INTERNATIONAL FOOD
POLICY RESEARCH INSTITUTE
sustainable solutions for ending hunger and poverty

Supported by the CGIAR

IFPRI Discussion Paper 01018

August 2010

Modeling the Global Trade and Environmental Impacts of Biofuel Policies

Antoine Bouët

Betina V. Dimaranan

Hugo Valin

Markets, Trade and Institutions Division

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

The International Food Policy Research Institute (IFPRI) was established in 1975. IFPRI is one of 15 agricultural research centers that receive principal funding from governments, private foundations, and international and regional organizations, most of which are members of the Consultative Group on International Agricultural Research (CGIAR).

PARTNERS AND CONTRIBUTORS

IFPRI gratefully acknowledges the generous unrestricted funding from Australia, Canada, China, Denmark, Finland, France, Germany, India, Ireland, Italy, Japan, the Netherlands, Norway, the Philippines, South Africa, Sweden, Switzerland, the United Kingdom, the United States, and the World Bank.

AUTHORS

Antoine Bouët, International Food Policy Research Institute
Senior Research Fellow, Markets, Trade and Institutions Division
a.bouet@cgiar.org

Betina V. Dimaranan, International Food Policy Research Institute
Research Fellow, Markets, Trade and Institutions Division
b.dimaranan@cgiar.org

Hugo Valin, International Institute for Applied Systems Analysis
Research Scholar, Forestry Program

Notices

[1] Effective January 2007, the Discussion Paper series within each division and the Director General's Office of IFPRI were merged into one IFPRI–wide Discussion Paper series. The new series begins with number 00689, reflecting the prior publication of 688 discussion papers within the dispersed series. The earlier series are available on IFPRI's website at http://www.ifpri.org/publications/results/taxonomy%3A468.

[2] IFPRI Discussion Papers contain preliminary material and research results. They have been peer reviewed, but have not been subject to a formal external review via IFPRI's Publications Review Committee. They are circulated in order to stimulate discussion and critical comment; any opinions expressed are those of the author(s) and do not necessarily reflect the policies or opinions of IFPRI.

Copyright 2010 International Food Policy Research Institute. All rights reserved. Sections of this material may be reproduced for personal and not-for-profit use without the express written permission of but with acknowledgment to IFPRI. To reproduce the material contained herein for profit or commercial use requires express written permission. To obtain permission, contact the Communications Division at ifpri-copyright@cgiar.org.

Contents

List of Tables

List of Figures

ABSTRACT

There is rising skepticism about the potential positive environmental impacts of first generation biofuels. Growing biofuel 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 the indirect land use change effects related to biofuel 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 to explicitly capture the role of different types of biofuel feedstock crops, energy demand and substitution, and carbon emissions. Land use changes are represented at the level of agroecological zones in a dynamic framework using land substitution with nesting of constant elasticity of transformation functions and a land supply module that takes into account the effects of economic land expansion. In this integrated global approach, we capture the environmental cost of different land conversions due to biofuels in the carbon budget, taking into account both direct and indirect carbon dioxide emissions related to land use change. We apply this methodology to look 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 liberalization benefits are ambiguous and depend highly on the parameters governing land use change, particularly in Brazil. We conclude by pointing out the critical aspects that have to be refined in order to improve our understanding of the environmental implications of biofuel development.

Keywords: biofuels, indirect land use change, trade liberalization

ACKNOWLEDGMENTS

The authors would like to thank Louise Curran, Simon Mevel, and Priscila Ramos for research assistance with an early version of this study. Financial support from the William and Flora Hewlett Foundation and the AGFOODTRADE Research Project (FP7 Grant Agreement No. 212036) funded by the European Commission is gratefully acknowledged.

ABBREVIATIONS AND ACRONYMS

AEZ	Agroecological Zone
CEPII	Centre d'Etudes Prospectives et d'Informations Internationales
CES	Constant Elasticity of Substitution
CET	Constant Elasticity of Transformation
CGE	Computable General Equilibrium
CO_2	Carbon Dioxide
E.U.	European Union
FAPRI	Food and Agricultural Policy Research Institute
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GTAP	Global Trade Analysis Project
HS	Harmonized System
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
ILUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LES	Linear Expenditure System
MIRAGE	Modeling International Relationships in Applied General Equilibrium
MToe	Million Tons of Oil Equivalent
N_2O	Nitrous Oxide
nec	not elsewhere classified
nes	not elsewhere specified
OECD	Organization for Economic Co-operation and Development
PE	Partial Equilibrium
PEM	Policy Evaluation Matrix
TFP	Total Factor Productivity
U.S.	United States of America

1. INTRODUCTION

There is rising skepticism about the potential positive environmental impacts of first generation biofuels. In addition to findings about the role of biofuels in the recent food price crisis (Headey and Fan 2008, Roberts and Schlenker 2009), doubts have been raised about biofuels' real contribution to climate change mitigation. This debate is occurring at a time when government commitments for biofuel production have strengthened over 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 (E.U.), 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 percent incorporation of bioenergy in E.U. transportation by 2020 (CEC 2008).

These different policies have been adopted thanks to the supposed benefits attributed to biofuels:

(1) Biofuels lessen dependence on oil imports.

(2) Biofuel production brings complementary revenues to farmers.

(3) Biofuels have a lower environmental footprint than fossil fuels because their use releases fewer greenhouse gases (GHGs) into the atmosphere. It is this third point that is intensively contested in the research community.

The environmental impacts of biofuels are heavily determined by 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, and so on) are expected to be more beneficial to the environment, but most of them are still at the development stage. Because recent life cycle assessments (LCAs) 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 in achieving a sustainable policy. Some production pathways, such as for corn ethanol in the United States, 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 regarding the question of indirect land use impacts. Indeed, several studies have recently argued that land use changes due to biofuel production would bring about negative overall impacts on the environment (Searchinger et al. 2008, Fargione et al. 2008). Growing biofuel crops could 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 an early stage. The assessment of the global environmental impacts of biofuel production requires an integrated framework that takes into account the agricultural and energy markets and their interactions, as well as emission impacts and climate change feedback. For this purpose, computable general equilibrium (CGE) models are particularly appropriate, as they explicitly incorporate the economic linkages between sectors. Although several partial equilibrium (PE) models have been applied to the analysis of the economic impacts of biofuel policies, these studies[1] typically focus on a selected part of the economy and do not capture the feedback effects across sectors. Global CGE models are appropriate for analyzing the economy-wide effects of biofuel policies on the agricultural and food sectors and also on other sectors of the economy, including the energy sector. In

[1] These include studies that have employed the following PE models: AgLink- Cosimo (OECD 2007), CAPRI (Common Agricultural Policy Regionalized Impact (Britz and Witzke 2008)), ESIM (European SIMulation ((Banse, Grethe, and Nolte 2004)), FAPRI (Food and Agricultural Policy Research Institute (Devadoss et al. 1989)), GLOBIOM (Global BIomass Optimization Model (Bottcher et al. 2008)), and IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade (Rosegrant et al. 2008)).

addition, global CGE models are better able to track the cross-country impacts of biofuel policies, not only on crop and biofuel markets but also for intermediate inputs and land markets. Several exercises have been conducted using such models to represent biofuel policy effects (for example, Banse et al. 2008, Gurgel, Reilly, and Paltsev 2007, Hertel, Tyner, and Birur 2010).

In this paper, we document an integrated CGE framework to assess the global trade and environmental impacts of biofuel policies, focusing on the indirect land use effects related to biofuel policies. We rely on a modified version of the trade policy CGE model MIRAGE, or modeling international relationships in applied general equilibrium (Decreux and Valin 2007), and on an expanded global trade analysis project (GTAP) 7 database (Narayanan and Walmsley 2008).

The modeling of energy demand in the MIRAGE model[2] was substantially modified to introduce different degrees of substitutability between sources of energy and the extent to which investment in capital can reduce demand for energy. The representation of the agricultural production process was improved to capture the substitutability between intensive and extensive production techniques. In terms of the energy market, demand for energy goods is represented with a specific calibration of a linear expenditure system–constant elasticity of substitution (LES–CES) optimized to better fit energy price and income elasticities. An exogenous scenario on oil prices allows for the study of the sensitivity of biofuel development to baseline assumptions and the possibility of substitution in energy sources.

In addition to the modeling of the relationship between biofuel and energy sectors, six new GTAP sectors were introduced in the database 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 a better representation of the biofuel feedstocks, a corn sector and an oilseeds-for-biofuels sectors were added to track changes in these specific crop markets. A fertilizer sector was also intoduced to allow for substitution with land under intensive or extensive crop production methods.

This model is used to explicitly address biofuels-related issues focusing primarily on the land use change dimensions and on their environmental effects. Specifically, it represents land use change in different agroecological zones (AEZs) by relying on Lee et al. (2008) data with substitution effects and expansion effects in an integrated framework. Land substitution is represented with a nested constant elasticity of transformation (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 order to address environmental issues, a module that estimates carbon emissions related to land use changes was 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 biofuel cultivation. Following Fargione et al. (2008), we represent the environmental cost of these land conversions in a carbon budget.

We apply our methodology to the assessment of the environmental costs of an ethanol mandate on the U.S. and E.U. transport fuel markets. 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 E.U. and its linkages with the vegetable oil markets.[3] We point out the critical parameters that have to be refined in order to improve the understanding of the implications of biofuel development. Unlike earlier studies that have looked at the trade and environmental impacts of biofuel policies (for example, Banse et al. 2008, Gurgel, Reilly, and Paltsev 2007, Hertel, Tyner, and Birur 2010), this study relies on a more sufficiently disaggregated database wherein first generation biofuel and feedstock crops are explicitly represented. Furthermore, the

[2] 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 Bchir et al. (2002) and more recently in Decreux and Valin (2007).

[3] The detailed modeling of different vegetable oil feedstocks is crucial to properly assess the perturbation induced by a biodiesel mandate. This was recently addressed in Al-Riffai, Dimaranan, and Laborde (2010).

modeling of land supply in this study allows not only for substitution but also for expansion of crop production into unused land, which is lacking in studies conducted with the GTAP model (for example, Hertel, Tyner, and Birur 2010).

The paper is organized as follows. In section 2, we briefly describe the initial modeling framework and the modifications that were done to introduce biofuels and improve the representation of the agricultural and energy markets in the MIRAGE model and database. In section 3, we explain how we capture land use change effects, including a description of the land use data and modeling assumptions. We show how direct and indirect carbon dioxide (CO_2) emissions from land use change are taken into account in the model in section 4. In section 5, we apply this modeling framework to a U.S. and E.U. 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 INTO THE DATABASE AND MODEL

The study relies on a modified version of the modeling international relationships in applied general equilibrium (MIRAGE) global computable general equilibrium (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 modifications that were done to introduce biofuels into the MIRAGE model[4] and GTAP 7 database.

Modified Global 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. Taheripour et al. (2007) documents the procedure applied in introducing the biofuel sectors in the GTAP 6 database, which has subsequently been used in several studies that use the GTAP model. The modification of the global database in this study differs from Birur, Hertel, and Tyner (2008) and Hertel, Tyner, and Birur (2010) in the use of the more recent database with a 2004 reference year, in the number of biofuel-related sectors introduced, and in various data assumptions regarding the structure of the biofuel sectors. Six new sectors were carved out of the GTAP sector aggregates—the liquid biofuels sectors (ethanol and biodiesel), major feedstock sectors (maize and oilseeds used for biodiesel), the fertilizer sector, and the transport fuel 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.[5]

External data for 2004 on tariffs as well as production, trade, and processing costs of ethanol, biodiesel, maize, various oilseed crops, and fertilizers for use in splitting these sectors from GTAP sectors were compiled from various sources. 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, 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.[6] 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 A.

[4] This study does not include additional modeling features (for example, coproducts, differentiated land expansion by agroecological zone) and new data refinements (decomposition of oilseed and vegetable oil sectors) that were more recently implemented in the MIRAGE biofuel model (see Al-Riffai, Dimaranan, and Laborde 2010). Comparisons should therefore be handled with prudence.

[5] 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 (Horridge 2005). Users are required to supply as much available data on consumption, production technology, trade, and taxes either in US$ 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 suitable for CGE analysis.

[6] Note that the SplitCom-based procedure used in this study, although found to be generally suitable for representing ethanol feedstock and oilseed aggregates, faced serious limitations in addressing the more complex structure of the value chain for biodiesel feedstock, which includes oilseed crops, coproducts of crushing operations, and vegetable oils. See Al-Riffai, Dimaranan, and Laborde (2010) for a more advanced representation of oilseed feedstock for biodiesel.

Table 1. Selected GTAP sectors and the sector splits in the modified biofuel database

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

Source: Compiled by authors.

