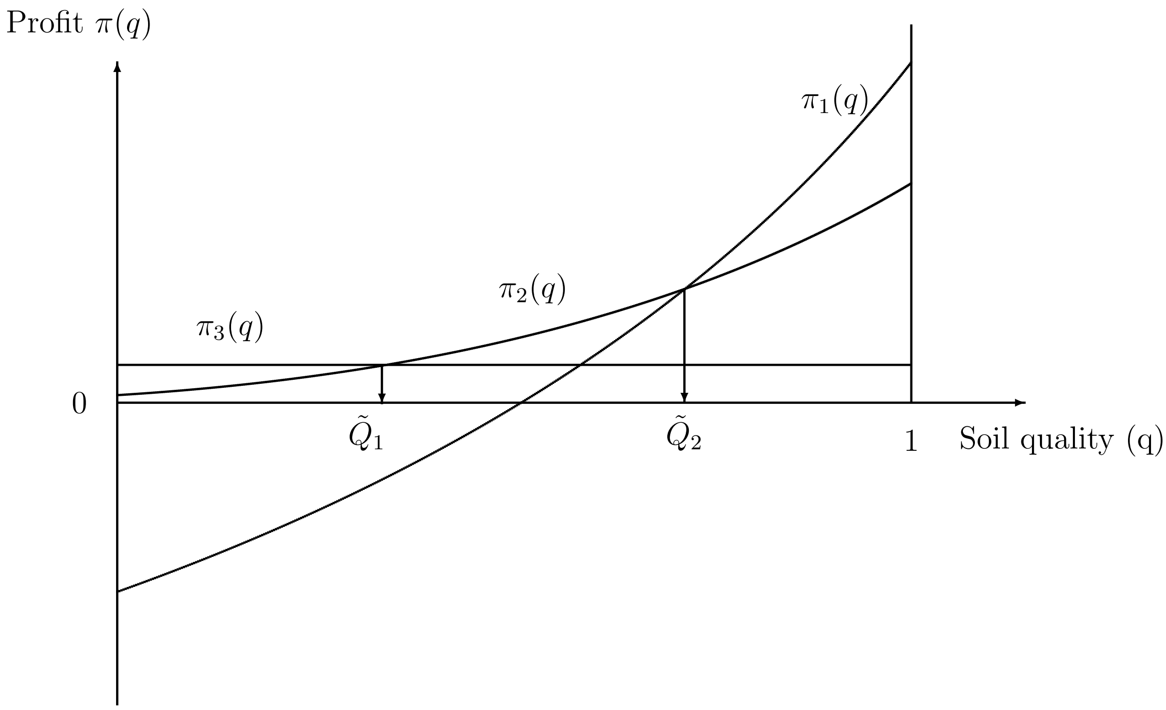


Figure 3: Profit functions and land-use

over time), it will only depend on economic parameters. Thus, the economic context (prices, costs, subsidies) will define the soil quality for which the land-use switch from one production to another. Given the distribution of soil quality, one gets the production areas. In particular, the share of land-use n produced on soils of quality belonging to $[\tilde{Q}_i, \tilde{Q}_{i+1}]$ will be $F(\tilde{Q}_{i+1}) - F(\tilde{Q}_i)$, that depends on the density of soil between the two spin qualities. These limits emerge from the area base model derived from the Ricardian rent hypothesis, in which land margins depend on differences in land quality.

If we consider theoretical soil distribution as described previously by Beta functions, the previous example (Fig. 3) can result in:

- A high proportion of land devoted to production 1 and production 3 in the case of a "U-shaped" soil quality distribution (red-plot of the Beta functions, with α and β lower than 1)
- A high proportion of land devoted to production 1 (with some production 2) if there is a high density of good soils (green plot, with $\alpha > 1$ and $\beta < 1$)
- A high proportion of land devoted to production 2 (with the small share of lands of "extreme" quality used to production 1 and 3) with an unimodal soil distribution characterized by a lot of "medium" quality soils (purple plot, with α and β greater than 1)

Agricultural total production Such an analysis results in threshold qualities $\tilde{Q}_i(p_1, \ldots, p_n, \ldots p_N)$. A crop would be produced on soil qualities $[\tilde{Q}_i, \tilde{Q}_{i+1}]$. It means that for a price system $(p_1, \ldots, p_n, \ldots, p_N)$, the total production of that agricultural good is[6]

$$Y_n^{total}(p) = \int_{\tilde{Q}_i(p)}^{\tilde{Q}_{i+1}(p)} f(q) Y_n^\star(p_n, q, f^\star(p_n, q)) dq \tag{11}$$

This expression can be integrated as follows:[7]

$$\begin{aligned}
Y_n^{total}(p) &= \int_{\tilde{Q}_i}^{\tilde{Q}_{i+1}} f(q) \left(q(Y_{sup} - Y_{inf}) + Y_{inf} - \frac{\omega}{p_n c_1} \right) dq & (12)\\
&= (Y_{inf} - \frac{\omega}{p_n c_1}) \int_{\tilde{Q}_i}^{\tilde{Q}_{i+1}} f(q) dq + (Y_{sup} - Y_{inf}) \int_{\tilde{Q}_i}^{\tilde{Q}_{i+1}} q f(q) dq & (13)\\
&= \left(Y_{inf} - \frac{\omega}{p_n c_1} \right) \left(F(\tilde{Q}_{i+1}, \alpha, \beta) - F(\tilde{Q}_i, \alpha, \beta) \right) \\
&\quad + (Y_{sup} - Y_{inf}) \frac{B(\alpha+1, \beta)}{B(\alpha, \beta)} \left(F(\tilde{Q}_{i+1}, \alpha+1, \beta) - F(\tilde{Q}_i, \alpha+1, \beta) \right) & (14)
\end{aligned}$$

