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Biofuels in the world markets:

A Computable General Equilibrium assessment of environmental costs related to land use changes.*

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Abstract

There is rising scepticism about the potential positive environmental impacts of first generation biofuels. Growing biofuels crops could induce diversion of other crops dedicated to food and feed needs. The relocation of production could increase deforestation and bring significant new volumes of carbon into the atmosphere. In this paper, we develop a methodology for assessing indirect land use effects related to biofuels policies in a Computable General Equilibrium framework. We rely on the trade policy model MIRAGE and on the GTAP 7 database, both of which have been modified and improved for this purpose. The model explicitly represents the role of different types of biofuel feedstock crops, energy demand, and carbon emissions. Land use changes are represented at the level of Agro-Ecological Zones in a dynamic framework using land substitution with nesting of Constant Elasticity of Transformation functions and a land supply module taking into account the effects of economic land expansion. In this integrated global approach, we capture the environmental cost of different land conversion due to biofuels in the carbon budget, taking into account both direct and indirect CO2 emissions related to land use change. We apply this methodology in looking at the impacts of biofuel (ethanol) policies for transportation in the United States and in the European Union with and without ethanol trade liberalization. We find that emissions released because of ethanol programs significantly worsen the total carbon balance of biofuel policies. Ethanol trade liberalisation benefits are ambiguous and depend highly on the parameters governing land use change, in Brazil in particular. We conclude by pointing out the critical aspects that have to be refined in order to improve our understanding of the environmental implications of biofuels development.

Key words: agricultural economics, biofuels, indirect land use change, trade liberalisation.

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1. Introduction

There is rising scepticism about the potential positive environmental impacts of first generation biofuels. Aside from findings about their role in the recent food price crisis, doubts have been raised about their real contribution to climate change mitigation. This debate happens at a time when government commitments for biofuel production have even strengthened for the last couple of years. In the United States, the Energy Independence and Security Act signed in 2007 set an objective of 36 billion gallons of production in 2022. In the European Union (EU), the directive on the promotion of the use of energy from renewable sources, endorsed in December 2008 by the European Parliament, confirmed the objective of a 10% incorporation of bioenergy in EU transportation by 2020.

These different policies have been adopted thanks to supposed benefits attributed to biofuels: (i) biofuels help to be less dependent from oil imports; (ii) biofuels production brings complementary revenues to farmers; (iii) biofuels have a lower environmental footprint than fossil fuels because their use release less greenhouse gases in the atmosphere. It is this third point that is intensively contested among the research community.

Indeed, environmental impacts of biofuels rely heavily on the type of pathway used to produce ethanol and biodiesel. First generation biofuels, based on usual food crop transformation, are land demanding and require intensive use of farming input. More advanced production technologies (cellulosic ethanol, Fischer-Tropsch diesel, etc) are expected to be more beneficial to the environment but most of them are still at the development stage. Because recent life cycle assessments (LCA) show high variation in the benefits of the different production pathways (Zah et al., 2007; Mortimer et al., 2008), the choice of biofuel feedstock is particularly important to achieve a sustainable policy. Some production pathways, such as for US corn ethanol, have indeed been criticized for their negative environmental impacts because of the high emissions of some ethanol refineries (Mortimer et al., 2008).

However, aside from the direct emissions generated by crop production, transformation and distribution, a more particular concern has emerged with the question of indirect land use impacts. Indeed, several studies recently argued that the land use changes due to biofuels production would bring about negative overall impacts on the environment (Searchinger et al., 2008; Fargione et al., 2008). Growing biofuels crops would induce diversion of other crops dedicated to food and feed needs. The relocation of production could increase deforestation and bring about significant new volumes of carbon in the atmosphere under more intensive agricultural management on previously uncultivated lands.

Representing all these various dimensions is a complex task and the development of analytic tools to properly address such questions is at its early stage. Research requires an integrated framework to take into account both agricultural and energy markets and their interactions, as well as emissions impact and climate change feedback. For this purpose, computable general equilibrium models are particularly appropriate as they explicitly incorporate the economic linkages between sectors. Several exercises have been conducted using such models to represent biofuels policy effects (Banse et al, 2007; Gurgel et al., 2007; Hertel et al., 2008).

The representation of land use and production possibilities remains a major challenge for studying land use change effects. Most computable general equilibrium models rely on a land rent approach (describing land as land rent uniquely and not accounting for physical aspects of land, notably in terms of expansion) and do not appropriately model land without economic use. Several types of substitution effects for economic use of land have however been tested. Darwin et al (1995) proposed an approach relying on Constant Elasticity of Transformation (CET) functions to represent substitution among crop sectors. The GTAP-PEM model (OECD, 2003) also follows this approach; it relies on a review of the literature concerning estimated elasticities of substitution for OECD countries (Salhofer, 2000; Abler 2000). Golub et al. (2006, 2007) also implement this framework but they distinguish land substitution between different zones within each country using data on the agro-ecological characteristics of land to more precisely represent the potential reallocation of land.

The impacts of biofuels expansion on non-economic land are not incorporated in standard Computable General Equilibrium (CGE) models. More advanced agricultural versions of such models have developed approaches to represent expansion possibilities. For example, the LINKAGE model from the World Bank incorporates some possible land expansion (van der Mensbrugghe, 2005): land endowment can vary according to aggregated land price, under an iso-elastic function or a logistic function with a maximum possible land endowment. Tabeau et al. (2006) study the implementation of a land supply curve based on marginal productivity information. This allows them to more explicitly represent asymptotic limits to land expansion and to account for decreasing returns to scale.

Recent studies on the effect of biofuels policies have built on these technical improvements (Banse et al., 2007; Hertel et al., 2008). However, they do not focus much on the environmental effects of these land use changes. On the other side, more precise assessment have been attempted in partial equilibrium studies but they lack important substitution and revenue effects that play a role for this type of assessments (Chantret and Gohin, 2009).

In this paper, we propose a CGE integrated framework to assess the indirect land use effects related to biofuels policies. We rely on a modified version of the trade policy CGE model MIRAGE from CEPII (Bchir et al., 2002; Decreux and Valin, 2007) and on an expanded GTAP 7 database (Narayanan and Walmsley, 2008). This model is used to explicitly address biofuels-related issues focusing primarily on the land use change dimension and on their environmental effects. Specifically, it represents land use change in different agro-ecological zones relying on Lee et al. (2008) data, with substitution effects and expansion effects in an integrated framework. Land substitution is represented with a nested CET function, whereas land expansion takes into account a more or less elastic land supply, as well as decreasing marginal productivity of available land. This design is used in a recursive dynamic framework covering a period of 20 years, taking into account the growing pressure of demographic and economic patterns on land resources.

In addition to the modelling of land use, the model incorporates a precise description of biofuels and energy sectors, with six new GTAP sectors introduced specifically for this study. An ethanol sector and a biodiesel sector were created in order to track changes in production and trade of these commodities. A transport fuel sector was also added to allow a more explicit representation of fuel blending. For better representing feedstocks, a corn sector and an oilseeds for biofuels sectors were added to track changes in these specific crop markets.

On the energy market side, demand for energy goods is represented with a specific calibration of LES-CES optimised to better fit energy price and income elasticities. An exogenous scenario on oil prices allows to study the sensitivity of biofuels development to baseline assumptions and the possibility of substitution in energy sources.

In order to address environmental issues, a module that estimates carbon emissions related to land use changes has been developed. This module, based on a simple calculation of carbon release from deforestation and from cultivation of land not previously used for agriculture allows us to assess the indirect impacts of biofuels cultivation. Following Fargione et al. (2008), we represent the environmental cost of these land conversion in a carbon budget.

We apply our methodology in the assessment of the environmental costs of an ethanol mandate on the US and EU transportation fuel market. In this paper, due to the more preliminary nature of the data on biodiesel production and trade and biodiesel feedstocks, we limit our focus to the ethanol market and do not look at the role of biodiesel consumption in the EU and its linkages with the vegetable oil markets. We point out the critical parameters that have to be refined in order to improve the understanding of the implications of biofuels development. Some elasticities and other behavioral parameters appear particularly critical. But a few baseline assumptions are also particularly important: for instance the evolution of oil prices is a main driver of the results. Last, because these sectors are particularly new and fast changing, adequately representing production and trade is a challenge that studies on the topic should ensure to properly address.

The paper is organised as follows. In Section 2, we briefly describe the initial modelling framework and then the modifications that were done to introduce biofuels and improve the representation of the agricultural and energy markets in the MIRAGE model[6] and database. In Section 3, we explain how we capture land use change effects including a description of the land use data and modelling assumptions. We show how direct and indirect CO2 emissions from land use change are taken into account in the model in Section 4. In Section 5, we apply this modelling framework to a US and EU ethanol mandate scenario with and without trade liberalization, and we present the results of sensitivity analyses concerning some elasticities and parameters. In section 6, we offer some conclusions and recommendations for future research.

2. Introducing biofuels in the model and database

The study relies on a modified version of the MIRAGE global CGE model which in turn depends on a modified version of the Global Trade Analysis Project (GTAP) database for global, economy-wide data. In this section we briefly document the changes that were done to introduce biofuels into the MIRAGE model and GTAP 7 database. A more comprehensive description of these revisions is available in Bouet et al. (2010).

2.1 The MIRAGE model

MIRAGE is a multi-sector, multi-region CGE model which operates in a sequential dynamic recursive set-up. From the supply side in each sector, the production function is a Leontief function of value-

[6] The MIRAGE model was developed at the Centre d'Etudes Prospectives et d'Informations Internationales (CEPII) in Paris. A full description of the model is available in Decreux and Valin (2007).

added and intermediate inputs. The intermediate inputs function is a nested two level Constant Elasticity of Substitution (CES) function of all goods: it means that substitutability exists between two intermediate goods, but that goods can be more substitutable when they are in a same category (agricultural inputs, services inputs). Value-added is also built as a nested structure of CES functions of unskilled labor, land, natural resources, skilled labor and capital. This nesting can incorporate some specific intermediate goods that are substitute of factors, such as energy or fertilizers, as explained below.

Factor endowments are fully employed. Capital supply is modified each year because of depreciation and investment. New capital is allocated among sectors according to an investment function. Growth rates of labor supply are fixed exogenously. Land supply is endogenous and modeled under a specific way for this paper. Skilled labor is the only factor that is perfectly mobile. Unskilled labor is imperfectly mobile between agricultural and nonagricultural sectors according to a CET function: unskilled labor's remuneration in agricultural activities is different from that in non-agricultural activities. The only factor whose supply is constant is natural resources. It is however possible to endogenously change the factor endowment in the baseline in order to reflect long term depletion of resources with respect to a price trajectory.

The demand side is modeled in each region through a representative agent whose propensity to save is constant. The rest of the national income is used to purchase final consumption. Preferences between sectors are represented by a linear expenditure system–constant elasticity of substitution (LES-CES) function, calibrated on USDA income and price elasticities to best reflect non-homothetic demand patterns with changes in revenue (Seale et al., 2003).

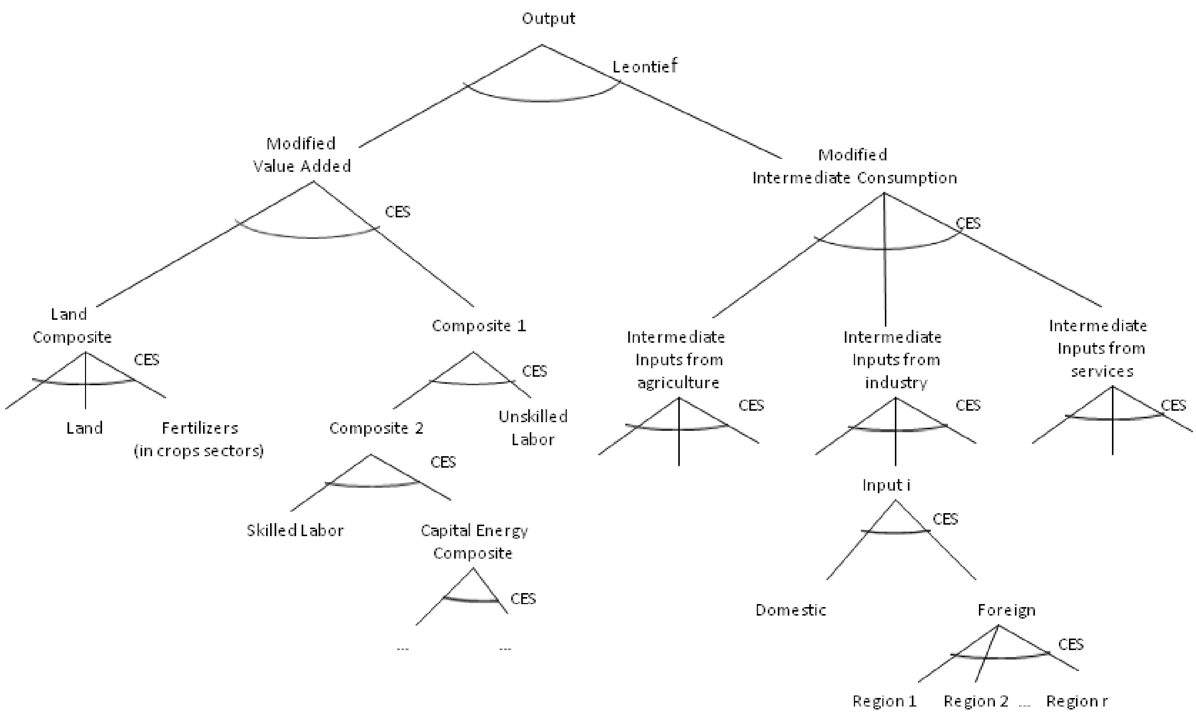
The sector sub-utility function used in MIRAGE is a nesting of four CES functions. Armington elasticities are drawn from the GTAP 7 database and are assumed to be the same across regions. The other elasticities used in the nesting for a given sector are linked to the Armington elasticity by a simple rule (see Bchir et al. 2002 for more details). Macroeconomic closure is obtained by assuming that the sum of the balance of goods and services is constant over time.