The MIRAGE Model

MIRAGE is a multisector, multiregion CGE model that operates in a sequential dynamic recursive set-up. From the supply side in each sector, the production function is a Leontief function of value-added and intermediate inputs. The intermediate inputs function is a nested two-level constant elasticity of substitution (CES) function of all goods. This means that substitutability exists between two intermediate goods, but that goods can be more substitutable when they are in a same category (agricultural inputs, service 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 allows the modeler to incorporate some intermediate goods that are substitutes of factors, such as energy or fertilizers, as explained in the section on model modifications.

Factor endowments are fully employed.[7] 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 depends on the real remuneration of land.[8] Skilled labor is the only factor that is perfectly mobile. Unskilled labor is imperfectly mobile between agricultural and nonagricultural sectors according to a constant elasticity of

[7] With the assumption of full employment that allows the model to hold the aggregate level of factors constant in each time period, the model abstracts from the impact of macroeconomic forces and policies that determine total employment but instead focuses on the impacts on the composition of employment across sectors. We therefore do not look at the effect of biofuel mandates on unemployment in rural areas of the E.U. and the United States nor focus on the development effects for subsistence farmers in Brazil as they access the formal agricultural sector. The assumption of full employment of labor could also amplify the benefits of trade liberalization by allowing for real wages to rise in response to increased demand for labor. The assumption of full employment is, however, consistent with the depiction by CGE models of medium- to long-run impacts of economic shocks.

[8] The modeling of land supply, which has been significantly modified in this study, is discussed in greater detail in Section 3.

transformation (CET) function. Unskilled labor's remuneration in agricultural activities is different from that of nonagricultural activities. The only factor whose supply is constant is the natural resources factor. 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 U.S. Department of Agriculture Economic Research Service (ERS/USDA) income and price elasticities to best reflect non-homothetic demand patterns with changes in revenue (Seale, Regmi, and Bernstein 2003).

The sector subutility 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.

Model Modifications

Because the MIRAGE model was developed primarily for trade policy analysis, several 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 with 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 because it 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 nest of CES functions and to allow for different degrees of substitutability between sources of energy (coal, gas, oil, electricity, and 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 biofuel feedstock production. In particular, increased demand for feedstock crops for biofuel 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 processes (increased yield through increased inputs under constant land supply).

The modified modeling of the production process for agricultural sectors is illustrated in Figure 1. Agricultural output is a Leontief combination of a *modified value added* and a *modified intermediate consumption*.[9] The former bundle is a combination of two composite factors: the land composite and the energy–primary factor composite.

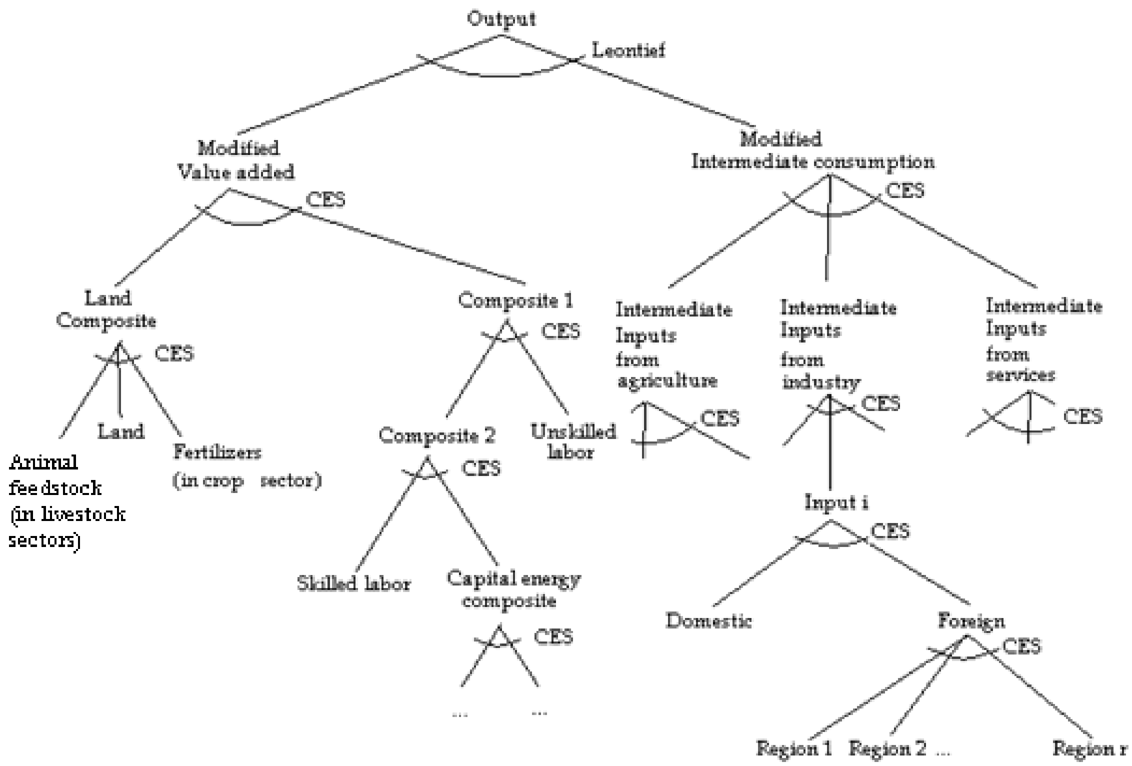
The land composite allows for substitution between land and animal feedstock in livestock production and between land and fertilizers in crop production. This enables a choice between intensive and extensive production processes to be tackled.

The energy–primary factor composite 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

[9] Although we follow the standard modeling assumption of a fixed proportion relationship between value-added and intermediate consumption, the modified value added incorporates not only all primary factors but also intermediate consumption products, such as energy, fertilizers, and animal feedstock, that 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. This revised treatment of the production function allows for the modeling of intensive and extensive production methods.

capital–energy composite (see Figure 2), we incorporate a nesting that incorporates different degrees of substitutability between coal, oil, gas, electricity, and petroleum products. Skilled labor and the capital-energy composite remain complementary, while both can be substituted for unskilled labor. Because 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.

Figure 1. Production function for an agricultural sector in the MIRAGE model



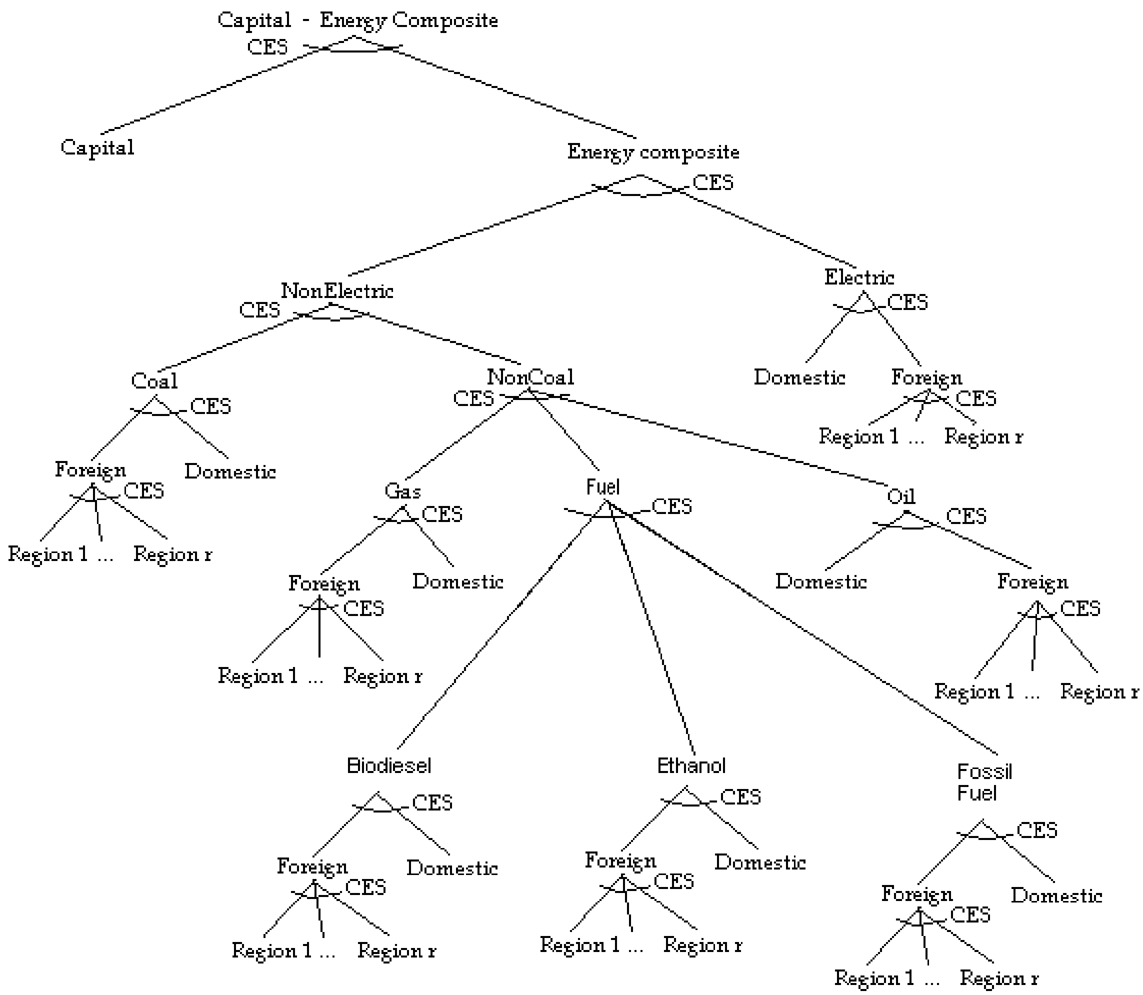
Source: Compiled by authors.

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 elasticities of substitution are 0.15 between capital and energy, 1.1 between energy and electricity, 0.5 between energy and coal, and 1.1 between fuel oil and gas. Our assumptions about elasticities in the MIRAGE model for biofuels are summarized in Appendix B.

Finally, a distinctive feature of this new version of MIRAGE is in the classification of intermediate consumption into agricultural inputs, industrial inputs, and service inputs. This introduces greater substitutability within sectors. For example, substitution is higher between industrial inputs (substitution elasticity of 0.6) than between industrial and service 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 nonagricultural sectors were also separately specified for the transportation sector, petroleum product sectors, gas distribution sectors, and all other industrial sectors. In the transportation sectors (road transport as well as air and sea transport), the demand for fuel, which is a CES composite of fossil fuel, ethanol, and biodiesel, is considered complementary.[10] In sectors that produce petroleum products, the intermediate consumption share of oil has been almost fixed.[11] 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 also been nearly fixed for similar reasons.[12] 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.

Figure 2. Structure of the capital–energy composite in the MIRAGE model



Source: Compiled by authors.

[10] 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.

[11] 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 petroleum products other than fossil fuel. The share of oil in this last composite is by far the biggest one.

[12] 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).

3. MODELING LAND USE CHANGE EFFECTS

Because a key element of the interdependence between biofuels and the food and energy sectors is the demand for land, a detailed representation of land use and land allocation is included in the model. Given that the underlying global trade analysis project (GTAP) database and the modeling international relationships in applied general equilibrium (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.

The representation of land use and production possibilities remains a major challenge for studying land use change effects. Most computable general equilibrium (CGE) models rely on a land rent approach (describing land as land rent uniquely and not accounting for the 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. (1996) proposed an approach relying on constant elasticity of transformation (CET) functions to represent substitution among crop sectors. The GTAP–policy evaluation model (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) and Golub, Hertel, and Sohngen (2007) also implement this framework, but they distinguish land substitution among different zones within each country using data on the agroecological characteristics of land to more precisely represent the potential reallocation of land.

The impacts of biofuel expansion on noneconomic land are not incorporated in standard 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, Eickhout, and Van Meijl (2006) study the implementation of a land supply curve based on marginal productivity information, which 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 biofuel policies have built on these technical improvements. For example, in the case of E.U. policies, Banse et al. (2008) assessed the impact of mandates under a CGE approach. However, they do not focus much on the environmental effects of these land use changes, and more importantly, the study is not based on sufficiently disaggregated input–output data (biofuels are not explicitly represented). Studies using the GTAP model (for example, Hertel, Tyner, and Birur 2010) lack the expansion dimension because only land under economic use can be mobilized to expand crop production. More precise assessments have been attempted in partial equilibrium studies (Hayes et al. 2009, Havlik et al. 2010), but they lack important substitution and revenue effects that play an important role in this type of assessment (Gohin and Chantret 2010). Some of these designs have, however, been used in the United States for different assessments. The institutional estimations with the GTAP model for the U.S. biofuel policy by the California Air Resource Board (Hertel et al. 2010) or with the Food and Agricultural Policy Research Institute (FAPRI) model for the U.S. Environment Protection Agency (Searchinger et al. 2008) both showed that land use effects could revert the overall benefits of biofuels; however, values vary (see Prins et al. 2010 for a review).

