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On the direct, indirect and induced impacts of public policies:

The European biofuel case.

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Abstract

This paper deals with the controversial indirect land use changes of the European biodiesel policy. Two studies sponsored by the European Commission finds significant, but contrasted, land use effects for the different vegetable oils used for biodiesel production. The first study uses an aggregate computable general equilibrium model capturing direct, indirect and induced effects. The second recent study uses a biotechnical partial equilibrium model offering a detailed representation of the indirect effects occurring through the livestock sectors. We develop an original economic emulator to understand the diverging key results of these studies and test their sensitivity. We find that the direct and indirect effects on vegetable oil markets explain most of the differences. We also find that indirect effects on the livestock sector and the induced effects do not significantly influence the biodiesel results. However results are critically sensitive to crop yield responses that are considerably underestimated in both studies. The cropland displacement due to the biodiesel policy computed by the recent study is overestimated by a factor of 5.

Keywords: Land use changes, biodiesel, Europe, emulator

JEL classification: Q11, Q16

Les effets directs, indirects et induits de la politique européenne du biodiesel

Résumé

Ce papier porte sur le changement d'affectation des sols indirect attribuable à la politique européenne du biodiesel. Deux études sponsorisées par la Commission Européenne trouvent des effets surfaces fort différents pour les huiles végétales utilisées dans la production de biodiesel. La première s'appuie sur une modélisation en équilibre général calculable prenant en compte les effets directs, indirects et induits. La seconde étude, plus récente, s'appuie sur un modèle biotechnique d'équilibre partiel caractérisé par une spécification détaillée des effets indirects passant par les secteurs de l'élevage. Nous développons un simulateur économique original pour comprendre ces différences de résultats et tester leur robustesse. Nous trouvons que les effets directs et indirects sur les marchés des huiles végétales expliquent une grande partie des différences. Les effets indirects sur les secteurs de l'élevage et les effets induits sont nettement plus limités. Tous les résultats sont très sensibles aux réponses des rendements aux variations de prix. Nous trouvons que le changement d'affectation des sols indirect calculé par la récente étude est surestimée d'un facteur 5.

Mots-clés : Usage des terres, biodiesel, Europe, simulateur économique

Classification JEL : Q11, Q16

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1. Introduction

In order to correct market failures and/or pursue policy objectives, policy makers define public policies with different instruments such as taxes and regulations. These policies have direct effects on targeted objectives. By modifying the initial allocation of scarce resources, they can also have significant indirect effects on these objectives, more generally possible unintended effects on the whole economy. These indirect effects, generally more difficult to assess, may even question the relevance of the policy. In this paper, we focus on the controversial European biofuel policy and its net effect on greenhouse gas emissions.

The main official objective of this biofuel policy is to foster the decarbonisation of the European transport sector. It defines common consumption mandates for both bioethanol and biodiesel, the latter being the main biofuel consumed in Europe. These biofuels are transport fuels made from the biomass, offering a renewable alternative to the fossil fuels. They are currently mainly produced from land-based crops, vegetable oils for biodiesel production and starchy/sugar crop products for ethanol production. These biofuel productions can potentially displace crop production to land with high carbon stocks (such as forests). The conversion of such land to cropping can lead in the medium run to unintended net emissions of carbons rather than desired savings. Emissions from land conversion can counterbalance the direct annual carbon uptake by the additional crop production.

This empirical issue has been extensively debated in the last ten years, in academic and policy circles, under the Iluc (indirect land use change) heading. These land use changes are not directly observable and are counterfactually computed with economic models. The European Commission (EC) has sponsored two studies to assess these effects. The first study (Laborde, 2011) was performed using a Computable General Equilibrium (CGE) model named Mirage-Biof (hereafter we refer to the Mirage study). The second study (Valin *et al.*, 2015) was performed using a Partial Equilibrium (PE) model named Globiom (hereafter we refer to the Globiom study). Both studies find limited land use changes and carbon emissions due to the ethanol mandate (around 15gCO2/MJ). However, they obtain contrasting results for the biodiesel mandate: around 55gCO2/MJ according to the Mirage study, up to 101gCO2/MJ according to the Globiom study. This last figure is even higher than the usual figure retained

for fossil fuels (around 90gCO2/MJ), suggesting that the fossil diesel is currently better than crop-based biodiesel in terms of carbon emissions. These two studies also differ in the impacts obtained for the different vegetable oils that can be used to produce biodiesel. In the Mirage study, the impacts are quite similar across the different vegetable oils. In the Globiom study, the indirect emissions amount to 65gCO2/MJ (respectively 150 and 231) for biodiesel made from rapeseed oil (respectively soybean and palm oil).

From a policy perspective, the results of the more recent, and a priori better informed, Globiom study question the current use of Mirage results in the European legislation. The results of both studies also question the proposals made in 2016 by the EC to cut by half the European mandates for both biofuels. They rather suggest the expansion of the ethanol mandate while stopping it for biodiesel. From an academic perspective, it is no surprise that these two studies find different results because they rely on different economic models. Both models are quite elaborated detailing many regions, activities, commodities and factor markets. These models require a lot of economic data and economic parameters (elasticities) that are difficult to gather. This difficulty is differently managed by each economic model. PE models, such as Globiom, generally offer a great detail of the sectors directly and indirectly affected by the policy while ignoring macroeconomic feedbacks, such as impacts on the income of institutions (mainly private households and government). By contrast, CGE models, such as Mirage, generally have a cruder representation of these sectors but capture macroeconomic feedbacks. These latter models capture so-called induced effects in addition to direct and indirect (business-to-business) effects already present in PE models. These induced effects rebound on the sectors by affecting the final demand of products. In other words, the Ilucs reported by the Globiom study are limited to the a priori well-measured indirect effects caused by the policy scenario. The Ilucs reported by the Mirage study are more comprehensive by integrating induced effects at the expense of a possible cruder evaluation of indirect effects.

In that context, our objective in this paper is to offer a quantitative comparative analysis of the results of these two studies, focusing on the diverging results of the predominant biodiesel consumption in Europe. We compare the direct, indirect and induced effects measured by these two studies. We also provide a critical analysis of these results with respect to available results in the academic literature. Our comparative analysis is not immediate because both the Mirage and Globiom models are not publicly available. Accordingly we develop an original emulator designed to capture key results of the more recent Globiom study. Emulators are common in climate science; they typically comprise a few key equations that replicate main features of the

detailed models but at global scale. In agricultural economics, Hertel and Baldos (2016) are the first to our knowledge to develop an emulator. Their emulator named Simple (for a Simplified International Model of Prices, Land use and the Environment) is a PE model, focuses on the arable crop sector and analyses global land use drivers, including biofuel policies. We follow this approach, developing our own emulator to explicitly integrate other farm sector (fodder), the competition between arable and pasture land and induced effects. Data and parameters of this new emulator are calibrated to replicate main effects obtained by the Globiom study on biodiesel. Then this emulator allows us the quantification of the critical assumptions that may explain the huge differences of results between the two studies, as well with those available in the academic literature, on the European biodiesel policy.

This paper is organised as follows. The next section analyses the biodiesel results obtained by these two studies, highlighting in particular the effects on livestock and animal feed sectors. We continue in section 3 by detailing our new emulator that is flexible enough to capture any type of indirect and induced effects. The calibration of the parameters specified in our emulator is explained in section 4. The quantitative analysis is conducted in section 5 where we assess if the additional induced effects captured in the Mirage study explain a large part of the differences or if direct and/or indirect effects already significantly differ between the two studies. Section 6 concludes.