This is the agricultural supply for that crop, at these prices. This function is well-defined. From the analytical form of that supply quantity, one can build a supply function depending on the prices. The prices enter only in the thresholds levels $\tilde{Q}(p)$. We have here an analytical expression of supply w.r.t. price, depending on the soil quality heterogeneity distribution.

Agricultural supply curve We here provide graphical illustration of the agricultural supply curve induced by land quality heterogeneity (Fig. 4). The results correspond to the supply functions for two different land endowment (in quality), in order to illustrate the sensitivity of the result to this heterogeneity. We consider a single agricultural product, with an opportunity cost on land-use.

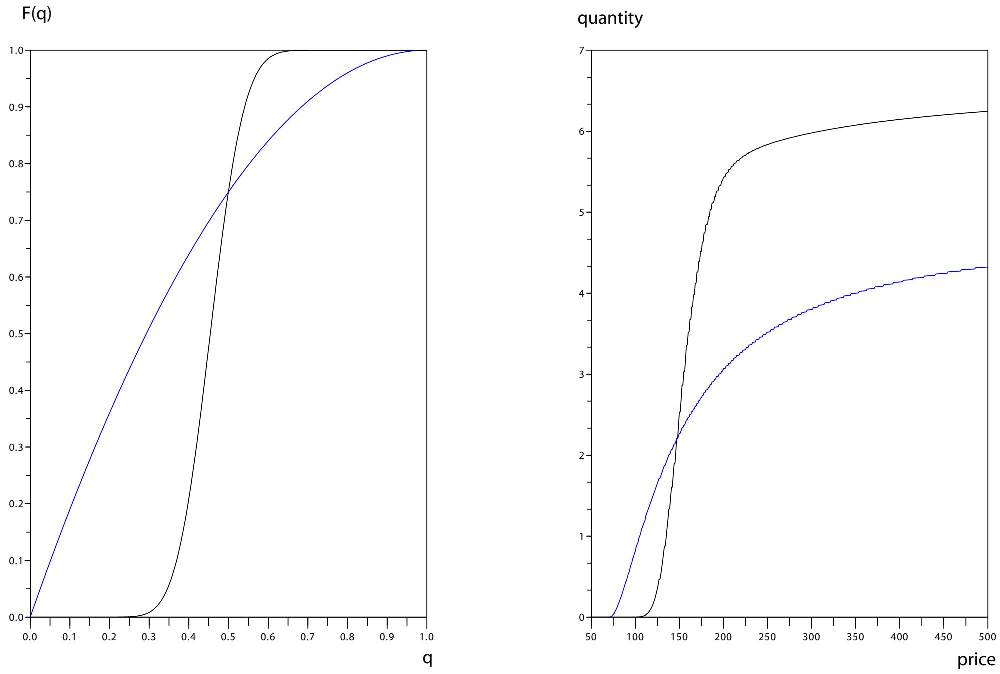
3 Implications for land-use change

3.1 Land-use change in a changing economic context

We now use this theoretical simple framework to describe land-use change when the economic context is modified. For the sake of simplicity, we consider only two

[6]The expression is given for a land endowment of 1. For an area A, the results is obtained by multiplying all quantities by A.

[7]We recall here that the density function $f(q)$ is supposed to be a beta function satisfying $f(q) = \frac{q^{\alpha-1}(1-q)^{\beta-1}}{B(\alpha,\beta)}$.



(a) soil quality endowments

(b) Supply functions

Figure 4: Agricultural supply functions

production possibilities, e.g., agricultural cropland and forest[8] ($N = 2$). Initially, production 1 is developed on the soils of quality $Q \leq \tilde{Q}$, and production 2 on soils with $Q > \tilde{Q}$. It results in an initial land use of a share $F(\tilde{Q})$ of land used to produce 1, and a share $1 - F(\tilde{Q})$ used to produce 2.

We consider that the economic context changes such that the spin quality becomes $\tilde{Q}'$ instead of $\tilde{Q}$. The new share of land is then $F(\tilde{Q}')$ of land used to produce 1, and a share $1 - F(\tilde{Q}')$ used to produce 2. It means that a share $F(\tilde{Q}') - F(\tilde{Q})$ of land is transfered from production of type 2 to production of type 1. We can write

$$F(\tilde{Q}') - F(\tilde{Q}) = \int_{\tilde{Q}}^{\tilde{Q}'} f(q)dq \tag{15}$$

Under the theoretical assumption of "small" variations dq of the spin quality, the quantity of land changed is $f(\tilde{Q})$, which is $\frac{dF(Q)}{dQ}_{|Q=\tilde{Q}}$. Such small variations are assumed in marginal analysis (Feng and Babcock, 2010). The stability of a land-use configuration is then measured using the density of land around the equilibrium. The result does not hold for important changes in the economic context, and large change in land use.