In this study, land resources are differentiated among different agroecological zones (AEZs) following the framework developed and described in Golub, Hertel, and Sohngen (2008). This allows us to account for the fact that not all land can be used for all purposes. In the land use modeling, we allow for the possibility of extension in total land supply to take into account the role of marginal land. For this purpose, we use data on land available for crops and marginal productivity information. This allows for a stronger linkage with the physical bases of crop production, while land substitution and extension can be tracked with respect to price variations in each region. The land use and the land extension are finally much more detailed than what appears in Hertel, Tyner, and Birur (2010) or Banse et al. (2008); they contain several innovations, such as accounting for noneconomic factors, and allow for indirect land use changes. 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.

Land Use Data

Land Rent Values

Land is usually represented in CGE models as a fixed factor endowment within the production function, expressed in value, whose remuneration is attributed to the household representative agent. Therefore, land data are usually not expressed in physical dimensions, and some assumptions need to be made in order to relate the physical quantity of land with the volume expressed in dollars within the model.

For the analysis of land use change, we rely on rent values using the data provided by Lee et al. (2008) and based on a description of national land differentiated by AEZs from Monfreda, Ramankutty, and Hertel (2007). The AEZs are differentiated by climate (tropical, temperate, and boreal) and six different humidity levels corresponding to different lengths of growing periods.

Because the database on AEZs from Lee et al. (2008) 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:

- 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 resource 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 directly at the crop level using the data from Monfreda, Ramankutty, and Hertel (2007). Because the Monfreda, Ramankutty, and Hertel database only provides data for the year 2000, we assume that 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.

Land Area Correspondence

The Monfreda, Ramankutty, and Hertel (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.[13]

In our modeling framework, we chose to rely on Food and Agricultural Organization of the United Nations (FAO) data because they constitute a unified database that provides time series data for land use from 1990 to 2005. These allow 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 (FAO 2009b). The land areas for each

[13] The consistency of such a linkage still requires further improvement because the variance in land rents per hectare can be high in this framework (see Lee et al. [2008] 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, AEZs, and crops. This is particularly the case for the vegetable and fruit sector, where land rents could be high because of proximity to urban areas, which are not represented in the model. The linkage between the two databases has been significantly improved in a more recent study (see Al-Riffai, Dimaranan, and Laborde [2010]).

category were introduced in the base year—arable land, permanent meadows and pasture, forest area (plantation and natural forest), and other land.[14] 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 biofuels model and FAO correspondence

Land Use Category in the Model	Land Considered under Economic Use	FAO Correspondence
Cropland	Yes	Arable land, permanent crops, and 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, and other land

[i] Source: FAO.
[ii] Sources: Computed from Monfreda, Ramankutty, and Hertel (2007) and GTAP-AEZ databases.
[iii] Sources: Computed from Sohngen et al. (2008) and GTAP-AEZ database.

Cropland corresponds to FAO arable land and permanent crops and is decomposed into subcategories respecting the shares provided in Monfreda, Ramankutty, and Hertel's tables and used in Lee et al. (2008). It can be distinguished among economic uses and is distributed among rice, wheat, maize, sugar crops, vegetables and fruits, oilseeds for biofuels, and other crops. Pastureland area is derived from FAO data and is distributed among different uses using GTAP information under the assumption that rents are the same for all lands used for pasture. FAO data on forest areas are distinguished between managed and unmanaged forest using data from Sohngen et al. (2008) 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. The value of unmanaged forest 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 the section on land expansion effect and Table B.2 for an illustration of the expansion effect). Unmanaged forests also contain more carbon stock that can be released in case of their destruction.

Cropland Expansion

In order to properly account for the possibility of land expansion, we use physical data from the International Institute for Applied Systems Analysis (IIASA)–FAO Global–AEZ 2000 database (Fischer et al. 2000), which provides estimates of the surface available for rain-fed crop cultivation per country.[15] Because information on the share of land located under forest is also available, we compute the share of marginal land that could be used for complementary production (further details are available in the section on land available for cropland expansion).

[14] Permanent croplands were classified together with 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.

[15] 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 chose 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).

Land-Use Change Modeling

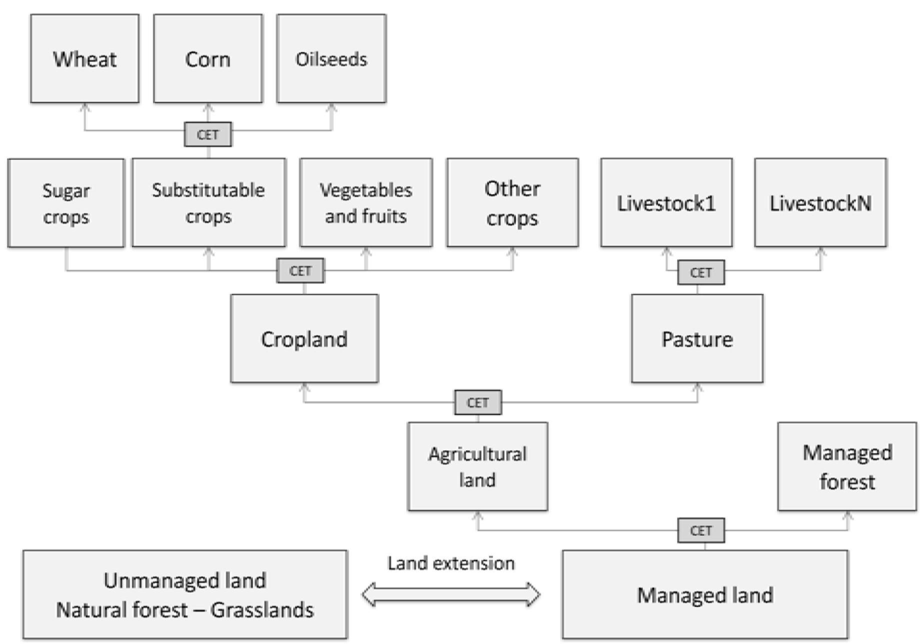
Land use change relative to agricultural production is decomposed in the model into two distinctive patterns: (1) the substitution effect, which refers to the change in land use distribution among different crops on existing arable land, and (2) the expansion effect of using more arable land made for cultivation and its impact on other types of land.

Land Substitution Effect

In order to represent the impact of demand for land on allocation choices, we rely on a neoclassical approach that 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 a different transformation elasticity. 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 is set to 20 following Golub, Hertel, and Sohngen (2007), reflecting the indifference of the producer to the location within the country.

Figure 3. Land substitution structure used for each AEZ



Source: Compiled by authors.

The design by different AEZ allows for 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 that will be arbitrary to some extent, given the high variance in the elasticity estimates available from econometric analyses (Salhofer 2000 and Abler 2000). We chose to base our parameters on the estimates chosen by the OECD for the PEM model (OECD 2003) used as a reference for the determination of agricultural support. However, the OECD model only covers developed countries plus Mexico, Turkey, and South Korea. Consequently, we 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

	Elasticity of Substitution				
Country	σ_{TEZ}	σ_{TEZH}	σ_{TEZM}	σ_{TEZL}	Notes
Oceania	0.59	0.35	0.17	0.05	OECD
China	0.23	0.22	0.21	0.05	Set similar to Rest of OECD (including the South Korea
Rest of OECD	0.20	0.15	0.11	0.05	OECD (Japan)
Rest of Asia	0.23	0.22	0.21	0.05	Set similar to Rest of OECD (including South Korea)
Indonesia	0.59	0.30	0.11	0.10	Set similar to Mexico
South Asia	0.59	0.30	0.11	0.10	Set similar to Mexico
Canada	0.58	0.32	0.14	0.05	OECD
United States	0.55	0.32	0.15	0.10	OECD
Mexico	0.59	0.30	0.11	0.10	OECD
E.U.	0.23	0.22	0.21	0.05	OECD (EU15 – European Union 15 states)
LACExp	0.59	0.30	0.11	0.10	Set similar to Mexico
LACImp	0.59	0.30	0.11	0.10	Set similar to Mexico
Brazil	0.59	0.30	0.11	0.10	Set similar to Mexico
EEurCIS	0.23	0.22	0.21	0.05	Set similar to E.U.
MENA	0.35	0.24	0.15	0.05	OECD (Turkey)
Rest of Africa	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

Sources: OECD (2003) and authors' estimations.

Note: σTEZ is the elasticity of substitution between substitutable crops; σTEZH is the elasticity of substitution between sugar crops, the bundle of substitutable crops, vegetables and fruits, and the bundle of other crops; σTEZM is the elasticity of substitution between croplands and pasture; σTEZL is the elasticity of substitution between agricultural land and managed forest. MENA = Middle East and North Africa. LACExp = Latin American Countries – Net agricultural exporters. LACImp = Latin American Countries – Net agricultural importers. EEurCIS = Eastern Europe and Community of Independent States. SAF = South Africa

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 TAv_r^{marg} was is computed using the following formula:

$$TAv_r^{marg} = \begin{cases} TAv_r^{Tot} - T_r^{Crop} - \frac{T_r^{Pasture}}{T_r^{Pasture} + T_r^{Grasslands}} * TAv_r^{Oth} - TAv_r^{Forest} * Sh_r^{Mngd\ for}, \ if > 0 \\ 0, \ elsewhere \end{cases} \quad (1)$$

where TAv_r^{Tot} is the total land available (from IIASA data), TAv_r^{Forest} is the land available under forest (from IIASA data), TAv_r^{Oth} is the land available not under forest and not cropland, T_r is the land area in a specific land type, such as provided in Monfreda, Ramankutty, and Hertel (2007), and $Sh_r^{Mngd\ for}$ is the share of forested land under management.

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

The fact that there are possibilities for expansion in land available for rainfed crops should not mask the fact that the 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 are introduced in the model by approximation using polynomial interpolation (see Figure B.1 in Appendix B for an illustration). We use data similar to that presented in Tabeau, Eickhout, and Van Meijl (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.

Land Expansion Effects

The land expansion module of the model is used to determine the area of arable land expansion into unmanaged land in each AEZ.[16] 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 decompose 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 the result 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:

$$LANDEXT_t + MANAGED_{LAND\,ini} = MANAGED_{LAND\,t}^{\ Exo} * \left(\left(\frac{P_{Cropland,t}}{P_t} \right)^{\sigma_{Landext} * \left(\frac{MargLand_{avail} - LANDEXT_t}{MargLand_{avail}} \right)} - 1 \right) \quad (2)$$

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,

[16] This module has been significantly redesigned in Al-Riffai, Dimaranan, and Laborde (2010) to include a representation of land expansion at the AEZ level, new expansion coefficients based on more recent country and AEZ specific elasticity estimates, and updated cropland-expansion distribution shares across land use types.

$MANAGED\_LAND_t^{Exo}$ 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, and $MargLand_{avail}$ is the area of land available for rain-fed crops in region r and not already in use (see equation 1).

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 Appendix B. 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.[17]

Finally, we distribute the share of extra land productivity gained at the national level into each AEZ depending on initial land endowments. This contributes to lower prices for cropland and compensates for the extra demand and the pressure for expansion.

Dynamics of Land Use Change

CGE 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 that impact 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—and 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, all changes in allocation come from the endogenous response to prices through 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).

[17] 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.

4. ESTIMATING EFFECTS ON GREENHOUSE GAS EMISSIONS

It is now widely held that both the direct effects of biofuels through their life cycles and the indirect land use change (ILUC) impacts on greenhouse gas (GHG) emission should be taken into account in a complete assessment of the environmental impacts of biofuel development. The life cycle assessment (LCA) is the analytical framework used for assessing the direct GHG emissions of the production and use of biofuels. Several reviews of LCA studies have found a broad range of estimates about the net energy balance results and GHG impacts among different biofuels and even for the same biofuel (Farrell et al. 2006, Larson 2006, Gnansounou et al. 2008, Bureau et al. 2010). The large differences in the net energy balance value estimates are found to be influenced by the degree to which inputs such as nitrogen and labor are controlled for and by the way the fossil energy consumption is allocated to various coproducts (Bureau et al. 2010). Similarly, Gnansounou et al. (2008) found that estimates of GHG emissions reduction are highly sensitive to allocation between coproducts, type of reference systems, choice of functional unit, and type of blend. Larson (2006) points to the wide range of values for key input parameters as the reason for the wide range of LCA GHG values. Rajagopal and Zilberman (2008) point out that the LCA approach is a valuable but flawed construct because the assumption of fixed coefficients disregards the effects of prices, technological changes, and policy changes on direct GHG emissions of biofuels.