2.2 Model Modifications

Since the MIRAGE model was developed primarily for trade policy analysis, several model modifications were done to address the specific needs of the study. One major modification is in the modeling of the energy sector. Following a review of approaches in the modeling of energy demand, the top-down approach demonstrated in the GTAP-E model (Burniaux and Truong, 2002) was adapted in the energy sector of MIRAGE. Compared to the more complex characterization of an efficient process of energy production, as required in the bottom-up approach, the top-down approach was determined to be adequate in this study since it rather focuses on the potential impacts of biofuel mandates on agricultural markets, trade, and the environment, specifically on land use changes.

Similar to the GTAP-E model, the MIRAGE model was modified to include energy in the value-added CES nest and allow for different degrees of substitutability between sources of energy (coal, gas, oil, electricity, petroleum products). However, beyond what is in the GTAP-E model, the MIRAGE model was also modified to model agricultural production processes and their interaction with potential land use changes associated with the expansion of biofuels feedstock production. In particular, increased demand for feedstock crops for biofuels production could potentially increase pressure for inputs and factors, including land supply. Land use patterns could be modified either through more extensive production (increased land supply under constant yield) or more intensive production process (increased yield through increased inputs under constant land supply). The modified modeling of the production process for agricultural sectors is illustrated in Figures 1 and 2.

Figure 1: Production function for an agricultural sector in MIRAGE



In the agricultural sectors, the output is a Leontief combination of a "Modified Value Added" and a "Modified Intermediate Consumption".[7] The former bundle is a combination of two composites:

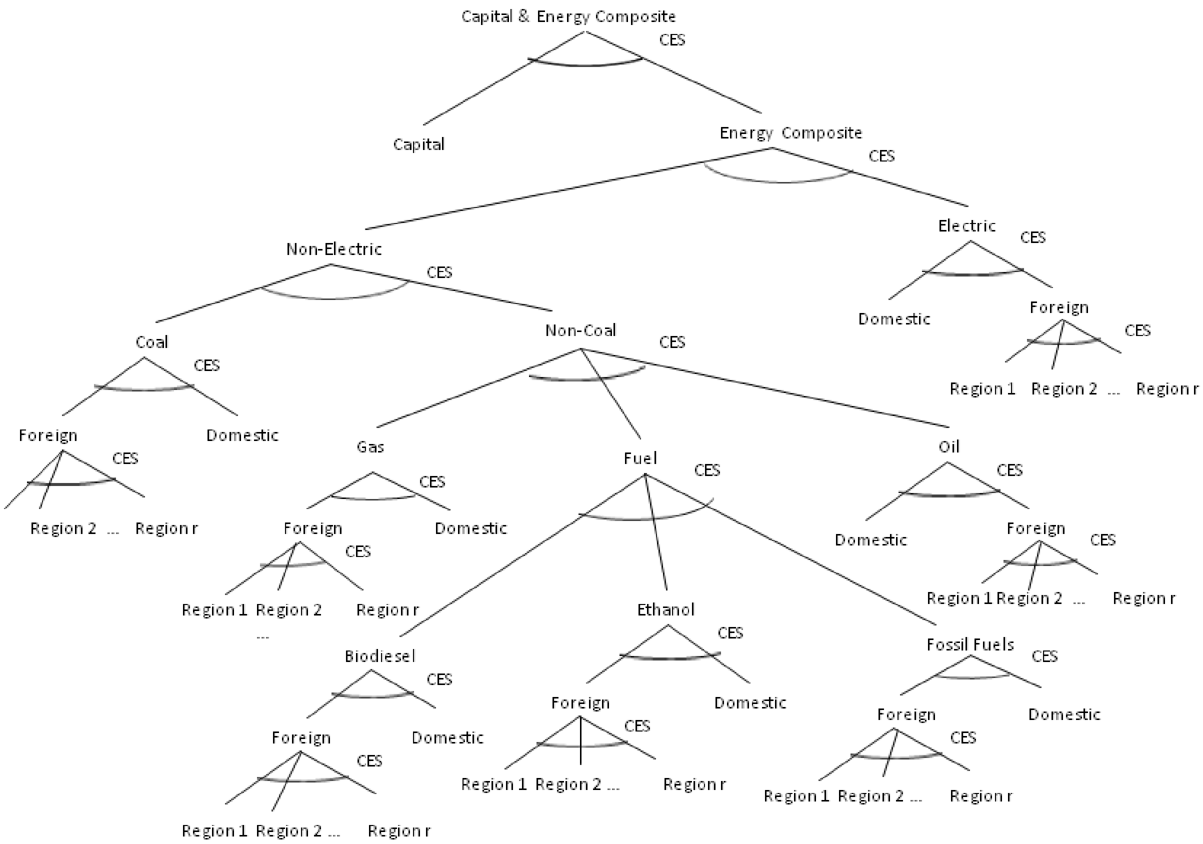
- A composite of land and animal feedstock in the livestock sectors or land and fertilizers in the crop sectors. It enables a choice between intensive and extensive production processes to be tackled.
- A composite good which includes other primary factors and energy. This choice combines the standard MIRAGE approach and the refinements introduced in the GTAP-E model (Burniaux and Truong, 2002). It incorporates a capital-energy composite according to which investment in capital can reduce the demand for energy. Under a capital-energy composite (see Figure 2), we incorporate a nesting which incorporates different degrees of substitutability between coal/oil/gas/electricity/petroleum products. Skilled labor and the capital-energy composite

[7] 'Modified Value Added' incorporates not only all primary factors but also the energy products, plus other products like fertilizers and animal feedstock, which substitute directly with primary factors in the production process. The 'Modified Intermediate Consumption' side does not incorporate all commodities used as intermediate consumption in the production process.

remain complementary while both can be substituted for unskilled labor. Since the MIRAGE model assumes a 'putty-clay' hypothesis under which old capital is immobile while new capital is mobile, it implies that the elasticity of demand for capital with respect to energy price is higher (in absolute value) in the long term than in the short term.

Fuel consumption is a CES composite of biodiesel, ethanol and fossil fuel. The elasticities of substitution in the different CES nesting levels specific to energy demand were adapted from Burniaux and Truong (2002). The elasticity of substitution between capital and energy is 0.15. Between energy and electricity it is 1.1. Between energy and coal it is 0.5 and between fuel oil and gas it is 1.1. Our assumptions about elasticities in the MIRAGE model for biofuels are summarized in Appendix II.

Figure 2: Structure of the capital & Energy composite in the MIRAGE model



Finally, it is worth noting that a distinctive feature of this new version of MIRAGE is in the classification of intermediate consumption into agricultural inputs, industrial inputs, and services inputs. This introduces greater substitutability within sectors. For example, substitution is higher between industrial inputs (substitution elasticity of 0.6), than between industrial and services inputs (substitution elasticity of 0.1). At the lowest level of demand for each intermediate, firms can compare prices of domestic and foreign inputs and, as far as foreign inputs are concerned, the prices of inputs coming from different regions.

The characterization of the production process and demand for energy in the non-agricultural sectors were also separately specified for the transportation sector, petroleum products sectors, gas distribution sectors and all other industrial sectors. Details are available in Bouet et al. (2009).

2.3 Introducing new sectors in the database

The GTAP 7 database, which describes global economic activity for the 2004 reference year in an aggregation of 113 regions and 57 sectors, was modified to accommodate the sectoral changes made to the MIRAGE model for this study. Six new sectors were carved out of the GTAP sector aggregates - the liquid biofuels sectors (ethanol and biodiesel), major feedstock sectors (maize, oilseeds used for biodiesel), the fertilizer sector, and the transport fuels sector. The modified global database with six new sectors (see Table 1) was created by sequentially splitting existing GTAP sectors with the aid of the SplitCom software.[8]

Table 1. GTAP Sector Splits and the New Sectors in the Modified Biofuels Database

GTAP Sector	Description	Intermediate Sector Splits	Final New** or Modified* Sectors
GRO	Cereal grains nes.	MAIZ: maize	MAIZ **
		OGRO: other grains	OGRO*
OSD	Oilseeds	BOSD: biodiesel oilseeds	BOSD**
		OSDO: other oilseeds	OSDO*
SGR	Sugar	ETH2: sugar ethanol (production)	ETHA**
		SGRO: other sugar	SGRO*
OFD	Other Food Products	ETH1: grain ethanol (production)	BIOD**
		BIOD: biodiesel (production)	OFDO*
		OFDO: other OFD	
B_T	Beverages and Tobacco	ETH1: grain ethanol (trade)	B_TN*
		ETH2: sugar ethanol (trade)	
		ETH3: other ethanol (trade)	
		B_TN: other beverages and tobacco	
CRP	Chemicals, Rubber, and Plastics	ETH3: other ethanol (production)	FERT**
		FERT: fertilizers	CRPN*
		BIOD: biodiesel (trade)	
		CRPN: other CRP	
P_C	Petroleum and Coal Products	TP_C: transport fuels	TP_C**
		OP_C: other fuels	OP_C*

External data for 2004 on production, trade, tariffs and processing costs of ethanol, biodiesel, maize, various oilseed crops and fertilizers for use in splitting these sectors from GTAP sectors have been compiled.[9] The primary feedstock crops used in the production of liquid biofuels in the major producing countries were identified from available literature. The input-output relationships in each biofuels producing country in the GTAP database were then examined to determine the feedstock processing sector from which the new ethanol and biodiesel sectors should be extracted. Thus,

[8] SplitCom, a software developed by J.M. Horridge at the Center for Policy Studies, Monash University, Australia, is specifically designed for introducing new sectors in the GTAP database by splitting existing sectors into two or three new sectors. Users are required to supply as much available data on consumption, production technology, trade, and taxes either in US dollar values for the new sector or as shares information for use in splitting an existing sector. The software allows for each GTAP sector to be split one at a time, each time creating a balanced and consistent database that is suitable for CGE analysis.

[9] See appendix 1 for a list of these data sources.

depending on the country, the ethanol sector was carved out either from the sugar (SGR) sector, the other food products (OFD) sector, or the chemicals, rubber and plastics (CRP) sector and then aggregated to create one ethanol sector. Some GTAP sectors, such as OFD and CRP, were split more than once to accommodate the creation of the new sectors. Table 1 shows the GTAP sectors that were split, the intermediate sectors that were created and a listing of the new and modified sectors in our new global database. The data sources, procedures and assumptions made in the construction of each new sector are described in Appendix I.

3. Modeling land use change effects

Since the underlying global GTAP database and the MIRAGE model include only one composite land endowment expressed in terms of land values allocated to each primary agriculture sector in each country, additional data and modeling innovations were required to capture the land use change effects of biofuel expansion. In this section, we document the data and sources used for a more disaggregated representation of agricultural land. We also present the methodology adapted in modeling land use change.

3.1 Land use data

3.1.1 Land rent values

For the analysis of land use change, we rely on rent values using the data provided by Lee et al. (2007) and based on a description of national land differentiated by agro-ecological zones (AEZs) from Monfreda et al. (2007). The AEZs are differentiated by climate (tropical, temperate and boreal) and 6 different humidity levels, corresponding to different lengths of growing periods.

Because the database on AEZs from Lee et al. (2007) is designed for GTAP 6 (with a 2001 reference year), we decomposed land rent values in GTAP 7 among different AEZs following the methodology documented in their paper. Specifically:

- For crop and perennial sectors, land rents were assumed to have the same distribution as in GTAP 6.
- For pasture in each region, land rents associated with pigs and poultry were removed from the data and reallocated to capital for this sector.
- For forest, natural resources endowments were removed and transformed into a land rent of the same value.

For new sectors such as maize and oilseeds for biofuels, land rents were split and distributed among AEZs using the data from Monfreda et al. (2007) directly at the crop level.

As the Monfreda database only provides data for the year 2000, this means that by assumption the distribution of crops remained unchanged among AEZs for a single region between 2000 and 2004. However, as the production of each region can vary differently, the distribution at the world level can change.

3.1.2 Land area correspondence

The Monfreda et al. (2007) database provides data on area harvested and production by surface and by quantity in each AEZ. In order to compute changes in physical land occupation, we built a supplementary database with physical correspondence for land occupation. The linkage between land rents and physical land units implicitly defines land rent per hectare that can be analyzed as a productivity indicator.[10]

In our modeling framework, we chose to rely on FAO data since it constitutes a unified database which provides time series data for land use from 1990 to 2005. This allows us to take into account dynamic trends in land use. Land areas were rescaled at the national level to be consistent with the FAO description of global land use, as provided in the database "FAOSTAT – ResourceSTAT – Land".[11] The land areas for each category were introduced in the base year: Arable land, Permanent meadows and pasture, Forest area (plantation and natural forest) and Other land.[12] Three main land use categories under economic use are therefore represented in the model and mapped with FAO data (see Table 2).

