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Effect of soil heterogeneity on the welfare economics of biofuel policies

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Abstract

Biofuel 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 relationships, we develop a theoretical framework with an explicit representation of land heterogeneity. The elasticity of the supply curve is shown to be non-constant, depending on land heterogeneity and the availability of land for agricultural expansion. This influences the welfare economics of biofuels policies, and the possible carbon leakage in land and fuel markets. We emphasize that the impacts of biofuel policies on welfare and land-use change depend strongly on the potential development of the agricultural sector in terms of expansion and intensification, and not only on its current size.

Keywords: Agricultural and energy market, Biofuels, Land use, Soil heterogeneity, Welfare.

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1. Introduction

In the last decade, several countries have supported biofuel production and set targets in terms of their use (Sorda et al., 2011). There are a number of political reasons pushing governments to promote biofuels, the main ones being climate change mitigation, employment in the agricultural sector, and energy security (Charles et al., 2007). As biofuel production at a large scale is not profitable in a context of relatively low gasoline prices (apart from the Brazil case), governmental targets would not be achieved without external incentives, and the recent increment in production has been driven by public policies and economic incentives (Kretschmer et al., 2009; Sorda et al., 2011). For example, in the United States, ethanol production is supported by strong tax credits (VEETC: Volumetric Ethanol Excise Tax Credit) as well as by production mandates (RFS: Renewable Fuel Standards). In the European Union, biofuel consumption is also mostly driven by blending mandates and tax exemption. Biofuel policies are strongly distortionary, and generate welfare effects (De Gorter and Just, 2009a,b; Böhringer et al., 2009). In particular, the increasing production of first generation biofuels from grain and oilseeds participates in the increment in food price, jeopardizing food security. The magnitude of these effects depends on the elasticities of agricultural supply, and thus on the extensive (land use change) and intensive (intensification of production) margins in the agricultural sector. Biofuel production also generates environmental externalities, such as green house gases emissions or biodiveristy losses (Fargione et al., 2008; Groom, Gray and Townsend, 2008; Petersen, 2008; Tilman et al., 2009). These negative effects are due to land use change on the one hand, and market effects on the other. Biofuel policies may result in carbon leakage in fuel and land markets. In this context, it is important to understand the interactions between market effects and agricultural land-use to assess the holistic effect of biofuel policies.

To assess the environmental effects of biofuel policies, 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 approaches are used in the literature to investigate the relationship between agricultural markets and land use change: Computable General Equilibrium (CGE) models and mathematical land-use share models based on partial equilibrium. The main difference between these approaches lies in their degree of complexity, the former approach being based on detailed simulation models, while the latter is based on stylized analytical models.[3] CGE models make it possible to assess the impacts of biofuels policies on land use in a general equilibrium, using land supply curves (Banse et al., 2008; Keeney and Hertel, 2009; Kretschmer and Peterson, 2010). The CGE approach provides powerful tools to simulate policy shocks, and to assess their impact on trade equilibrium. However, these models often assume Constant Elasticities of Substitution and Constant Elasticities of Transformation, and the key drivers of computed phenomena, like land use change, are not always apparent. Simpler mathematical analyses, such as land-use share models, make it possible to understand the key elements of the impacts of biofuel policies on land-use change. Evidence from the empirical literature strongly supports the notion that private land-use decisions are determined by the financial returns to different land uses (i.e., the Ricardian rent), and land quality consistently explains the aggregate distribution of land-use (Stavins and Jaffe, 1990; Wu and Segerson, 1995; Hardie and Parks, 1997). 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

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[3] Lapan and Moschini (2012) provide an analytical assessment of the welfare effect of biofuel policies in a general equilibrium model without considering land and land-use effects.

area will depend on the distribution of land quality within this area.[4] Feng and Babcock (2010) use such a land-use share model to assess qualitatively the marginal effects of biofuel policies on land-use change and intensification, around equilibrium. 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 effects of biofuel policies. De Gorter and Just (2009b) conclude their article on this point, emphasizing that the shape of the agricultural supply curve is influenced by available land for expansion, which modifies the supply elasticity, and then the deadweight costs of biofuels policies.

The present paper proposes a formal framework to examine how the agricultural soil quality heterogeneity of a country influences the welfare implications of biofuel policies and their effect on land-use change. Our analysis is in line with the welfare analysis of De Gorter and Just (2009a,b), completed by accounting explicitly for soil heterogeneity and its influence on agricultural supply. For this purpose we build on the framework of Feng and Babcock (2010). By specifying the form of the soil quality distribution, we extend their analysis in two directions. Firstly, the proposed extension allows us to determine agricultural supply functions and land supply curves as function of the quality heterogeneity distribution. We build such functions accounting for agricultural land expansion and extensive margins, as well as for intensification and intensive margins (i.e., the increase of input use and yield in response to output price increase). We show that the land quality heterogeneity distribution influences the shape of the agricultural

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[4] Spatially explicit models without soil heterogeneity *à la von Thunen* can also be used to determine the effect of biofuel production on local land use (Lankoski and Ollikainen, 2008).

supply function, which is likely to be non-linear.[5] Application of our approach to US and France data illustrates our analytical results and emphasizes the flexibility of the proposed approach. Secondly, the proposed extension allows us to examine the effect of biofuel policies when equilibrium is modified more than marginally. We discuss how the heterogeneity of land quality influences the analysis of welfare implications of tax credit (De Gorter and Just, 2009a; Feng and Babcock, 2010) and blend mandate (De Gorter and Just, 2009b; Feng and Babcock, 2010). As the elasticity of supply curve is not constant, deadweight costs of biofuel policies vary with the availability of additional land in quantity and quality. In particular, the effect of biofuel policies on both land and energy markets have to be assessed to determine if there are carbon leakages in these markets. Our main message is that the consequences of biofuels policies depend on both the global land endowment of the country under study and the position of the equilibrium on the non linear agricultural supply curve. The possibility to develop further the agricultural sector is thus more important than its current size.

The framework proposed here would be helpful for further research examining analytically the indirect land-use change impact of biofuel policies in a context of trade between countries, or world areas, with different land endowment.

2. Motivation: The welfare economics of biofuel depends on agricultural supply

To motivate our analysis, we develop further the arguments of the introduction, by refering to the example of biofuel tax credits. The welfare implications of a biofuel tax credit has been studied by De Gorter and Just (2009a).

We consider a biofuel sector which produces biofuels from an agricultural com-

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[5] Using area based models with heterogeneous land quality to build agricultural supply function is a contribution to the literature as such functions are usually constructed from profit functions, or by aggregating technological functions (Arnade and Kelch, 2007; LaFrance and Pope, 2008).

modity, 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 assumed equal to the price of oil-based gasoline p^G when there is no mandatory blend.[6] This equation defines a break-even price for the agricultural commodity at level $p^A = \bar{p} \equiv bp^B$. We consider a partial equilibrium of the energy and food sectors.

Fig. 1 presents the welfare analysis of biofuel tax credit, as presented by 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 for 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.