2. Comparison of the Mirage and Globiom results on the biodiesel scenarios

Biodiesel is produced using conventional or advanced feedstocks, leading to respectively first and second-generation biodiesel. The world production of second-generation biodiesel is currently limited and most studies consider that this production will remain limited in the coming two decades. These studies focus on first-generation biodiesel that is produced mainly from rapeseed, soybean and palm oil at the world level. Both Mirage and Globiom studies report the land use emissions and Ilucs generated by these different feedstocks. Even if both economic models are not linear, the simulated feedstock specific shocks are sufficiently small to allow a meaningful comparison (the shock amounts to 0.5% of diesel consumption in the Mirage study, 1% in the Globiom study). The Ilucs of these feedstock specific shocks are reported in the first part of Table 1.

To better understand the differences of results, we also report price impacts provided by these studies. We underline here that the Mirage study details these price impacts only for the global

EU biofuel policy scenario (not for each feedstock specific scenario). This scenario is much larger by simulating a larger biodiesel mandate (the shock amounts to 5.3% of diesel consumption) as well as including the ethanol mandate. Another complication arises because both studies rely on different baselines to perform counterfactual simulations (these baselines are not fully available). Accordingly the key price impacts reported in the second part of Table 1 cannot be directly compared.

Table 1 : Key results of the biodiesel scenarios simulated by the Mirage and Globiom studies

	Palm oil biodiesel		**Soybean oil biodiesel**		**Rapeseed oil biodiesel**	
	Mirage	Globiom	Mirage	Globiom	Mirage	Globiom
Land impacts						
Land use emissions (gCO2eq/MJ)	54	231	56	150	54	65
Land effects (ha/toe)						
Initial requirement	*0.24*	*0.48*	*0.45*	*0.45*	*0.85*	*0.9*
Cropland displacement	0.08	0.35	0.16	0.62	0.16	0.65
Market impacts						
Price effects (%)						
EU veg oil	4.4	n.a.	9.7	n.a.	16.4	28.0
World veg oil	4.5	2.1	7.3	10.8	9.2	7.0

Note : Figures in italics are not directly available in the publications and thus approximations based on world crop yields per hectare in the baseline.
Source: Laborde (2011) and Valin et al. (2015).

2.1. Comparison of palm oil results

The land use emission obtained in the Globiom study is more than four times greater than in the Mirage study. This is indeed the same ratio for cropland displacement (respectively 0.35 and 0.08 ha/toe). Both studies find that the cropland displacements are lower than the initial land requirement thanks to market-mediated responses (by roughly 0.15 ha/toe). It appears that the biggest difference comes from the initial land requirement, in other words the baseline crop yields. World palm oil yield is close to 2.5 t/ha in the Globiom study, to 5t/ha in the Mirage study. The direct land effects assumed in the two baselines are very different and very likely explain most of the diverging land use emissions for this feedstock.

2.2. Comparison of soybean oil results

Turning to the soybean oil, we again observe that the ratio of land use emissions (0.37) is rather close to the ratio of cropland displacement (0.26). For this feedstock, the direct land effects are similar across the two studies due to similar crop yields in the baseline. Interestingly the market-mediated responses are very different. According to the Globiom study, the cropland displacement is greater than direct land requirement. This is very likely due to the additional co-production of soybean meal and positive effects on the livestock productions (by 0.62 Mt of meat and 1.28 Mt of milk). This protein rich co-product used in animal feeding stimulates the livestock production as well as the production of energy rich feed materials, typically feed cereals (by 1 Mt). Hence the production of biodiesel from soybean oil stimulates the production and acreage of cereals. By contrast, the land allocated to cereals decreases in the Mirage study (despite the additional ethanol demand), leading to less cropland displacement. This simple comparison suggests that the effect on animal feed sectors are very important. Accordingly it is worth explaining the modelling of these sectors in both models.

One must first acknowledge that the modelling of these sectors is a difficult task, mainly due to the presence of non-marketed fodder crops in many regions of the world. World databases such as FAO databases provide information on fodder areas such as corn silage, permanent and temporary pasture. However information on the biomass production obtained on these areas and their uses by animals (presumably mostly ruminant) is missing in many regions. Another related complication is that the economic values of fodder crops are also missing. Even if these fodder productions are usually not marketed, they still have opportunity costs that partly explain their on-farm economic profitability and their substitution with other feed materials. These issues (quantity, opportunity price, substitution possibilities) also challenge other food-related debates, such as global food security or the livestock contribution to climate change. The Mirage and Globiom studies cope with these issues as follows.

In the CGE tradition, the Mirage approach relies on economic input output tables. These tables indicate in value terms the intermediate consumption of commodities by different activities, such as grains by non-ruminant activities. Fodder crops produced and consumed by animal farms are usually not isolated. Indeed the difference between animal production and commodity intermediate uses gives the gross value added of these farms. This value added is then shared between land returns and other factor returns. This distribution determines the initial unitary return to fodder acreages. In other words, the Mirage approach does not explicitly measure fodder production and price but assume land returns to fodder areas. As concerned the

substitution between fodder and other feed materials, it is implicitly governed by the CGE-traditional Constant Elasticity of Substitution (CES) function between fodder acreages, mineral fertilizers and other feed materials (Al-Riffai *et al.*, 2010). This requires another critical assumption on the substitution elasticity between these inputs/factors. The Mirage approach to deal with fodder crops has some merits: it is consistent with the balance sheets of animal farms and is parsimonious by requiring only two assumptions (the fodder land return and the substitution elasticity). This approach obviously suffers from some drawbacks: the nutritional requirements for animal feeding (energy/protein/fibers) are not ensured because they are not measured (the number of animals neither) and the calibration of the substitution elasticity is not econometrically supported. The Mirage study recognizes these tricky issues when assessing the role of new co-products from ethanol, testing the sensitivity of results to the substitution between crops and coproducts. This is indeed the first future research direction suggested in the conclusion of this study.

The merits and drawbacks of the Globiom approach to animal feeding modelling are basically the opposites. Globiom relies on biotechnical models and data on resource availabilities (Herrero *et al.*, 2013). On the supply side, fodder productions are simulated using agronomic models taking into account many data such as soil quality, climate conditions at very detailed level. On the demand side, the demand of all feed materials are simulated using zootechnic models taking into account feed composition/quality, the number and dynamics of animals. Some adjustments are very likely required to balance supply and demand. The main merits of the Globiom approach to deal with fodders are the explicit representation of animals, the nutritional consistencies and the possibility to compute fodder opportunity costs. On the other hand, this approach is far from parsimonious: many biotechnical parameters are required and data are missing to econometrically estimate them. Then some assumptions are required. For instance, the Globiom study assumes that in grass-based livestock systems, the substitution with coproducts (hence with soybean meals) is not possible, limiting the overall price elasticity of feed demands. The second drawback is that non-nutritional factors that may limit substitution between feed materials in the short/medium term (such as labor availability, capital equipment) are ignored. The omission of these non-nutritional factors also raises the potential economic inconsistency of computed fodder opportunity costs with observed farm balance sheets. The Globiom study also recognizes these difficulties associated with the animal feed sectors and, indeed improves the modelling by refining the co-product substitution pattern.