[8]The analysis is still valid for more production possibilities, with one to one comparisons.

A challenging issue is then to determine how the spin quality $\tilde{Q}$ varies with respect to a change in the context. It will allow us to define how much the land-use changes with respect to a change in the economic context. However, there may be various factors influencing the economic context (change in prices, in costs, in subsidies...). Fig. 5 gives the shares of the two land-uses w.r.t. price of the agricultural commodity. Cropland area is increasing with the price, while forest area is decreasing.

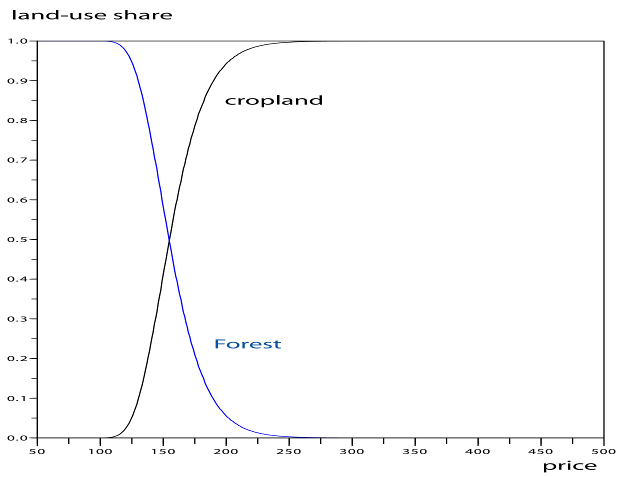


Figure 5: Land-use shares

3.2 The Land Supply Curve

A concept widely used in Computable General Equilibrium Models taking into account land explicitly is the land supply curve. This is the quantity of land offered with respect to the real land rental rate. In the agricultural economic context (for example with the GTAP framework), these curves are defined for a region using empirical land productivity curves, based on computations of potential yields using GEAZ data. The land supply curve is then calibrated using an inverse n-degree polynomial function of the land rental rate, which requires to estimate n+2 parameters.

It is possible to give a formal expression of an equivalent land supply curve in our framework. Consider that agricultural land use correspond to soil qualities $[\tilde{Q}_1(p), \tilde{Q}_2(p)]$. The land supply for a given price is $L(p) = F(\tilde{Q}_2(p)) - F(\tilde{Q}_1(p))$. The land supply elasticity is then $\frac{dL}{dp} = \frac{d\tilde{Q}_2}{dp} f(\tilde{Q}_2) - \frac{d\tilde{Q}_1}{dp} f(\tilde{Q}_1)$. Note that when p increases, both terms of the sum are positive, as $\tilde{Q}_2$ increases and $\tilde{Q}_1$ decreases. The land supply is thus increasing with the price (or the rental rate as the profit function is monotonic in q). Such an analysis is presented in Fig. 6.

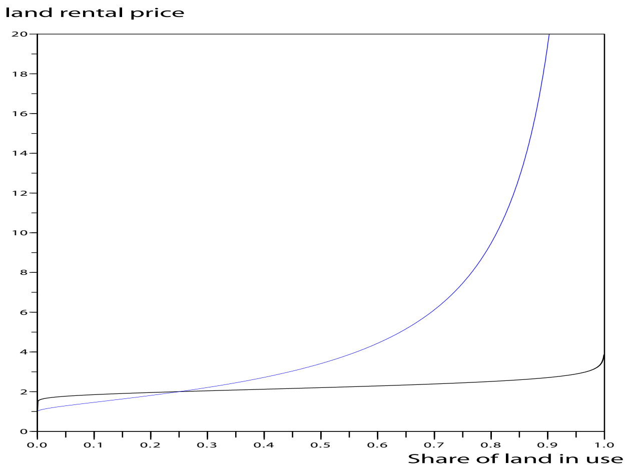


Figure 6: Land supply curve for two different soil quality distributions

Note that our model can be calibrated using GEAZ data. The difference in the two approaches is the timing of the estimation process in the analysis. In our approach, we first assume a functional form for the land heterogeneity distribution (which requires to estimate 2 parameters) and then analytically derive the form of the land supply curve. In the GTAP approach, the land supply curve is first built from data, and then a particular functional form is calibrated to estimate it.