Although the LCA methodology has limitations, it is GHG emissions through ILUC that has attracted greater debate in the literature and in policymaking. Searchinger et al. (2008) and Fargione et al. (2008) call attention to the need to account for the unintended consequences of biofuel production in terms of generating GHG emissions when forests and pristine lands are cleared for increased food production. The quantification of these ILUC effects has since become a contentious issue in the scientific community and in the policy debate. The Gallagher review of studies on ILUC concludes that further understanding of the implications of indirect effects is necessary since "quantification of GHG emissions from indirect land use change requires subjective assumptions and contains considerable uncertainty" (Gallagher 2008, 13). Criticisms of the methodology and assumptions employed figure prominently in discussions about the low carbon fuel standard of the California Air Resource Board and rule-making by the U.S. Environmental Protection Agency on the renewable fuel standard. Aside from methodological issues in accounting for ILUC impacts, the validity of including the ILUC effects in rule-making has also been discussed. Using a conceptual model that links food and energy markets to derive guidelines for the development of climate change and land use policies, Hochman, Sexton, and Zilberman (2010) point out that introducing an emission tax and a land use tax may be required for globally optimal outcomes. The authors also found that policies that either enhance agricultural productivity or biofuel productivity could lessen the resource constraint.

In this section, we document our methodology for capturing the direct and indirect impacts of land use change in our model.

Direct Production Effects

Reduction of GHG is one of the three most often mentioned objectives of biofuel 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. 2010 for a review). However, different processes in different regions can lead to various results in LCAs.

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 (CEC 2008), which provides reduction coefficients associated with different production pathways in the E.U.[18] For some feedstocks or regions, we use

[18] Two types of values are provided for different feedstock crops 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

additional sources to obtain more relevant data (for example, maize for the United States and for other regions of the world). We rely on the data provided in the latest report on the *State of Food and Agriculture* (FAO 2008). We also rely on Zah et al. (2007), who provide this type of information for soya.

Table 4. Reduction of CO_2 associated with different feedstocks—values used in calculations

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

Sources: CEC (2008), FAO(2008), and Zah et al. (2007).

For each country, the reduction of emissions associated with the one ton of fossil fuel equivalent of ethanol or biodiesel is 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).[19] The formula applied is the following:

$$Em_{s,biof,fs}^{Direct} = \left[IC_{s,biof,fs} * SF_{s,fs} + \sum_r M_{biof,r,s} * Sh_{biof,fs,r}^{Feedstock} * SF_{r,fs}\right] * EF_{Fossil\ fuel} \quad (3)$$

where *biof* refers to ethanol or biodiesel, feedstock refers to maize, wheat or sugar crop, *r*, *s* are countries, $IC_{s,biof,fs}$ is the quantity of feedstock *fs* consumed in region s for domestic production of biofuel *biof*, $Sh_{biof,fs,r}^{Feedstock}$ is the proportion of biofuel volume produced with the designated feedstock in region r, $SF_{r,fs}$ is the emission saving coefficient associated with a feedstock used in a region (see Table 4), $M_{biof,r,s}$ refers to the trade flow from region r to region s, and $EF_{Fossil\ fuel}$ 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).

Indirect Emissions from Land Use Change

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

---

producers. For the E.U., we assumed the use of more effective transformation processes.

[19] 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 LCA 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).

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 GHG, although nitrous oxide (N_2O) releases are recognized as significant contributors.[20] 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 GHG emissions, we rely on the Intergovernmental Panel on Climate Change guidelines for *National Greenhouse Gas Inventories* (IPCC 2006). We use the tier 1 method, which does not require knowledge of the exact carbon dioxide (CO_2) stock in each region but provides generic estimates for different climate zones that can be matched with the AEZs in the model (see Appendix C for the exact formula).

Although the model computes change in land use for economic sectors (cropland, pasture, managed forest) using the land expansion formula given in the previous section, 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, and scrubland) has to be separately computed.

We allocate the change in land use between the different noneconomic land use categories using historical information on land use change. Land use changes are assumed to take place in locations that have undergone changes in the past. If one-half of the expansion in cropland and pasture expansion in a region came from a decrease of primary forest and one-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 forests and for managed forests, 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 is accounted for is emission from mineral carbon in soil. We use the IPCC tier 1 methodology (IPCC 2006) and indicative release of carbon relative to different management practices to determine the additional emissions induced by the cultivation of new land (see Appendix C for the exact formula). The different practices we identify are noncultivation 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 carbon budget analysis 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.

[20] Use of fertilizer for growing biofuel feedstocks is already taken into account in the LCA for direct emissions. However, if an increase in land used in feedstock production induces an increase in fertilizer use and productivity from other crops, the effect on GHG is not taken into account.

5. ILLUSTRATION: IMPACTS OF ETHANOL PROGRAMS IN THE EUROPEAN UNION AND THE UNITED STATES

We apply our methodology on E.U. and U.S. ethanol programs under the current trade regime and under 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 (gross domestic product (GDP), population, and labor force growth) and is not supported by policies like mandatory incorporation. The average total factor productivity (TFP) in the economy is computed endogenously to reach the real GDP target in the baseline. A differentiation of the evolution of TFP was made between sectors of production (agriculture, industry, services) and agricultural sectors (crops, livestock) based on projections from Hertel, Ludena, and Golub (2006). We employ a recursive dynamic simulation to run the model from 2004 until 2020. We assume that oil prices remain stable at $60 a barrel (2007 International Energy Agency scenario) (IEA 2008), a price that is too low for most biofuel process pathways to be economically profitable. This is done by computing the level of natural oil resources under exploitation endogenously along the baseline. In this reference situation, biofuel production remains at its 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. The first scenario is a domestic mandate (DM) adopted in the United States and in the E.U. We simulate the implementation of mandatory provisions for fuel retailers to reach 30 billion gallons of ethanol production in 2022 on the U.S. side (which we represent as a 48 million tons of oil equivalent (Mtoe) target when interpolated to 2020).[21] This policy is implemented by imposing a certain level of incorporation of ethanol in fossil fuel under a constant level of tax exemptions. The share of biodiesel in total fuel consumption is assumed to be stable. On the E.U. side, the mandate of 10 percent of incorporation is applied separately to gasoline and diesel transport using the share of vehicles in each type of fuel. Under this model assumption, the shock introduced corresponds to a 2020 target of 35 Mtoe for all biofuels, of which around 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.

In the second scenario, referred to as free trade mandate (FTM), the same domestic mandate is implemented, but the United States and the E.U. completely open their markets to ethanol produced abroad. It is important to assess the impacts of such a trade policy shock because a substantial augmentation in the consumption of biofuels in large economies like the E.U. and the United States may have significant impacts on international trade in these products and in agricultural production worldwide as these countries seek more efficient biofuel sources. In this scenario, the E.U. cuts its tariff of 19.2 €/hl (62.4 percent in *ad valorem* equivalent) on undenatured ethanol (95 percent of ethanol imports in 2004) and the United States gives up its special duty of 14.27 US$/hl (around 34.6 percent *ad valorem*).

The geographical and sectoral aggregations used in the study are provided in Tables D.1 and D.2 in Appendix D. Due to space constraints, we focus only on the results for the more relevant regions and sectors in the study. The geographical and sectoral aggregations include 18 regions (which include Brazil, China, the E.U., Indonesia, and the United States), and 35 sectors (which include air and sea transportation, biodiesel, coal, ethanol, fertilizer, fossil fuel, gas, maize, oil, oilseeds for biodiesel, road transportation, sugar, sugarcane and sugar beet, vegetable oils, and wheat).

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 United States in particular, a large share of the

[21] 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 United States would not be capable of producing more than 30 billion gallons in 2022, with the largest part of it supplied from corn ethanol and imports (see http://www.reuters.com/article/environmentNews/idUSTRE4BG4EQ20081217).

production is obtained from local refining (33.5 Mtoe and 31.1 Mtoe, depending on scenarios), whereas in the E.U., 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 liberalization).

Table 5. Domestic production of biofuels for main producers of ethanol (Mtoe), 2020

		Biofuel Production Levels				
		Ref	DM	DM	FTM	FTM
Biofuel	Region	Lev	Lev	Var (%)	Lev	Var (%)
Ethanol	U.S.	14.24	33.52	135.5	31.13	118.6
Ethanol	E.U.	1.19	10.38	770.7	3.76	215.6
Ethanol	Brazil	17.68	27.20	53.9	39.78	125.0
Biodiesel	U.S.A.	0.92	0.86	-6.8	0.99	7.4
Biodiesel	E.U.	16.23	15.96	-1.7	16.01	-1.4

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic-oriented mandate; FTM = free trade mandate; Lev = level; Var = variation.

The effect of trade liberalization is more significant for the E.U. because a substantial 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 United States (multiplied by 22 in 2020) and the E.U. (multiplied by 25 in 2020). Exports from the Caribbean countries (included in LACImp for Latin America Food Importers) to the United States do not rise as much under the FTM scenario because of erosion of their trade preferences to the United States (+149 percent in 2020).

Table 6. Bilateral ethanol export flows to the E.U. and the United States (Mtoe), 2020

			Volume Ethanol Exports				
	Region		Ref	DM	DM	FTM	FTM
Fuel	Exporter	Importer	Lev	Lev	Var (%)	Lev	Var (%)
Ethanol	LACImp	U.S.	3.60	13.31	269.5	8.97	149.0
Ethanol	Brazil	U.S.	0.28	0.99	252.3	6.42	2193.6
Ethanol	Brazil	E.U.	0.51	6.25	1,115.6	13.52	2527.5

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic-oriented mandate; FTM = free trade mandate; Lev = level; Var = variation; LACImp = Latin America Food Importers.

As reported in Table 7, the production of ethanol requires additional production of its feedstocks in the E.U., in the United States, and in their trade partners. These feedstocks are mainly sugarcane in Brazil, maize in the United States, and sugar beet, wheat, and maize in the E.U. 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 United States as well as sugarcane in Brazil and in the LACImp region increases by more than 20 percent compared to the baseline (in 2020). U.S. production of maize and E.U. production of sugar beet (sugar crops on Table 7) increase by less under the FTM scenario (17.2 percent instead of 21.3 percent for maize in the United States and 5.5 percent instead of 18.5 percent for sugar beet in the E.U.), while Brazilian production of sugarcane (sugar crops in Table 4) is particularly augmented when import barriers are removed in the E.U. and the United States (+52.8 percent under FTM instead of 21.5 percent under the DM scenario).

The expansion of domestic (E.U. and U.S.) 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 percent as more ethanol imports are allowed in the United States; maize production in the United States increases by less in the DM scenario.

Table 7. Domestic production of feedstocks for ethanol production (million $), 2020

		Feedstock Production Levels				
		Ref	DM	DM	FTM	FTM
Feedstock	Regions	Lev	Lev	Var (%)	Lev	Var (%)
Wheat	South Asia	44,218	44,389	0.4	44,306	0.2
Wheat	E.U.	30,122	30,885	2.5	30,357	0.8
Wheat	MENA	18,090	18,400	1.7	18,230	0.8
Wheat	China	17,331	17,464	0.8	17,404	0.4
Maize	U.S.A.	29,940	36,313	21.3	35,091	17.2
Maize	China	19,695	19,679	-0.1	19,683	-0.1
Maize	Rest of Africa	15,595	15,588	0.0	15,590	0.0
Maize	E.U.	14,612	15,304	4.7	14,821	1.4
Maize	Mexico	11,840	12,151	2.6	12,112	2.3
Sugar crops	South Asia	21,841	21,970	0.6	22,000	0.7
Sugar crops	E.U.	9,710	11,505	18.5	10,243	5.5
Sugar crops	Brazil	7,710	9,370	21.5	11,779	52.8
Sugar crops	LACImp	5,966	7,799	30.7	6,893	15.5

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic-oriented mandate; FTM = free trade mandate; Lev = level; Var = variation; MENA = Middle East and North Africa; LACImp = Latin America Food Importers.

As shown in Table 8, the ensuing trade patterns for feedstocks follow the new demand configuration. Exports of wheat to the E.U. significantly increase under the ethanol mandate (scenario DM) in order to support the domestic feedstock market. European imports of wheat increase by 46.4 percent from Eastern Europe and Russia (region EEurCIS), 34.5 percent from Canada, and 36.1 percent from Brazil. Symmetrically, exports of maize to the United States increase very significantly (+52.4 percent from Canada and +107.6 percent from LACImp), although the maize market relies mainly on domestic production in the United States. Exports of other crops decrease when these crops are produced in a country where ethanol is produced (for example, Brazil and 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. Export of feedstock crops to the E.U. and the United States do not increase by as much as in the DM scenario when it is coupled with tariff cuts on ethanol (scenario FTM).

The new demand of feedstocks leads to a significant increase in prices on the world markets. The conversion of U.S. maize to biofuels increases the world price by 11.2 percent in 2020 and the expansion of wheat production for E.U. ethanol leads to a 2.7 percent increase in the price of wheat. These estimates may seem low in comparison with the absolute volatility observed during the food crisis, but they represent long-term adjustments once all factors have been reallocated and endogenous productivity increases have taken effect. Notably, these estimates are consistent with those of the forest and agricultural sector model (FASOM) that predicts an 8 percent increase for maize in 2022 (U.S. Environmental Protection Agency 2010), although lower than other, more pessimistic, projections (15 to 28 percent in Rajagopal et al. 2009). Under the trade liberalization scenario, the tension on markets would be partially released, as maize price inflation will drop to +8.8 percent and wheat price increases will be as low as +1.2 percent. The sugarcane sector, less critical for food security issues, benefits from this liberalization, with the price of sugar in Brazil increasing from +12.2 percent without liberalization to +30.3 percent in the case of liberalization of the ethanol market.