To recapitulate the previous discussion on animal feed modelling, fodder supplies and demands are not observed. They are only indirectly estimated. Some figures suggest that they are quite important. For instance, Herrero *et al.* (2013) find that grasslands provide one-half of biomass for animals at the world level. At the European level, agricultural economic accounts estimate that fodder values represent around one third of feed values. These are only estimates. Given this potentially important missing information, it is impossible to argue for the superiority of one modelling approach over the other in terms of both economic and biotechnical plausibility. In their comparative analysis of long-term food projections with different economic models, Hertel *et al.* (2016) observe that PE models, including Globiom, tend to have much smaller price elasticities compared to CGE models. Our comparison of Globiom and Mirage studies on European biodiesel scenarios reveals the same features. The feed demands are very likely price inelastic in the Globiom study. The additional soybean meal due to soybean oil production for biodiesel does not displace much other protein sources; it is mainly absorbed by additional livestock production. By contrast, the feed demands are very likely more price elastic in the Mirage study and additional soybean meal does not require additional livestock production.

The different evolutions of livestock production in these two studies may also be explained by four other drivers. First, as already underlined, the market results in the case of the Mirage study are for the complete biofuel scenario, including the ethanol mandate. The latter favors an increase of cereal prices, the production costs of animal production and then a reduction of livestock/meat consumption. Second, the negative impacts on livestock/meat production/consumption obtained by the Mirage study may also be partly due to the income effects. For instance, this study finds a negative Iluc for sugarbeet ethanol due to the following mechanisms. This scenario leads to a decrease of oil price that penalizes the GDP (and household incomes) in Sub Sahara Africa. These households then reduce their (income elastic) meat demand, releasing some pasture for cropping. These counterintuitive, but theoretically plausible, effects are not obtained in the biodiesel feedstock specific scenarios, suggesting that the geography of income effects matters. These income effects are not measured in the Globiom study. Third the Mirage CGE model specifies final demand system where the demand of each final good depends on the price of all goods and income. In particular the meat demand depends on its own price but also the price of vegetable oils. Depending on the substitution relationship between these products, the price increase of vegetable oils could partly explain the decrease of meat demands. These cross-price effects are ignored in the Globiom study. Fourth the Mirage CGE study captures all economic activities, including the livestock processing and

retailing activities. Even if perfect competition is assumed to prevail in these activities, this means that the price variation perceived by final consumers is much muted compared to the price variation faced by livestock producers. The absolute value of the price elasticity of livestock demand is lower than the absolute value of the price elasticity of meat demand. The two studies may have similar own price elasticity of demand but at different processing levels. Accordingly we cannot exclude that the Mirage CGE approach requires a larger livestock price decrease than Globiom to simulate a variation in livestock/meat consumption.

To sum up the comparative analysis of soybean oil results, the Globiom study finds much larger Ilucs than the Mirage study, very likely due to the different effects on livestock sectors. This may come from different hicksian price elasticities of feed demand and possibly, to a lesser extent, on the different effects on the drivers of livestock/meat consumption.

2.3. Comparison of rapeseed oil results

The comparison of the rapeseed oil results reveals another interesting modelling feature. The direct land requirements are basically comparable across the two studies. Like the previous results on soybean oil, we again observe very different impacts on cropland displacement. The same reasons probably apply. However the land use emissions are quite similar across the two studies. In the Globiom study, the biodiesel made from rapeseed oil appears much less carbon-polluting that the biodiesel made from soybean oil, despite similar Ilucs. This study explains that the Ilucs of rapeseed oil scenario are mostly felt in Europe where many low-carbon abandoned lands are available for cropping. By contrast, the Ilucs of the soybean oil scenario are mostly felt in America where the soybean expansion is mainly detrimental to high-carbon other natural vegetation.

This distribution of impacts makes sense considering the geography of these oilseed productions. One may still wonder why the low-carbon European abandoned land is not significantly used in the soybean oil scenario. One possible explanation is given by the price evolutions of the different vegetable oils (last part of Table 1). Recall that the absolute values cannot be compared because the shocks are not the same. We observe that the prices of the different vegetable oils vary in rather similar ways in all countries in the Mirage study. By contrast, these prices vary significantly both across vegetable oils and countries according to the Globiom study. In particular, the rapeseed oil scenario leads to 28 per cent increase of the European rapeseed oil price and only 7 per cent increase of the world price (very likely the

world palm oil price increases less than 2 per cent in this scenario). This suggests that the Globiom study consider that the different vegetable oil markets are not integrated. Accordingly it is possible with this study that the simulated increase of the world soybean oil price following the soybean oil scenario does not lead to a "comparable" increase of the European rapeseed oil price. Hence it is not economically profitable to crop European abandoned land.

The question then is to know if such price differences across vegetable oils and regions are likely in the future. At least, available recent evidence suggest that this is not likely: Biggs *et al.* (2016) report that these prices are highly correlated. The Globiom study improves the modelling of vegetable oil demands by allowing some limited substitution across these commodities in regional food demands (in the EU in particular). However they allow limited substitution compared to the Mirage study and may not allow significant substitution possibilities in all other countries. This may parallel the limited substitution/hicksian elasticities already discussed before on the livestock sectors. As regard the relative evolution of prices across the different regions, the Mirage CGE model relies on the so-called Armintgon specification. This specification assumes that the perceived quality of commodities may vary by agents, leading to potential price differences between countries. The Armington substitution elasticities adopted in the Mirage study are significant (equal to 10), limiting the price differences. The Globiom PE trade modelling relies on the specification of trade costs. These trade costs very likely change with trade volumes, to mimic some features of the Armington specification. Again it seems that there is ex post limited arbitrage between the different sources of a given vegetable oil (in other words, an ex post limited Armington elasticity).

2.4. Insights from the academic literature

So far our comparative analysis reveals three main drivers that may explain the observed difference of results: the direct effects of palm oil yield per hectare, the indirect effects across vegetable oil markets due various substitution elasticities on final demand and trade, the "livestock" effects. The latter may be due to different indirect effects occurring through the animal feed sectors, different induced effects through livestock/meat consumption and the ethanol mandate.

The Iluc controversy about the biofuel policy also exists in other regions of the world, including the U.S. In the last ten years, a large economic literature contributes to the Iluc, as well as on the food versus fuel, debates. On the biofuel-livestock nexus, the available results

are rather mixed. Analysing the European and U.S. policies, Taheripour *et al.* (2011) find a negative link at the world level between the livestock productions and the increased biofuel mandates. This link is positive for Europe due to a very massive price drop of the European oilseed meal. The livestock production decreases elsewhere due to an increase of cereal prices following the U.S. ethanol policy. Timilsina *et al.* (2012) confirm the global negative effects with possible regional positive effects of all biofuel policies in the world. Focusing on the European policy, two studies conducted by the services of the EC (Blanco Fonseca *et al.*, 2010; Helaine *et al.*, 2013) report that the effects depend on the modelling frameworks but are generally negligible.

This large economic literature also spends considerable attention on the impacts of unobserved price elasticities on Iluc results. All studies logically conclude that results are sensitive to these elasticities. Using the Gtap-Bio CGE model and focusing on the U.S. corn ethanol policy, Golub and Hertel (2012) find that the trade Armington elasticities matter. These authors reveal that crop yield elasticities are much more critical than these trade elasticities. Later Gohin (2014) confirm these crucial elasticities for the EU biodiesel case. In particular he analyses the results of the Mirage study, highlighting a critical underestimation of crop yield elasticities due to limited substitution elasticities between land and mineral fertilizers. On this aspect, the Mirage and Globiom studies converge: yield changes can only partially sustain the production increases required for biofuel production. Both studies are quite price inelastic (respectively elastic) at the intensive (respectively extensive) margin. Recent evidence (Babcock, 2015) supports the opposite, with significant intensive margin due to price-induced technological changes.