3.3 Supply change w.r.t. price change

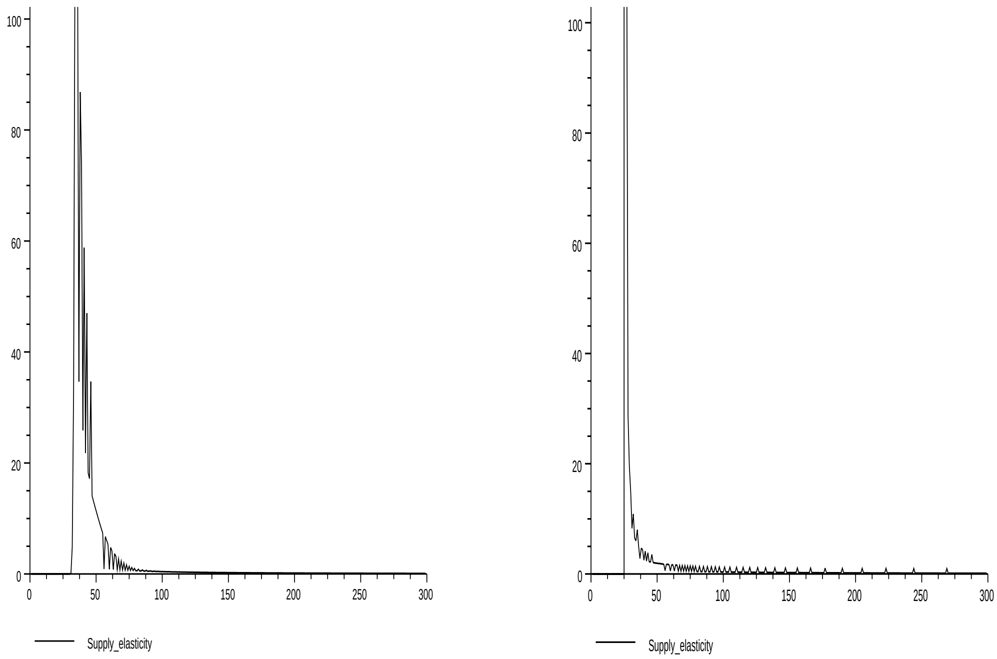
We now study the sensitivity of the production, and the associated land-use change, to the market price for that agricultural good. From a technical point of view, the first steps of the analysis would be to define the derivative of the $\tilde{Q}$ with respect to p (which may not require to know the analytical form, but only the expression that characterizes them). Taking the derivative of the production function (11) w.r.t. the agricultural price p_n leads to (Differentiation of definite integral containing a parameter ; differentiation 12.211 ; Gradshteyn and Ryzhik, 2007, p.1130):[9]

[9]Formally, this result requires that the functions $\tilde{Q}(p_n)$ are twice differentiable on the close set $[0, 1]$, and the function $f(q)Y_n^{\star}(p_n, q, f^{\star}(p_n, q))$ is integrable in q on the interval and differentiable in p. This is the case for Beta distributions.

$$
\begin{aligned}
\frac{dY_n^{total}}{dp_n} &= \frac{d}{dp_n}\int_{\tilde{Q}_i(p_n)}^{\tilde{Q}_{i+1}(p_n)} f(q)Y_n^\star(p_n,q,f^\star(p_n,q))dq \\
&= \frac{d\tilde{Q}_{i+1}(p_n)}{dp_n} f(\tilde{Q}_{i+1}(p_n))Y_n^\star\left(p_n,\tilde{Q}_{i+1}(p_n),f^\star(p_n,\tilde{Q}_{i+1}(p_n))\right) \\
&\quad -\frac{d\tilde{Q}_i(p_n)}{dp_n} f(\tilde{Q}_i(p_n))Y_n^\star\left(p_n,\tilde{Q}_i(p_n),f^\star(p_n,\tilde{Q}_i(p_n))\right) \\
&\quad +\int_{\tilde{Q}_i(p_n)}^{\tilde{Q}_{i+1}(p_n)} f(q)\frac{\partial Y_n^\star(p_n,q,f^\star(p_n,q))}{\partial p_n}dq \\
&= \frac{d\tilde{Q}_{i+1}(p_n)}{dp_n} f(\tilde{Q}_{i+1}(p_n))\left(Y_{inf}+\tilde{Q}_{i+1}(p_n)(Y_{sup}-Y_{inf})-\frac{\omega}{p_n c_1}\right) \\
&\quad -\frac{d\tilde{Q}_i(p_n)}{dp_n} f(\tilde{Q}_i(p_n))\left(Y_{inf}+\tilde{Q}_i(p_n)(Y_{sup}-Y_{inf})-\frac{\omega}{p_n c_1}\right) \\
&\quad +\frac{\omega}{c_1 p_n^2}(F(\tilde{Q}_{i+1}(p_n))-F(\tilde{Q}_i(p_n)))
\end{aligned} \tag{16}
$$

This result has the following interpretation: an increase in the agricultural product price has two effect. The first effect is linked to an *extension* of the acreage of this production, on both higher and lower quality land, i.e., changes at the extensive margin. This effect is represented by the two first terms of expression (16). The second effect is linked to an *intensification* of production on already used lands, due to an increase of fertilizer use, i.e., intensive changes. This effect is represented by the third term in expression (16). This result is close to the Feng and Babcock (2010) analysis. This is the local elasticity of supply. Note however that previous results provide the agricultural supply curve, which makes it possible to compute this elasticity for any price, accounting for the land heterogeneity effect away from equilibrium. Fig. 7 represents the price elasticity of supply along the agricultural supply curve.

The elasticity is nil if the price is too low to induce any allocation of land to the production. Once the price is sufficiently high, the elasticity of supply is initially very high (as a small increase in price induces a relatively huge increase in production). The elasticity of supply then decreases as the price increases, until it is almost nil (when all land is allocated to the production and yield increase comes only from intensification). There is a threshold effect around the spill price with an almost infinite elasticity. The shape of the elasticity curve is also influenced by the availability of land, and thus the heterogeneity.