On the energy side, prices will also be affected, which should lead to a significant leakage on the oil market. Indeed, mandate policies are found to depress world oil prices by around 1.7 percent in both trade policy scenarios. This result is, however, strongly contingent on the modeling of oil supply, which in this study relies on standard specifications (for example, low supply elasticity) without representation of the strategic behavior of oil-producing countries to control world prices.

Table 8. Changes in feedstock trade following ethanol mandate implementation (mio $), 2020

			Feedstock Trade				
			Ref	DM	DM	FTM	FTM
Feedstock	Exporter	Importer	Lev	Lev	Var (%)	Lev	Var (%)
Wheat	EEurCIS	E.U.	223	326	46.4	245	10.1
Wheat	Canada	U.S.A.	120	121	0.9	121	0.8
Wheat	Canada	E.U.	105	142	34.5	109	3.4
Wheat	Brazil	E.U.	87	118	36.1	88	2.0
Wheat	MENA	E.U.	64	91	43.7	69	8.5
Maize	Brazil	E.U.	287	333	16.0	286	-0.4
Maize	Canada	U.S.A.	222	338	52.4	313	41.4
Maize	LACExp	E.U.	196	222	13.6	196	0.3
Maize	U.S.A.	E.U.	120	83	-30.8	81	-32.6
Maize	LACImp	U.S.A.	113	235	107.6	207	82.4
OthCrop	LACImp	U.S.A.	5,013	5,059	0.9	5,095	1.6
OthCrop	Rest of Africa	E.U.	4,558	4,674	2.5	4,628	1.5
OthCrop	LACImp	E.U.	2,723	2,679	-1.6	2,696	-1.0
OthCrop	Brazil	E.U.	2,552	2,517	-1.4	2,392	-6.3
OthCrop	E.U.	U.S.A.	1,262	1,292	2.3	1,299	2.9
VegFruits	LACImp	E.U.	4,504	4,441	-1.4	4,464	-0.9
VegFruits	U.S.A.	E.U.	3,579	3,572	-0.2	3,562	-0.5
VegFruits	Mexico	U.S.A.	3,348	3,356	0.2	3,350	0.1
VegFruits	LACImp	U.S.A.	2,645	2,629	-0.6	2,644	0.0
VegFruits	MENA	E.U.	2,526	2,571	1.8	2,557	1.2
OilseedBio	Brazil	E.U.	11,480	11,527	0.4	11,338	-1.2
OilseedBio	U.S.A.	E.U.	3,210	2,910	-9.3	2,956	-7.9
OilseedBio	LACExp	E.U.	2,488	2,508	0.8	2,503	0.6
OilseedBio	EEurCIS	E.U.	527	545	3.4	544	3.1
OilseedBio	Canada	E.U.	475	465	-2.2	468	-1.7

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic-oriented mandate; FTM = free trade mandate; Lev = level; Var = variation; MENA = Middle East and North Africa; LACImp = Latin America Food Importers; EEurCIS = East Europe and Community of Independent States; LACExp for Latin America Food Exporters; VegFruits = vegetables and fruits; OilseedBio = oilseeds for biodiesel; OthCrop = other crops.

These changes in trade patterns lead to some welfare changes related to terms of trade variation. As shown in Table 8, Brazil, the E.U., and the United States benefit most from the changes in crop prices on the international markets. However, African and importing countries from Latin America suffer from the increased prices of crops.

Table 9. Terms of trade and welfare variation under mandate scenarios, 2020

	Terms of Trade		Welfare	
Regions	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
U.S.A.	0.4	0.3	-0.06	-0.05
Mexico	-0.5	-0.5	-0.29	-0.26
E.U.	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

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic-oriented mandate; FTM = free trade mandate; Lev = level; Var = variation; MENA = Middle East and North Africa; LACImp = Latin America Food Importers; EEurCIS = East Europe and Community of Independent States; LACExp = Latin America Food Exporters

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 United States and the E.U. do not benefit from their terms of trade improvement when welfare is considered. Brazil and food-exporting countries in Latin America are significant winners under the trade liberalization scenario, with 0.61 percent and 0.22 percent real income gains in 2020, respectively. However, food-importing countries from Latin America (mostly Caribbean countries) will be major losers due to the deterioration of their terms of trade and erosion of their trade preferences to the United States under trade liberalization. However, as shown in Table 10, welfare variations do not reflect the effect of biofuel policies on farm revenues across countries. U.S. and E.U. farmers benefit significantly from the mandate implementation, with a 10 percent increase in U.S. crop farming revenue in 2020. Brazil and Latin American importing countries also benefit from this policy. These results show that ethanol mandates represent a transfer from consumers to farmers and, from this perspective, are similar to other instruments of agricultural support.

Table 10. Crop farming revenues under mandate scenarios (billion $), 2020

	Crop Farming Revenues				
	Ref	DM	DM	FTM	FTM
Regions	Lev	Lev	Var (%)	Lev	Var (%)
U.S.	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
E.U.	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

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic-oriented mandate; FTM = free trade mandate; Lev = level; Var = variation; MENA = Middle East and North Africa; LACImp = Latin America Food Importers; EEurCIS = East Europe and Community of Independent States; LACExp = Latin America Food Exporters.

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 United States in Table 11, one sees that the need for new production is particularly significant. The increase in land used for maize (+15.9 percent) displaces other crops, especially wheat and oilseeds, and competes with pastures and forested lands. In the E.U., the domestic production of ethanol relies more on an increase in sugar beet production (+13.1 percent for a domestic-oriented mandate) as well as wheat and maize (+1.5 percent and +3.0 percent, 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 (thousand hectares), 2020

		Cropland Use				
		Ref	DM	DM	FTM	FTM
Feedstock	Regions	Lev	Lev	Var (%)	Lev	Var (%)
Rice	U.S.	1,788	1,784	-0.20	1,785	-0.15
Wheat	U.S.	32,790	31,453	-4.08	31,573	-3.71
Maize	U.S.	39,277	46,987	19.63	45,514	15.88
OthCrop	U.S.	59,878	58,568	-2.19	58,878	-1.67
VegFruits	U.S.	5,949	5,915	-0.57	5,924	-0.42
OilseedBio	U.S.	51,335	48,160	-6.19	48,802	-4.93
Sugar_cb	U.S.	1,247	1,241	-0.51	1,242	-0.37
Rice	E.U.	436	436	-0.13	436	-0.04
Wheat	E.U.	27,099	27,511	1.52	27,221	0.45
Maize	E.U.	8,978	9,251	3.04	9,058	0.89
OthCrop	E.U.	54,700	54,516	-0.34	54,676	-0.04
VegFruits	E.U.	12,531	12,480	-0.41	12,513	-0.14
OilseedBio	E.U.	11,100	10,972	-1.15	11,089	-0.10
Sugar_cb	E.U.	2,329	2,635	13.12	2,417	3.74

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic-oriented mandate; FTM = free trade mandate; Lev = level; Var = variation; VegFruits = vegetables and fruits; OilseedBio = oilseeds for biodiesel; OthCrop = other crops; Sugar_cb: sugarcane and sugar beet.

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 12, E.U. cropland expands by 0.53 percent in the DM scenario, and U.S. cropland increases by 0.96 percent. Pasture decreases by 0.45 percent in the E.U. and 0.60 percent in the United States, and managed forest decreases as well by 0.07 percent in the E.U. and 0.05 percent in the United States. Expansion of economic land into unexploited areas (unmanaged forest or other types of land) complements the substitution effects. Agricultural land (cropland, pasture, and managed forest) expands by 0.06 percent in the E.U. (200,000 hectares), 0.03 percent in the United States (220,000 hectares), and 0.16 percent in Brazil (470,000 hectares).

Table 12. Variation in land types area (mio km²) for some regions, 2020

		Land Use				
		Ref	DM	DM	FTM	FTM
Land Types	Regions	Lev	Lev	Var (%)	Lev	Var (%)
Pasture	E.U.	0.71	0.70	-0.45	0.71	-0.13
Cropland	E.U.	1.17	1.18	0.53	1.17	0.20
Other	E.U.	1.17	1.17	-0.17	1.17	-0.07
Forest managed	E.U.	1.47	1.47	-0.07	1.47	-0.04
Forest primary	E.U.	0.07	0.07	0.00	0.07	0.00
Forest total	E.U.	1.55	1.54	-0.07	1.55	-0.04
Total exploited land	E.U.	3.35	3.35	0.06	3.35	0.02
Pasture	U.S.	2.39	2.38	-0.60	2.38	-0.47
Cropland	U.S.	1.92	1.94	0.96	1.94	0.76
Other	U.S.	1.88	1.88	-0.14	1.88	-0.11
Forest managed	U.S.	2.97	2.97	-0.05	2.97	-0.04
Forest primary	U.S.	–	–	–	–	–
Forest total	U.S.	2.97	2.97	-0.05	2.97	-0.04
Total exploited land	U.S.	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

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic-oriented mandate; FTM = free trade mandate; Lev = level; Var = variation.

Budget of Land Use Change

Biofuel cultivation can lead to some direct emissions savings by replacing the use of fossil fuels. The emissions coefficients reported in Table 4 are used to compute the total emissions savings by crop as a result of the E.U. and U.S. ethanol programs (see previous section on direct production effects for the methodology).

As shown in Table 13, direct global emission savings are highest for sugarcane (62 percent) in the DM scenario. With the expansion of sugarcane production under the trade liberalization scenario, direct emissions savings from sugarcane are even higher at 84 percent. For other feedstock crops, the free trade scenario results in lower direct emissions because production of these feedstocks increases by less under this scenario.

Table 13. Direct annual emissions savings from U.S. and E.U. biofuel policies, by feedstock, 2020 (in $MtCO_2eq$)

		Emissions			
		DM	DM	FTM	FTM
Region	Biofuel – Feedstock	Lev	Share (%)	Lev	Share (%)
World	Ethanol – Wheat	-3.742	8.6	-0.919	1.8
World	Ethanol – Maize	-7.222	16.5	-5.508	10.9
World	Ethanol – Sugar Beet	-5.404	12.4	-1.573	3.1
World	Ethanol – Sugarcane	-27.256	62.4	-42.293	83.9
World	Ethanol – Other Crops	-0.058	0.1	-0.123	0.2
World	Ethanol – All crops	-43.682	100.0	-50.415	100.0

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic-oriented mandate; FTM = free trade mandate; Lev = level.

Alternatively, we present the change in CO_2 emissions in the total economy as a result of ethanol policies in Table 14. Several trends appear in this table. First, there is a strong leakage effect because the decrease in demand for oil in the United States and in the E.U. makes fuel cheaper for other countries. Emissions of China and South Asia therefore considerably increase in response to biofuel policy. Second, because 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 United States and the E.U. are significantly affected considering the cost of their policy support. Third, when correcting for the income effect, one can observe that savings from E.U. and U.S. policies are higher than just the substitution effect. One of the explanations is that price of fuel for these countries increases with the mandate, and consumers then 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.[22]

These direct emissions savings can be outweighed by emissions from indirect land use effects. Indeed, land use changes can generate significant GHG emissions that call into question the environmental benefits from biofuel 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 using the Intergovernmental Panel on Climate Change methodology (as explained in the section on indirect emissions from land use change).

[22] 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.

Table 14. Emissions savings for each scenario using an aggregated computable general equilibrium calculation

Annual $MtCO_2eq$ in 2020	Sectoral Focus		CGE Values with Income Effect		CGE Values without Income Effect (fixed GDP)	
	DM	FTM	DM	FTM	DM	FTM
Oceania	-0.03	-0.03	0.83	0.74	0.90	0.83
China	0.03	0.03	24.41	23.12	29.14	26.11
Rest of OECD	-0.04	-0.07	7.54	6.98	9.99	9.23
Rest of Asia	-0.02	-0.04	5.80	5.48	6.91	6.43
Indonesia	0.00	0.00	2.82	2.65	3.95	3.67
Malaysia	0.00	0.00	0.97	0.85	1.69	1.52
South Asia	-0.37	-0.33	11.92	11.18	10.78	10.39
Canada	0.02	0.01	2.84	2.59	3.63	3.37
U.S.A.	-5.60	-4.65	-62.76	-61.13	-54.66	-53.68
Mexico	-0.01	-0.05	1.17	1.19	2.51	2.40
E.U.	-10.32	-2.22	-53.98	-49.28	-50.89	-46.82
LACExp	-0.01	-0.17	1.16	1.33	0.86	1.15
LACImp	-12.11	-6.02	4.87	4.29	6.26	6.08
Brazil	-14.67	-36.02	0.60	-1.16	0.44	-1.84
EEurCIS	0.00	-0.04	9.33	8.76	32.36	30.24
MENA	0.00	-0.08	7.99	7.86	36.39	33.93
Rest of Africa	-0.06	-0.02	1.65	1.56	4.32	4.08
South Africa	-0.08	-0.53	0.54	0.71	0.33	0.44
World	-43.28	-50.22	-32.31	-32.26	44.92	37.54

Source: Authors' calculations.
Note: Sectoral emissions are allocated to the country where the ethanol is produced. For example, if LACImp countries produce ethanol from Brazilian sugarcane and export it to the United States, then emission savings are allocated to LACImp. This is different from the CGE values as emissions there are allocated to the country making use of the energy commodity. So, in the previous example, a share of emissions is allocated to Brazil for sugarcane production, a share to LACImp for ethanol production, and a share to the United States for distribution. In the last two columns, the income effect is neutralized using an adjustment of total factor productivity (TFP). Countries benefiting from a positive income effect from biofuel policy will produce more emissions because their TFP decrease, but they consume more input as a result of their structural growth. MENA = Middle East and North Africa; LACImp = Latin America Food Importers; EEurCIS = East Europe and Community of Independent States; LACExp = Latin America Food Exporters.