Overall, the current academic literature does not clearly favour one study relative to the other on the livestock effects. This literature gives few indications that trade elasticities matter but no real indications on the other drivers susceptible to explain the different results. On the other hand, this literature clearly points that crop yield elasticities are critical and underestimated in both studies. In order to gain better comprehension of these different results, a new quantitative analysis is required, to which we turn now.

3. Modelling framework

Both the Mirage CGE and Globiom PE economic models are very elaborated by detailing many commodities, regions, activities, production factors. They share many assumptions, such as

profit/utility maximisation, perfect competition on all markets, steady state computations. The economic mechanisms revealed by these economic models are thus of the same nature. Their main differences come from the magnitude of these mechanisms (for instance absence of income effects in the Globiom study). These models (initial data, baseline data, structural parameters) are not fully documented. Rather trying to recode approximatively all specific features, we follow Hertel and Baldos (2016) by developing an economic emulator. The purpose of this emulator is to focus on the main economic mechanisms. Parameters are calibrated to replicate key results. We choose the more recent and detailed Globiom results on specific biodiesel feedstock scenarios. Then we will be able to analyse their sensibility, for instance by turning on/off income effects.

Our economic emulator is a CGE-type model that can be easily switch to a PE-type model (by assuming that household income are fixed and by removing the corresponding equation). Compared to the Simple emulator of Hertel and Baldos, the main features of our emulator are the explicit modelling of animal feeding (fodder crops), the explicit modelling of the land competition and finally the possibility to include induced effects. On the other hand, we do not explicitly distinguish different regions to save on data and parameters. We will not be able to explore trade elasticities explicitly. Nevertheless we will be able to test the substitution elasticities at the demand side between the different vegetable oils.

3.1. General features

The principle of an emulator is to simplify to keep only key features. In that sense, we consider a limited number of products in our model: 3 vegetable oils (palm oil, soybean oil, rapeseed oil), 2 oilseed meals (soybean meal, rapeseed meal), 1 cereal (coarse grains for animal feeding), 1 fodder crop (including grass, hay, corn silage, …) 1 livestock product (a composite of dairy-ruminant- non ruminant products) and 1 other good (including all other food and non-food products and services). These products are offered by the following activities: palm oil, soybean (growing and crushing), rapeseed (growing and crushing), cereal, animal and other activities. These activities can thus be multiproduct, use potentially many inputs (mineral fertilisers are for instance in the aggregate of other products) and two production factors: land and other factors (aggregate of labor and capital). We will explain later how we deal with the different land qualities.

As usual, we assume that producers maximise their profit subject to technological constraints and market prices. This maximisation programs determine their output supply and input/factor demands. The factor returns determine the income of a representative household. This household maximises his utility defined over commodities subject to an expenditure constraint. This program determines final demands. Prices ensure equilibrium on commodity and factor markets. As regards the macroeconomic closure, we assume exogenous investments that determine savings. CGE and PE models, such as Mirage and Globiom, only determines relative prices. We choose the aggregate of other products as the numeraire. Our CGE emulator can be easily switch to a PE emulator close to Simple, for instance by removing the income equation (the fodder equilibrium equation) and fixing the income values (the fodder price).

3.2. Modelling of crop technologies

The Globiom model relies on agronomic models to define crop technologies. Many technologies (intensive/extensive) are possible, each one characterised by fixed coefficients. Producers may switch from one technology to another depending on price incentives. This switch determines the supply intensive margin. By contrast, the Mirage model relies on CES functions to represent the crop technologies; the substitution elasticity is crucial to determine the supply intensive margin. At first sight, one may consider that the two approaches are non-compatible. However the compatibility was theoretically demonstrated more than half a century ago. Houthakker (1955), then followed by Levhari (1968) and Sato (1969), demonstrates that a CES function at the national level is fully compatible with fixed technologies at the field level. The condition is that one production factor is heterogeneous. This idea has been investigated in the agricultural economic literature. Berck and Helfand (1990) introduce heterogeneous stochastic (climatic) dimensions in their framework to prove that aggregate CES functions (even more general functional forms) are fully compatible with fixed technologies at the field level. In the same vein, Hertel *et al.* (1996) show that the aggregate substitution elasticity between land and fertilizer can be significant, even if it is limited at the field level.

Accordingly our emulator specifies crop supplies with a CES function, similar to the Mirage CGE model and Simple emulator. Three inputs enter the CES functions: land, other goods, other factors. Because the price of the two latter do not vary much in our scenarios, the unique substitution elasticity allowed by the CES function is flexible enough. As regard the soybean

and rapeseed activities, we assume as usual fixed multi-output coefficients (in other words that the composition of oilseeds in terms of oils and meals does not change in the medium run).

3.3. Modelling of livestock technologies

Fodder crops are mostly non-marketed, being produced and consumed in animal farms. In the Globiom model, the fodder production technologies are represented as other crop production technologies: some land, fertilizers (at least implicitly other inputs/factors such as pesticides/labor) are required for pasture/hay/silage production. Accordingly we develop a specification for fodder production similar to crop production, with a CES function between land, other goods and other factors. The fodder supply function depends on the price of these inputs/factors and the "opportunity" price of fodder that balance supply and demand on our representative animal farm. In other words, we split the animal farm into two activities: fodder production and animal production activities. We assume that other goods/factors can easily switch from one activity to the other on these farms or that they can easily buy/hire them on the markets.

Regarding the animal production activity, the Globiom model assumes that the different animals have different nutritional requirements in terms of energy, proteins and fibers. These activities also require other goods (such as energy/veterinary products) and factors (such as labor, stables). The substitution pattern between the different feed materials is determined by zootechnical models and is quite general. For instance, the rapeseed meal is a substitute of the soybean meal for all animal production technologies. The rapeseed meal is also a substitute of corn in the swine production technology but a complement in the beef, dairy and poultry production technologies. The substitutions of fodder crops with the concentrated feeds are possibly also quite general.

It is a priori important that our emulator captures flexible substitution patterns between main feeds in order to be able to replicate key Globiom results. When the price of only one input/factor varies, then an aggregate CES function is flexible enough to reproduce technically simulated substitution relationships. But when the price of many input/factor varies like protein meals, fodder crops and cereals, then the specification of a simple CES function is not flexible enough. It is usual with CGE models in general, including Mirage, to introduce strong separability assumptions on production technologies, developing nested CES functions. This approach maintains global regularity of production functions and increases flexibility. But the

flexibility is only partial. To overcome this issue, we implement latent separability as explained in Gohin (2005). To limit the number of information needed to implement this approach, we assume that animal nutritional requirements are fulfilled with three feeds: cereals, fodder crops and (a CES-aggregate of) protein meals. Because the market prices of other goods (energy/veterinary products for instance) and other factors (animal farm building for instance) are nearly constant in our simulation results, we do not consider the potential substitution possibilities between these feeds and the other goods/factors.