Table 2. Land use categories used in MIRAGE-BioF and FAO correspondence

Land use category in the model	Land considered under economic use	FAO correspondence
Cropland	Yes	Arable land, Permanent crops, Fallow land
Pasture	Yes	Pastureland[i] * share of pasture under management[ii]
Managed forest	Yes	Forest * share of forest under management[iii]
Unmanaged forest	No	Forest * (1 - share of forest under management[ii])
Other land	No	Rest of pastureland, grassland, shrubland, urbanized areas, other land.

[i] Source: FAO.
[ii]: computed from Monfreda et al., 2007; GTAP-AEZ database.
[iii]: computed from Sohngen et al., 2007; GTAP-AEZ database.

[10] The consistency of such a linkage still requires further improvement since the variance in land rents per hectare can be high in this framework (see Lee et al., 2007 for an analysis of the variance in the initial GTAP-AEZ database). However, we chose the most reasonable approach to simultaneously take into account balanced data on production provided by the GTAP database and physical information describing the real occupation of land. Some adjustments were however necessary and some outliers were corrected in order to ensure a suitable homogeneity of productivity by hectare across regions, AEZ and crops. This is particularly the case for the "Vegetable and fruits" sector, where land rents could be high because of proximity to urban areas, which are not represented in the model.

[11] http://faostat.fao.org/site/377/default.aspx

[12] Permanent crops were added to Arable land although they obviously follow different dynamics. However, as the Vegetable and Fruits sector is aggregated as a single sector in the GTAP database, it is not possible to distinguish fruit plantations (part of perennials) and vegetable production (part of annual crops). A similar issue arises with cash crops.

Cropland corresponds to FAO Arable land and Permanent Crops and is decomposed into subcategories respecting the shares provided in Monfreda's tables and used in Lee et al. It can be distinguished between economic uses, and are distributed between rice, wheat, maize, sugar crops, vegetable and fruits, oilseeds for biofuels, and other crops. Pastureland area is derived from FAO data and distributed among different uses using GTAP information assuming that rents are the same for all lands used for pasture. FAO data on forest areas distinguish between managed and unmanaged forest using data from Sohngen et al. (2007) on forest management practice. Tropical forests and forests with limited accessibility are considered to be unmanaged whereas temperate mixed forests with accessibility and forest plantations are considered to be managed forests. This distinction is useful for assessing land economic values. Unmanaged forest value is null at the beginning but a share of it can be incorporated progressively as new managed forest rents accrue in the economic model (see section 3.2.3 and Table 20 for illustration of the expansion effect). Unmanaged forests also contain more carbon stock that can be released in case of their destruction.

3.1.3 Cropland expansion

In order to properly account for the possibility for land expansion, we use physical data from the Global-AEZ 2000 database (IIASA – FAO), which provides estimates of the surface available for rain-fed crop cultivation per country.[13] Since information on the share of land located under forest is also available, we computed the share of marginal land that could be used for complementary production (see subsection 3.2.2 for further details).

3.2 Land use change modeling

Land use change relative to agricultural production was decomposed in the model under two distinctive patterns: (i) the substitution effect which refers to the change in land use distribution between different crops on existing arable land, and (ii) the expansion effect of using more arable land made for cultivation and its impact on other types of land.

3.2.1 The substitution effect

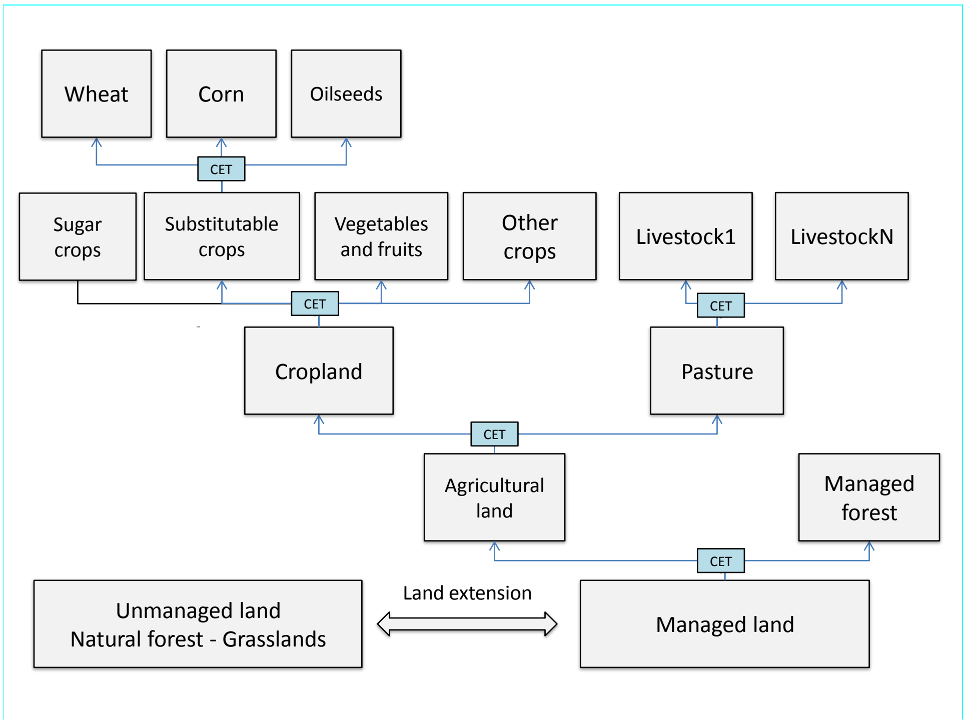
In order to represent the impact of demand for land on allocation choices, we rely on a neo-classical approach which simulates the land allocation decision as an optimization program for the producer. For this, we use the CET function which assumes that the producer maximizes its profit under a technological constraint, by adapting its cultivation choices to changes in land rent levels. In addition to the CET aggregate for land rents volume, we also computed an equivalent aggregate as a simple sum of volumes to keep a homogenous indicator with land areas.

The optimization is done by producers within each AEZ and country. Four levels are distinguished - substitutable crops, crops, pasture and forest - each of which has different transformation elasticity.

[13] Data and methodology are available at http://www.iiasa.ac.at/Research/LUC/GAEZ/index.html. Several sets of data can be used depending of the level of input (low input, intermediate input and high input) and the degree of suitability (very suitable, suitable, moderately suitable, and marginally suitable). We choose as a reference level for available land the group of very suitable + suitable + moderately suitable land, under a mixed input level (a filter provided by IIASA applying different levels of input to different levels of suitability).

As illustrated in Figure 3, this substitution tree contains the different productive sectors represented in the model with land endowments. As production functions are national, land endowments are aggregated across AEZs using a CES function, with a high degree of substitution (elasticity set to 20 following Golub et al., 2007), reflecting the indifference of the producer to the location within the country.

Figure 3: Land substitution structure used for each AEZ



The design by different AEZ allows a better representation of the substitution incompatibilities across crops, when climate and environmental conditions differ. However, assigning elasticities to such a tree is a delicate exercise which will be arbitrary to some extent given the high variance in the elasticities provided by econometric analysis (see Salhofer, 2000 and Abler, 2000). We chose to base our parameters on the estimates chosen by the OECD for the PEM model (Policy Evaluation Model), used as a reference for the determination of agricultural support. However, the OECD model only covers developed countries plus Mexico, Turkey and Korea. We consequently had to assume certain similarities for several countries. The land substitution elasticities are reported in Table 3.

Table 3 : Elasticities used in the substitution tree

	σ_{TEZ}	σ_{TEZH}	σ_{TEZM}	σ_{TEZL}	Note
Oceania	0.59	0.35	0.17	0.05	OECD
China	0.23	0.22	0.21	0.05	Set similar to RoOECD (inc. Korea)
RoOECD	0.2	0.15	0.11	0.05	OECD (Japan)
RoAsia	0.23	0.22	0.21	0.05	Set similar to RoOECD (inc. Korea)
Indonesia	0.59	0.3	0.11	0.1	Set similar to Mexico
SouthAsia	0.59	0.3	0.11	0.1	Set similar to Mexico
Canada	0.58	0.32	0.14	0.05	OECD
US	0.55	0.32	0.15	0.1	OECD
Mexico	0.59	0.3	0.11	0.1	OECD
EU	0.23	0.22	0.21	0.05	OECD (EU15)
LACExp	0.59	0.3	0.11	0.1	Set similar to Mexico
LACImp	0.59	0.3	0.11	0.1	Set similar to Mexico
Brazil	0.59	0.3	0.11	0.1	Set similar to Mexico
EEurCIS	0.23	0.22	0.21	0.05	Set similar to EU
MENA	0.35	0.24	0.15	0.05	OECD (Turkey)
RoAfrica	0.35	0.24	0.15	0.05	Set similar to MENA
SAF	0.35	0.24	0.15	0.05	Set similar to MENA

Note: σ_{TEZ} is the elasticity of substitution between substitutable crops; σ_{TEZH} is the elasticity of substitution between sugar crops, the bundle of substitutable crops, vegetables and fruits and the bundle of other crops; σ_{TEZM} is the elasticity of substitution between croplands and pasture; σ_{TEZL} is the elasticity of substitution between agricultural land and managed forest.
(Source: OECD and authors' assumptions)

3.2.2 Land available for cropland expansion

To represent the possibility of expansion of cropland within unmanaged land, the quantity of available land for total managed land expansion was computed using the formula:

marginal_land_avail(r) = MAX(0, land_avail_tot(r) - land("Cropland",r)
*- land_avail_noncropforest(r)*land("Pastureland",r)/(land("Pastureland",r)+land("SavnGrasslnd",r))*
*- land_avail_forest(r)*forest_mgnt_sh(r));*

where *land_avail_tot(r)* is the total land available (from IIASA data)
land_avail_forest(r) is the land available under forest (from IIASA data)
land_avail_noncropforest(r) is the land available not under forest and not cropland
land(".",r) is the land area in a specific land type (such as provided in Monfreda et al. (2007))
forest_mgnt_sh(r) is the share of forested land under management

This information can also be computed at the level of AEZs using information for macro-regions provided by IIASA. We incorporate this information in the model in order to differentiate the possibilities of land expansion amongst AEZs.

The fact that there are possibilities for expansion in land availability should not mask the fact that best lands (in the IIASA nomenclature, the very suitable and suitable land) are generally already in cultivation. Marginal land is therefore intrinsically of lower quality and marginal productivity is therefore expected to decrease with land expansion.

In order to reproduce this phenomenon in the modeling, land marginal productivity profiles were introduced in the model by approximation using polynomial interpolation (see Figure 2 in Appendix III for an illustration). We used data similar to the one presented in Tabeau et al. (2006) relying on land productivity distribution from the IMAGE model (MNP, 2006). Marginal productivity is used to compute the effective value of additional hectares put into production.

3.2.3 The land expansion effect

The land expansion module of the model is used to determine the area of arable land expansion into unmanaged land in each AEZ. One of the biggest difficulties is that land use change cannot be projected in the future at the AEZ level because the FAO time series data are only available at the national level. Consequently, we decomposed the problem into several steps:

First, we determine the land use substitution at the regional level and compute what land types are converted to arable land or the reverse within managed land, following changes in the relative prices of land. Demand for new land will raise the price of land at the national level and lead to managed land expansion. Marginal expansion is considered as being the results of an extra demand for cropland and therefore driven by a unique cropland price and a unique elasticity for each country.

The equation driving this mechanism takes into account an exogenous component reproducing the historical trend and an endogenous component for the marginal expansion due to demand for cropland:

$$LANDEXT_t + MANAGED\_LAND_{ini} = MANAGED\_LAND_t^{Exo} * \left(\left(\frac{P_{Cropland,t}}{P_t} \right)^{\sigma_{Landext} * \left(\frac{MargLand_{avail} - LANDEXT_t}{MargLand_{avail}} \right)} - 1 \right)$$

Where

$LANDEXT_t$ *is managed land expansion into unmanaged land: this land is allocated to cropland*

$MANAGED\_LAND_{ini}$ *is the initial managed land endowment at base year*

$MANAGED\_LAND_t^{Exo}$ *is the exogenous land evolution trend based on historical data*

$P_{Cropland,t}$ *is the average price of land in cropland*

P_t *is the deflator index of the region*

$\sigma_{Landext}$ *is an elasticity of land expansion*

$MargLand_{avail}$ *is the area of land available for rain-fed crops in region r and not already in use (see calculation above)*

Thus, expansion of managed land depends positively on the real price of cropland and the available land not currently used for crop cultivation.

Second, we compute the equivalent productive land that is associated with the extra surface of land made available through expansion. For this, we use marginal productivity curves introduced in section 3.1.3. We compute a relative yield with respect to the mean yield already used. The mean yield is computed on the curve by integrating the curve between the origin and the level of current land use. The marginal yield divided by the mean yield therefore provides the coefficient that is applied to yield when assuming some land expansion.[14]

Last, the share of extra land-productivity gained at the national level is distributed into each AEZ depending on initial land endowments, which contributes to lower prices for cropland and compensates for the extra demand and the pressure for expansion.

3.2.4 The dynamics of land use change

Computable general equilibrium models are usually used to assess the effects of policy shocks by relying on a single calibration year and treating other behavioral variables as endogenous. However, when addressing issues such as land use change in a dynamic framework, a number of issues which impact on the land use dynamics, but are independent of commodity market effects, cannot be properly introduced. This is the case, for example, for measures related to environmental protection, land management, and urbanization.