(a) France (b) Other parameters

Figure 7: Price elasticity of agricultural supply

4 The welfare implication of biofuel policies

In what follows, we assume that the agricultural good can be used either as a consumption good or as an input to produce biofuels. We introduce an inverse demand function for food. This demand function is decreasing. Fig. 8 represents the market equilibrium of agricultural production and food demand, for two countries having different land endowment and thus different agricultural supply curves. In order to fully understand the role of land heterogeneity, we assume that every thing else is the same in the two countries (in particular, the equilibrium price for food).[10] What matters in our theoretical analysis is that the slopes of the agricultural production functions on the right hand side of the equilibrium are different in the two configurations, and depend on underlying land heterogeneity

[10]The analysis could have been done with two different countries facing a same market price (at equilibrium). Only the quantities produced in both countries would differ. In this case, it is possible to modify the problem, without modifying the results, by a simple translation of the "quantity" axis for one country, in order to obtain the same kind of representation as in Fig.8. It can be interpreted as an analysis of "additional" production with respect to the equilibrium. More generally, the result holds for any transformation of the axis which does not modify the areas (translations are admissible; transformations modifying the units -like homothety- are not).

(land availability and productivity).

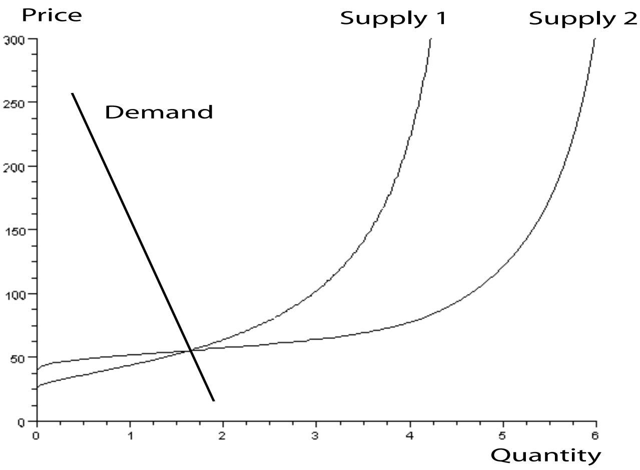


Figure 8: Inverse supply functions for two countries with different land endowments, facing a demand for food.

We also consider a biofuel sector which produces biofuels from the agricultural good, with a constant return technology. For the sake of simplicity we assume that the quantity of biofuel produced B is a linear function of the quantity of agricultural commodity used Q^B, i.e., $B = bQ^B$, where b is the rate of conversion of agricultural biomass in biofuels. Such a simple technology is used, for example, in De Gorter and Just (2009a,b) and Feng and Babcock (2010). The profit of biofuel producers is given by $\pi^B = p^B B - p^A Q^B$, where p^B is the selling price of biofuel, which is assume equal to the price of oil-based gasoline p^G when there is no mandatory blend.[11] This equation defines a break-even price for the agricultural commodity at level $p^A \equiv \bar{p} = bp^B$. We consider a partial equilibrium. This simple framework allows us to build on the analysis of De Gorter and Just (2009a,b) and examine how the consideration of land heterogeneity modifies the welfare of biofuels policies.

4.1 The economics of biofuel tax credit

The welfare implication of a biofuel tax credit is studied by De Gorter and Just (2009a). They show that tax credit generates "rectangular" deadweight costs when the intercept of the ethanol supply curve is initially above the gasoline price. The size of the rectangular deadweight costs (the "water" in the tax credit concept of De

[11] Other inputs could be consider in the biofuel production as in Feng and Babcock (2010), without modifying the results of the present analysis. Only the break-even price level would change.

Gorter and Just (2009a)) depends on the slope of the supply function around the equilibrium. We have shown that this slope depends on the soil quality distribution (eq.16). The consequences of a biofuel tax credit in terms of loss of welfare will thus strongly depend on the land endowment of the country under consideration, and more particularly on the availability of land of the marginal quality.

Fig. 9 presents the welfare analysis of biofuel tax credit, following the lead of De Gorter and Just (2009a). Notations are as follows; D^A and D^F are respectively the demand for food and fuel. S^A and S^G are respectively the supply for food and fossil fuel (gasoline). S^B is the supply of biofuels resulting from the excess production of agricultural output. S^B_σ is that supply when a tax credit σ is applied. S^F is the resulting (blended) fuel supply.

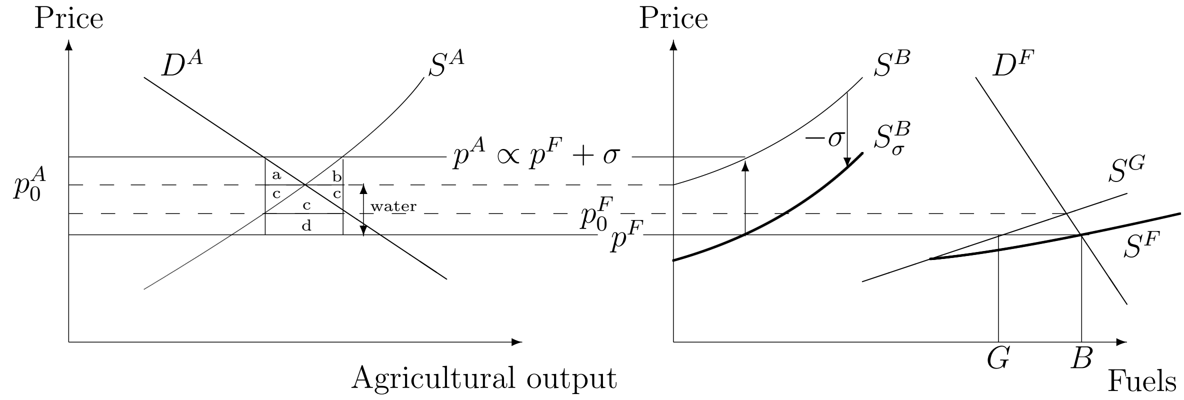


Figure 9: Welfare effect of a Tax credit.