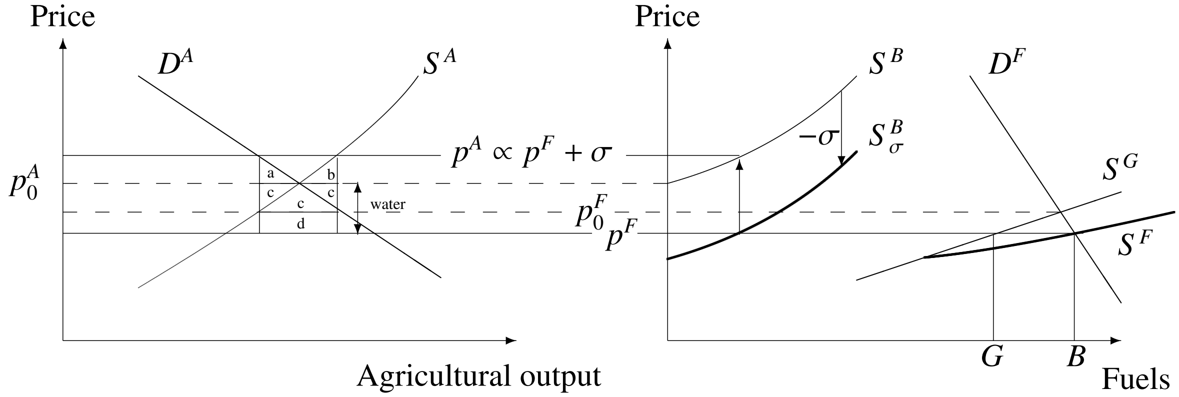

Figure 1: Welfare effect of a Tax credit (inspired from De Gorter and Just, 2009a)

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[6] Other inputs could be considered in the biofuel production without modifying the results of the present analysis. Only the break-even price level would change.

Under the assumption of linear biofuel technology, prices of the agricultural output on the left panel and of the fuels on the right panel 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. Note that the reduction in gasoline use is lower than the quantity of biofuels used (the market equilibrium moves to the right). There is a carbon leakage due to a market effect in the fuel market.

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 cost[7] of underconsumption of food is given by area a and the deadweight cost of overproduction in the agricultural sector is given by area b. Such costs are usual when a policy such as a subsidy modifies an optimal equilibrium. De Gorter and Just (2009a) show that biofuel tax credit also generates "rectangular" deadweight costs when the price of biofuel without intervention is higher than the fuel price. The two rectangular areas labeled by c and d correspond to the "water" in the tax credit (i.e., the amount of tax credit which has no direct effect, as the price of biofuels without intervention is higher than the fuel price). The area made by elements labeled c represents the rectangular deadweight costs. Area d represents the transfer of tax payers funds to fuel consumers.[8]

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[7] In welfare economics, the deadweight costs of a policy correspond to net losses of welfare with respect to an optimal situation, i.e., losses for some agents (consumers, producers or tax payers) which are not compensated by gains for other agents.

[8] 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

Note that this analysis does not give information on the land use market, even if this information is implicitly incorporated in the agricultural supply function, and the way supply increases when the biofuel policy is applied. The importance of the "water" in the tax credit, and thus the inefficiency of the biofuel policy in terms of biofuel production, and that of other deadweight costs depend on the slope of the supply function. So do the carbon leakages, in both fuel and land markets. We argue that this slope depends on the soil quality distribution. The consequences of a biofuel policy in terms of loss of welfare will thus strongly depend on the land endowment of the country under consideration. This is what we are going to detail in the paper.

3. Soil heterogeneity, agricultural land use and agricultural supply

Our objective is to describe how the land endowment of a country, and in particular soil heterogeneity, influences the efficiency and welfare effects of biofuel policies. To represent soil quality heterogeneity, we adopt the theoretical framework first developed by Lichtenberg (1989). We consider yield heterogeneity as the unique dimension of heterogeneity. A scalar measure represents land quality, and density and cumulative distribution functions of this parameter represent land quality heterogeneity.

3.1. Heterogeneous soil quality

Consider an agricultural region, of total area L, where soil quality is heterogeneous and results in different productivities for the alternative crops, or land uses. Following the tradition in land-use share models (Lichtenberg, 1989; Feng and Babcock, 2010; Lankoski et al., 2010; Lankoski and Ollikainen, 2011), we assume that soil quality is represented by a parameter normalized into the interval $[0, 1]$, with 0 for the worst agricultural quality and 1 for the best quality. We consider that the acreage of land that is of

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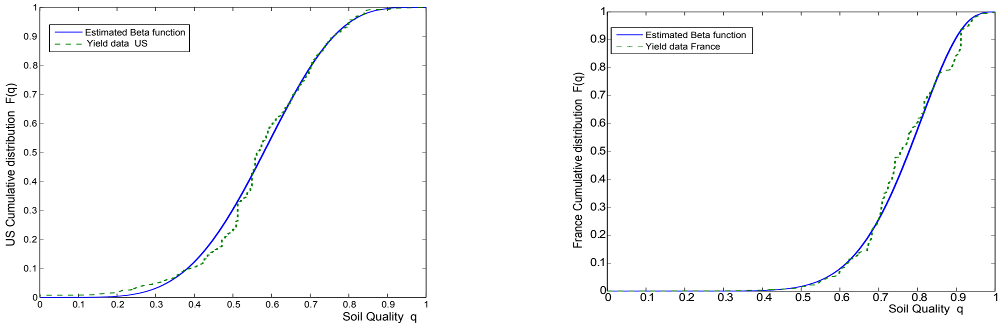
change when the tax credit is introduced, and the welfare transfer between tax payers and fuel consumers (area d) vanishes. In such a case, there is no carbon leakage in the fuel market.

quality $q \in [0, 1]$ is given by a density function $\phi : [0, 1] \mapsto \mathbb{R}$, and that the proportion of acreage of quality lower than a threshold Q is given by the continuous and increasing cumulative distribution function $\Phi(Q) = \frac{1}{L} \int_0^Q \phi(q)dq$. In most spatial econometrics applications, some variables are included to characterize this distribution (Wu and Segerson, 1995). 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 example, 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 an econometric analysis. We here consider theoretical distribution of soil quality, and use the Beta distribution (see Appendix). Beta distributions are particular cases of the Dirichlet distributions, for two parameters, α and β. To estimate the value of the parameters, an easy way is to compute 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 $\beta = (1 - \bar{x})\left(\frac{\bar{x}(1-\bar{x})}{v}\right)$. The Beta distribution has the great advantage to make it possible to represent a wide range of heterogeneity patterns with only two parameters (see Fig.11 in the appendix), providing a powerful theoretical tool for application (Eugene, Lee and Famoye, 2002; Hennessy, 2009). This theoretical framework is thus simple to apply and quite flexible. As an illustration, Fig. 2 provides

Beta functions calibrated on the observed yield heterogeneity of US[9] and France.[10]



(a) US

(b) France

Figure 2: Yield heterogeneity and calibrated cumulative Beta distributions

Both distributions are normalized on the same range of "quality" (approximated by the observed yield). Note, however, that these distribution does not reflect the difference in the size of the land area considered (US has much more agricultural land). One can see that the two distributions are quite different. France has a land endowment which is more homogeneous than US, and, in average, of better quality. This difference in quality heterogeneity has to be accounted for, along with differences in areas, in the definition of production possibilities.

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[9] We used the 2008 USDA data on corn yield at the county level to build an empirical soil quality distribution (3062 plots). The observed productivity is extrapolated to the total agricultural area of the county. Using the previously described estimation method, we obtain $\alpha_{US} = 6.22$ and $\beta_{US} = 4.59$. This rough estimation only aims at obtaining an idea of the shape of the soil heterogeneity in US, and at showing that calibration of Beta functions is possible even from public data.

[10] We used French data on agricultural productivity at the "small agricultural region" level. French agricultural surface is represented by 330 elements characterized by their agronomic quality (soil and climatic characteristics) and their area. This gives the empiric cumulative distribution of soil quality approximated by potential grain yield. The calibration, which is simply based on the given estimation method, emphasizes the flexibility of the approach. We obtain $\alpha_F = 10.86$ and $\beta_F = 3.33$.

We shall use these two distributions to illustrate our theoretical results, and refer to them as “US”-like and “France”-like distributions for simplicity. Interpretations, however, should be careful due to the simplicity of the model, and stay in a theoretical perspective.