In the model, we take these effects into account in the baseline by considering that land use change for the main land categories (land under economic use: cropland plus pasture plus managed forest, unmanaged forest, other land - grassland, shrubland, deserts -) follows the patterns reported in the FAO time series. Variation rates are computed using observed variation from 2000 to 2004.

Consequently, changes in the baseline follow the historical trends in the period of the study for these main aggregates, whereas in the scenarios, the endogenous component for land use expansion adds the market effect of the changes in prices. For land area under economic use (cropland, pasture, managed forest), all changes in allocation come from the endogenous response to prices through the substitution effects. Therefore, historical land use changes do not affect the distribution of land under economic use across their alternative uses (cropland, pasture, managed forest).

4. Estimating effects on greenhouse gas emissions

It is now widely held that both the direct effects of biofuels through its lifecycle and the indirect land use change impacts on greenhouse gas emission should be taken into account in a complete assessment of the environmental impacts of biofuels development. In this section, we document our methodology for capturing the direct and indirect impacts of land use change in our model.

4.1 Direct production effects

Reduction of greenhouse gases is one of the three often mentioned objectives of biofuels policies (along with fossil fuel dependency reduction and reform of agriculture). However, the environmental efficiency of cultivating crops to replace fossil fuel has been widely questioned. Several studies have tried to calculate the emissions associated with each type of crop cultivation (see Bureau et al., 2008, for a review). However, different processes in different regions can lead to various results in life cycle assessments.

[14] An important assumption here is that we always consider cropland to be installed on the most productive land, whereas managed forests and pasture are assumed to occupy the second best lands. Other land types are assumed to be installed on lower value land.

Where available, we use data from official sources for direct emissions coefficients related to biofuels. These coefficients and their sources are reported in Table 4. Our first source of data is the European Commission's Renewable Energy Directive,[15] which provides reduction coefficients to be applied in such methodologies.[16] For a certain number of feedstocks or regions, we used additional sources to obtain more relevant data (e.g. maize for the US and for other regions of the world). We relied on the data provided in the latest report on the *State of Food and Agriculture* (FAO, 2008b). We also used an article often cited from Zah et al. (2007) which provides this type of information for soya.

Table 4. Reduction of CO2 associated with different feedstocks – Values used in calculations

Feedstock	Coefficient	Source	Note
Wheat (EU)	-45%	EU Dir (2008)	Typical value - natural gas with conventional boiler
Wheat (Other)	-21%	EU Dir (2008)	Typical value
Maize (EU)	-56%	EU Dir (2008)	
Maize (US)*	-12%	FAO (2008b)	
Maize (Other)*	-29%	FAO (2008b)	
Sugar Beet	-48%	EU Dir (2008)	Typical value
Sugar Cane	-74%	EU Dir (2008)	
Other crops **	-6%	Zah et al (2007)	
Soya **	-44%	Zah et al (2007)	
Rapeseed	-44%	EU Dir (2008)	Typical value
Palm Oil	-57%	EU Dir (2008)	Process with no methane emissions to air at oil mill

Sources: European Commission, (2008). Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. FAO (2008b),The State of Food and Agriculture*
*** Zah et al (2007) data were used when FAO and OECD data were missing: Zah R., Boni H., Gauch M., Hischier R., Lehmann and Wager P. (2007), Life Cycle Assessment of Energy Products: Environmental Assessment of Biofuels*

For each country, the reduction of emissions associated with one ton of fossil fuel equivalent of ethanol or biodiesel was computed with consideration for the proportion of feedstock used by the national industry and with respect to the origin of feedstocks (domestic production or imports).[17] The formula applied was the following:

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[15] Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources, http://ec.europa.eu/energy/climate_actions/doc/2008_res_directive_en.pdf.

[16] Two types of values are provided for different feedstocks and production pathways. We generally used typical values rather than default values because we wanted data representing the state of the current industry rather than marginal inefficient producers. For the EU, we assumed the use of more effective transformation processes.

[17] An alternative approach is to directly measure the direct emissions effect in the model, which includes the energy inputs of all sectors. However, two difficulties prevented us from choosing this methodology. First, the life cycle assessment coefficients provided by specific studies are supposed to be far more accurate than the input structure coefficient available in the GTAP database. Second, we want to separate the partial equilibrium effects (changes in energy inputs without economic perturbation) from the general equilibrium effects (substitution of inputs and loss of real income due the distortion imposed on the economy by the mandate policy).

Direct emission (s,biofuel,feedstock) =
*[Quantity of feedstock consumed in domestic biofuel production * CoeffEmission (feedstock, s)*
*+ sum(r, Export(biofuel, r, s) * sharefeedstock(biofuel, feedstock, r) * CoeffEmission (feedstock, r))]*
** FossilFuelEmissionFactor*

Where :

- *biofuel* refers to ethanol or biodiesel, feedstock refers to maize, wheat or sugar crop
- *r*, *s* are countries,
- *sharefeedstock(biofuel, feedstock, r*) is the proportion of biofuel volume produced with the designated feedstock in region r.
- *CoeffEmission(feedstock, r)* is the emission coefficient associated with a feedstock used in a region (see Table 4)
- *Export* refers to the trade flow from region r to region s
- *FossilFuelEmissionFactor* is the quantity of carbon emitted for 1 energy equivalent unit of fossil fuel (we consider 20 grams of Carbon per MegaJoule of fossil fuel).

4.2 Indirect emissions from land use change

One of the strengths of the modeling used in this paper is the representation of land use change, allowing us to assess the emissions from indirect effects. Indeed, conversion from forest to cropland or from pasture to cropland generates emissions, which can partly or completely alter the overall environmental impacts of biofuels production.

We restrict our analysis to two types of land use emissions - emissions from converted forest to other types of land and emissions associated with the cultivation of new land. We do not consider other types of greenhouse gases, although nitrous oxide (N_2O) releases are recognized as significant contributors.[18] This means that our assessment is conservative and may well be an underestimate of the real value of land use emissions associated with biofuels.

In order to determine greenhouse gas emissions, we rely on the Intergovernmental Panel on Climate Change (IPCC) guidelines for National Greenhouse Gas Inventories.[19] We used the Tier 1 method which does not require knowledge of the exact CO2 stock in each region but provides generic estimates for different climate zones that can be matched with the AEZs in the model (see Appendix IV for the exact formula).

Although the model computes change in land use for economic sectors (cropland, pasture and managed forest) using the land expansion formula given in subsection 3.2.2, it does not specify the origin of the new land that is brought into cultivation. The change in other type of land (primary forest and other land as an aggregate of savanna, grassland, scrubland) has to be separately computed.

[18] Use of fertiliser for growing biofuel feedstocks is already taken into account in the life cycle assessment for direct emissions. However, if an increase in land used in feedstock production induces an increase in fertiliser use and productivity from other crops, the effect on greenhouse gases is not taken into account.

[19] http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. See in particular the 2006 IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 Agriculture, Forestry and Other Land Use.

We allocate the change in land use between the different non-economic land use categories using historical information on land use change. Land use changes are assumed to take place in locations which underwent changes in the past. If half of the expansion in cropland and pasture expansion in a region came from a decrease of primary forest and half came from a decrease of grassland in the last decade, we assume that this share is maintained in future trends. This allows us to estimate the share of economic land expansion brought about by deforestation.

Emissions from deforestation are determined by accounting for the quantity of carbon per hectare removed in each AEZ in the model for primary forest and for managed forest, both above ground and below ground. When forest is converted to another use, we assume that the stock of carbon (both above ground and below ground) in this type of forest is released completely. In order to compare these emissions with flows emitted or saved each year, we use the carbon debt approach of Fargione et al. (2008) wherein the repayment time of emitted carbon is measured from the project initiation.

The second type of emission that was considered is emission from mineral carbon in soil. We used the Tier 1 methodology from IPCC and indicative release of carbon relative to different management practices to determine the additional emissions induced by the cultivation of new land (see Appendix IV for the exact formula). The different practices we identified were non-cultivation of land, cultivation of land with full tillage, rice cultivation under irrigation and land set-aside. The level of input was considered to be medium for each case (emission factor equal to unity).

By applying emission factors to mineral carbon in soil, it is possible to compute the quantity of carbon released after 20 years. These two calculations together then allow comparison of the direct effect of biofuel cultivation with the indirect effect of land use change induced by this energy policy, using a carbon budget analysis. Indeed, at the final year of the simulation, carbon emissions from the policy are compared to the marginal annual flow of savings in order to determine how many additional years will be required to reimburse the initial carbon cost of land use change.

5. Illustration with the impacts of US and EU ethanol programs

In this part we apply our methodology on EU and US ethanol programs under the current trade regime and after trade liberalization. We begin with a baseline or reference scenario where we assume that the production of biofuels depends only on the evolution of economic forces and is not supported by policies like mandatory incorporation. Beginning in 2004, we employ recursive dynamics to run the model until 2020. We assume that oil prices remain stable at $60 a barrel (2007 IEA scenario), a price which is too low for most biofuel process pathways to be economically profitable. In this reference situation, biofuel production is stabilized at its 2007 level and no further biofuel development occurs.

It is against this baseline that we compute the effects of two alternative scenarios regarding the development of ethanol for transport fuel. In the first one, referred to as DM for domestic mandate, we simulate the implementation of mandatory provisions for fuel retailers to reach 30 billion gallons (around 60 Mtoe – Millions of tons of oil equivalent) of ethanol production in 2022 on the US side.[20]

[20] Although the Renewable Fuel Standard enacted in 2007 set an objective of 36 billion gallons in 2022, the Energy Information Agency officially announced that this objective was unrealistic in such a timeframe and that the US would not be capable of producing more than 30 billion gallon in 2022, with the largest part of it

This policy is implemented using a constant level of tax exemptions for ethanol consumption. The share of biodiesel in the total fuel consumption is assumed to be stable. On the EU side, the mandate of 10% of incorporation is considered as applied separately to gasoline and diesel transport. Under this model assumption the mandate corresponds to a 2020 target of 35 Mtoe for all biofuels, of which 16 Mtoe is ethanol and 19 Mtoe is biodiesel. In our reference situation, the mandate of 19 Mtoe of biodiesel is implemented in our baseline in order to assess only the impacts of ethanol demand.

The trade liberalization scenario, referred to as FTM for free trade mandate, is similar to the first one except that the US and the EU completely open their markets to ethanol produced abroad. This means that the EU cuts its tariff of 19.2 €/hl (62.4% in ad valorem equivalent) on undenatured ethanol (95% of ethanol imports in 2004, source COMEXT) and that the US gives up their special duty of 14.27 USD/hl up (around 34.6% ad valorem, source OECD). Due to space considerations we focus only on results for the more relevant regions and sectors in the study. The geographical and sectoral aggregations used in the study are provided in Tables 18 and 19 in Appendix III.

5.1 Effect on production, demand, imports and welfare

In this framework the mandates lead to the development of a significant increase in the production of ethanol at the domestic level. As shown in Table 5, for the US in particular, a large share of the production is obtained from local refining (33.5 Mtoe and 31.1 Mtoe depending on scenarios), whereas in the EU, the production is lower due to a smaller mandate for ethanol and a larger share of imports (10.4 Mtoe of local production for a domestic mandate and 3.8 Mtoe with trade liberalisation).

Table 5. Domestic production of biofuels for main producers of ethanol (Mtoe)

		2020 Ref Lev	2020 DM Lev	2020 DM Var	2020 FTM Lev	2020 FTM Var
Ethanol	**US**	14.24	33.52	*135.5%*	31.13	*118.6%*
Ethanol	**EU**	1.19	10.38	*770.7%*	3.76	*215.6%*
Ethanol	**Brazil**	17.68	27.20	*53.9%*	39.78	*125.0%*
Biodiesel	**US**	0.92	0.86	*-6.8%*	0.99	*7.4%*
Biodiesel	**EU**	16.23	15.96	*-1.7%*	16.01	*-1.4%*

Note: Ref = Baseline; DM = Domestic-oriented mandate; FTM = Free Trade Mandate; Lev = Level; Var = Variation.
Source: authors' calculation

The effect of trade liberalization appears very clearly for the EU because a significant share of ethanol is already imported in the reference scenario. As reported in Table 6, the main benefits from trade liberalization accrue to Brazil, especially for exports to both the US and EU. Exports from the Caribbean countries (included in LACImp for Latin America Food Importers) to the US experience do not rise as much under the FTM scenario because of erosion of their trade preferences to the US.

supplied from corn ethanol and imports.

(see http://www.reuters.com/article/environmentNews/idUSTRE4BG4EQ20081217).

Table 6. Bilateral ethanol exports flows to the EU and to the US (Mtoe)

	Exporter	Importer	2020 Ref Lev	2020 DM Lev	2020 DM Var	2020 FTM Lev	2020 FTM Var
Ethanol	**LACImp**	**US**	4.84	17.18	*254.7%*	11.24	*132.0%*
Ethanol	**Brazil**	**US**	0.40	1.35	*238.6%*	8.57	*2044.0%*
Ethanol	**Brazil**	**EU2**	0.81	9.60	*1090.3%*	15.39	*1807.5%*

Note: Ref = Baseline; DM = Domestic-oriented mandate; FTM = Free Trade Mandate; Lev = Level; Var = Variation, LACImp for Latin America Food Importers.
Source: authors' calculation.