3.4. Modelling the land market

The modeling of the land market is obviously critical when measuring land use changes. This is far from obvious due to the presence of pervasive policy regulations, the heterogeneity of the land factor and the dynamics of this heterogeneity. On the policy side, if no additional cropland is available due to strict policy regulations, then the Iluc debate is solved. On the other hand, with loose land regulations, price incentives may justify land conversions. The EU biofuel policy contains land regulations that apply to acreage directly used for producing biodiesel. They do not apply to Iluc. On the heterogeneity side, we already mention this aspect when we justify our modelling of crop production technologies. This heterogeneity implies in particular that all fields are not equal from a qualitative viewpoint and their prices should differ (at least in a first best world). This heterogeneity can be partially controlled by economic agents, for instance by modifying the carbon content with organic fertilizers. That partly depends on economic incentives. If they are huge, this can also justify significant land use changes and conversion costs to reap future benefits. This is at the core of the Iluc debate. By increasing the profitability of cropland activities, the biofuel policy may contribute to the decline of pasture land or forest land. These land use changes depend on the profitability of potential activities and the costs of changing the land qualities (for instance, by cutting and selling immature tree, cleaning forest, etc). The higher these costs are, the lower the land use changes will be.

The measurement of these costs, more generally frictions, on the land market is not an easy task due to the lack of data and the dynamic aspects for instance. Economic models cope with this issue in different ways. The Globiom model directly specifies the conversion costs associated to land use changes across main activities. These costs are presumably high (respectively low) when the land use changes involve the conversion of forest areas (abandoned land) to cropland. These costs also vary positively: the higher the land use changes, the higher the conversion

costs. The Mirage model relies on the CGE-traditional CET transformation function. The approach captures in a reduced way these endogenous costs associated to land use changes, through the elasticity of transformation. It recognizes the heterogeneity of the land factor, introducing a distinction between physical and so-called effective acreages. The drawback of this CET approach is that physical land cannot be directly traced and preserved during transformation (Zhao *et al.*, 2017). This CET approach does not measure the real costs that economic agents face when changing land uses.

In our CGE-type emulator, we develop a new modelling of the land market, following the land use and acreage choice literature (Carpentier and Letort, 2012 and 2014). That is, we assume the existence of a representative landowner maximizing his total land return subject to a land conversion cost function. The cost function is a mono-input, multi output quadratic cost function. To save on data and parameters, we assume that only the aggregate of other factors (labor/capital) are needed to perform the land conversion. The multi-output are the different physical (not effective) land use categories. In the calibration part, we will assume that the cost is null when no changes are made with respect to the baseline. All deviations from this baseline will generate some costs. In practice we consider five productive land use categories, namely palm oil, soybean, rapeseed, cereal and fodder acreages. The total farmland (cropland and pasture) is not exogenously constrained. The expansion on nonfarm land is governed by the parameters (elasticities) of the cost function. Like the CES approach for modelling the crop production technology, our aggregate (quadratic) approach in our emulator is motivated by the heterogeneity of the land market in the different regions. We will calibrate the parameters of our aggregate cost function to replicate key results of the Globiom detailed study.

3.5. Commodity demand modelling

The last notable feature of our CGE-type emulator comes from the modelling of commodity demands. In the Globiom study, the demand comprises the final demand by households and by firms. The final demand by household is assumed to depend only on its own-price. The exception is for vegetable oils where some substitution is introduced between them. By contrast, the Mirage study specifies a globally regular but semi-flexible complete demand system with nested CES functions within a Linear Expenditure System (LES). In that model, the final demand of one commodity depends on the prices of all commodities and the household income.

In our CGE type emulator, we have three types of demanded commodities: animal products, other goods and the different vegetable oils. We first assume a CES aggregate of the different vegetable oils. The substitution elasticity will govern the correlation between the prices of the different vegetable oils. Then we develop two specifications for the total demand of commodities. In the first, PE-type, version of our emulator, we assume that the commodity demands depend only on their own price (with constant price elasticities). The income variation is not accounted for, resulting in violation of the Walras Law. In the second specification, we specify a globally regular and fully flexible form to allow any price and income elasticities. We again rely on the latent separability concept, implemented with nested CES functions, and the introduction of hidden goods to capture nonhomothetic effects (Gohin, 2005). This approach allows the introduction of income effects while controlling for the absence of cross price effects between food commodities. In this second CGE-type version, we check that the Walras Law is satisfied.

4. Calibration assumptions

In order to implement our emulator, we need to define initial data and deep parameters (price-substitution-income elasticities).

4.1. Data assumptions

As regards the initial data, both Globiom and Mirage studies assess the land use emissions of biodiesel relative to baseline situations defined for the year 2020. These baselines are simulated with their models assuming different exogenous drivers. These critical baselines are not fully documented. We check recent figures (from Production Supply Demand PSD online database) to determine roughly initial data on production volumes, prices and acreages (see Table 2). The only exception is on the palm oil production, where we assume that the initial yield is only 2.5t/ha to replicate key Globiom results.

Table 2 : Assumed initial data

Product	Production (Mt)	Price (€/t)	Acreage (Mha)	Land return (€/ha)
Palm oil	50	700	20	*350*
Soybean oil	50	800	110	*150*
Soybean meal	200	350		
Rapeseed oil	40	900	60	*128*
Rapeseed meal	50	300		
Feed cereals	800	175	200	*105*
Milk	800	300		
Non Ruminant	200	1500		
Ruminant	60	3000		

The implementation of our emulator also requires the initial structure of production costs. We follow the Simple example where, by default, we rely on the GTAP database to determine these unobserved data. That is, we assume that the cost shares of land, other goods and other factors amount to 0.15, 0.35 and 0.50 in the soybean, rapeseed and cereal activities. These respective shares are 0.2, 0.30 and 0.50 in the perennial palm oil sector. To appreciate these assumptions, we report in the last column of Table 2 the implied unitary land return for each crop sector. In the animal sector, we assume that the cost share of other factors amount to 0.25. We explain below how we determine the critical initial value of fodder crops. For the sector of other goods, we use many ratios of the GTAP database. We assume first that the private expenditure on livestock products represent 5 per cent of total private expenditure at the world level. This defines the initial private expenditure on other goods. From this assumption and GTAP database ratios, we compute other initial values (production, intermediate consumption, investment).

It remains to determine the data for the fodder sector: initial production volume, opportunity price, acreage and cost structure. We develop an original approach to calibrate the value of fodder production. We want them to replicate the Globiom results on the soybean oil specific scenario because it leads to most significant livestock effects. Moreover the results of this scenario are the most detailed. In practical terms, we develop a log linearized PE emulator similar to the Simple one. It focuses on the livestock sector. It is comprised of 4 equations (the hicksian demands for cereals, meals and fodder and the zero profit condition) and 4 variables (the substitution elasticity between fodder and cereals, the substitution elasticity between fodder and meals, the fodder initial value and the fodder price evolution). The exogenous variables/parameters in this calibrating PE emulator are an assumption on the substitution elasticity between cereals and meals (we choose 0.4 based on Beckman *et al.*, 2011; Mathews and McConnell, 2012; Suh and Moss, 2016) and our approximate reading of Globiom results.