3.2. Agricultural land use

In a land use share model, land of a given quality is allocated to the use that generates the largest return. Total production will depend on the share of land devoted to each alternative use, and on the intensity of production.

For the sake of simplicity, we consider a single agricultural output (think about grain production on cropland, that can be used for consumption and biofuel production) along with an alternative agricultural land use (such as grassland or forestry).[11] The price of the agricultural commodity is denoted by p, and is considered as given for a single producer.

For cropland, yield is assumed to be correlated positively with the soil quality parameter q. For our theoretical analysis, the yield function is inspired by the Spillman-Mitscherlich form (Llewelyn and Featherstone, 1997; Frank, Beattie and Embleton, 1990; Kastens, Schmidt and Dhuyvetter, 2003) as in Bond and Farzin (2008). We consider two factors influencing production: the soil quality q that is exogenously given for a field, and the quantity of added fertilizer f (which is used as a proxy for intensity), the production per area unit of cropland on a soil of quality q is

$$Y(q,f) = \underbrace{\left(Y^{inf} + q(Y^{sup} - Y^{inf})\right)}_{\text{effect of soil quality}} \underbrace{\left(1 - \epsilon_1 e^{-\epsilon_2 f}\right)}_{\text{effect of intensification}} \tag{1}$$

where Y^{inf} and Y^{sup} are respectively the lower and higher yield for agricultural output over the soil quality range of the region, and parameters ϵ_i denote constant parameters

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[11] The results could be extended to any given finite number n of alternative land-uses.

representing yield response to fertilizers. With formulation (1), the effect of soil quality represents the maximal potential yield of a field of quality q, i.e., the yield obtained when no input is limiting. The effect of intensification is captured by the second term, which defines the proportion of the potential yield achieved with intensity level f (fertilizer use for simplicity).[12]

Each production is associated to an economic value. In general, output yields and optimal input levels vary with land quality, and thus the return varies with land quality as well. If the quality is defined in terms of agricultural productivity, return from agricultural use would be an increasing function of quality. We define the gross return (per area unit) of a production as a function of the yield (per area unit), the price of output p, a linear cost of fertilizers ωf, and a fixed cost γ. The gross return per area unit reads

$$\pi(p,q,f) = p\left(Y^{inf} + q(Y^{sup} - Y^{inf})\right)\left(1 - \epsilon_1 e^{-\epsilon_2 f}\right) - \omega f - \gamma. \tag{2}$$

The optimal fertilizer use on a field depends on its soil quality and the output price ($f^\star(p,q)$). Computations are provided in the appendix. Having characterized input choice, we will henceforth take them as given and fixed, focusing instead on the soil heterogeneity distribution and its impact on yield and land use. The optimal return associated to cropland is then a function $\pi^\star(p,q,f^\star(p,q))$ of the soil quality and output price, which defines the per area unit return of cropland on a soil of quality q for a given output price p. 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 return of the land-use. The optimal agricultural return of land is a monotonic and convex increasing function of the soil quality (see appendix).

The land quality distribution provides a formal means of aggregating individual land

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[12] The parameter ϵ_1 represents the yield reduction, with respect to the potential maximal yield of the field, when no fertilizers are applied, while the parameter ϵ_2 represents the marginal effect of fertilizer on yield.

use decisions. The rule is to allocate land to the use providing the highest return. We consider that the alternative land use yield a return π_0, assumed not to depend on the soil quality (consider, for example, the return of forest or grassland). Private land owners, when maximizing their return from land, define both optimal land use and optimal input use (fertilizers), maximizing the quasi-rents of the economic model. According to Segerson, Plantinga and Irwin (2006), such a framework defines threshold qualities separating two land uses, for any price system.[13]

The economic context (prices, costs, subsidies) thus defines the soil quality for which land-use switches from extensive, perennial uses to cropland. The return from one use will exceed the return from the other use 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. Given the distribution of soil quality $\Phi(q)$, one gets the production areas. In particular, the share of cropland, produced on soils of quality belonging to $[Q(p), 1]$ is $1 - \Phi(Q(p))$, and depends on the density of soil with quality larger than the threshold quality Q.

The production of the area is thus influenced by the economic context (which determines the soil quality threshold), but also by the soil heterogeneity, which determines the quantity of land below and above the quality threshold, and thus the relative share of land devoted to each use.

3.3. Agricultural supply

From now on, we shall focus on the agricultural production of grain, which is assumed to be used both for food consumption and biofuel production (e.g., corn or rape-

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[13] Given monotonicity and convexity properties of the return functions $\pi^\star$, there is a threshold quality $Q \in [0, 1]$ between the two alternative land uses if and only if $\pi_0 > \pi^\star(0, p, f^\star(p, 0))$ and $\pi_0 < \pi^\star(1, p, f^\star(p, 1))$. Perennial land use is strictly preferred to cropland on $[0, Q[$. Cropland is strictly preferred to the alternative land use on $]Q, 1]$. Both land uses have the same return on a soil of quality Q.

seed). Cropland will cover the interval $[Q(p), 1]$. This means that, for an agricultural commodity price (p), the total production of the agricultural good is obtained by integrating the yield from all land in the quality interval.[14]

$$
\begin{aligned}
Y^{total}(p) &= \int_{Q(p)}^{1} \phi(q) Y^{\star}(p, q, f^{\star}(p, q)) dq && (3) \\
&= \left(Y^{inf} - \frac{\omega}{p\epsilon_2}\right)(1 - \Phi(Q(p), \alpha, \beta)) \\
&\quad + \left(Y^{sup} - Y^{inf}\right) \frac{B(\alpha + 1, \beta)}{B(\alpha, \beta)} (1 - \Phi(Q(p), \alpha + 1, \beta)) && (4)
\end{aligned}
$$

This is the analytical expression of agricultural supply for grain, as a function of output price, the Beta function $B(\cdot, \cdot)$ and the Beta distribution $\Phi(\cdot, \cdot, \cdot)$, with adequate parameters related to the actual soil quality heterogeneity. This function is well-defined and fully characterized by the analytical expression of the Beta function and distribution. We have here an analytical expression of supply with respect to price, depending on the soil quality heterogeneity distribution. Graphical illustration of the agricultural supply curve induced by the land quality heterogeneity of US and France are presented in Fig. 3.

The first distribution, obtained with the parameters calibrated on French data, corresponds to a more homogeneous land of relatively high quality. The second distribution, obtained with the US data, corresponds to a more heterogeneous land quality distribution (Fig. 3a,b). Total land quantity is different for the two countries. Fig. 3c presents the resulting supply functions of grain. Fixed cost parameters are adjusted to calibrate the supply functions on the 2005 production and price equilibrium.[15] Production starts at a

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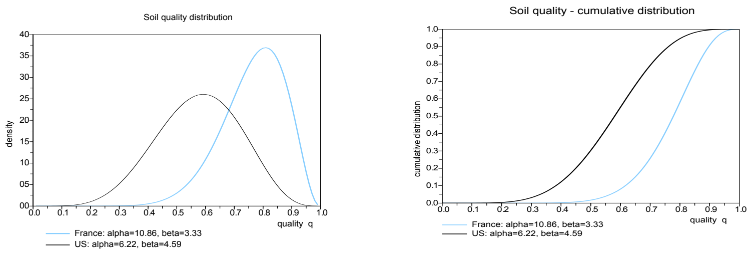
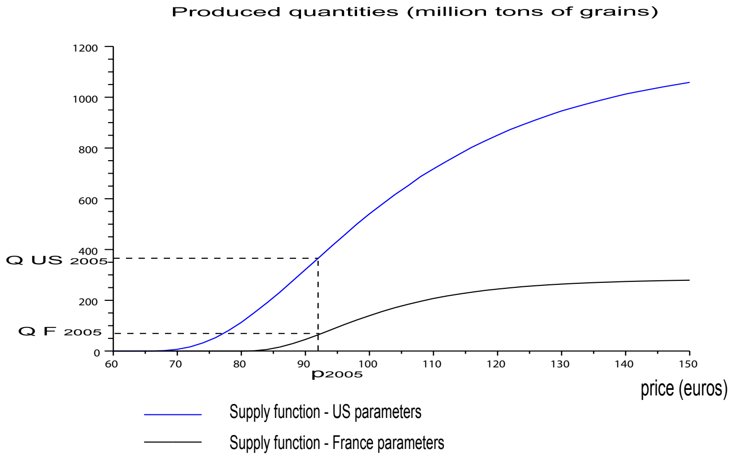
[14] Mathematical details for the integration are given in the appendix. The expression is given for a land endowment of 1. For an area L, the results is obtained by multiplying all quantities by L.