The computation of annualized emissions from land use change, reported in Table 15, clearly shows the fact that the emissions flow of CO_2 reduction is lower than the CO_2 emissions flow from land use change. In this exercise, total CO_2 emissions from indirect land use change (ILUC) are estimated at 54.5 MTCO2eq (sum of deforestation and new land cultivation under the FTM scenario), while direct savings in CO_2 emissions is estimated at 50.4 MtCO2eq under this policy shock (from Table 13).

Table 15. Emissions in MtCO2eq from land use change in 2020 annualized (over the 2007-2020 period)

Region	Deforestation Emissions		New Land Cultivation Emissions	
	DM	FTM	DM	FTM
Oceania	0.220	0.148	0.326	0.234
China	0.173	0.062	0.192	0.139
Rest of OECD	0.340	0.239	0.219	0.155
Rest of Asia	0199	0.167	0.135	0.118
Indonesia	0.372	0.322	0.100	0.088
South Asia	0.039	0.034	0.062	0.032
Canada	0.624	0.452	0.706	0.523
U.S.A.	1.980	1.584	6.714	5.310
Mexico	0.802	0.650	0.241	0.199
E.U.	1.465	0.873	2.844	1.073
LACExp	0.581	0.554	0.715	0.559
LACImp	3.804	2.333	1.375	0.815
Brazil	12.391	25.150	3.365	6.784
EEurCIS	-0.287	-0.165	1.889	1.341
MENA	-0.184	-0.100	0.292	0.192
Rest of Africa	4.145	3.362	0.908	0.731
South Africa	-0.029	-0.074	0.234	0.581
World	26.635	35.590	20.318	18.874

Source: Authors' calculations.
Note: DM = domestic-oriented mandate; FTM = free trade mandate; MENA = Middle East and North Africa; LACImp = Latin America Food Importers; EEurCIS = East Europe and Community of Independent States; LACExp = Latin America Food Exporters.

However, this approach does not take into account the dynamics of emissions. Land use change conversion releases most of the CO_2 emissions once, whereas the savings from biofuel cultivation occur under a continuous flow year after year. That is why we also assess the CO_2 emissions in a carbon budget approach following Fargione et al. (2008), who define 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. We first compute the emissions balance at the end of the implementation period, deriving the quantity of carbon to be repaid once land use change has occurred. Second, we confront this value to the annual savings from further biofuels production after 2020, when there is no further ILUC effect. This approach gives a payback time for E.U. and U.S. programs of 12 years by 2020. These results are obtained without considering the effect of fertilizer emissions related to intensification of cultivation (see Table 16).

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

	DM	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 in 2020 (MtCO2 per annum)	-43.3	-50.2
Carbon debt payback time after 2020 (years)	11.7	10.7

Source: Authors' calculations.
Note: DM = domestic-oriented mandate; FTM = free trade mandate. Carbon already reimbursed corresponds to carbon progressively saved through the biofuel substitution with fossil fuels during the implementation period.

Sensitivity Analysis on Elasticities of Land Supply and Fertilizer

The results obtained in the previous section depend on some parameters whose values are not always well documented in the literature. We undertake a sensitivity analysis that allows us to take into account the uncertainty that characterizes the estimation of some of the behavioral parameters of the study. We focus on two key dimensions—the elasticity of land supply and the elasticity of substitution between land and fertilizers. We test how the results change with a higher and a lower elasticity of land supply (L+ and L-) and a higher and lower elasticity of yield response (F+ and F-).

In the L+ scenario, land supply elasticities are doubled for countries in the North and multiplied by five for developing countries. In the L- scenario, the opposite is done; the elasticities of land supply are divided by two for the North and by five for the South. The difference in magnitude between developed and developing regions is introduced to reflect the higher uncertainty on parameters for developing countries. For example, there is strong debate about the endogenous productivity gains that could relieve the pressure for land expansion.

For the F- scenario, most endogenous productivity gains are disabled and elasticity between land and fertilizer is set to 0, whereas elasticity between land–fertilizer and capital–labor 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 is given in Table 17. In the scenario F+ and L-, not surprisingly, land use responds more to the policy changes; the carbon debt is therefore higher and takes longer to be repaid. Indeed, more fertilizer 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.

The sensitivity analysis also indicates that the effects of trade liberalization are ambiguous depending on the behavioral parameters. Depending on the elasticity assumptions, land expansion and deforestation induced in foreign countries by more imports can be either detrimental or beneficial to the overall emissions balance depending on the responsiveness of agents to price changes in these developing economies.[23]

[23] Further analysis show that this ambiguity is strongly resolved with a refined modeling of land use expansion in Brazil (Al-Riffai et al., 2010).

Table 17. Sensitivity analysis on carbon budget decomposition and payback time, 2020

	Land and Fertilizer Scenarios							
Carbon Budget	F+ DM	F+ FTM	F- DM	F- FTM	L+ DM	L+ FTM	L- DM	**L- 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 in 2020 (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

Source: Authors' calculations.
Note: Ref = baseline; DM = domestic mandate; FTM = free trade agreement; Lev = level; Var = variation.

6. CONCLUSIONS

We developed an integrated approach aimed at assessing the impact of biofuel policies on agricultural markets and trade and on their environmental effects. This approach is more comprehensive than that in previous computable general equilibrium studies because it relies on more disaggregated sectoral data. Moreover, a substantial effort has been made in order to appropriately model land use change and land extension and to evaluate the impacts of these land use changes on CO_2 emissions.

The study looks at the potential direct and indirect greenhouse gas (GHG) 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 used here, especially for assessing indirect land use change (ILUC) impacts, is at an early stage and will have to be refined as better definition on the role of ILUC in the regulations is achieved. As such, the results should be interpreted with some caution. Our initial results show that ethanol production has environmental benefits only under certain restrictive assumptions. In four of 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 coproducts of biofuel production needs to be adequately incorporated because it can minimize the extent of indirect land use effects. Additionally, the study does not take into account the potential technical changes in response to the impacts of biofuel development. Increased agricultural productivity could potentially alleviate the land use and GHG emissions effects. However, there are also some other factors that are not yet adequately incorporated in the model that could potentially worsen the impact of biofuels from an environmental point of view. This is the case with peatland emissions and the emissions related to fertilizer intensification. The potential or limitation of endogenous yield also requires more scrutiny.

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

From a trade policy point of view, our results tend to argue for trade liberalization because imported ethanol made from more emission-saving feedstock (sugarcane) can replace some of the necessary expansion of ethanol production in the United States and E.U., which rely on less effective feedstock (for example, maize, wheat, and sugar beet). Sensitivity analyses, however, show that this result is not straightforward and depends on the deforestation pattern in developing countries, with Brazil in first position for ethanol. Annual savings from sugarcane 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 U.S. market if such a liberalization scheme were implemented.

APPENDIX A: CONSTRUCTION OF NEW SECTORS

The data sources, procedures, and assumptions made in the construction of each of the new sectors—ethanol, biodiesel, maize, oilseeds for biodiesel, fertilizer, and transport fuel—introduced in the expanded GTAP 7 database are described in this appendix.

Ethanol

Data on ethanol production for 2004, in millions of gallons, were obtained from industry statistics provided by the Renewable Fuels Association (RFA 2005) for annual ethanol production by country. The data covers 33 individual countries plus an aggregated sum that covers production for all other ethanol-producing countries. Production of ethanol for the residual set of producing countries was computed based on export share information for the ethanol-exporting countries that are not covered in the production data. To be consistent with the global trade analysis project (GTAP) global database, which carries data in value flows, ethanol production data were converted to US$ (millions) using 2004 price data from the OECD (2006), from which data on ethanol processing costs for the major ethanol producers (Brazil, E.U., and the United States) were compiled. Bilateral trade for ethanol in 2004 was obtained from the reconciled Base pour l'Analyse du Commerce International (BACI) trade database (Gaulier and Zignano 2009), which is developed and maintained at Centre d'Etudes Prospectives et d'Informations Internationales. Tariff data on ethanol were obtained from the MAcMap-HS6 database (Boumellassa, Laborde, and Mitaritona 2009).

Ethanol producers were first classified according to the primary feedstock crops used in production. The input–output 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 input–output table. Thus, CRP is 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 Canada, the E.U., and the United States 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 matrixes 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 to 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 by splitting 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 (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.

Biodiesel

Data on biodiesel production in the E.U., in million tons, were obtained from published statistics of the European Biodiesel Board (EBB 2008). Biodiesel production data for non-E.U. countries for 2004 were estimated based on 2007 production data for these countries as obtained from F.O. Licht[24] and deflated using the 2004–2007 biodiesel production average-growth rate for the E.U. 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). Because 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 in progress on this aspect to better represent the domestic and world biodiesel markets.

Unlike ethanol, the feedstock crops used in biodiesel production (for example, rapeseed and soybean) 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 because a larger proportion of oilseeds produced in each region is used as intermediate input in the OFD, not the VOL, sector in E.U. 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 matrixes 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 performed a separate split for biodiesel production under OFD and biodiesel trade under CRP. These two biodiesel sectors were then aggregated into one biodiesel sector (BIOD).

Maize and Oilseed 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 biofuel expansion on feedstock production, prices, and land use. Wheat and sugarcane/sugar beet are both separate sectors in the GTAP database. Maize and oilseeds, however, both belong to sectors that also include crops that are not used as feedstock in biofuel 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.

Maize production volume and price data for 2004, as well as production data for other cereals (barley, buckwheat, canary seed, fonio, millet, mixed grains, oats, and cereal grains, nec) were compiled from FAO production statistics (FAO 2009a). 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

[24] As cited in OECD (2008).

[25] The HS codes on which biodiesel is 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 and incompatible with the production data.

database (Gaulier and Zignano 2009) 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 share information and trade share information to split the GRO sector into MAIZ and OGRO. We assumed 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 compiled 2004 production volume and price data from FAO production statistics for oilseed crops used for biodiesel production (rapeseed, soybeans, safflower seed, cottonseed, palm kernel, and sunflower seed), as well as for other oilseed crops (castor oil seed, coconut, copra, groundnut, linseed, melonseed, mustard seed, and poppy seed). Bilateral trade data for oilseeds used in biodiesel, as well for the GTAP OSD sector, were obtained from the BACI trade database (Gaulier and Zignano, 2009). As for the maize sector, the production share and trade share information was used to split the OSD sector into BOSD and OSDO. We also assumed that the production technology for BOSD and OSDO in each country are the same as those used for the original sector, OSD.

Fertilizer

Nonorganic fertilizers are part of the large CRP sector in GTAP. A separate treatment of fertilizers is necessary to more adequately assess the implications of biofuel 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 price data from FAO resource statistics (FAO 2009c) and published data (Schnitkey 2008). Bilateral trade data for fertilizers and for the GTAP CRP sector were obtained from the BACI database (Gaulier and Zignano 2009). Tariff data were obtained from the 2004 MAcMap-HS6 database (Boumellassa, Laborde, and Mitaritona 2009).[26] The fertilizer production values and trade share information were used to split the CRP sector into FERT and CRPN (other CRP). We assumed that the production technologies for FERT and CRPN in each country are the same as those for the original sector, CRP. However, we assumed 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[27] were 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 (Boumellassa, Laborde, and Mitaritona 2009), respectively. The transport fuel production values and trade share information were used to split the P_C sector into TP_C and OP_C. We assumed 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 assumed 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.

---

[26] These cover tariff lines for animal and vegetable fertilizers (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)

[27] Data obtained from national fuel consumption data reported in International Fuel Prices, 2005, 4th edition, (Metschies Consult 2005).