We read the following results: livestock production (+0.25%), cereal and meal uses (+0.1% and +1.5%), livestock, cereal and meal prices (-0.5%, 0.5%, -10%) and fodder acreage (-0.05%). The last one is very approximate as we don't know the initial fodder acreage. We retain the Mirage estimate of 1 billion ha. Interestingly the resolution of this PE livestock emulator gives that the value of fodder crop is close to the combined value of meals and cereals in animal feeding, a result consistent with Herrero *et al.* (2013). Without prejudice, we then divide this production value between price and volume using a price index (a very standard practice). Regarding the production costs of fodder, we have no clues. We start with the crude assumption that the land/other factor shares in production costs amount to 0.5.

4.2. Parameter assumptions

Turning to the calibration of the deep parameters of our emulator, we first assume a limited substitution elasticity in the crop production technologies (0.05). This value is taken from the Mirage study because both Mirage and Globiom studies find similar relative crop yield effects. On the livestock production technology, we use the results of the previous PE livestock emulator: the substitution elasticities are equal to 1.1 between fodder and cereals, 0.1 between fodder and meals (and assumed to be 0.4 between cereals and meals). The substitution elasticity between rapeseed and soybean meals equals 2. At the demand side, we adopt the price and income elasticities of Muhammad *et al.* (2011). These elasticities pertain to the final demand only, not the intermediate demand of vegetable oils by other industries. Results of the Globiom study on the palm oil biodiesel scenario suggest that these other intermediate demand are quite elastic. Accordingly we increase the absolute value of the own price elasticities of vegetal oil demand. Concretely, we assume the following values: -0.2 (0.2) for the own price (income) Marshallian elasticity of vegetable oils; -0.45 (0.55) for the own price elasticity (income) Marshallian elasticity for the livestock products. We assume a limited substitution elasticity (0.9) between the different vegetable oils (intermediate value of Globiom elasticities).

It remains us to determine the deep parameters of the land conversion (quadratic) cost functions. We adopt an original calibration approach of these parameters, similar to the spirit of the original approach to measure the initial fodder economic value. We temporary assume isoelastic land supply functions (with 0.1 own price elasticity from the Simple model) for all land uses, except fodder use. For this last one, we temporary assume exogenous supply. We end up with an operational emulator that is conditional on fodder acreage. We simulate the

three Globiom biodiesel feedstock specific scenarios, imposing the Globiom results on pasture land. These three simulations provide us land opportunity price and acreage evolutions. We use these information to calibrate the parameters of the land conversion quadratic cost function. Our calibrated elasticities are reported in Table 3.

Table 3 : Assumed land conversion price elasticities

	Palm oil	Soybean	Rapeseed	Cereal	Fodder
Palm oil	0.185	0.090	0.010	-0.176	-0.109
Soybean	0.002	0.265	0.007	-0.158	-0.116
Rapeseed	0.002	0.047	0.091	-0.087	-0.053
Cereal	0.000	0.061	0.007	0.010	-0.079
Fodder	-0.002	-0.033	-0.004	-0.061	0.100

These calibrated elasticities imply for instance that palm oil expansion is mostly to the detriment of nonfarm land, more marginally on fodder land (the elasticities must be applied to the initial acreage defined above). When the price of soybean land increases due to the soybean oil biodiesel shock, the soybean land use increases as well as the cereal land use. This is to the detriment of the fodder areas as well as nonfarm land. This replicates one key Globiom result. The own price elasticity for cereals appears much lower than other own price elasticities, suggesting that it may be a "leading" crop in many regions. We have no strong evidence against these ex post calibrated elasticities. They are consistent with the key results of the detailed biotechnical Globiom model and may be valid only for a limited domain of price variations.

5. Results

We are now ready to explore some factors that may explain the different results obtained by the Globiom and Mirage studies. We simulate an exogenous increase of demand by 3.5 Mt for each vegetable oil as in the Globiom study (of the investment demand in the CGE emulator). As a robustness check, we also simulate the Globiom vegetable oil scenario (assuming that demands for rapeseed, soybean and palm oils increase by 1.75, 0.87 and 0.87 Mt).

We start with the PE emulator closest to the Globiom model. Then we successively modify the initial yield of palm oil, the substitution elasticity between vegetable oils. We then introduce induced effects by turning to the CGE emulator. We finally perform some sensitivity analyses.

5.1. Initial partial equilibrium results

Our first results reported in the Table 4 are close to key Globiom results (reported in Table 1). They are not identical, notably because the elasticities in our PE emulator are not constant. We find various world price effects for the different vegetable oils: much higher for soybean oil than palm oil. We also find an increase of cereal and livestock productions, mostly with the soybean oil scenario. In this scenario, the world price of soybean meal significantly decreases due to inelastic feed demand. The fodder price increases due to reduced supply (increased land competition). These results of the rapeseed oil scenario are logically intermediate between the palm oil and soybean oil scenarios. Our land use effects are also quite close to Globiom results, with smaller effects with the palm oil scenario. It appears that our emulator is quite linear in the sense that the results of the vegetable oil scenario are close to the linear combination of the results of individual scenarios.

Table 4 : Initial partial equilibrium results

	Palm oil	Soybean oil	Rapeseed oil	Vegetable oil
Prices (%)				
Palm oil	4.29	2.03	1.61	2.36
Soybean oil	1.83	12.41	4.30	5.58
Rapeseed oil	1.33	3.87	9.33	5.86
Soybean meal	-0.95	-6.20	-2.79	-3.12
Fodder	0.21	0.76	0.43	0.45
Production (%)				
Palm oil	4.93	2.48	2.02	2.83
Soybean oil	0.05	0.92	-0.35	0.06
Rapeseed oil	0.50	0.85	4.27	2.45
Cereals	0.04	0.19	0.10	0.10
Animal	0.02	0.21	0.10	0.11
Fodder	-0.03	-0.02	-0.02	-0.03
Acreage (%)				
Palm oil	4.13	2.09	1.71	2.38
Soybean oil	0.04	0.76	-0.29	0.04
Rapeseed oil	0.33	0.60	3.00	1.69
Cereals	0.02	0.16	0.09	0.09
Fodder	-0.04	-0.06	-0.05	-0.05
Land use (Mha)				
Cropland	1107	1939	2001	1713
Fodder	-437	-575	-456	-473
Nonfarm land	-670	-1364	-1545	-1240
Land effects (ha/toe)				
Cropland displacement	0.35	0.62	0.64	0.54

5.2. Partial equilibrium results with Mirage palm oil yield

We perform the same scenarios, assuming now that the baseline palm oil yield reaches 5t/ha as in the Mirage study. This initial yield level is high compared to recent observed yields (around 3.8t/ha when including kernel oil in the PSD database) at the world level. On the other hand, recent observed yields are higher in Malaysia and Indonesia (close to 4.5t/ha) and are always growing. When performing these scenarios, we keep all deep parameters at their initial values. This correction implies that the initial situation is different, with for instance greater vegetable oil supply, greater return to palm oil acreage. The results are reported in Table 5 (to be compared to Table 4).