[15] The quantity of grain (cereals) produced in 2005 was respectively 366.516 million tones in US and 64.13 million tones in France. The mean annual price for wheat that year was 3.36 US$ per bushel (i.e., 92 euros per tonnes).



(a) soil quality endowments (b) soil quality endowments



(c) Supply functions

Figure 3: Agricultural supply functions

lower price for the US distribution and is increasing on a large range of prices (due to a more heterogeneous land quality). On the contrary, for French calibrated heterogeneity parameters, production takes off at a higher price, and decelerates once the largest part of land is already in use (more homogeneous land quality).

These supply functions should not be interpreted as annual supply as a function of (anticipated) prices. The elasticity of production is relatively low in the short-run, in particular because of the inelastic reply in terms of planted acreage in the short-run. One should consider these supply functions as long-run response to prices, useful for comparative statics on equilibria.

4. Implications for land-use change and land market carbon leakage

4.1. Land-use change in a changing economic context

Increase in production in response to price is due to intensification and increase in the land-use share of cropland. Land-use change depends on the availability of land "around" (but not marginally) the threshold quality Q.

To describe land-use change when the economic context is modified, consider two economic contexts characterized by output prices p_1 and p_2. Initially, cropland covers soils of quality $q \in [Q(p_1), 1]$, with an initial share $1 - \Phi(Q(p_1))$ of land used for that production. When the economic context changes, so does the quality threshold. The new land use share is $1 - \Phi(Q(p_2))$, which corresponds to a land use change (expressed in "favor" of cropland, with negative value if its share of land use decreases):

$$LUC^{p_1 \to p_2} = \Phi(Q(p_1)) - \Phi(Q(p_2)) = \underbrace{\int_{Q(p_2)}^{Q(p_1)} \phi(q)dq}_{\text{Extension on lower quality land}} \tag{5}$$

The usual analysis made in the literature (e.g., Feng and Babcock, 2010) considers "small" variations dq of the quality thresholds, land-use change being locally measured by the density of land around the equilibrium. The result does not hold for important changes in the economic context, associated to large changes in land use. The framework examined herein allows us to define the magnitude of land-use changes with respect to a change in the economic context. Fig. 4 gives the shares of two land-uses (named "cereal cropland" and "alternative agricultural use" for simplicity) with respect to the equilibrium price of cereals. Cropland area increases with the price, while the area of the other use decreases. Note that the curves have a "S" shape, which means that local (marginal) analysis cannot be extended using linear approximations.

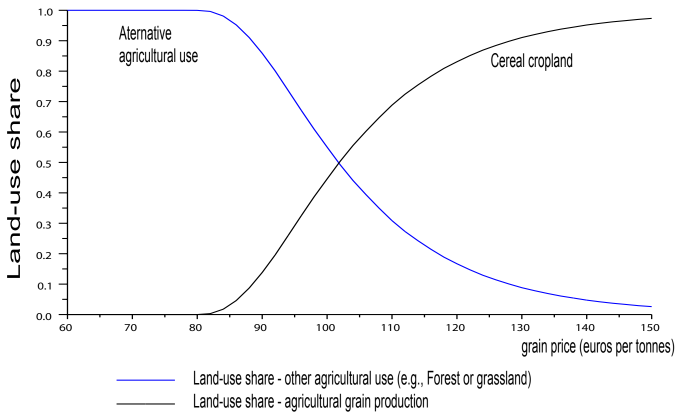


Figure 4: Land-use shares (France estimated parameters)

4.2. *The Land Supply Curve*

A concept widely used in Computable General Equilibrium Models to represent land use explicitly is the land supply curve (Banse et al., 2008). This is the quantity of land offered with respect to the real land rental rate.[16]

It is possible to give a formal expression of an equivalent land supply curve in our framework. Consider that agricultural land use corresponds to soil qualities $[Q(p), 1]$.

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[16] In the agricultural economic context (for example within 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. Beta functions of land quality heterogeneity can also be calibrated using GEAZ data. The difference with the CGE approach is the timing of the estimation process in the analysis. Here, a functional form for the land heterogeneity distribution (requiring the estimation of two parameters) is assumed first and the form of the land supply curve is then analytically derived. In the GTAP approach, the land supply curve is first built from data, and then a particular functional form is calibrated to estimate it.

The land supply for a given price is $L(p) = 1 - \Phi(Q(p))$. The slope of the land supply curve is then $\frac{\partial L}{\partial p} = -\frac{\partial Q(p)}{\partial p}\phi(Q(p))$. Note that when p increases, this term is positive, as $Q(p)$ decreases. The land supply is thus increasing with the price (or the rental rate as the return function is monotonic in q). Illustration of this result is presented in Fig. 5. In this figure, the rental price is normalized by the price needed to put the first unit of land (that of best quality) into production.

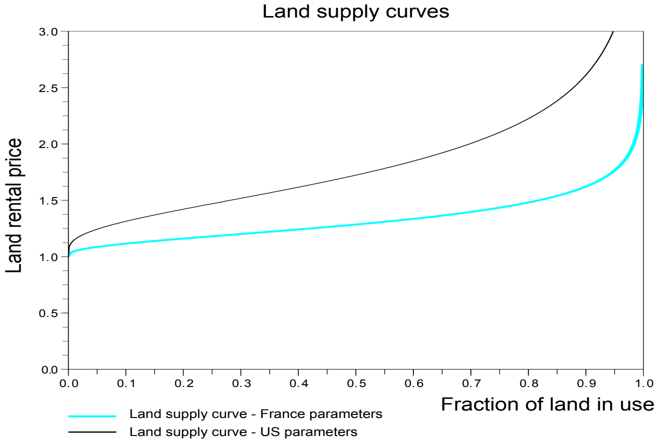

Figure 5: Land supply curve for two different soil quality distributions

This figure shows that a country with more homogeneous land quality (as France) will have a flatter land supply curve than a country with more heterogeneous land quality (as US). For example, doubling the land rental price implies that almost all land is put into production in France, while only 70% of land is put into production in US.

From a general point of view, the shape of the land supply curves presented here is similar to the land supply curves used in CGE (Banse et al., 2008), emphasizing the complementarity and robustness of both approaches.