As reported in Table 7, the production of ethanol requires additional production of its feedstocks in the EU, in the US, and for their trade partners. These feedstocks are mainly sugar cane in Brazil, maize in the US, and sugar beet, wheat and maize in the EU. Following the implementation of the new mandates, the demand for these feedstocks increases and puts pressure on the food markets. Domestic production of maize in the US, and sugarcane in Brazil and in the LACImp region increases by more than 20% compared to the baseline.

Table 7. Domestic production of feedstocks for ethanol production (mio $)

		2020 Ref Lev	2020 DM Lev	2020 DM Var	2020 FTM Lev	2020 FTM Var
Wheat	**South Asia**	44218	44389	*0.4%*	44306	*0.2%*
Wheat	**EU**	30122	30885	*2.5%*	30357	*0.8%*
Wheat	**MENA**	18090	18400	*1.7%*	18230	*0.8%*
Wheat	**China**	17331	17464	*0.8%*	17404	*0.4%*
Maize	**US**	29940	36313	*21.3%*	35091	*17.2%*
Maize	**China**	19695	19679	*-0.1%*	19683	*-0.1%*
Maize	**Rest of Africa**	15595	15588	*0.0%*	15590	*0.0%*
Maize	**EU**	14612	15304	*4.7%*	14821	*1.4%*
Maize	**Mexico**	11840	12151	*2.6%*	12112	*2.3%*
Sugar crops	**South Asia**	21841	21970	*0.6%*	22000	*0.7%*
Sugar crops	**EU**	9710	11505	*18.5%*	10243	*5.5%*
Sugar crops	**Brazil**	7710	9370	*21.5%*	11779	*52.8%*
Sugar crops	**LACImp**	5966	7799	*30.7%*	6893	*15.5%*

Note: Ref = Baseline; DM = Domestic-oriented mandate; FTM = Free Trade Mandate; Lev = Level; Var = Variation; MENA for Middle East and North Africa; LACImp for Latin America Food Importers.
Source: authors' calculation.

The expansion of domestic (EU and US) production of feedstocks is greater when no liberalization scheme is implemented. Indeed, trade liberalization of ethanol encourages the production of feedstocks in more efficient regions. Sugarcane production in Brazil increases by 53% as more ethanol imports are allowed in the US; maize production in the US increases by less than in the domestic mandate scenario.

Trade patterns for feedstocks follow the new demand configuration (see Table 8). Exports of wheat to the EU significantly increase under the ethanol mandate in order to support the domestic feedstock market. Symmetrically, exports of maize to the US increase very significantly, although the maize market relies mainly on domestic production in the US. Exports of other crops decrease when these crops are produced in a country where ethanol is produced (e.g. Brazil, the LACImp region) because of competition with feedstock production. However, exports increase when they are destined to an ethanol producer because production of these crops decline in the destination country.

Table 8. Changes in feedstock trade following ethanol mandate implementation (mio $)

	Exporter	Importer	2020 Ref Lev	2020 DM Lev	2020 DM Var	2020 FTM Lev	2020 FTM Var
Wheat	**EEurCIS**	**EU**	223	326	*46.4%*	245	*10.1%*
Wheat	**Canada**	**US**	120	121	*0.9%*	121	*0.8%*
Wheat	**Canada**	**EU**	105	142	*34.5%*	109	*3.4%*
Wheat	**Brazil**	**EU**	87	118	*36.1%*	88	*2.0%*
Wheat	**MENA**	**EU**	64	91	*43.7%*	69	*8.5%*
Maize	**Brazil**	**EU**	287	333	*16.0%*	286	*-0.4%*
Maize	**Canada**	**US**	222	338	*52.4%*	313	*41.4%*
Maize	**LACExp**	**EU**	196	222	*13.6%*	196	*0.3%*
Maize	**US**	**EU**	120	83	*-30.8%*	81	*-32.6%*
Maize	**LACImp**	**US**	113	235	*107.6%*	207	*82.4%*
OthCrop	**LACImp**	**US**	5013	5059	*0.9%*	5095	*1.6%*
OthCrop	**Rest of Africa**	**EU**	4558	4674	*2.5%*	4628	*1.5%*
OthCrop	**LACImp**	**EU**	2723	2679	*-1.6%*	2696	*-1.0%*
OthCrop	**Brazil**	**EU**	2552	2517	*-1.4%*	2392	*-6.3%*
OthCrop	**EU**	**US**	1262	1292	*2.3%*	1299	*2.9%*
VegFruits	**LACImp**	**EU**	4504	4441	*-1.4%*	4464	*-0.9%*
VegFruits	**US**	**EU**	3579	3572	*-0.2%*	3562	*-0.5%*
VegFruits	**Mexico**	**US**	3348	3356	*0.2%*	3350	*0.1%*
VegFruits	**LACImp**	**US**	2645	2629	*-0.6%*	2644	*0.0%*
VegFruits	**MENA**	**EU**	2526	2571	*1.8%*	2557	*1.2%*
OilseedBio	**Brazil**	**EU**	11480	11527	*0.4%*	11338	*-1.2%*
OilseedBio	**US**	**EU**	3210	2910	*-9.3%*	2956	*-7.9%*
OilseedBio	**LACExp**	**EU**	2488	2508	*0.8%*	2503	*0.6%*
OilseedBio	**EEurCIS**	**EU**	527	545	*3.4%*	544	*3.1%*
OilseedBio	**Canada**	**EU**	475	465	*-2.2%*	468	*-1.7%*

Note: Ref = Baseline; DM = Domestic-oriented mandate; FTM = Free Trade Mandate; Lev = Level; Var = Variation; MENA for Middle East and North Africa; LACImp for Latin America Food Importers; EEurCIS for East Europe and Community of Independent States; LACExp for Latin America Food Exporters; VegFruits for Vegetables and Fruits; OilseedBio for Oilseeds for biodiesel ; OthCrop for Other Crops.

Source: authors' calculation.

These changes in trade patterns lead to some welfare changes related to terms of trade variation. As shown in Table 9, Brazil, the EU, and the US benefit most from the changes in crop prices on the international markets. On the other side, African and importing countries from Latin America suffer from the increased prices of crops.

The welfare gains are lower than the terms of trade gains for countries implementing biofuel mandates because of the distortions introduced by the mandatory blending. That is why the US and the EU do not benefit from their terms of trade improvement when welfare is considered. Brazil is a significant winner under the trade liberalization scenario, whereas importing countries from Latin America (mostly Caribbean countries) will be major losers in case of trade liberalization.

Table 9. Terms of trade and welfare variation under mandate scenarios

	Terms of trade		Welfare	
	2020	2020	2020	2020
	DM	FTM	DM	FTM
Oceania	*0.2%*	*0.2%*	*0.04%*	*0.03%*
China	*0.1%*	*0.1%*	*0.00%*	*0.01%*
Rest of OECD	*0.1%*	*0.1%*	*0.00%*	*0.00%*
Rest of Asia	*0.1%*	*0.1%*	*0.05%*	*0.05%*
Indonesia	*0.0%*	*0.0%*	*-0.09%*	*-0.08%*
Malaysia	*0.0%*	*0.0%*	*-0.33%*	*-0.30%*
South Asia	*0.4%*	*0.4%*	*0.09%*	*0.08%*
Canada	*0.0%*	*0.0%*	*-0.04%*	*-0.04%*
US	*0.4%*	*0.3%*	*-0.06%*	*-0.05%*
Mexico	*-0.5%*	*-0.5%*	*-0.29%*	*-0.26%*
EU	*0.1%*	*0.0%*	*-0.01%*	*-0.02%*
LACExp	*0.7%*	*0.4%*	*0.27%*	*0.22%*
LACImp	*-0.1%*	*-0.2%*	*-0.03%*	*-0.11%*
Brazil	*1.1%*	*2.2%*	*0.30%*	*0.61%*
EEurCIS	*-0.6%*	*-0.6%*	*-0.41%*	*-0.38%*
MENA	*-1.2%*	*-1.1%*	*-0.79%*	*-0.72%*
Rest of Africa	*-0.8%*	*-0.8%*	*-0.48%*	*-0.45%*
South Africa	*0.2%*	*0.3%*	*0.04%*	*0.08%*
World			*-0.06%*	*-0.05%*

Note: Ref = Baseline; DM = Domestic-oriented mandate; FTM = Free Trade Mandate; Lev = Level; Var = Variation; MENA for Middle East and North Africa; LACImp for Latin America Food Importers; EEurCIS for East Europe and Community of Independent States; LACExp for Latin America Food Exporters.

Source: authors' calculation.

However, as shown in Table 11, welfare variations do not reflect the effect of biofuel policies on farm revenues across countries. US and EU farmers benefit significantly from the mandate implementation. Brazil and Latin American importing countries also benefit from this policy even if trade liberalization only favors Brazil. These facts show that ethanol mandates represent a transfer from consumers to farmers and, from this perspective, is similar to other instruments of agricultural support.

Table 10. Crop farming revenues under mandate scenarios (Bn $)

	2020 Ref Lev	2020 DM Lev	2020 DM Var	2020 FTM Lev	2020 FTM Var
US	146.7	161.3	*9.99%*	158.0	*7.75%*
LACImp	56.7	59.3	*4.57%*	58.4	*2.85%*
Brazil	69.5	72.6	*4.32%*	75.3	*8.29%*
EU	205.3	213.8	*4.12%*	208.8	*1.68%*
Canada	17.0	17.5	*3.19%*	17.4	*2.37%*
LACExp	23.9	24.6	*2.85%*	24.4	*2.24%*
Mexico	27.2	27.9	*2.37%*	27.8	*1.99%*
MENA	76.8	78.4	*2.14%*	78.1	*1.69%*
South Africa	7.0	7.1	*1.94%*	7.2	*3.95%*
EEurCIS	62.4	63.5	*1.71%*	63.3	*1.32%*
Oceania	20.7	21.0	*1.50%*	20.9	*1.08%*
Rest of Africa	109.6	110.9	*1.21%*	110.7	*1.02%*
Rest of OECD	106.3	107.4	*0.97%*	107.1	*0.72%*
Malaysia	3.8	3.9	*0.69%*	3.9	*0.61%*
Rest of Asia	54.3	54.6	*0.62%*	54.5	*0.51%*
Indonesia	50.9	51.2	*0.59%*	51.2	*0.51%*
China	379.7	381.7	*0.53%*	381.2	*0.40%*
South Asia	337.0	338.1	*0.33%*	337.9	*0.27%*

Note: Ref = Baseline; DM = Domestic-oriented mandate; FTM = Free Trade Mandate; Lev = Level; Var = Variation; MENA for Middle East and North Africa; LACImp for Latin America Food Importers; EEurCIS for East Europe and Community of Independent States; LACExp for Latin America Food Exporters.
Source: authors' calculation

5.2 Effect on land use for ethanol-producing regions and their trade partners

These different policies increase pressure on land domestically but also through new demand at the international level. This favors expansion of production in other parts of the world through trade.

Looking at maize production in the US, the need for new production are particularly significant. The increase in land for maize (+15.9%) displaces other crops, especially wheat and oilseeds, and competes with pastures and forested lands.

In the EU, the domestic production of ethanol relies more on an increase in sugar beet production (+13.1% for a domestic-oriented mandate) as well as wheat and corn (+1.5% and +3% respectively). Therefore, oilseeds and other crops are less cultivated. In the case of trade liberalization, more ethanol is imported and domestic production is less affected by the mandates.

Table 11. Change in cropland use following ethanol mandates (thds ha)

		2020 Ref Lev	2020 DM Lev	2020 DM Var	2020 FTM Lev	2020 FTM Var
Rice	**US**	1788	1784	*-0.20%*	1785	*-0.15%*
Wheat	**US**	32790	31453	*-4.08%*	31573	*-3.71%*
Maize	**US**	39277	46987	*19.63%*	45514	*15.88%*
OthCrop	**US**	59878	58568	*-2.19%*	58878	*-1.67%*
VegFruits	**US**	5949	5915	*-0.57%*	5924	*-0.42%*
OilseedBio	**US**	51335	48160	*-6.19%*	48802	*-4.93%*
Sugar_cb	**US**	1247	1241	*-0.51%*	1242	*-0.37%*
Rice	**EU**	436	436	*-0.13%*	436	*-0.04%*
Wheat	**EU**	27099	27511	*1.52%*	27221	*0.45%*
Maize	**EU**	8978	9251	*3.04%*	9058	*0.89%*
OthCrop	**EU**	54700	54516	*-0.34%*	54676	*-0.04%*
VegFruits	**EU**	12531	12480	*-0.41%*	12513	*-0.14%*
OilseedBio	**EU**	11100	10972	*-1.15%*	11089	*-0.10%*
Sugar_cb	**EU**	2329	2635	*13.12%*	2417	*3.74%*

Note: Ref = Baseline; DM = Domestic-oriented mandate; FTM = Free Trade Mandate; Lev = Level; Var = Variation; VegFruits for Vegetables and Fruits; OilseedBio for Oilseeds for biodiesel ; OthCrop for Other Crops; Sugar_cb: sugar cane, sugar beet. Source: authors' calculation.

This land competition also puts pressure on other types of land and the substitution effect between crop types is complemented by substitution with pasture and managed forests. Therefore, as shown in Table 13, EU cropland expands by 0.53% in the domestic oriented mandate scenario, and US cropland increase by 0.96%. Pasture decreases by 0.45% in the EU and 0.60% in the US, and managed forest does as well by 0.07% in the EU and 0.05% in the US.