Table 5 : Partial equilibrium results with corrected value of initial palm oil yield

	Palm oil	Soybean oil	Rapeseed oil	Vegetable oil
Prices (%)				
Palm oil	1.40	0.85	0.67	0.89
Soybean oil	0.77	10.52	2.87	4.15
Rapeseed oil	0.56	2.57	8.26	4.82
Soybean meal	-0.40	-5.20	-2.03	-2.36
Fodder	0.11	0.63	0.33	0.34
Production (%)				
Palm oil	2.96	1.90	1.55	1.97
Soybean oil	0.02	0.84	-0.41	0.00
Rapeseed oil	0.21	0.36	3.87	2.06
Cereals	0.02	0.16	0.08	0.08
Animal	0.00	0.18	0.08	0.08
Fodder	-0.02	-0.02	-0.02	-0.02
Acreage (%)				
Palm oil	2.68	1.74	1.41	1.80
Soybean oil	0.01	0.69	-0.34	0.00
Rapeseed oil	0.14	0.26	2.70	1.42
Cereals	0.01	0.13	0.07	0.07
Fodder	-0.03	-0.05	-0.04	-0.04
Land use (Mha)				
Cropland	646	1532	1672	1338
Fodder	-267	-470	-372	-364
Nonfarm land	-378	-1063	-1300	-974
Land effects (ha/toe)				
Cropland displacement	0.21	0.49	0.53	0.41

The higher initial palm oil yield implies that the direct (land requirement) effect is lower. Moreover the same demand shock (3.5 Mt) is relatively smaller, due to bigger initial production. So the price effects should be less important to cope with the same absolute demand shock. Without surprise, we find more limited price effects: the world palm oil price increases by 1.40 per cent (compared to 4.29 per cent previously). Impacts on the other

vegetable markets are also muted (they are all less than 1 per cent). Despite a limited substitution elasticity between vegetable oils at the final demand side, we also find muted effects for the other scenarios. For instance, the soybean oil price increases by 10.52 per cent (compared to 12.41 per cent) in the soybean oil scenario. In this scenario, the cereal and livestock production still increases, due to meal effects in the animal feed demand. Interestingly we find that the cropland displacements all decrease by the same level (around 0.12ha/toe). They become closer to the Mirage ones.

5.3. Partial equilibrium results with greater substitution between vegetable oils

The Globiom study finds large price differences across vegetable oils while observed price over the last decades show strong correlation between these prices. In the Mirage study, the simulated vegetable oil prices are more similar, despite a much larger simulated scenario. To try to reproduce these similar price evolutions, we increase the substitution elasticity between vegetable oils to 5, an intermediate value between the final demand and Armington substitution elasticities retained in the Mirage study. With greater substitution possibilities, the contribution of each vegetable oil to the biodiesel mandate is different in the two studies. In the vegetable oil scenario (last column of Table 6), we adopt the endogenous shares obtained by the Mirage study (0.47 for rapeseed oil, 0.34 oil for palm and 0.18 for soybean oil).

Results reported in the Table 6 must be again compared to initial results reported in Table 4. As expected, the higher substitution possibilities lead to more uniform results across feedstock specific scenarios. In particular, the price effects become rather similar across vegetable oils. The palm oil specific scenario has now greater positive impacts on cereal and livestock productions, leading to a greater land use effects (cropland displacement amounts to 0.38ha/toe).

Table 6 : Partial equilibrium results with greater substitution elasticity

	Palm oil	Soybean oil	Rapeseed oil	Vegetable oil
Prices (%)				
Palm oil	3.46	3.24	3.36	3.36
Soybean oil	2.83	5.48	4.18	3.92
Rapeseed oil	2.62	3.73	5.55	4.17
Soybean meal	-1.54	-2.89	-2.42	-2.19
Fodder	0.27	0.42	0.39	0.35
Production (%)				
Palm oil	4.02	3.80	3.96	3.93
Soybean oil	0.05	0.22	-0.06	0.03
Rapeseed oil	1.06	1.39	2.41	1.74
Cereals	0.05	0.09	0.09	0.08
Animal	0.04	0.09	0.08	0.07
Fodder	-0.03	-0.03	-0.03	-0.03
Acreage (%)				
Palm oil	3.36	3.19	3.32	3.30
Soybean oil	0.03	0.18	-0.06	0.02
Rapeseed oil	0.72	0.95	1.66	1.19
Cereals	0.04	0.08	0.07	0.06
Fodder	-0.04	-0.05	-0.05	-0.05
Land use (Mha)				
Cropland	1220	1553	1736	1512
Fodder	-422	-496	-515	-477
Nonfarm land	-743	-1056	-1221	-1035
Land effects (ha/toe)				
Cropland displacement	0.38	0.49	0.55	0.48

On the other hand, these land use effects are lower in the two other specific scenarios (by around 0.10 ha/toe), due to lower rebound effects on cereal and livestock sectors. Overall the soybean oil production is nearly unchanged, even in the soybean specific scenario. In the aggregate vegetable oil scenario (last column), we find production increases of the palm and rapeseed oils only. Without being similar, these results are closer to the Mirage ones where the greatest production increase is obtained for palm oil, followed by the aggregate of rapeseed and sunflower seed oils and finally by the soybean oil.

5.4. General equilibrium results with induced effects

All results obtained so far do not take into account the budget constraint of the representative household. We implicitly assume that the final expenditure by our household can freely increase or decrease. Let us consider the aggregate vegetable oil scenario. With the initial PE emulator, the final expenditure on vegetable oils increase by 3.74 per cent due to the price effects (aggregate food consumption of vegetable oils decreases by 0.90 per cent). On the other hand, the final expenditure on animal products decrease by 0.13 per cent: the price decrease (by

0.24 per cent) is greater in absolute value than the consumption increase (due to price inelastic demand of animal products). Overall, private expenditure increases by 0.02 per cent (the initial share of vegetable oil in total consumption is less than 1 per cent).

On the resource side, one may anticipate that available resources for final consumption should decrease for two reasons. First biodiesel consumption (exogenous investment demand) must be financed. Second factor returns may decrease due to the modification of initial, first best, allocation of scarce resources. In fact we find an increase of factor returns: more land is cultivated following the shocks, leading to the creation of more value added. The additional cultivated land involves some additional conversion costs, but this increases the value of other factors. The factor returns increase by 0.02 per cent and the resources available for final consumption by 0.005 per cent. The difference serves to finance exogenous biodiesel consumption.

It appears that the household budget constraint is not fully satisfied. However the disequilibrium is very modest (by 0.015 per cent). Accordingly the introduction of induced/general equilibrium effects in our PE emulator does not change significantly the results (not reported because very close to Table 4). For instance, the final demand of animal products increases by 0.10 per cent with the CGE emulator, compared to 0.11 with the PE emulator. We obtain a very thin reduction of final consumption of other goods (by 0.02 per cent).

5.5. Sensitivity analysis

Our progressive comparative analysis reveals that both the direct and indirect market effects occurring through vegetable oil markets matter. On the other hand, the induced effects are not significant. We combine the three previous modifications and simulate the aggregate vegetable oil scenario. Results are reported in the second part, first column of Table 7. It appears that the three modifications give us results closer to the Mirage study. In particular the cropland displacement is reduced by nearly one half (from 0.54 to 0.30 ha/toe) but remains much higher than the Mirage result (around 0.14 ha/toe). The effects on cereal and livestock effects may be responsible for this difference. We explore the sensitivity of previous results to the critical assumptions made when building our emulator.

The first sensitivity analysis relates to the assumption of fodder value. As mentioned earlier, it is quite difficult to gather data on these crops. In the central case, we assume that the economic

value of these crops is equal to the values of concentrated feeds for animal feeding. To save space, we consider only one alternative: the economic value of these crops is only one-half of the values of other feeds (it is not possible to double these values, otherwise the balance sheets of animal farms is not satisfied). Results are reported in the second column of Table 7. We find that this assumption has limited impacts on results with both versions of our emulator. We find that the livestock production increases slightly more, because the fodder has less value in animal production costs. Accordingly the meal price effect is larger, stimulating more animal production. Because the substitution between animal feed is limited, then the reduction of fodder acreage is more limited.