4.3. Supply change with respect to price change

We now study the sensitivity of the production, and the associated land-use change, to the market price for agricultural good. Taking the derivative of the production function (4) with respect to the agricultural price p leads to [17]

$$\begin{aligned}
\frac{dY^{total}}{dp} &= \frac{d}{dp}\int_{Q(p)}^{1} Y^{\star}(p,q,f^{\star}(p,q))\phi(q)dq \\
&= \underbrace{-\frac{dQ(p)}{dp}\phi(Q(p))\left(Y^{inf} + Q(p)(Y^{sup} - Y^{inf}) - \frac{\omega}{\epsilon_2 p}\right)}_{\text{Extensive margins on lower quality land}} \\
&\quad \underbrace{+\frac{\omega}{\epsilon_2 p^2}(1 - \Phi(Q(p)))}_{\text{Intensive margins}} \qquad (6)
\end{aligned}$$

This result has the following interpretation: an increase in the grain price has two effects. The first effect is linked to an *extension* of the acreage of cropland on lower quality lands, i.e., changes at the extensive margin. This effect is represented by the first term of expression (6).[18] The second effect is linked to an *intensification* of production on already used lands, due to an increase of fertilizer use, i.e., intensive margins. This effect is represented by the second term in expression (6). This result is consistent with the findings of Feng and Babcock (2010). One can define the local elasticity of supply from eq. (6). Note, however, that our 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. 6 represents the price elasticity of supply along the agricultural supply curve, i.e., $\frac{dY^{total}}{dp}\frac{p}{Y^{total}}$.

The long-run elasticity of supply is higher for France parameters for equilibrium prices under 112 euros per tonnes of grain. This is related to the land supply effect stressed in the previous section. Land is of relatively more homogeneous quality

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[17] Mathematical details of the computation are provided in the appendix.

[18] Note that $\frac{dQ(p)}{dp}$ is negative; the two terms of the sum are thus positive.

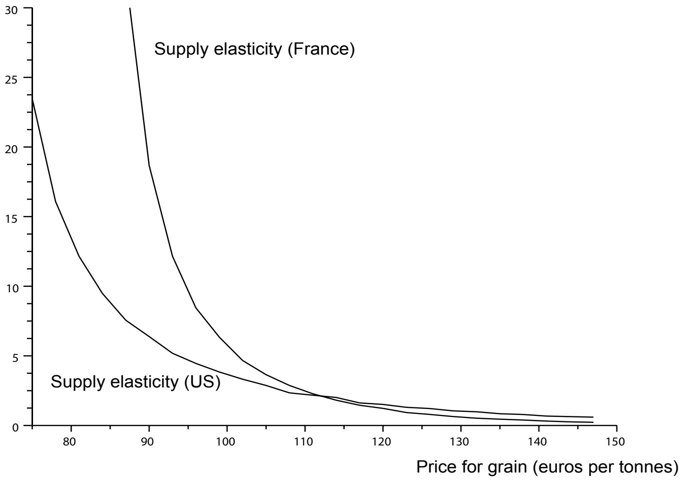

Figure 6: Price elasticity of agricultural supply

in France, and the range of prices implying land-use change to cropland is relatively smaller. Within that range of price (and the associated range of soil quality represented in Fig. 3a), a small increase in long-run equilibrium prices would induce a large quantity of land converted to cropland. On the contrary, for US parameters, the reply to long-run equilibrium price changes is smoother, due the the more heterogeneous land quality. Land of lower qualities are put in production more gradually as price increases. The shape of the elasticity curve is influenced by the availability of land, and thus the soil heterogeneity.

5. Effect of soil heterogeneity on the welfare implication of biofuel policies

Now that we have described how soil heterogeneity shapes the agricultural grain production function, we shall use this result to discuss the welfare implications of biofuel policies, and in particular how land endowment influences these implications. The simple framework described in section 2 is used to build on the analysis of De Gorter and Just (2009a,b) and examine how land quality heterogeneity modifies the welfare implications of biofuels policies.

Assume that grain can be used either as a consumption good or as an input to produce biofuels. To avoid scale effects and make comparison between US and France data possible, we use per capita production.[19] This implies that the welfare effects described below are for a representative agent. We introduce a linear per capita inverse demand function for food. This demand function is decreasing. Fig. 7 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).[20] What matters in our theoretical analysis is that the shapes of the agricultural supply curves are different in the two cases, and depend on underlying land heterogeneity.

It is interesting to note that France agricultural supply is more elastic both in absolute terms, and in per capita terms in the range of prices considered.

5.1. The tax credit case

We first examine the effect of the land-heterogeneity on the welfare economics of biofuel tax credit. We shall consider two theoretical cases corresponding to different practical questions.

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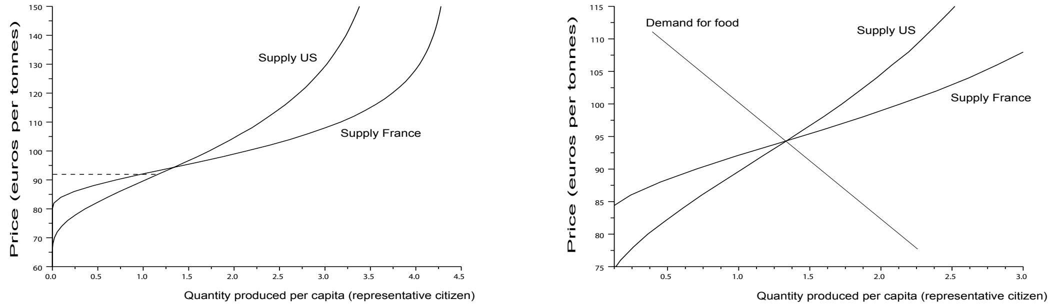
[19] Using the CIA World Fact Book, we consider the US population to be 313.232 million inhabitants, and the French population to be 65.312 million inhabitants.

[20] This assumption has almost no effects on the results. Considering different equilibrium prices, one could simply translate the “quantity” axis for one country to superpose the equilibrium without modifying the results of the welfare analysis, as translations of the axis does not modify the areas. The resulting exercise can be interpreted as an analysis of “additional” production with respect to the equilibrium.



(a) Per capita supply, with 2005 reference production

(b) Zoom

Figure 7: Inverse supply functions for two countries with different land endowment, facing a demand for food.

- The case of a given tax credit.
- The case of a tax credit defined to achieve a given biofuel production.

5.1.1. Given tax credit

We do again the welfare analysis presented in section 2 with two supply functions. One supply function corresponds to a less elastic, "US-like supply," while the other corresponds to a more elastic, "French-like" supply. Fig. 8 presents this analysis. Elements of interest from the benchmark situation of a more elastic supply are represented with thinner or dashed lines to make visual comparison easier.

The first effect of a less elastic agricultural supply curve is that the cost of biofuel production is higher. As a consequence, for the same tax credit, less biofuels are produced per capita. The deadweight cost of underconsumption (area *a*) clearly increases (food price increases and food consumption decreases). This means that a tax credit would have more impact on a representative consumer's surplus in a country having a "US"-like land endowment than in a country having a "French"-like land endowment. The effect on the deadweight cost of overproduction (area *b*) is ambiguous (price and

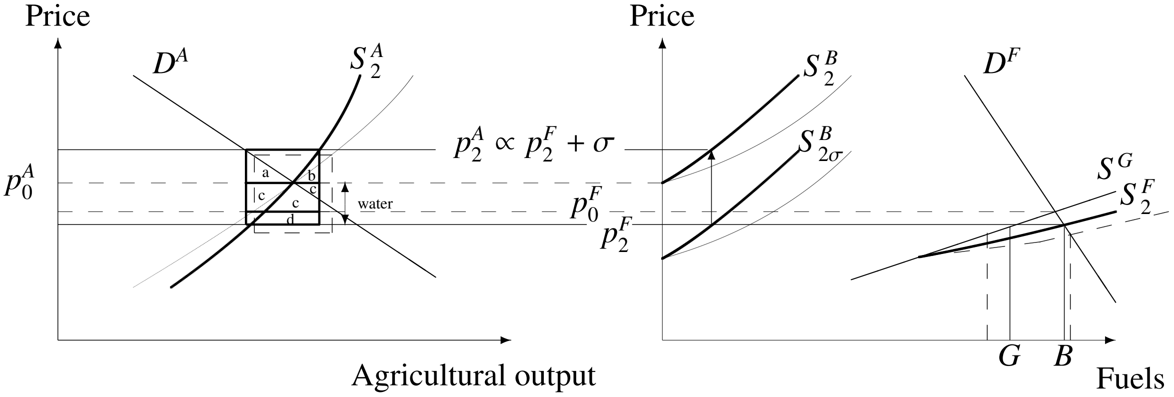


Figure 8: Effect of the land heterogeneity and agricultural supply shape on the welfare economics of tax credit, for a given tax credit level.