Expansion of economic land into unexploited areas (unmanaged forest or other types of land) complements the substitution effects. Agricultural land (cropland and pasture and managed forest) expands by 0.06% in the EU (200,000 hectares), 0.03% in the US (220,000 hectares), and 0.16% in Brazil (470,000 hectares).

Table 12. Variation in land types area (mio km²) for some regions

		2020 Ref Lev	2020 DM Lev	2020 DM Var	2020 FTM Lev	2020 FTM Var
Pasture	**EU**	0.71	0.70	*-0.45%*	0.71	*-0.13%*
Cropland	**EU**	1.17	1.18	*0.53%*	1.17	*0.20%*
Other	**EU**	1.17	1.17	*-0.17%*	1.17	*-0.07%*
Forest managed	**EU**	1.47	1.47	*-0.07%*	1.47	*-0.04%*
Forest primary	**EU**	0.07	0.07		0.07	
Forest total	**EU**	1.55	1.54	*-0.07%*	1.55	*-0.04%*
Total exploited land	**EU**	3.35	3.35	*0.06%*	3.35	*0.02%*
Pasture	**US**	2.39	2.38	*-0.60%*	2.38	*-0.47%*
Cropland	**US**	1.92	1.94	*0.96%*	1.94	*0.76%*
Other	**US**	1.88	1.88	*-0.14%*	1.88	*-0.11%*
Forest managed	**US**	2.97	2.97	*-0.05%*	2.97	*-0.04%*
Forest total	**US**	2.97	2.97	*-0.05%*	2.97	*-0.04%*
Total exploited land	**US**	7.28	7.28	*0.03%*	7.28	*0.03%*
Pasture	**Brazil**	1.94	1.94	*-0.09%*	1.93	*-0.18%*
Cropland	**Brazil**	0.84	0.85	*0.80%*	0.85	*1.63%*
Other	**Brazil**	1.43	1.43	*-0.15%*	1.43	*-0.30%*
Forest managed	**Brazil**	0.19	0.19	*-0.18%*	0.19	*-0.52%*
Forest primary	**Brazil**	4.11	4.11	*-0.06%*	4.11	*-0.12%*
Forest total	**Brazil**	4.30	4.30	*-0.07%*	4.29	*-0.14%*
Total exploited land	**Brazil**	2.97	2.97	*0.16%*	2.98	*0.31%*

Note: Ref = Baseline; DM = Domestic-oriented mandate; FTM = Free Trade Mandate; Lev = Level; Var = Variation.
Source: authors' calculation.

5.3 CO2 emissions and carbon budget of land use change

Biofuels cultivation can lead to some direct emissions savings by replacing the use of fossil fuels. The emissions coefficients reported in Table 4 were used to compute the total emissions savings by crop as a result of the EU and US ethanol programs (see section 4.1 for the methodology).

As shown in Table 13, direct global emission savings are highest for sugarcane in the domestic mandate scenario at 62%. With the expansion of sugarcane production under the trade liberalization scenario, direct emissions from sugarcane are even higher at 84%. For other feedstock crops, the free trade scenario results in lower direct emissions since production of these feedstocks increase by less under this scenario.

Table 13. Direct annual emissions savings from US and EU biofuel policies by type of feedstock (tCO2 eq)

		2020 DM Lev	2020 DM Share	2020 FTM Lev	2020 FTM Share
World	**Ethanol – Wheat**	-3,742,146	8.6%	-918,674	1.8%
World	**Ethanol – Maize**	-7,222,083	16.5%	-5,507,679	10.9%
World	**Ethanol - Sugar Beet**	-5,403,728	12.4%	-1,573,108	3.1%
World	**Ethanol - Sugar Cane**	-27,255,603	62.4%	-42,292,511	83.9%
World	**Ethanol - Other Crops**	-57,940	0.1%	-123,253	0.2%
World	**Ethanol - All crops**	**-43,681,500**	**100.0%**	**-50,415,226**	**100.0%**

Note: Ref = Baseline; DM = Domestic-oriented mandate; FTM = Free Trade Mandate; Lev = Level.
Source: authors' calculation.

Table 14. Emissions savings per country for each scenario using an aggregated CGE calculation

MtCO2/an in 2020	**Sectoral focus**		**CGE values with income effect**		**CGE values without income effect (fixed GDP)**	
	DM	**FTM**	**DM**	**FTM**	**DM**	**FTM**
Oceania	0	0	1	1	1	1
China	0	0	24	23	29	26
Rest of OECD	0	0	8	7	10	9
Rest of Asia	0	0	6	5	7	6
Indonesia	0	0	3	3	4	4
Malaysia	0	0	1	1	2	2
South Asia	0	0	12	11	11	10
Canada	0	0	3	3	4	3
US	-6	-5	-63	-61	-55	-54
Mexico	0	0	1	1	3	2
EU	-10	-2	-54	-49	-51	-47
LACExp	0	0	1	1	1	1
LACImp	-12	-6	5	4	6	6
Brazil	-15	-36	1	-1	0	-2
EEurCIS	0	0	9	9	32	30
MENA	0	0	8	8	36	34
Rest of Africa	0	0	2	2	4	4
South Africa	0	-1	1	1	0	0
World	**-43**	**-50**	**-32**	**-32**	**45**	**38**

NB: Sectoral emissions are allocated to the country where the ethanol is produced. For example, if LACImp countries produce ethanol from Brazilian sugar cane and export them to the US, then emission savings are allocated to LACImp. This is different from the CGE values as emissions there allocated to the country making use of the energy commodity. So, in the previous example, a share of emissions is allocated to Brazil for sugar cane production, a share to LACImp for ethanol production, and a share to the US for distribution. In the last two columns, the income effect is neutralised using an adjustment of Total Factor Productivity (TFP). Countries benefiting from a positive income effect from biofuels policy will produce more emissions because their TFP decrease but they consume more input as a result of their structural growth; MENA for Middle East and North Africa; LACImp for Latin America Food Importers; EEurCIS for East Europe and Community of Independent States; LACExp for Latin America Food Exporters.
Source: authors' calculation.

Alternatively, we present in Table 14 the change in CO2 emissions in the total economy as a result of ethanol policies. Several trends appear in this table.

First, there is a strong leakage effect, because the decrease in demand for oil in the US and in the EU makes fuel cheaper for other countries. Emissions of China and South Asia therefore considerably increase in response to biofuel policy. Second, since the model also takes into account revenue effects, we can observe that a part of the savings from mandates comes from the economic cost of the biofuel policy. The US and the EU are significantly affected considering the cost of their policy support. Third, when correcting for the income effect, one can observe that savings from EU and US policies are higher than just the substitution effect. One of the explanations is that price of fuel for these countries increase with the mandate and consumers curb their demand for fuel. A second point comes from the very approximate values for energy consumption in the biofuel production pathway when relying only on the model.[21]

Table 15. Emissions in tCO2eq from land use change in 2020 annualised (over the 2007-2020 period)

	Deforestation emissions		**New land cultivation emissions**	
	2020 DM	**2020 FTM**	**2020 DM**	**2020 FTM**
Oceania	220,187	147,552	325,594	234,395
China	172,903	61,826	192,276	139,459
Rest of OECD	339,948	238,736	218,874	155,093
Rest of Asia	198,612	166,806	134,936	117,737
Indonesia	372,087	321,848	100,193	87,928
South Asia	38,772	33,821	62,350	32,461
Canada	624,051	452,104	705,587	523,202
US	1,979,867	1,583,728	6,714,303	5,309,671
Mexico	801,583	649,672	241,330	199,499
EU	1,465,003	873,425	2,843,712	1,072,558
LACExp	580,587	554,376	715,341	559,374
LACImp	3,803,826	2,332,519	1,375,410	814,762
Brazil	12,391,466	25,150,376	3,364,535	6,783,709
EEurCIS	-286,555	-165,088	1,888,693	1,340,669
MENA	-184,069	-100,173	292,257	191,597
Rest of Africa	4,145,415	3,362,179	908,297	730,871
South Africa	-28,701	-74,165	234,462	580,962
World	26,634,983	35,589,543	20,318,150	18,873,946

Note: DM = Domestic-oriented mandate; FTM = Free Trade Mandate; MENA for Middle East and North Africa; LACImp for Latin America Food Importers; EEurCIS for East Europe and Community of Independent States; LACExp for Latin America Food Exporters.
Source: authors' calculation.

[21] Countries with significant gain in terms of trade (especially in the FTM scenario) are found to emit more when GDP is fixed. This is mainly because their volume increase in production is compensated by a TFP decrease, which makes them use more raw materials to produce the same value added.

These direct emissions savings can be outweighed by emissions from indirect land use effects. Indeed, land use changes can generate significant greenhouse gases emissions that question the environmental benefits from biofuels policies. In the case of ethanol, we have seen above how the biofuel programs could lead to cultivation of new land and to some new deforestation. The cultivation of new land and the release of carbon from deforestation are measured by the IPCC methodologies as explained in section 4.2.

The computation of annualized emissions from land use change, reported in Table 16, clearly shows the fact that the emission flow of CO2 reduction is lower than the CO2 emission flow from land use change. However, this approach is too simple because it does not take into account the dynamics of emissions. Land use change conversion release most of CO2 emissions once, whereas the savings from biofuel cultivation occur under a continuous flow year after year.

That is why we also propose to assess the CO2 emissions in a carbon budget approach, following Fargione et al. who defined the carbon debt payback time as the number of years of cropland cultivation required to compensate for losses in ecosystem carbon stocks during land conversion. This approach gives a payback time for EU and US programs of 12 years by 2020. These results are obtained without considering the effect of fertilizers emissions related to intensification of cultivation (see Table 16).

Table 16. Carbon budget decomposition and payback time for ethanol mandates

	2020 DM	**2020 FTM**
Total carbon release from deforestation (MtCO2eq)	346.3	462.7
Total carbon release from cultivation of new land (MtCO2eq)	406.4	377.5
Carbon already reimbursed (MtCO2eq)	-244.6	-301.5
Marginal carbon reimbursement rate (MtCO2 per annum)	-43.3	-50.2
Carbon debt payback time after 2020 (years)	*11.7*	*10.7*

Note: DM = Domestic-oriented mandate; FTM = Free Trade Mandate.

Source: authors' calculation.

5.5 Sensitivity analysis on elasticities of land supply and fertilizers

The results obtained in the previous section depend critically on some parameters that are not always well documented. For example, there is strong debate about the endogenous productivity gains that could relieve the pressure for land expansion. Also, the land expansion elasticity is a theoretical parameter that is very difficult to measure. That is why we test the sensitivity of our results to these two parameters. We test how the results change with a higher and a lower elasticities of land supply (L+ and L-) and a higher and lower elasticity on yield response (F+ and F-).

In the L+ scenario, land supply elasticities are doubled for countries in the North and multiplied by 5 in developing countries. In the L- scenario, the opposite is done and the elasticities of land supply are divided by 2 for the North and by 5 in the South. The difference in magnitude between developed and developing regions is introduced to reflect the higher uncertainty on parameters for developing countries.

For the F- scenario, most of endogenous productivity gains is disabled and elasticity between land and fertilizer is set to 0, whereas elasticity between land-fertiliser and capital-labour is decreased to 0.05 in the South and 0.01 in the North (GTAP default values are around 0.2).

The carbon budget associated with each of these sensitivity analyses are given in Table 17. In the scenario F+ and L-, not surprisingly, land use responds more to the policy changes and carbon debt is therefore higher and takes longer to be repaid. Indeed, more fertilizer effect allows crops to require smaller areas of new land. Concerning scenario F- and L+, the impacts are greater, either because fertilizers are not very effective, or because land expansion is more sensitive to prices. The extent of carbon debt in 2020 for ethanol is estimated to be between 3 and 33 years according to our results.

Table 17. Sensitivity analysis on carbon budget decomposition and payback time for ethanol mandates

	F+	F+	F-	F-	L+	L+	L-	L-
	2020 DM	2020 FTM	2020 DM	2020 FTM	2020 DM	2020 FTM	2020 DM	2020 FTM
Total carbon release from deforestation (MtCO2eq)	281.9	462.7	332.5	431.7	1035.2	1427.8	116.0	148.4
Total carbon release from cultivation of new land (MtCO2eq)	270.5	299.0	438.0	425.0	635.8	665.5	312.8	272.8
Carbon already reimbursed (MtCO2eq)	-225.8	-283.8	-199.4	-203.9	-249.9	-320.4	-242.7	-292.8
Marginal carbon reimbursement rate (MtCO2 per annum)	-39.0	-46.5	-32.4	-30.1	-44.7	-54.6	-42.7	-48.2
Carbon debt payback time after 2020 (years)	*8.4*	*10.3*	*17.6*	*21.7*	*31.8*	*32.5*	*4.4*	*2.7*

Note: Ref = Baseline; DM = Domestic mandate; FTM = Free Trade Agreement; Lev = Level; Var = Variation.

Source: authors' calculation.

6. Conclusion

We develop an integrated approach aimed at assessing the relevance of biofuel policies with respect to their environmental effects. The study looks at the potential direct and indirect greenhouse gas emissions impacts of domestic mandate and trade liberalization policies for first generation biofuels, focusing on ethanol. There are many assumptions involved in such an assessment: the methodology is at its early stages and the results should be interpreted with some caution. However, first results tend to show that ethanol production has environmental benefits only under certain restrictive assumptions. In four from our five sets of parameters tests, the payback time for ethanol production was found superior to or nearly equal to 10 years in 2020.