Table 7 : Sensitivity analysis of results to data and deep parameters assumptions

	Central values	Fodder value	Feed elasticities	Land elasticities	Ethanol shock	Yield elasticities
Initial PE emulator						
Prices (%)						
Palm oil	2.36	2.21	2.28	1.41	2.51	0.93
Production (%)						
Palm oil	2.83	2.84	2.79	3.07	2.80	2.98
Animal	0.11	0.16	0.11	0.11	0.06	0.14
Acreage (%)						
Palm oil	2.38	2.41	2.35	2.79	2.32	0.92
Land use (Mha)						
Cropland	1713	1860	1914	2046	1658	454
Fodder	-473	-342	-892	-278	-1078	-52
Nonfarm land	-1240	-1515	-1022	-1767	-580	-401
Land effects (ha/toe)						
Cropland displacement	0.54	0.59	0.61	0.65	0.44	0.14
CGE emulator with modified palm oil yield and substitution between veg. oils						
Prices (%)						
Palm oil	1.33	1.29	1.31	0.75	1.42	0.68
Production (%)						
Palm oil	2.85	2.85	2.83	3.05	2.85	2.81
Animal	0.03	0.05	0.03	0.02	-0.02	0.04
Acreage (%)						
Palm oil	2.59	2.59	2.57	2.90	2.57	1.31
Land use (Mha)						
Cropland	958	1015	1039	1074	900	348
Fodder	-286	-226	-453	-213	-904	-85
Nonfarm land	-671	-789	-587	-861	4	-263
Land effects (ha/toe)						
Cropland displacement	0.30	0.32	0.33	0.34	0.24	0.11

The second sensitivity analysis focuses on the substitution elasticities between fodder and other feeds. We double these elasticities, based on the remark by Hertel and Baldos that PE models generally exhibit lower price responses. We again find limited effects on results (third column of Table 7). Most notable is the impact on fodder acreage which decreases more due to the

more intense competition from meals in animal feeding. Cropland displacement is then higher, because it becomes more easy to expand on fodder acreage. On the other hand, the reduction of nonfarm land (forests, abandoned lands) is more limited.

The third sensitivity analysis focuses on the land mobility elasticities (in our emulator, conversion cost elasticities). Again we report in the fourth column of Table 7 the results when we double all elasticities. As expected, we obtain larger cropland displacement effects. It becomes more easy to switch from one land use category to another one. In particular, the nonfarm land decreases a little more to the benefit of cropland. On the other hand, we observe that the effects on the livestock sector are nearly unchanged.

In all results obtained so far, we always obtain an increase of livestock production. The Mirage study reports a reduction of livestock production when simulating the whole biofuel scenario. This scenario includes the ethanol mandate. Our emulator is not well designed to capture the ethanol shock (sugar and cereals co products are not included). As a crude sensitivity analysis, we assume an exogenous demand of cereals by 1 Mt (assumed to be net of coproducts for animal feeding). The results are reported in the fifth column of Table 7. We find a lower increase of the livestock production with the PE emulator. We find now a decrease of the livestock production with the CGE emulator. This makes sense because the ethanol mandate removes feed availabilities. On the other hand, the biodiesel mandate bring feed resources for animal feeding. As in the Mirage and Globiom studies, we find lower land effects due to the additional ethanol mandate. The additional cropland is mostly to the detriment of fodder lands with both versions of the emulator.

In the last sensitivity analysis, we focus on crop yield elasticities. The academic literature shows the critical impact of these elasticities. In both Mirage and Globiom studies, they restrict the intensive margin compared to the extensive margin. In our emulator, we now increase the substitution elasticities in crop technologies from 0.05 to 0.55 (value retained in the Simple emulator). We again find critical influence of this deep parameter on land use results (last column of Table 7). With both versions of our emulator, the cropland displacement is reduced by more than two thirds. Using the modified CGE version of our emulator, palm oil yield increases by 1.50 per cent (by 0.08t/ha), compared to an acreage increase of 1.31 per cent. The ratio between the intensive and extensive margin is indeed comparable to the ratio obtained with the Globiom model when performing long-term food projections (Hertel *et al.*, 2016). In these last results, the land use effects are considerably lower while the livestock production still increases marginally.

6. Conclusion

This paper deals with the controversial indirect land use changes of the European biodiesel policy. Two studies sponsored by the European commission finds significant, but contrasted, land use effects for the different vegetable oils used for biodiesel production. The first study uses the Mirage computable general equilibrium model capturing direct, indirect and induced effects, the latter being associated with the macroeconomic (income) feedback effects. This first study finds similar land use emissions for all vegetable oils around 55 gCO2eq/MJ. The second recent study uses the Globiom biotechnical partial equilibrium model offering a detailed representation of the indirect effects occurring through the livestock sectors while neglecting induced effects. This second study finds very different figures ranging from 65 gCO2eq/MJ for rapeseed oil up to 231 gCO2eq/MJ for palm oil. These figures question the EC proposal to continue rather stopping the biodiesel mandate.

In order to understand these important differences, we first investigate the two modelling approaches and find three distinctive features: the baseline yield for palm oil, the substitution possibilities between vegetable oils at the demand and trade sides and finally the livestock positive effects. The last feature may result from induced effects only captured in the Mirage study. We then develop an original economic emulator to understand the diverging key results of these studies and test their sensitivity. Data and parameters of this emulator are calibrated to replicate main Globiom recent results. Then we progressively introduce the three identified features and find that the direct and indirect effects on vegetable oil markets explain most of the differences. We also find that the indirect effects on the livestock sectors and induced effects do not significantly influence the results. The livestock effects appear more sensitive to the ethanol consumption if made from cereals. As the academic literature already stresses, these results are critically sensitive to crop yield responses. They are considerably underestimated in both studies. Using a conservative substitution elasticity between land and other factors in crop production technologies, we find that the cropland displacement due to the biodiesel policy computed by the recent study is overestimated by a factor of 5. The land use emissions of biodiesel are very likely not as important as quantified in this recent EC-sponsored study.

Our results show that the critical modelling assumptions are those made on the sectors directly concerned by the policy shocks (initial yields, substitution between vegetable oils, intensive vs extensive margins on arable crop sectors). This makes sense and recalls that “first-order” effects on these sectors must be carefully measured before adding potentially “second-order” effects occurring on other sectors. In the present case, our results suggest that the livestock

effects must be introduced but only after a satisfactory measurement of arable crop market effects. The modelling of the biofuel-crop-livestock nexus is complex, in particular due to the presence of poorly measured fodder crops. More generally, physical and economic data are missing to develop detailed and statistically robust economic models on livestock (to a lesser extent on other farm) sectors. In this situation, simulated results from detailed biotechnical models such as Globiom are useful to provide first consistent figures. The challenge from an academic viewpoint remains to ensure that the aggregation of these microeconomic simulated results are consistent with aggregate long run statistical relationships (Wu and Adams, 2002). A better articulation between micro-macro, simulated-econometric, short-long run economic models should improve the robustness of our quantitative assessments and policy recommendations. This articulation can benefit from the development of emulators as done in this paper, as well by the documentation of the crucial price elasticities (Robinson *et al.*, 2014).

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