quantity effects are opposite). The rectangular deadweight cost (areas *c*) decreases due to a decrease in biofuel production. The transfer of tax payers funds to fuel consumers (area *d*) decreases for two reasons: first, because the quantity of consumed biofuels decreases and, second, because the difference between initial and new fuel price is lower ($p_0^F - p_2^F$). There is thus a price effect. As the quantity of biofuels consumed is lower than in the more elastic 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, increasing consumer's losses. As the fuel price is higher than in the first case, the water is the tax credit is lower. A higher fuel price also means that carbon leakage in the fuel market is reduced.

5.1.2. Tax credit with a given biofuel target

Still in the context of biofuel tax credit, we now assume 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.1 as a benchmark). In that case, previous analysis is modified as presented in Fig. 9.

The fuel price is the same as in the benchmark, elastic supply case. However, to

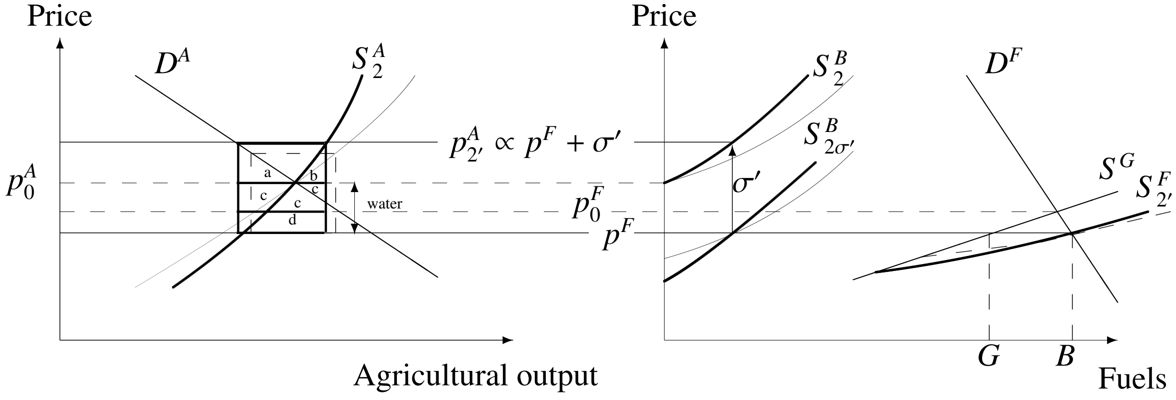


Figure 9: Effect of the land heterogeneity and agricultural supply shape on the welfare economics of tax credit, when a given quantity of biofuel is targeted.

obtain the required quantity of biofuels with the second land endowment, the tax credit must be higher ($\sigma' > \sigma$). The food price is then 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 cost 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 on the welfare economics of biofuel tax credit, we state that

- For a given tax credit level, the more elastic the agricultural supply (the larger the quantity of additional land available), the larger the quantity of biofuels produced (the more important the response to the policy instrument), the more important the water in the tax credit. This implies more important rectangular deadweight cost and transfer of tax payer funds to fuel consumers. However, the traditional deadweight costs of underconsumption and overproduction are smaller than with inelastic supply.

- 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 additional land available), the lower the tax credit needed, and the lower the deadweight costs of underconsumption of food and of overproduction. The rectangular deadweight cost 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 land to increase agricultural land-use share, also matters. These two dimensions are not necessarily related as the former is linked to the land already in production (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). Roughly speaking, the welfare effect of biofuel tax credit on a representative citizen is more negative in a country with a “US”-like land endowment (relatively heterogeneous land quality, implying lower elasticity of supply) than in a country with a “French”-like land endowment (more homogeneous land quality, which implies a higher supply elasticity on the considered range of prices).

5.2. The mandatory blending case

Blend mandate for biofuels usually takes the form of a minimum blending requirement, which is the ratio of biofuels to total fuel consumption. 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.[21] 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. 10 represents the economics of blend mandate for two agricultural supply curves S_i^A corresponding to different land endowments (S_1^A is more elastic, corresponding to "French"-like supply). D^A and D^F are respectively the demand for food and fuel. ηD^F is the demand for biofuels, driven by the share of biofuels in the fuel demand. 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. These supply curves are determined so that, for a given produced quantity x, the price is equal $p^F(x) = \eta p^B(\eta x) + (1 - \eta) p^G((1 - \eta)x)$.

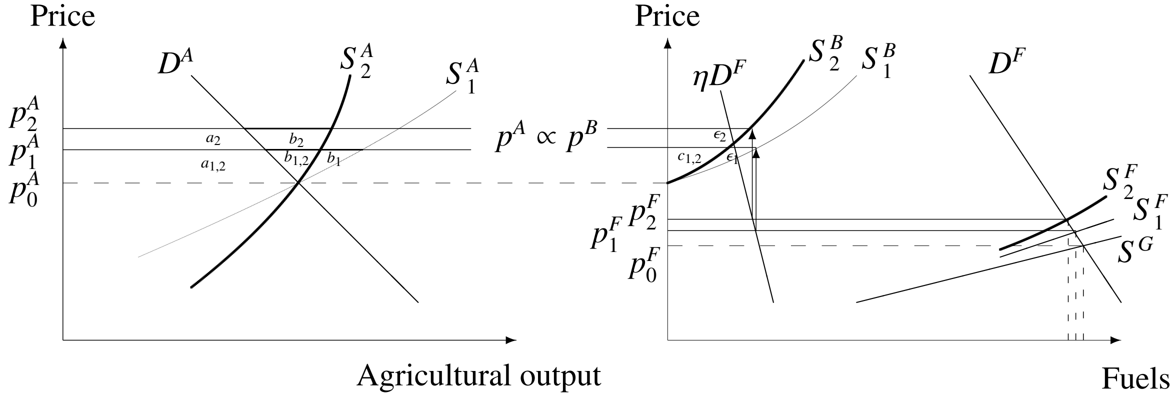


Figure 10: Effect of the land heterogeneity and agricultural supply shape on the welfare economics of biofuel mandatory blending.

The mandate increases the price of the mixed fuel, and thus reduces the quantity of fuel consumed. The quantity of gasoline use reduction is larger than the quantity of

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[21] If the blending objective is achieved with a subsidy (or tax credit), we refer to the analysis in the previous section (Fig. 9).

biofuel blended. In a sense, there is a “negative” carbon leakage in the fuel market. The more elastic the agricultural supply (i.e., the larger the quantity of additional land available to agricultural production - case S_1^A), the lower this effect, the higher the quantity of biofuel consumed and the lower the agricultural price.