Several parameters still have to be examined more closely in future work. First, the role of co-products of biofuels production needs to be adequately incorporated because it can minimize the extent of indirect land use effects. However, there are also some other factors that are not yet adequately incorporated in the model which could potentially worsen the impact of biofuels from an environmental point of view. This is the case of peatland emissions and the emissions related to fertilizers intensification. The potential or limitations of endogenous yield also requires more scrutiny.

Moreover, the first illustration proposed here focused on the case of ethanol. Biodiesel policies could potentially have greater detrimental impacts on the environment since biodiesel production has been linked to deforestation in Brazil due to soybean crop expansion (Morton, 2006) and peatland degradation in Indonesia due to expansion of palm oil production for biodiesel (Fitzherbert, 2008 and Koh and Wilcove, 2008).

From a trade policy point of view, our results tend to argue for trade liberalization since imported ethanol made from more emission-saving feedstock (sugarcane) can replace some of the necessary expansion of ethanol production in the US and EU which rely on less effective feedstock (e.g maize, wheat, sugar beet). Sensitivity analyses however show that this result is not straightforward and highly depends on the deforestation pattern in developing countries, with Brazil in first position for ethanol. Annual savings from sugar cane can be expected to be higher but further investigations are necessary to understand how much tropical forest would be affected in this specific region, following cropland expansion. From an economic point of view, such trade liberalization should be accompanied with provisions for Caribbean countries that would suffer significant erosion of preferences on the US market if such a liberalization scheme was implemented.

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Appendix I: Sectoral split for new sector creation

Ethanol

Data on ethanol production for 2004, in millions of gallons, were obtained from industry statistics provided by the Renewable Fuels Association for annual ethanol production by country.[22] The data covers 33 individual countries plus a sum for "other countries". Production data for the other countries were shared out to other ethanol producers based on export shares information for the ethanol exporting countries that are not covered in the production data. To be consistent with the GTAP global database which carry data in value flows, ethanol production data was converted to US$ millions using 2004 price data from the OECD (OECD, 2006) from which data on ethanol processing costs for the major ethanol producers (US, Brazil, EU) were compiled. Bilateral trade for ethanol in 2004 was obtained from the reconciled BACI trade database which is developed and maintained at CEPII. Tariff data on ethanol were obtained from the MAcMap-HS6 database.

Ethanol producers were first classified according to the primary feedstock crops used in production. The input-outputs accounts in the GTAP database were then examined for each ethanol producer to determine which processing sector used a large proportion of the feedstock as intermediate input. This is then the processing sector that is split to create the ethanol sector in that country. For example, a large share of sugarcane production in Brazil goes to an established sugar ethanol processing sector, which is incorporated in GTAP's chemicals, rubber and plastic (CRP) sector in the Brazilian I-O table. Thus CRP is therefore the sector that was split in Brazil to extract the sugar ethanol sector. However, similar analysis indicated that it was the sugar processing (SGR) sector that should be split in other sugar ethanol producing countries in Latin America. Production of grain-based ethanol in the United States, Canada and in the European Union was introduced in the data by splitting the other food products (OFD) sector where wheat and cereal grain processing takes place.

Total consumption of ethanol in each region was computed from the data on production, total exports and total imports. Ethanol was assumed to go directly to final household consumption and not as an intermediate input into production. Production cost data in terms of the share of feedstock, energy and other processing costs were used to construct technology matrices for ethanol. These vary by country depending on the primary feedstock used in production. The external data on consumption and production technologies (and trade) for the ethanol sector in each country were adjusted as needed depending on the value totals for each flow for the sector that was being split. For example, the production of ethanol from wheat for country X is constrained by the total value of wheat going with other food processing in the country.

Most of the international trade of ethanol is classified in the Harmonized System (HS) under HS6 codes 220710 and 220720 which cover undenatured and denatured ethyl alcohol, respectively. We used the sum of trade for the HS6 sectors for each bilateral flow. Although ethanol production from different feedstocks is introduced spliting the appropriate food processing sectors (SGR, OFD, CRP), as guided by the input-output relationships for each region, ethanol trade is actually classified under trade of the GTAP beverages and tobacco (B_T) sector. It is the B_T sector that we split to take ethanol trade and tariff information into account.

Ethanol production (e.g. split from OFD) and ethanol trade (split from B_T) are then aggregated to create a grain ethanol sector. A similar procedure was followed to create a sugar ethanol sector from the GTAP SGR sector and the special case of sugar ethanol sector (from CRP) for Brazil. A single ethanol (ETHA) was then created by aggregating the three ethanol sectors together.

[22] See: http://www.ethanolrfa.org/industry/statistics/#EIO citing F.O. Licht. Renewable Fuels Association, Homegrown for the Homeland: Industry Outlook 2005, (Washington, DC: 2005), p. 14.

Biodiesel

Data on biodiesel production in the European Union, in million tons, were obtained from published statistics of the European Biodiesel Board.[23] Biodiesel production data for non-EU countries for 2004 was estimated based on 2007 production data for these countries, obtained from F.O. Licht,[24] deflated using 2004-2007 biodiesel production average growth rate for the EU. The volume data were converted to US$ millions using 2004 price data. Information on biodiesel processing costs was obtained from the OECD (2006). Data on total exports and total imports of biodiesel in 2004 were obtained by deflating 2007 biodiesel trade data in OECD (2008). Since international trade in biodiesel is a more recent phenomenon, we were not able to obtain consistent bilateral trade data for biodiesel.[25] Further research is under progress on this aspect to better represent the biodiesel domestic and world markets.

Unlike ethanol, the feedstock crops used in biodiesel production (e.g. rapeseed, soybeans) are all classified under one GTAP oilseeds (OSD) sector. As documented below, the OSD sector was also split to separately treat oilseed crops that are used in biodiesel production. The input-output accounts in the GTAP database were examined to determine which processing sector the feedstock primarily goes to as an intermediate input in each biodiesel production sector. Although some processing of oilseeds takes place in the GTAP vegetable oils and fats (VOL) sector in many countries, the creation of a biodiesel sector was more readily supported by splitting the OFD sector since a larger proportion of oilseeds produced in each region are used as intermediate inputs in the OFD and not the VOL sector in the EU countries.

Total consumption of biodiesel in each region was computed from the data on production, total imports and total exports. Similar to ethanol, it was assumed that biodiesel goes directly to final household consumption and not as an intermediate input into production. Production cost data in terms of the share of feedstock, energy and other processing costs were used to construct technology matrices for biodiesel. These vary by country depending on the primary feedstock used in production, in this case oilseed crops or a combination of oilseed crops and processed vegetable oils.

Trade in biodiesel is classified under HS 382490 which falls under the GTAP CRP sector. Hence, we perform a separate split for biodiesel production under OFD and biodiesel trade under CRP. These two biodiesel sectors are then aggregated into one biodiesel sector (BIOD).

Maize and Oilseeds for Biofuels

The most important feedstock crops for biofuel production have to be treated separately in the database in order to more accurately assess the impacts of biofuels expansion on feedstock production, prices and on land use. Wheat and sugarcane\sugarbeet are both separate sectors in the GTAP database. Maize (corn) and oilseeds, however, both belong to sectors which also include crops that are not used as feedstock in biofuels production. We apply similar methodology and assumptions in introducing maize and oilseeds for biodiesel as new sectors in the database. The GTAP cereal grains (GRO) sector was split to create the maize (MAIZ) and other cereal grains (OGRO) sectors and the GTAP oilseeds (OSD) sector was split to create the oilseeds for biodiesel (BOSD) and other oilseeds (OSDO) sectors.

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[23] Available online at: http://www.ebb-eu.org/stats.php

[24] As cited in OECD (2008).

[25] The HS codes on which biodiesel in traded is not yet clear, especially for the United States. Bilateral trade information obtained for chemical products and preparations of the chemical or allied industries (HS code 382490) is not limited to biodiesel only and the trade values were deemed too large incompatible with the production data.

Maize production volume and price data for 2004, as well as production data for other cereals (barley, buckwheat, canary seeds, fonio, millet, mixed grains, oats, and cereal grains, nec) were compiled from FAO Production Statistics.[26] This allowed us to compute the shares of maize production to total cereal grains production in each country. Similarly, bilateral trade data from the BACI trade database for maize and for the GTAP GRO sector allowed us to compute trade shares for maize trade to total GRO trade for each bilateral trade flow. We then used the production shares information and trade shares information to split the GRO sector into MAIZ and OGRO. We assume that the production technology for MAIZ and OGRO in each country are the same as those used for the original sector, GRO.

For oilseeds, we compile 2004 production volume and prices data from FAO Production Statistics for oilseed crops used for biodiesel production (rapeseed, soybeans, safflower seed, cottonseed, palm kernel, sunflower seed) as well as for other oilseed crops (castor oil seed, coconuts, copra, groundnuts, linseed, melonseed, mustard seed, poppy seed). Bilateral trade data for oilseeds used in biodiesel, as well for the GTAP OSD sector, were obtained from the BACI trade database. As for the maize sector, the production share and trade share information were used to split the OSD sector into BOSD and OSDO. We also assume that the production technology for BOSD and OSDO in each country are the same as those used for the original sector, OSD.

Fertilizer

Non organic fertilizers are part of the large CRP sector in GTAP. A separate treatment of fertilizers is necessary to more adequately assess the implications of biofuels expansion on the interactions between fertilizers and land in crop production. The production values for 2004 for nitrogen, phosphate and potash fertilizers were obtained from production and prices data from the FAO Resource Statistics and published data.[27] Bilateral trade data for fertilizers and for the GTAP CRP sector were obtained from the BACI database. Tariff data were obtained from the 2004 MAcMap-HS6 database[28]. The fertilizer production values and trade shares information were used to split the CRP sector into FERT and CRPN. We assume that the production technologies for FERT and CRPN in each country are the same as those for the original sector, CRP. However, we assume that unlike CRPN, FERT is used only as an intermediate input in the crop production sectors.

Transport Fuel

Fuels used for transport are part of GTAP's petroleum and coal sector (P_C). A separate treatment of transport fuels is necessary to provide a better assessment of the likely substitution between transport biofuels and transport fuels from fossil fuels. Data on the value of consumption of fossil fuels[29] was used along with trade data to obtain the value of transport fuel production by country. Bilateral trade data and tariffs for transport fuel were obtained from the BACI and MAcMap-HS6 databases, respectively. The transport fuel production values and trade shares information were used to split the P_C sector into TP_C and OP_C. We assume that the production technologies for TP_C and OP_C in each country are the same as those for the original sector, P_C. However, we assume that in contrast to OP_C, TP_C is the main fuel product comprising 90 percent of fuels used as intermediate input in the GTAP transport sectors (land, water and air transport) and in final household demand. TP_C and OP_C are equally split as fuel inputs used in the production of all other sectors.

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[26] Available online at: http://faostat.fao.org/site/567/default.aspx

[27] FAO fertilizer production data available online at: http://faostat.fao.org/site/575/default.aspx. Price data obtained were from: http://www.farmdoc.uiuc.edu/manage/newsletters/fefo08_13/fefo08_13.html.

[28] These cover tariff lines for animal and vegetable fertilizer (310100), nitrogenous fertilizer (310210, 310221, 310229, 310230, 310240, 310250, 310260, 310270, 310280, 310290), phosphatic fertilizer (310310, 310320, 310390), potassic fertilizer (310410, 310420, 310430, 310490), and fertilizer nes (310510, 310520, 310530, 310540, 310551, 310559, 310560, 310590)

[29] From national fuel consumption data reported in International Fuel Prices 2005, 4th edition, available at: http://www.international-fuel-prices.com

Appendix II: Elasticities and specific production functions

Definition	Value	Source
Supply side		
Value added elasticity of substitution	1.1	MIRAGE Standard assumption
Skilled labour - Capital elasticity of substitution	0.6	MIRAGE Standard assumption
C elasticity of substitution in CES within ct good types	2	Authors' assumption
CT elasticity of substitution in LES-CES between ct types	calibrated	computed from USDA and FAPRI
IC elasticity of substitution within intermediate category	0.6	MIRAGE Standard assumption
	0.1	For energy intermediate inputs
	0.1	For biodiesel agricultural inputs
	2	For ethanol agricultural inputs
ICT elasticity of substitution between intermediate categories	0.1	MIRAGE Standard assumption
Capital Good elasticity of subsitution	0.6	MIRAGE Standard assumption
Fix factor elasticity (land, natural resources)	0.1< <2	derived from GTAP values
Elasticity of land-feedstock-fertilizer composite	0.05	Study specific assumption for developed countries
	0.4	Study specific assumption for developing countries
Animal feed elasticity of substitution in supply	1.1	Study specific assumption
Elasticity of CES substitution for AEZ between zones	20	Golub et al. (2007)
Elasticity between different fuel types for intermediate consumption	2	Study specific assumption
Elasticity between biofuels with mandate for final consumption	2	Study specific assumption
Elasticity between biofuels with mandate for intermediate consumption	2	Study specific assumption
Capital and Energy elasticity of substitution	0.15	Bumiaux and Truong (2002)
Second Energy bundle and electricity elasticity of substitution	1.1	Bumiaux and Truong (2002)
Third Energy bundle and coal elasticity of substitution	0.5	Bumiaux and Truong (2002)
Fuel oil gas elasticity of substitution	1.1	Bumiaux and Truong (2002)
	0.5	For petroleum coke products
	0.9	For elec gas
Demand side		
Quality elasticity of substitution		computed from gtap values
Armington elasticity of substitution		computed from gtap values
Import elasticity of substitution	Gtap values	Hertel (2006)
Import elasticity of substitution	5	Ethanol, study assumption
Factors		
CET Labour elasticity of substitution	0.5	MIRAGE Standard assumption
CET Land elasticity of transformation (first level - high substitution)	0.2 to 0.6	OECD PEM model
CET Land elasticity of transformation (second level - medium-high substitution)	0.15 to 0.35	derived from OECD PEM model
CET Land elasticity of transformation (third level - medium substitution)	0.11 to 0.21	OECD PEM model
CET Land elasticity of transformation (fourth level - low substitution)	0.1 or 0.05	OECD PEM model
Land expansion elasticity	0.1 or 0.05	Study specific assumption

In transportation sectors (Road transport and Air and Sea Transport) the demand for fuel which is a CES composite of fossil fuel, ethanol and biodiesel, is considered complementary. The modified Value Added is a CES composite with very low substitution elasticity (0.1) between the usual composite (unskilled labor and a second composite which is a CES of skilled labor and a capital and energy composite) and fuel which is a CES composite with high elasticity of substitution (1.5) of ethanol, biodiesel and fossil fuel. However, this last bundle is not effective for the air and the water transportation sectors as they initially do not consume biofuels.