APPENDIX B: ELASTICITIES USED IN THE MODEL

Table B.1. Substitution and transformation elasticities used in the MIRAGE biofuels model

Definition	Value	Source
Supply side		
Value added elasticity of substitution	1.1	MIRAGE standard assumption
Skilled labor—Capital elasticity of substitution	0.6	MIRAGE standard assumption
Elasticity of substitution in CES within aggregate good types	2	Authors' assumption
Elasticity of substitution in LES-CES between aggregate good types	calibrated	Computed from USDA and FAPRI
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
Elasticity of substitution between intermediate categories	0.1	MIRAGE standard assumption
Capital good elasticity of substitution	0.6	MIRAGE standard assumption
Fix factor elasticity (land, natural resources)	0.1< to <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-energy elasticity of substitution	0.15	Burniaux and Truong (2002)
Second energy bundle and electricity elasticity of substitution	1.1	Burniaux and Truong (2002)
Third energy bundle and coal elasticity of substitution	0.5	Burniaux and Truong (2002)
Fuel oil gas elasticity of substitution	1.1	Burniaux and Truong (2002)
	0.5	For petroleum coke products
	0.9	For electricity and gas
Demand side		
Quality elasticity of substitution	various	Computed from GTAP values
Armington elasticity of substitution	various	Computed from GTAP values
Import elasticity of substitution	GTAP values	Hertel, Ludena, and Golub (2006)
Import elasticity of substitution	5	Ethanol, study assumption
Factors		
CET Labor elasticity of substitution	0.5	MIRAGE standard assumption
CET Land elasticity of transformation (1st level—high substitution)	0.2 to 0.6	OECD PEM model
CET Land elasticity of transformation (2nd level—medium-high substitution)	0.15 to 0.35	Derived from OECD PEM model
CET Land elasticity of transformation (3rd level—medium substitution)	0.11 to 0.21	OECD PEM model
CET Land elasticity of transformation (4th level—low substitution)	0.10 or 0.05	OECD PEM model
Land expansion elasticity	0.10 or 0.05	Study specific assumption

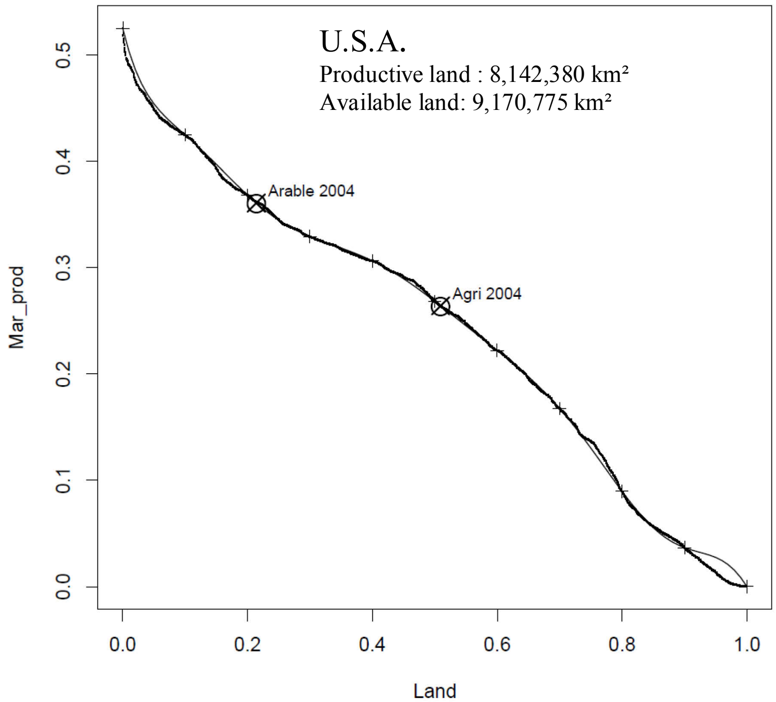
Source: Compiled by authors.

Table B.2. 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 (%)	
						DM	FTM	DM	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
South Asia	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
U.S.A.	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
E.U,	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

Source: Authors' estimations based on MIRAGE model.
Note: * Land under economic use does not include urbanized areas.

Figure B.1. Example of productivity distribution profile for the United States



Source: Authors' creation based on IMAGE model.
Note: The Y axis is a relative index of potential productivity for a 0.5 x 0.5 degree grid cell in the IMAGE model. The 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 first circle represents the marginal position of arable land use expansion, under the assumption that the most productive land is used for cropland. The second circle represents 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.

APPENDIX C: EMISSIONS COEFFICIENT USED FOR THE DIFFERENT AGROECOLOGICAL ZONES

Measurement of Carbon Stock in Forest Biomass

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) (C.1)

where *Forest type* can be managed forest or primary forest, *DMStock* (DM for dry matter) is given in Table C.1, as well as *below ground ratio*, and 0.47 is the coefficient used to compute carbon mass by dry matter and 44/12 converts carbon to CO_2.

Table C.1. Carbon stock in forest for different climatic regions

Agroecological 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 (IPCC 2006).
Note: * tons of dry matter per hectare

Measurement of Organic Carbon Contained in Mineral Soil

The formula used is the following:

$$\text{Carbon stock in soil deviation for crop i} = \text{Landarea(i,z)*CStock(z,"Soil")} \\ \text{*((1-Gel(i,r))*(EF(z,"Cultivation")-1) + (Gel(i,r)*(EF(z,Setaside)-1))) * 44/12 /20} \qquad (C.2)$$

where *Cstock* is the carbon stock from Table C.2, *EF* is the emission factor (1 is the default value for noncultivated land) and 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 CO_2 tons, and the 20 denominator represent the number of years for carbon in soil to be released.

Table C.2. Carbon stock in soil and emission factors used in the model

Agroecological 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	67	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 (IPCC 2006).
Note: * tons of carbon per hectare

APPENDIX D: REGIONAL AND SECTORAL AGGREGATION

Table D.1. Geographical aggregation

Region name	GTAP regions
Oceania	Australia, New Zealand, Rest of Oceania
China	China
RoOECD	Rest of OECD: Japan, South Korea, Switzerland, Rest of European Free Trade Area (EFTA) including Norway and 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	United States
Mexico	Mexico
E.U.	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

Source: Compiled by authors.

Table D.2. Sectoral disaggregation and correspondence with GTAP sectors

Sector code	Sector name	GTAP Sector (newly created sector in *italics*)
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

Source: Compiled by authors.

REFERENCES

Abler, D. G., 2000. *Elasticities of substitution and factor supply in Canadian, Mexican and US Agriculture*. Report to the Policy Evaluation Matrix (PEM) Project Group. Paris: OECD.

Al-Riffai, P., B. Dimaranan, and D. Laborde. 2010. *Global trade and environmental impact study of the EU biofuels mandate.* Final Draft Report Submitted to the Directorate General for Trade, European Commission. <http://www.ifpri.cgiar.org/sites/default/files/publications/biofuelsreportec.pdf>. Accessed March 2010.

Banse, M., H. Grethe, and S. Nolte. 2004. *European Simulation Model (ESIM) in GAMS: Model Documentation.* Model documentation prepared for DG AGRI, European Commission. Gottingen and Berlin. <http://wwwuser.gwdg.de/~mbanse/publikationen/dokumentation-esim.pdf>. Accessed May 2010.

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

Bchir, M. H., Y. Decreux, J.-L.Guerin, and S. Jean. 2002. MIRAGE, un modele d'equilibre general calculable pour l'evaluation des politiques commerciales. *Economie Internationale* 89-90 (1Q-2Q): 109–153.

Birur, B., T. Hertel, and W. Tyner. 2008. *Impact of biofuel production on world agricultural markets: A computable general equilibrium analysis.* GTAP Working Paper No.53. West Lafayette, Ind.: Purdue University, Center for Global Trade Analysis.

Bottcher, H., K. Aoki, S. De Cara, M. Guti, P. Havlik, G. Kindermann, U. Schneider, and M. Obersteiner. 2008. *GHG Mitigation Potentials and Costs from Land-Use, Land-Use Change and Forestry (LULUCF).* Laxenburg, Austria: International Institute for Applied Systems Analysis.

Boumellassa, H., D. Laborde, and C. Mitaritona. 2009. *Panorama de la protection mondiale en 2004 : MAcMAP-HS6, Version 2.* Document de Travail du CEPII, 2009-22.

Britz, W. and P. Witzke, eds. 2008. *CAPRI model documentation 2008: Version 2.* Bonn: Institute of Food and Resource Economics. <http://www.capri-model.org/>. Accessed May 2010.

Bureau, J.-C., A.-C. Disdier, C. Gauroy, and D. Treguer. 2010. A quantitative assessment of the determinants of the net energy value of biofuels. *Energy Policy* 38(5): 2282–2290.

Burniaux, J. M. and T. Truong. 2002. *GTAP-E: An energy-environment version of the GTAP model.* GTAP Technical Paper No 16. West Lafayette, Ind.: Purdue University, Center for Global Trade Analysis.

Commission of the European Communities (CEC). 2008. *Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources*. Brussels: CEC. <http://ec.europa.eu/energy/climate_actions/doc/2008_res_directive_en.pdf>. Accessed June 2010.

Darwin, R., M. Tsigas, J. Lewandrowski, and A. Raneses. 2002. Land use and cover in ecological economics. *Ecological Economics* 17(3): 157–181.

Decreux, Y., and H. Valin. 2007. *MIRAGE, updated version of the model for trade policy analysis focus on agriculture and dynamics.* Technical Report 2007-15. Paris: Centre d'Etudes Prospectives et d'Informations Internationales.

Devadoss, S., P. Westhoff, M. Helmar, E. Grundmeier, K. Skold, W. H. Meyers, and S. R. Johnson. 1989. *The FAPRI Modeling System at CARD: A Documentation Summary*. Technical Report 89-TR 13. Ames, Iowa: Center for Agricultural and Rural Development.

European Biodiesel Board (EBB). 2008. *Statistics: The EU biodiesel industry*. < http://www.ebb-eu.org/stats.php>.Retrieved March 2008.

Food and Agriculture Organization of the United Nations (FAO). 2008. *The state of food and agriculture. Biofuels: prospects, risks and opportunities*. Rome: FAO-UN.

________. 2009a. *FAO Statistical Databases (FAOSTAT) - ProdSTAT* . Rome: FAO-UN. <http://faostat.fao.org/site/567/default.aspx >.Accessed January 2009.

________. 2009b. *FAO Statistical Databases (FAOSTAT) - ResourceSTAT - Land* . Rome: FAO-UN. <http://faostat.fao.org/site/377/default.aspx >.Accessed January 2009.

________. 2009c. *FAO Statistical Databases (FAOSTAT) - ResourceSTAT - Fertilizers.* Rome: FAO-UN. <http://faostat.fao.org/site/575/default.aspx >Accessed January 2009.Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. *Science* 319 (5867): 1235.

Farrell, A. E., R. J. Plevin, A. D. Jones, M. O'Hare, and D. M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311: 506–508.

Fischer, G., H. van Velthuizen, F. Nachtergaele, and S. Medow. 2000. *Global agro-ecological zones (global-AEZ)*[CD-ROM]. Technical report. Rome: FAO/International Institute for Applied Systems Analysis.

Fitzherbert, E., M. Struebig, A. Morel, F. Danielsen, C. Bruhl, P. Donald, and B. Phalan. 2008. How will oil palm expansion affect biodiversity? *Trends in Ecology and Evolution* 23 (10): 538–545.

Gaulier, G. and S. Zignano. 2009. *BACI: International Trade Database at the Product-level: the 1994-2007 Version*. Document de Travail du CEPII, 2009-xx.

Gallagher, E. 2008. *The Gallagher review of the indirect effects of biofuels production.* East Sussex: Renewable Fuels Agency.

Gohin, A., and F. Chantret. 2010. The long-run impact of energy prices on world agricultural markets: The role of macroeconomic linkages. *Energy Policy* 38(1): 333–339.Golub, A., T. Hertel, H.-L. Lee, S. Rose, and B. Sohngen. 2006. *The Opportunity Cost of Land Use and the Global Potential for Greenhouse Gas Mitigation in Agriculture and Forestry.* GTAP Working Paper No. 36. West Lafayette, Ind.: Purdue University, Center for Global Trade Analysis.

Golub, A., T. Hertel, and B. Sohngen, 2007. *Global economic integration and land use change.* Paper presented at the 10th Annual Conference on Global Economic Analysis, 7-9 June 2007, Purdue University, West Lafayette, Ind.

________. 2008. *Land use modeling in recursively-dynamic GTAP framework.* GTAP Working Paper No.48. West Lafayette, Ind.: Purdue University, Center for Global Trade Analysis.

Gnansounou, E., A. Dauriat, L. Panichelli, and J. Villegas. 2008. Energy and greenhouse gas balances of biofuels: Biases induced by LCA modelling choices. *Journal of Scientific and Industrial Research* 67: 885–897.

Gurgel, A., J. M. Reilly, and S. Paltsev. 2007. Potential land use implications of a global biofuels industry. *Journal of Agricultural and Food Industrial Organization* 5(2):1-34.