In the agricultural market, representative consumer’s surplus is reduced by areas a_i (a_1 for case S_A^1 and a_2 for case S_A^2). The higher the production elasticity, the lower these losses. Producer’s returns totally capture these consumer’s losses, along with profit on the biofuel market (areas b_i). Areas b_i correspond to the part of the producer surplus due to the biofuel market. These areas are equal, in value, to the producer’s surplus on the biofuel market (areas c_i), which are equal to a part of the fuel consumers losses. The more inelastic the biofuel supply (case S_2^B, “US”-like), 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 of the mandate on the fuel market will depend on biofuel supply elasticity and thus on the availability of additional land. Moreover, the effect on the agricultural market is beneficial to the agricultural producers, who gain from food and fuel consumer losses. The more inelastic the agricultural supply (the scarcer the land in the considered range quality), the higher these transfers. A mandatory blending is thus more beneficial to producers in a “US”-like country.

6. Concluding remarks

We developed a theoretical analysis of the impact of soil quality heterogeneity on agricultural supply curve, and examined how it modifies the welfare analysis of biofuel policies. Extending the theoretical framework of Feng and Babcock (2010) by considering an explicit soil quality distribution allows us to analyze the effect of biofuel policies beyond marginal analysis of the equilibrium. This provides a more accurate quantitative estimation of the impact of biofuel policies on land-use change, and food and biofuels production and consumption. This also allows us to complete the welfare analysis of tax credit policies (De Gorter and Just, 2009a) and mandatory blending (De Gorter and Just, 2009b) by describing the role of soil heterogeneity. By shaping the agricultural supply curve, land endowment influences the welfare economics of biofuel tax credit and biofuel blend mandate. The main message is that the scarcer the land available for agricultural expansion, the less elastic the supply curve and 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,[22] and to examine how the framework can be applied when there are more agricultural products and market effects. 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 to examine the induced environmental effects of biofuel production and trade, in particular on indirect land-use change.

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[22] 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 (Banse et al., 2008; Keeney and Hertel, 2009).

Appendix

The Beta distribution

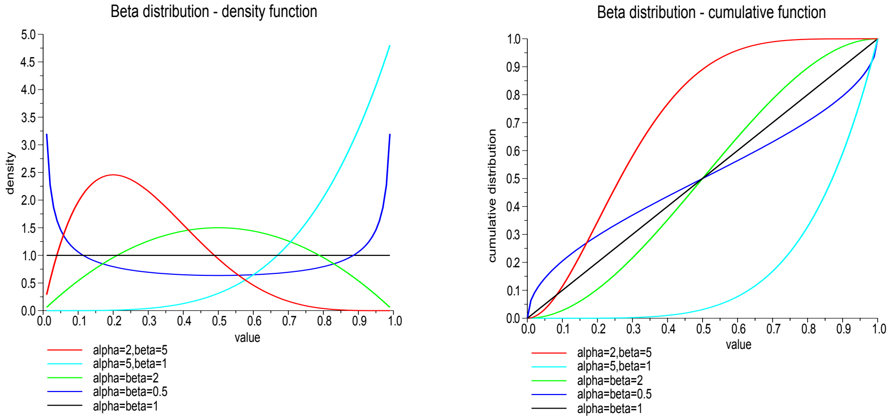
For a Beta function, the density function of q is

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

where the 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

$$\Phi(Q,\alpha,\beta) = \int_0^Q \phi(q,\alpha,\beta)dq = \frac{\mathrm{B}_Q(\alpha,\beta)}{\mathrm{B}(\alpha,\beta)}$$

Fig.11(a) represents examples of distributions for various values for parameters α and β, including uniform, U-shaped, asymmetric (concave or convex), unimodal, and linear distributions. Fig.11(b) represents the associated cumulative distributions.



(a) Soil quality distribution

(b) Cumulative soil quality distribution

Figure .11: Beta function for various parameters (α,β)

Optimal input use

The optimality condition on the use of fertilizers is

$$\frac{\partial \pi(p,q,f)}{\partial f} = 0$$

which implies after some basic computation

$$f^\star(p,q) = \frac{-1}{\epsilon_2} \ln\left(\frac{\omega}{\epsilon_1 \epsilon_2 p\left(Y^{inf} + q(Y^{sup} - Y^{inf})\right)}\right)$$

Using the previous expression, one can compute the optimal production level of a given crop on soil quality Q:

$$Y^\star(p,q,f^\star(p,q)) = \left(Y^{inf} + q(Y^{sup} - Y^{inf})\right) - \frac{\omega}{\epsilon_2 p}$$

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

$$\begin{aligned}
\pi^\star(p,q,f^\star(p,q)) &= pY^\star(p,q,f^\star(p,Q)) - \omega f^\star(p,q) \\
&= p\left[\left(Y^{inf} + q(Y^{sup} - Y^{inf})\right) - \frac{\omega}{\epsilon_2 p}\right] \\
&\quad + \frac{\omega}{\epsilon_2} \ln\left(\frac{\omega}{\epsilon_1 \epsilon_2 p\left(Y^{inf} + q(Y^{sup} - Y^{inf})\right)}\right) - c.
\end{aligned}$$

Monotonicity:

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

$$\frac{d\pi^\star(p,q,f^\star(p,q))}{dq} = p(Y^{sup} - Y^{inf}) - \frac{\omega}{\epsilon_2}\left(\frac{Y^{sup} - Y^{inf}}{Y^{inf} + q(Y^{sup} - Y^{inf})}\right)$$

We thus have the following positivity condition: $\frac{d\pi^\star(p,q,f^\star(p,q))}{dq} \geq 0 \Leftrightarrow Y^{inf} + q(Y^{sup} - Y^{inf}) \geq \frac{\omega}{p\epsilon_2}$. This condition will be respected if the optimal yield is positive, which will be true on $[0,1]$ if $Y^{inf} \geq \frac{\omega}{p\epsilon_2}$, which is always true if the profit is positive. If such a condition holds, the profit function (with optimal fertilizer use) is increasing with respect to soil quality.

Convexity:

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

$$\frac{d^2\pi^\star(p,q,f^\star(p,q))}{dq^2} = \frac{\omega}{\epsilon_2}\frac{(Y^{sup}-Y^{inf})^2}{(Y^{inf}+q(Y^{sup}-Y^{inf}))^2},$$

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

Integration of eq. 4:

Expression (4) is integrated as follows:[23]

$$\begin{aligned}
Y^{total}(p) &= \int_{Q(p)}^{1}\phi(q)\left(q(Y^{sup}-Y^{inf})+Y^{inf}-\frac{\omega}{p\epsilon_2}\right)dq \\
&= \left(Y^{inf}-\frac{\omega}{p\epsilon_2}\right)\int_{Q(p)}^{1}\phi(q)dq+(Y^{sup}-Y^{inf})\int_{Q(p)}^{1}q\phi(q)dq \\
&= \left(Y^{inf}-\frac{\omega}{p\epsilon_2}\right)(1-\Phi(Q(p),\alpha,\beta)) \\
&\quad +\left(Y^{sup}-Y^{inf}\right)\frac{B(\alpha+1,\beta)}{B(\alpha,\beta)}(1-\Phi(Q(p),\alpha+1,\beta))
\end{aligned}$$

Computation of the supply change with respect to price change (eq. 6)

The result is obtained using a differentiation of definite integral containing a parameter (Gradshteyn and Ryzhik, 2007, differentiation 12.211; p.1130):[24]

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

[24] Formally, this result requires that the functions $Q_{\rightarrow}(p):[0,p^{max}]\mapsto\mathbb{R}$ are continuous and differentiable with respect to p, and the function $\phi(q)Y^\star(p,q,f^\star(p,q))$ is integrable in q on the interval and differentiable in p. This is the case for continuous return functions and Beta distributions.

$$\begin{aligned}
\frac{dY^{total}}{dp} &= \frac{d}{dp}\int_{Q(p)}^{1}\phi(q)Y^{\star}(p,q,f^{\star}(p,q))dq \\
&= -\frac{dQ(p)}{dp}\phi(Q(p))Y^{\star}\left(p,Q(p),f^{\star}(p,Q(p))\right) \\
&\quad +\int_{Q(p)}^{1}\phi(q)\frac{\partial Y^{\star}(p,q,f^{\star}(p,q))}{\partial p}dq \\
&= -\frac{dQ(p)}{dp}\phi(Q(p))\left(Y^{inf}+Q(p)(Y^{sup}-Y^{inf})-\frac{\omega}{p\epsilon_2}\right) \\
&\quad +\frac{\omega}{\epsilon_2 p^2}\Big(1-\Phi(Q(p))\Big)
\end{aligned}$$

References

Antle, J., S. Capalbo, S. Mooney, E. Elliott, and K. Paustian. 2003. “Spatial heterogeneity, contract design, and the efficiency of carbon sequestration policies for agriculture.” *Journal of Environmental Economics and Management* 46:231-250.