Under our assumption of linear biofuel technology, prices of the agricultural output on the left panel and of the fuels on the right panels are proportional. The introduction of a tax credit for biofuels modifies the fuel consumption: total fuel consumption increases and fuel price decreases from p_0^F to p^F. The quantity of gasoline consumed decreases (gasoline consumption corresponds to the part from the origin to point G). Biofuel consumption is equal to the difference between total fuel consumption and gasoline consumption, i.e., segment GB. The price of agricultural output is driven by the break-even price of the biofuel industry, and is proportional to $p^F + \sigma$. Food price increases from p_0^A to p^A. Following De Gorter and Just (2009a), we interpret these changes in equilibrium in terms of welfare.

The deadweight costs of underconsumption of food is given by area a and the deadweight costs of overproduction in the agricultural sector is given by area b. The two rectangular areas c and d corresponds to the "water" in the tax credit (i.e., the amount of tax credit which has no direct effect as the price of biofuels is higher than the fuel price). Area c represents the "rectangular deadweight costs" introduced by De Gorter and Just (2009a). Area d represents the transfer of tax payers funds to fuel consumers.[12]

We now examine the effect of the land-heterogeneity on these areas. We do again the welfare analysis with the other supply function. Fig. 10 presents this analysis. Elements of interest from former situation are represented with thinner or dashed lines to make visual comparison easier.

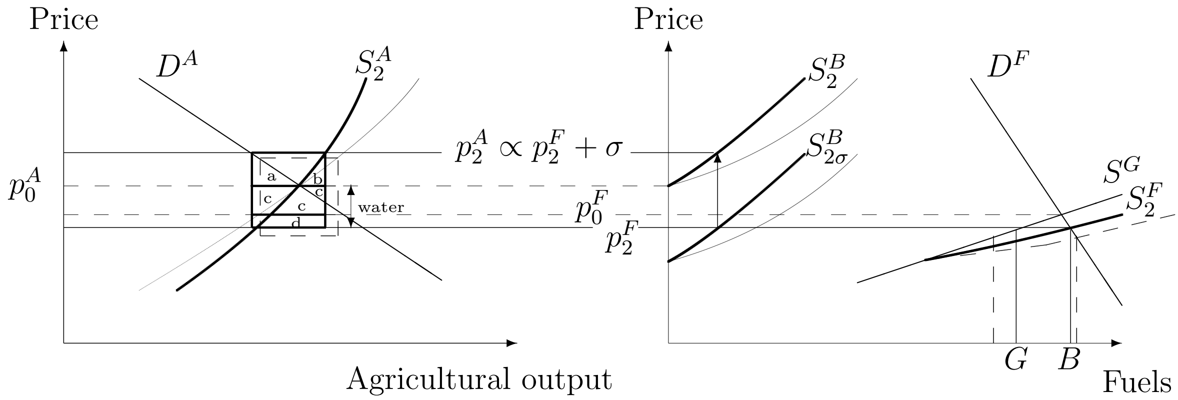


Figure 10: Effect of the land heterogeneity and agricultural supply shape on the welfare economics of tax credit, for a given tax credit level.

The first effect of a less elastic agricultural supply curve is that the cost of biofuel production is higher. For the same tax credit, less biofuels are produced.

There is a price effect. As the quantity of biofuels consumed is lower than in the previous case, the increase in fuel consumption and decrease in fuel price is lower. The biofuel price ($p_2^F + \sigma$) is then higher than in the previous case, so as the food price. The water is the tax credit is lower (because the fuel price is higher than in the first case).

The deadweight costs of underconsumption (area a) clearly increases (food price increases and food consumption decreases). The effect on the deadweight costs of overconsumption (area b) is ambiguous (price and quantity effects are opposite). The rectangular deadweight costs (area c) decreases due to a decrease in biofuel production. The transfer of tax payers funds to fuel consumers (area d) decreases for two reasons: because the quantity of consumed biofuels decreases and because the difference between initial and new fuel price is lower ($p_0^F - p_2^F$).

Let us provide a last result on biofuel tax credit. Assume now that the level of the tax credit is not given, but is defined such that a given amount of biofuel is consumed (we take the amount of biofuel consumed in the case exposed in Fig.9 as a benchmark). In that case, previous analysis is modified as presented in Fig. 11.