Havlik, P., U. A. Schneider, E. Schmid, H. Bottcher, S. Fritz, R. Skalsky, K. Aoki, S. De Cara, G. Kindermann, F. Kraxner, S. Leduc, I. McCallum, A. Mosnier, T. Sauer, and M. Obersteiner. 2010. Global land-use implications of first and second generation biofuel targets. *Energy Policy*, forthcoming.

Hayes, D., B. Babcock, J. Fabiosa, S. Tokgoz, A. Elobeid, T. Yu, F. Dong, C. Hart, E. Chavez, S. Pan, M. Carriquiry, and J. Dumortier. 2009. Biofuels: Potential production capacity, effects on grain and livestock sectors, and implications for food prices and consumers. *Journal of Agricultural and Applied Economics* 41(2): 1–27.

Headey, D., and S. Fan. 2008. Anatomy of a crisis: The causes and consequences of surging food prices. *Agricultural Economics.* 39(s1): 375–391.

Hertel, T. W., A. A. Golub, A. D. Jones, M. O'Hare, R .J. Plevin, and D. M. Kammen. 2010. Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-mediated Responses. *BioScience* 60(3):223-231.

Hertel, T., C. E. Ludena, and A. Golub. 2006. *Economic growth, technological change, and patterns of food and agricultural trade in Asia*. Technical Report. Manila, Philippines: Asian Development Bank.

Hertel, T., W. Tyner, and D. Birur. 2010. Global impacts of biofuels. *Energy Journal* 31(1): 75–100.

Hochman, G., S. Sexton, and D. Zilberman. 2010. *The economics of trade, biofuel, and the environment*. University of California at Berkeley Department of Agricultural and Economics and Policy (CUDARE) Working Paper No.1100. Berkeley: University of California.

Horridge, J. M. 2005. *SplitCom: Programs to disaggregate a GTAP sector.* Melbourne, Australia: Monash University, Centre of Policy Studies.

Intergovernmental Panel on Climate Change (IPCC). 2006. *2006 IPCC Guidelines for national greenhouse gas inventories,* Volume 4. Geneva: Intergovernmental Panel on Climate Change.< http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>. Accessed November 2009.

International Energy Agency (IEA). 2008. *World Energy Outlook 2008*. Paris: International Energy Agency.

Koh, L., and D. Wilcove. 2008. Is oil palm agriculture really destroying tropical biodiversity? *Conservation Letters* 1(2): 60–64.

Larson, E.D. 2006. A review of LCA studies on liquid biofuel systems for the transport sector. *Energy for Sustainable Development* X (II): 109–126.

Lee, H., T.W. Hertel, S. Rose, and M. Avetisyan. 2008. *An integrated global land use data base for CGE analysis of climate policy options.* GTAP Technical Paper No. 42. West Lafayette, Ind.: Purdue University, Center for Global Trade Analysis.

Metschies Consult. 2005. *International Fuel Prices 2005, 4th Edition*. <http://internationalfuelprices.com/>. Retrieved March 2008.

Monfreda, C., N. Ramankutty, and T. Hertel. 2007. *Global agricultural land use data for climate change analysis.* GTAP Technical Paper No. 40. West Lafayette, Ind.: Purdue University, Center for Global Trade Analysis.

Mortimer, N. D, A. Ashley, A. Evans, A. T. Hunter, and V. L. Shaw. 2008. *Support for the review of indirect effects of biofuels.* Stocksfield, U.K.: North Energy.

Morton, D. C., R. S. DeFries, Y. E. Shimabukuro, L. O. Anderson, E. Arai, F. del Bon Espirito-Santo, R. Freitas, and J. Morisette. 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon, *Proceedings of the National Academy of Science of the United States of America* 103(39): 14637–14641.

Narayanan G. B., and T. L. Walmsley, eds. 2008. *Global trade, assistance and protection: The GTAP 7 database.* West Lafayette, Ind.: Purdue University, Center for Global Trade Analysis.

Netherlands Environmental Assessment Agency (MNP). 2006. *Integrated modelling of global environmental change: An overview of IMAGE 2.4.* MNP publication number 500110002/2006. Bilthoven: Netherlands Environmental Assessment Agency.

Organisation of Economic Co-operation and Development (OECD). 2003. *Agricultural policies in OECD countries 2000. Monitoring and Evaluation.* Paris: Organization for Economic Co–operation and Development.

________. 2006. *Agricultural market impacts of future growth in the production of biofuels.* Paris: Organization for Economic Co–operation and Development.

________. 2007. *Documentation of the AgLink-CosimoModel.* Paris: Organization for Economic Co–operation and Development.

________. 2008. *Economic Assessment of Biofuel Support Policies*, Paris: Organization for Economic Co–operation and Development.

Prins, A. G., E. Stehfest, K. Overmars, and J. Ros. 2010. *Are models suitable for determining ILUC Factors?* Netherlands Environmental Assessment Agency publication number 500143006. Bilthoven: MNP.

Rajagopal, D., and D. Zilberman. 2008. *The use of environmental life-cycle analysis for evaluating biofuels.* Berkeley: University of California, Giannini Foundation of Agricultural Economics.

Rajagopal, D, S. Sexton, G. Hochman, D. Roland-Holst, and D. Zilberman. 2009. Model estimates food-versus-biofuel trade-off. *California Agriculture* 63 (4):199–201.

Renewable Fuels Association (RFA). 2005. *Homegrown for the Homeland: Industry Outlook 2005*. <http://www.ethanolrfa.org/pages/statistics>. Retrieved March 2008.

Roberts, M. J., and W. Schlenker, 2009. World supply and demand of food commodity calories. *American Journal of Agricultural Economics* 91(5): 1235–1242.

Rosegrant, M. W., C. Ringler, T. B. Sulser, T. Zhu, and S. A. Cline. 2008. *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description.* Washington, DC: International Food Policy Research Institute.

Salhofer, K. 2000. *Elasticities of substitution and factor supply elasticities in European agriculture: A review of past studies.* Diskussionspapier Nr. 83-W-2000. Vienna, Austria: Universität für Bodenkultur, Institut für Wirtschaft, Politik und Recht.

Schnitkey, G. 2008. *Fertilizer production costs have large increases. Farm Business Management*. Urbana, IL: Department of Agricultural and Consumer Economics, University of Illinois <http://www.farmdoc.illinois.edu/manage/newsletters/fefo08_13/fefo08_13.html>. July 11, 2008.

Seale, J., A. Regmi, and J. A. Bernstein. 2003. *International evidence on food consumption patterns.* Technical Bulletin No. TB1904. Washington, DC: Economic Research Service, United States Department of Agriculture.

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

Sohngen, B., C. Tennity, M. Hnytka, and K. Meeusen. 2008. *Global forestry data for the economic modeling of land use.* GTAP Working Paper No. 41. West Lafayette, Ind.: Purdue University, Center for Global Trade Analysis.

Tabeau, A., B. Eickhout, and H. van Meijl. 2006. *Endogenous agricultural land supply: Estimation and implementation in the GTAP model.* Paper presented at the 9th Annual Conference on Global Economic Analysis, June 2006, Addis Ababa, Ethiopia.

Taheripour, F., D. K. Birur, T. W. Hertel, and W. E. Tyner. 2007. *Introducing liquid biofuels into the GTAP Database*. GTAP Research Memorandum No.11. West Lafayette, Ind.: Purdue University, Center for Global Trade Analysis.

U.S. Environmental Protection Agency. 2010. *Renewable fuel standard program* (RFS). <http://www.epa.gov/otaq/fuels/renewablefuels/index.htm>. Accessed June 2010.

van der Mensbrugghe, D. 2005. *LINKAGE Technical Reference Document: Version 6.0*. Washington, DC: The World Bank. Mimeo.

Zah, R., H. Boni, M. Gauch, R. Hischier, M. Lehmann, and R. Wager. 2007. *Life cycle assessment of energy products: Environmental assessment of biofuels.* Technical report. Bern: Materials Science and Technology, Federal Office for Energy.

RECENT IFPRI DISCUSSION PAPERS

For earlier discussion papers, please go to http://www.ifpri.org/publications/results/taxonomy%3A468.
All discussion papers can be downloaded free of charge.

1017. *Analyzing nutritional impacts of policies: An empirical study for Malawi*. Olivier Ecker and Matin Qaim, 2010.

1016. *Optimal rainfall insurance contracts for maize producers in Ghana's northern region: A mathematical programming approach*. Francis M. Muamba and John M. Ulimwengu, 2010.

1015. *Impacts of climate change on agriculture and policy options for adaptation: The case of Vietnam*. Bingxin Yu, Tingju Zhu, Clemens Breisinger, and Nguyen Manh Hai, 2010.

1014. *Spatial price transmission and market integration in Senegal's groundnut market*. Ousmane Badiane, John M. Ulimwengu, and Fleur Wouterse, 2010.

1013. *Strategies for adapting to climate change in rural Sub-Saharan Africa: A review of data sources, poverty reduction strategy programs (PRSPs) and national adaptation plans for agriculture (NAPAs) in ASARECA member countries.* Jonathan Makau Nzuma, Michael Waithaka, Richard Mbithi Mulwa, Miriam Kyotalimye, and Gerald Nelson, 2010.

1012. *Do health investments improve agricultural productivity?: Lessons from agricultural household and health research.* Paul E. McNamara, John M. Ulimwengu, and Kenneth L. Leonard, 2010.

1011. *Investigating the role of poultry in livelihoods and the impact of avian flu on livelihoods outcomes in Africa: Evidence from Ethiopia, Ghana, Kenya, and Nigeria.* Ekin Birol, Dorene Asare-Marfo, Gezahegn Ayele, Akwasi Mensa-Bonsu, Lydia Ndirangu, Benjamin Okpukpara, Devesh Roy, and Yorbol Yakhshilikov, 2010.

1010. *Constraints to fertilizer use in Nigeria: Insights from agricultural extension service*. Afua B. Banful, Ephraim Nkonya, and Victor Oboh, 2010.

1009. *Do household definitions matter in survey design? Results from a randomized survey experiment in Mali*. Lori Beaman and Andrew Dillon, 2010.

1008. *Livestock development planning in Uganda: Identification of areas of opportunity and challenge.* Todd Benson and Samuel Mugarura. 2010.

1007. *Migratory responses to agricultural risk in northern Nigeria*. Andrew Dillion, Valerie Mueller, and Sheu Salau. 2010.

1006. *Do comprehensive Africa agriculture development program (CAADP) processes make a difference to country commitments to develop agriculture?: The case of Ghana*. Shashidhara Kolavalli, Kathleen Flaherty, Ramatu Al-Hassan, and Kwaku Owusu Baah, 2010.

1005. *The new Nicaraguan water law in context: Institutions and challenges for water management and governance*. Paula Novo and Alberto Garrido, 2010.

1004. *Potential of carbon markets for small farmers: A literature review.* Alessandro De Pinto, Marilia Magalhaes, and Claudia Ringler, 2010.

1003. *Understanding gender differences in agricultural productivity in Uganda and Nigeria*. Amber Peterman, Agnes Quisumbing, Julia Behrman, and Ephraim Nkonya, 2010.

1002. *Old problems in the new solutions? Politically motivated allocation of program benefits and the "new" fertilizer subsidies*. Afua Branoah Banful, 2010.

1001. *The role of public–private partnerships in promoting smallholder access to livestock markets in developing countries: methodology and case studies*. Karl M. Rich and Clare A. Narrod, 2010.

1000. *Mapping the policy process in Nigeria: Examining linkages between research and policy*. Noora-Lisa Aberman, Eva Schiffer, Michael Johnson, and Victor Oboh, 2010.

999. S*ales location and supply response among semisubsistence farmers in Benin: A heteroskedastic double selection model.* Hiroyuki Takeshima and Alex Winter-Nelson, 2010.

998. *A review of collective action in rural Ghana*. Adam Salifu, Gian Nicola Francesconi, and Shashidhara Kolavalli, 2010.

997. *Eight years of Doha trade talks: Where do we stand?* Antoine Bouet and David Laborde Debucquet, 2010.

996. *Price, inventories, and volatility in the global wheat Market*. Kyösti Pietola, Xing Liu, and Miguel Robles, 2010.

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

www.ifpri.org

IFPRI HEADQUARTERS

2033 K Street, NW
Washington, DC 20006-1002 USA
Tel.: +1-202-862-5600
Fax: +1-202-467-4439
Email: ifpri@cgiar.org

IFPRI ADDIS ABABA

P. O. Box 5689
Addis Ababa, Ethiopia
Tel.: +251 11 6463215
Fax: +251 11 6462927
Email: ifpri-addisababa@cgiar.org

IFPRI NEW DELHI

CG Block, NASC Complex, PUSA
New Delhi 110-012 India
Tel.: 91 11 2584-6565
Fax: 91 11 2584-8008 / 2584-6572
Email: ifpri-newdelhi@cgiar.org