In sectors which produce petroleum products, intermediate consumption share of oil has been almost fixed. The modified intermediate consumption is a CES composite (with low elasticity, 0.1) of a composite of agricultural commodities, a composite of industrial products, a composite of services and a composite of energy products which is a CES function (with low elasticity) of oil, fuel (composite of ethanol, biodiesel, and fossil fuel with high elasticity, 1.5) and of petroleum products other than fossil fuel. The share of oil in this last composite is by far the biggest one. This implies that when demand for petroleum products increases, demand for oil increases by nearly as much.

In the gas distribution sector the demand share for gas input has been nearly fixed. It has been introduced at the first level under the "modified intermediate consumption" composite, at the same level as agricultural inputs, industrial inputs and services inputs. This CES composite is introduced with a very low elasticity of substitution (0.1).

In all other industrial sectors we keep the production process illustrated in Figure 1, except that there is no land composite and that fuel is introduced in the intermediate consumption of industrial products.

Appendix III: Additional tables and figures

Table 18. Geographical aggregation of the study

Region name	GTAP regions
Oceania	Australia, New Zealand, Rest of Oceania.
China	China
RoOECD	Rest of OECD: Japan, Korea, Switzerland, Rest of EFTA inc. Norway, Turkey.
RoAsia	Rest of Asia: Taiwan, Rest of East Asia, Cambodia, Lao People's Democratic Republic, Myanmar, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia.
Indonesia	Indonesia
Malaysia	Malaysia
South Asia	Bangladesh, India, Pakistan, Sri Lanka, Rest of South Asia.
Canada	Canada
US	US
Mexico	Mexico
EU	European Union (27 Member States)
LACExp	Latin America Food Exporters: Argentina, Paraguay, Uruguay.
LACImp	Latin America Food Importers: Chile, Colombia, Ecuador, Panama, Peru, Venezuela, Rest of South America, Costa Rica, Guatemala, Nicaragua, Rest of Central America, Rest of the Caribbean.
Brazil	Brazil
EEurCIS	East Europe and Community of Independent States: Belarus, Croatia, Russian Federation, Ukraine, Rest of Eastern Europe, Rest of Europe, Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia.
MENA	Middle East and North Africa: Iran, Islamic Republic of, Rest of Western Asia, Egypt, Morocco, Tunisia, Rest of North Africa.
SAF	South Africa.
Rest of Africa	Rest of Africa: Nigeria, Senegal, Rest of Western Africa, Central Africa, South Central Africa, Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Rest of South African Customs Union.

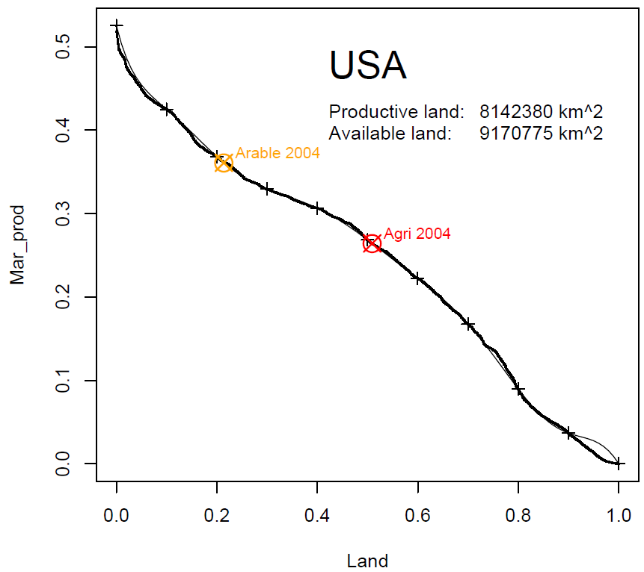
Table 19. Nomenclature and correspondance with GTAP of sectors used

Sector code	Sector name	GTAP Sector (bold name is newly created sector)
Rice	Rice	PDR, PCR
Wheat	Wheat	WHT
Maize	Maize	**MAIZ**
OthCrop	Other crops	**OGRO**, **OSDO**, PFB, OCR
VegFruits	Vegetables and Fruits	V_F
OilseedBio	Oilseeds for biodiesel	**BOSD**
Sugar_cb	Sugar Cane Sugar Beet	C_B
CattleMeat	Cattle Meat	CTL
OthAnim	Other Animal Products	OAP
OthCattle	Other Cattle	RMK, WOL
Forestry	Forestry	FRS
Fishing	Fishing	FSH
Coal	Coal	COA
Oil	Oil	OIL
Gas	Gas	GAS
Ethanol	Ethanol	**ETHA**
Biodiesel	Biodiesel	**BIOD**
OthMin	Other Mining Products	OMN
MeatDairy	Meat and Dairy Products	CMT, OMT, MIL
VegOil	Vegetable Oil	VOL
Sugar	Sugar	**SGRO**
OthFood	Other Food	**OFDO**, **B_TN**
Manuf	Other Manufactured goods	TEX, WAP, LEA, FMP, MVH, OTN, ELE, OME, OMF
WoodPaper	Wood and Paper	LUM, PPP
Fuel	Fuel	**TP_C**
PetrNoFuel	Petroleum Products other than Fuel	**OP_C**
Fertiliz	Fertilizers	**FERT**
RawMat	Raw Materials	**CRPN**, NMM, I_S, NFM
ElecGas	Electricity and Gas Distribution	ELY, GDT
PrivServ	Private Services	WTR, TRD, CMN, OFI, ISR, OBS, ROS
Construction	Construction	CNS
RoadTrans	Road Transportation	OTP
AirSeaTran	Air and Sea Transportation	WTP, ATP
PubServ	Public Services	OSG
Housing	Housing	DWE

Table 20. Economic effects of land use expansion on agricultural value added

	Land with economic use* (mio km²)	Unmanaged land available for crops (mio km²)	Variation of managed land 2004-2020	Land rent share in GDP in 2004	Contribution to GDP increase 2004 - 2020	Agricultural sectors value added increase		Contribution of managed land use expansion	
						Scenario DM	Scenario FTM	Scenario DM	Scenario FTM
Oceania	5.08	0.38	0.82%	0.06%	0.00%	1.11%	0.81%	0.85%	0.84%
China	6.85	0.00	0.26%	0.17%	0.00%	0.39%	0.29%	0.00%	0.00%
RoOECD	1.04	0.03	1.80%	0.04%	0.00%	0.84%	0.62%	1.02%	1.02%
RoAsia	1.99	0.20	5.30%	0.17%	0.03%	0.54%	0.44%	1.57%	1.57%
Indonesia	0.54	0.18	19.07%	0.50%	0.18%	0.50%	0.43%	1.53%	1.52%
Malaysia	0.08	0.01	-6.13%	0.19%	-0.04%	0.37%	0.32%	0.00%	0.00%
SouthAsia	2.70	0.06	0.57%	0.78%	0.01%	0.27%	0.22%	0.04%	0.04%
Canada	0.96	0.32	-1.79%	0.05%	-0.01%	2.09%	1.59%	-0.64%	-0.63%
US	7.18	0.24	2.54%	0.02%	0.01%	6.69%	5.18%	1.00%	1.03%
Mexico	1.67	0.10	4.19%	0.09%	0.02%	1.98%	1.65%	2.15%	2.14%
EU	3.41	0.20	-2.63%	0.05%	-0.01%	2.78%	1.20%	2.19%	2.04%
LACExp	2.21	0.39	15.34%	0.19%	0.12%	2.25%	1.75%	2.25%	2.08%
LACImp	2.71	1.29	1.42%	0.15%	0.01%	3.33%	2.14%	3.21%	3.17%
Brazil	2.83	2.98	14.47%	0.10%	0.08%	3.51%	6.64%	3.09%	3.13%
EEurCIS	8.95	0.92	0.31%	0.13%	0.00%	1.21%	0.98%	0.37%	0.37%
MENA	4.15	0.00	-0.68%	0.03%	0.00%	1.74%	1.42%	0.00%	0.00%
RoAfrica	9.43	4.36	15.83%	0.37%	0.09%	1.02%	0.87%	0.93%	0.98%
SAF	1.01	0.01	0.03%	0.04%	0.00%	1.31%	2.36%	0.04%	0.04%

* It is to note that in our classification, 'land under economic use' does not include urbanized areas.



Note : Y axis is a relative index of potential productivity for a 0.5 x 0.5 degree grid cell in the IMAGE model. X axis represents the productive land (cultivation potential > 0) and is normalized from 0 to 1. Black dots (thick line) represent the initial data of the distribution, sorted from the highest value to the lowest value, on a 0.5 x 0.5 degree grid cell basis. The thin line represents the interpolation curve defined as a 11th degree polynomial function, and interpolation points are represented with black cross. The yellow circle represents the marginal position of arable land use expansion, under the assumption that the most productive land is used for cropland. The red point represent the marginal position of agricultural land expansion (cropland, pasture and managed forest) under the assumption that the most productive land is used for this category.

Figure 2. Example of productivity distribution profile for the US.

Appendix IV: Emission coefficient used for the different agro-ecological zones

Measurement of carbon contained in forests

The formula for computation of the CO_2 stock in forest is:

CO2 Stock (z, Forest type) =
*Forest area (z, Forest type) * DMStock(z, Forest type)*0.47*44/12*(1+Below ground ratio)*

Where *Forest type* can be managed forest or primary forest, *DMStock* (DM for dry matter) is given in Table 21, as well as *below ground ratio*; 0.47 is the coefficient used to compute carbon mass by dry matter and 44/12 converts carbon to CO2.

Table 21. Carbon stock in forest for different climatic regions

Agro ecological zone	Above ground (t dry mat/ha)		Below ground / Above ground
	Primary forest	Managed forest	
AEZ1	70	30	40%
AEZ2	70	30	40%
AEZ3	130	60	30%
AEZ4	130	60	30%
AEZ5	180	120	22%
AEZ6	300	150	37%
AEZ7	70	30	32%
AEZ8	70	30	32%
AEZ9	120	100	30%
AEZ10	120	100	30%
AEZ11	155	110	30%
AEZ12	220	140	22%
AEZ13	0	0	30%
AEZ14	15	15	30%
AEZ15	50	40	30%
AEZ16	50	40	30%
AEZ17	50	40	30%
AEZ18	50	40	30%

Source : adapted from table 4.4 and table 4.12 of the IPCC Guidelines.

Measurement of carbon contained in soil

The formula used is the following:

*Carbon stock in soil deviation for crop i = Landarea(i,z)*CStock(z,"Soil")*((1-Gel(i,r))*(EF(z,"Cultivation")-1) + (Gel(i,r)*(EF(z,Setaside)-1))) * 44/12 /20*

Where *Cstock* is the carbon stock from Table 22, *EF* is the emission factor (1 is the default value for non cultivated land). EF is similar for all crops except for rice for which it is set at 1.1; *Gel(i,r)* is the share of land set aside for culture of the crop I; 44/12 is the conversion factor to convert C tons into CO2 tons; the 20 denominator represent the number of year for carbon in soil release.

Table 22. Carbon stock in soil and emission factors used in the model

Agro ecological zone	Carbon in soil (t C/ ha)	Emission factors		
		Cultivation	Land set aside	Rice
AEZ1	38	0.58	0.93	1.1
AEZ2	38	0.58	0.93	1.1
AEZ3	38	0.58	0.93	1.1
AEZ4	38	0.58	0.93	1.1
AEZ5	47	0.48	0.82	1.1
AEZ6	60	0.48	0.82	1.1
AEZ7	38	0.8	0.93	1.1
AEZ8	50	0.8	0.93	1.1
AEZ9	95	0.69	0.93	1.1
AEZ10	95	0.69	0.93	1.1
AEZ11	66.5	0.69	0.82	1.1
AEZ12	88	0.69	0.82	1.1
AEZ13	0	0.8	0.93	1.1
AEZ14	68	0.8	0.93	1.1
AEZ15	68	0.69	0.93	1.1
AEZ16	68	0.69	0.93	1.1
AEZ17	68	0.69	0.82	1.1
AEZ18	68	0.69	0.82	1.1

Source: adapted from table 2.3 of the IPCC Guidelines