Arnade, C., and D. Kelch. 2007. “Estimation of Area Elasticities from a Standard Profit Function.” *American Journal of Agricultural Economics* 89(3):727-737.

Banse, M., van Meijl, H., Tabeau, A., and G. Woltjer. 2008. “Will EU biofuel policies affect global agricultural markets?” *European Review of Agricultural Economics* 35(2):117-141.

Böhringer, C., Rutherford, T., and R. Tol. 2009. “The EU 20/20/2020 targets: An overview of the EFM22 assessment.” *Energy Economics* 31:S268-S273.

Bond, C., Farzin, H., 2008. “Alternative sustainability criteria, externalities, and welfare in a simple agroecosystem model: a numerical analysis.” *Environmental and Resource Economics* 40(3):383-399.

Charles, M.B., Ryan, R., Ryan, N., Oloruntoba, R., 2007. “Public policy and biofuels: The way forward?” *Energy Policy*, 35:5737-5746.

De Gorter, H., and D. Just. 2009a. “The welfare economics of a biofuel tax credit and the interaction effects with price contingent farm subsidies.” *American Journal of Agricultural Economics* 91(2):477-488.

De Gorter, H., and D. Just. 2009b. “The economics of a blend mandate for biofuels.” *American Journal of Agricultural Economics* 91(3):738-750.

Donaldson, A.B., G. Flichman, and J.P.G. Webster. 1995. “Integrating Agronomic and Economic Models for Policy Analysis at the Farm Level: the Impact of CAP Reform in Two European Regions.” *Agricultural Systems* 48:163-178.

Eugene, N., C. Lee, and F. Famoye. 2002. “Beta-Normal Distribution and Its Applications.” *Communications is Statistics-Theory and Methods* 31(4):497-512.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. “Land clearing and the biofuel carbon debt.” *Science* 319(5867):1235-1238.

Feng, H., and B. Babcock. 2010. “Impacts of ethanol on planted acreage in market equilibrium.” *American Journal of Agricultural Economics* 92(3):789-802.

Frank, M., B. Beattie, and M. Embleton. 1990. “A comparison of alternative crop response models.” *American Journal of Agricultural Economics* 72(3):597-603.

Fraser, R. 2009. “Land Heterogeneity, Agricultural Income Forgone and Environmental Benefice: An Assessment of Incentive Compatibility Problems in Environmental Stewardship Schemes.” *Journal of Agricultural Economics* 60(1):190-201.

Gradshteyn, I., and I. Ryzhik. 2007. *Table of Integrals, Series, and Products*, Seventh Edition, Alan Jeffrey and Daniel Zwillinger (eds.). Academic Press.

Groom, M., E. Gray, and P. Townsend. 2008. “Biofuels and Biodiversity: Principles for creating better policies for biofuel production.” *Conservation Biology* 22(3):602-609.

Hardie, I., and P. Parks. 1997. “Land Use with Heterogeneous Land Quality: An Application of an Area Base Model.” *American Journal of Agricultural Economics* 79:299-310.

Hennessy, D.A. 2009. “Crop Yield Skewness Under Law of the Minimum Technology.” *American Journal of Agricultural Economics* 91(1):197-208.

Kastens, T., J. Schmidt, and K. Dhuyvetter. 2003. "Yield models implied by traditional fertilizer recommendations and a framework for including nontraditional information." *Soil Science Society American Journal* 67:351-364.

Kretschmer, B., D. Narita, and S. Peterson. 2009. "The economic effects of the EU biofuel target." *Energy Economics* 31:S285-S294.

Kretschmer, B., and S. Peterson. 2010. "Integrating bioenergy into computable general equilibrium models – A survey." *Energy Economics* 32:673-686.

Keeney, R., and T. Hertel. 2009. "The indirect land use impacts of united-States biofuels policies; the importance of acreage, yield, and bilateral trade responses." *American Journal of Agricultural Economics* 91(4):895-909.

LaFrance, J.T., and R.D. Pope. 2008. "Homogeneity and Supply." *American Journal of Agricultural Economics* 90(3):606-612.

Lankoski, J., Lichtenberg, E., Ollikainen, M., 2010. Agri-environmental program compliance in a heterogeneous landscape. *Environmental and Resource Economics*, 47:1-22.

Lankoski, J., Ollikainen, M., 2008. "Bioenergy crop production and climate policies: a von Thunen model and the case of reed canary grass in Finland." *European Review of Agricultural Economics*, 35(4):519-546.

Lankoski, J., Ollikainen, M., 2011. Biofuel policies and the environment: Do climate benefits warrant increased production from biofuel feedstocks? *Ecological Economics*, 70:676-687.

Lapand, H., Moschini, G., 2012. Second-best biofuel policies and the welfare effects of quantity mandates and subsidies. *Journal of Environmental Economics and Management*, in press.

Llewelyn, R., and A. Featherstone. 1997. “A comparison of crop production functions using simulated data for irrigated corn in Western Kansas.” *Agricultural Systems* 54:521-538.

Lichtenberg, E. 1989. “Land Quality, Irrigation Development, and Cropping Patterns in the Northern High Plains.” *American Journal of Agricultural Economics* 71:187-194.

Petersen, J.-E., 2008. “Energy production with agricultural biomass: environmental implications and analytical challenges.” *European Review of Agricultural Economics*, 35(3):385-408.

Plantinga, A., and E. Irwin. 2006. “Overview of Empirical Methods.” In *Economics of Rural Land-Use Change*, Bell K., Boyle K. and Rubin J. (Eds), Chapter 7, p.113-134. Ashgate Publishing.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. “Use of U.S. croplands for biofuels increases Greenhouse Gases through emissions from land-use change.” *Science* 319:1238-1240.

Segerson, K., A. Plantinga, and E. Irwin. 2006. “Theoretical Background.” In *Economics of Rural Land-Use Change*, Bell K., Boyle K. and Rubin J. (Eds), Chapter 6, p.79-111. Ashgate Publishing.

Sorda, G., Banse, M., Kemfert, C., 2010. “An overview of biofuel policies across the world.” *Energy Policy* 38:6977-6988.

Stavins, R., and A. Jaffe. 1990. “Unintended Impacts of Public Investments on Private Decisions: The Depletion of Forested Wetlands.” *American Economic Review* 80(3):337-352.

Tilman, D., R. Socolow, J. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Searchinger, C. Somerville, and R. Williams. 2009. “Benefical Biofuels – The Food, Energy, and Environment Trilemma.” *Science* 325:270-271.

Wu, J., and K. Segerson. 1995. “The Impact of Policies and Land Characteristics on Potential Groundwater Pollution in Wisconsin.” *American Journal of Agricultural Economics* 77:1033-1047.