[12]Note that if fuel demand is totally inelastic (the demand function is vertical) or if the country is price taker (the gasoline price is exogenous, which corresponds to a flat supply curve), the fuel price does not change when the tax credit is introduced, and the welfare transfer between tax

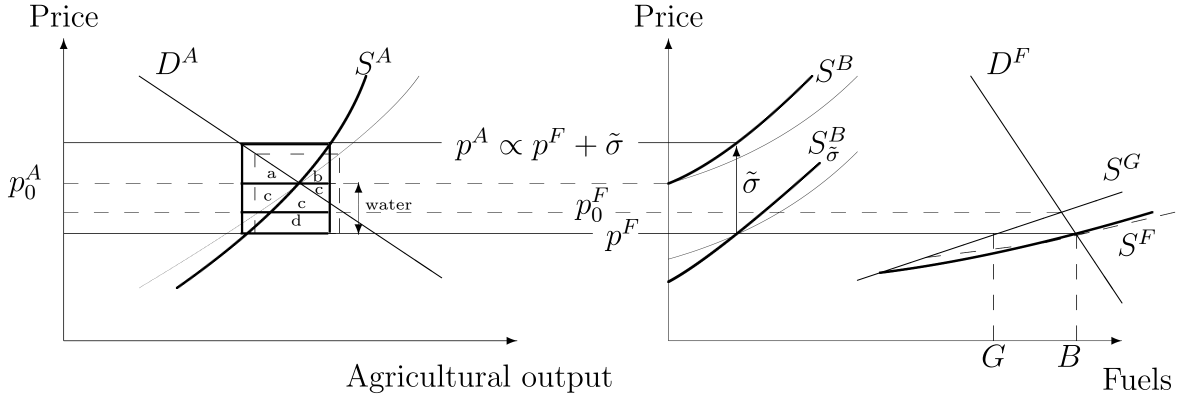


Figure 11: Effect of the land heterogeneity and agricultural supply shape on the welfare economics of tax credit, when a given quantity of biofuel is targeted.

The fuel price is the same as in the benchmark. However, to obtain the required quantity of biofuels with the second land endowment, the tax credit must be higher ($\tilde{\sigma} > \sigma$). The food price is thus higher. As the quantity of biofuels produced and the difference between initial food price and fuel price are the same as in the benchmark, the water in the tax credit is the same, and the size of rectangular areas (c and d) are the same (there is only a translation toward the left-hand-side of the graph). This means that transfer of tax payer funds to fuel consumers and rectangular deadweight costs depend on the actual quantity of biofuels consumed and on the difference between the resulting fuel price and the biofuel break-even price (i.e., the water), but not on the tax credit level directly. Roughly speaking, it depends on the effect of the policy and not on the level of the policy instrument to achieve this effect. On the contrary, the deadweight costs of underconsumption (area a) and overproduction (area b) increase with the tax credit level.

To sum up on the influence of land heterogeneity of the welfare economics of biofuel tax credit, we state that

- For a given tax credit level, the more elastic the agricultural supply (the higher the quantity of marginal land available), the higher the quantity of biofuels produced (the higher the response to the policy instrument), the higher the water in the tax credit, and the higher the rectangular deadweight costs and transfer of tax payer funds to fuel consumers. However, the traditional deadweight costs of underconsumption and overproduction are smaller than with inelastic supply (land scarcity).
- For a given quantity of biofuel consumed (and thus a given price of fuel), the more elastic the agricultural supply (the higher the quantity of marginal land

payers and fuel consumers (area d) vanishes.

available), the lower the tax credit needed, and the lower the deadweight costs of underconsumption of agricultural product and of overproduction. The rectangular deadweight costs and the transfer of tax payer funds to fuel consumers do not depend on the land heterogeneity if a biofuel production objective is given, but only on the biofuel production objective.

De Gorter and Just (2009a) conclude their article saying that the welfare effect of a tax credit for biofuels depend on the size of the country under study and on its trade status on both gasoline and agricultural output markets. We can add that the agricultural potential of the country, in terms of available lands of marginal quality, also matters. These two dimensions are not necessarily related as the former is linked to the already in production lands (and the competitiveness of the agricultural sector), while the latter is linked to the quantity and quality of land available for conversion (and thus on the opportunities of agricultural development).

Feng and Babcock (2010) examine the impact of such a policy instrument on land use. They show that total crop area increases when ethanol price increases. Our results are consistent with their findings. Moreover, we can quantify the effect the tax credit on land use, away from equilibrium, using result (15).

4.2 The economics of mandatory blending

Blend mandate for biofuels usually takes the form of a minimum blending requirement (called the renewable fuel standard (RFS) in U.S. legislation), which is the ratio of biofuels to total fuel consumption.[13]

In this section, we assume that there is a blend mandate for biofuels and that fuels have to contain a part $0 < \eta < 1$ of biofuel. Denoting p^B the price of biofuels, the price of mixed fuel is given by $p^F = \eta p^B + (1-\eta)p^G$. Fig. 12 represents the economics of blend mandate. D^A and D^F are respectively the demand for food and fuel. ηD^F is the share of biofuels in the demand of fuel. S_i^A and S^G are respectively the supply for food and fossil fuel (gasoline). S_i^F is the supply of mixed fuel, including the mandate. These supply curves are determined so that, for a given produced quantity x, the price is equal $p^F(x) = \eta p^B(\eta x) + (1-\eta)p^G((1-\eta)x)$.

The mandate increases the price of the mixed fuel, and thus reduces the quantity of fuel consumed. The more elastic the agricultural supply (i.e., the larger the quantity of marginal land available to agricultural production), the lower this effect, the higher the quantity of biofuel consumed and the lower the agricultural price.

On the agricultural market, consumer's surplus is reduced by area a_i. The higher the production elasticity, the lower these losses. Producer's profits totally

[13]If the blending objective is achieved with a subsidy (or tax credit), we refer to the analysis in the previous section, Fig. 11.

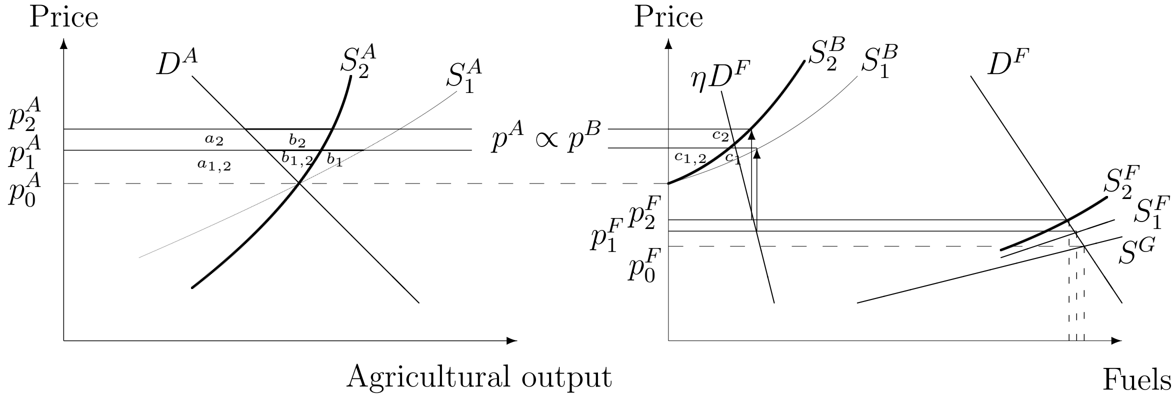


Figure 12: Effect of the land heterogeneity and agricultural supply shape on the welfare economics of biofuel mandatory blending.

capture these consumer's losses, along with profit on the biofuel market (areas b_i). Area b corresponds to the part of the producer surplus due to the biofuel market. These areas are equal, in value, of the producer's surplus on the biofuel market (area c_i), which are equal to a part of the fuel consumers losses. The more inelastic the biofuel supply, the larger these gains for agricultural producers. The gains or losses for fossil fuel producers depend on the elasticities of gasoline supply and fuel demand curves (see De Gorter and Just, 2009b). They are influenced by the land heterogeneity via the biofuel production function and biofuel price.

To sum up on the influence of land heterogeneity of the welfare economics of biofuel blend mandate, we can say that the effect on the mandate on the fuel market will depend on biofuel supply elasticity and thus on the availability of land of marginal quality. Moreover, the effect on the agricultural market is beneficial to the agricultural producers, which gain from food and fuel consumer losses. The more inelastic the agricultural supply (the scarcer the land), the higher these transfers.

Feng and Babcock (2010) show that crop area increases with a mandate. Here again, we can quantify this land-use change effect.

5 Concluding remarks

In the present paper, we develop a theoretical analysis of the impact of soil quality heterogeneity on agricultural supply curve, and we examine how it makes it possible to refine welfare analysis of biofuel policies. The theoretical framework is in the spirit of Feng and Babcock (2010) but is extended, by considering an explicit soil quality distribution. It allows us to analyze the effect of biofuel policies beyond marginal analysis of the equilibrium, having a more accurate quantitative estimation of the impact of biofuel policies on land-use change, and food and biofuels production and consumption. In particular, we refine the welfare analysis of tax credit policies (De Gorter and Just, 2009a) and mandatory blending (De Gorter and Just, 2009b). We show that soil heterogeneity, by shaping the agricultural supply curve, influences the welfare economics of biofuel tax credit and biofuel blend mandate. The main message is that the scarcer the land of marginal quality (i.e., the less elastic the supply curve), the higher the transfer form consumers to producers. Moreover, for a given tax credit, the scarcer the land, the lower the "water" in the tax credit (because the policy is less effective), and the higher the deadweight costs of underconsumption and overproduction.

Of course, further research are needed, both for practical application and theoretical analysis. From a practical point of view, it would be interesting to get a assessment of land quality heterogeneity for different countries[14], and to examine how the framework can be applied when there are more agricultural products and market effects, as in Feng and Babcock (2010). From a theoretical point of view, future research will use the developed framework in a bilateral trade approach, in the spirit of Keeney and Hertel (2009), with two countries having different land endowment. The non linearity of supply curves may induce interesting results when the magnitude of biofuel consumption increases beyond marginal effect. Such development should account for trade and strategic interactions and examine the induced environmental effects of biofuel production and trade (Keeney and Hertel, 2009; Valin et al., 2009), in particular on indirect land-use change and its biodiversity impacts.

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[14]At a global scale, soil heterogeneity parameters could be defining using the Global Agro-Ecological Zoning (GAEZ) data, which were used to calibrate the GTAP land-use data (Keeney and Hertel, 2009).

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