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A dynamic simulation of the ILUC effects of biofuel use in the USA

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HIGHLIGHTS

- Biofuel production in the USA leads to increases in agricultural land area in some regions.
- Real income effects of the policy lead to reductions in agricultural land area in a few regions.
- Estimates of the indirect land use change (ILUC) range from −0.126 to 0.170 ha per 1000 gallons in the benchmark case.
- Land and fossil resource supply elasticities have significant effects on the estimates of ILUC.
- Dynamics are important in estimating the indirect land use change effects of biofuels.

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ABSTRACT

The global indirect land use change (ILUC) implications of biofuel use in the United States of America (USA) from 2001 to 2010 are evaluated with a dynamic general equilibrium model. The effects of biofuels production on agricultural land area vary by year; from a net expansion of 0.17 ha per 1000 gallons produced (2002) to a net contraction of −0.13 ha per 1000 gallons (2018) in Case 1 of our simulation. In accordance with the general narrative about the implications of biofuel policy, agricultural land area increased in many regions of the world. However, oil-export dependent economies experienced agricultural land contraction because of reductions in their revenues. Reducing crude oil imports is a major goal of biofuel policy, but the land use change implications have received little attention in the literature. Simulations evaluating the effects of doubling supply elasticities for land and fossil resources show that these parameters can significantly influence the land use change estimates. Therefore, research that provides empirically-based and spatially-detailed agricultural land-supply curves and capability to project future fossil energy prices is critical for improving estimates of the effects of biofuel policy on land use.

1. Introduction

Current biofuel policy in the USA seeks to reduce imports of crude oil and to lower emissions of greenhouse gases (GHG) from liquid transportation fuels. These objectives are reflected in the U.S. Energy Independence and Security Act (EISA) of 2007. The renewable fuel standard (RFS) section of the EISA sets annual targets for total biofuel use that climb from 9 billion gallons in 2008 to 36 billion gallons by 2022. In addition, consumption targets and reductions in life-cycle GHG emissions relative to petroleum products are set for different types of biofuels. Conventional biofuel is ethanol derived from corn starch and its production is capped at 15 billion gallons per year. Conventional biofuels are required to reduce GHG emissions by at least 20 percent relative to gasoline. Advanced biofuels are defined as renewable fuels not derived from corn starch, including biomass-based diesel and cellulosic-based ethanol, among other categories.[1] Advanced biofuels are required to reduce GHG emissions by at least 50 percent relative to the gasoline equivalent. These EISA rules are often collectively referred to as the RFS2 because the preceding U.S. Energy Policy Act of 2005 included a more modest RFS target of 7.5 billion gallons per year by 2012. Apart from the federal renewable fuel mandates, several USA states, including California and New York, passed legislation between 2001 and 2004 to replace methyl tertiary butyl ether (MTBE) with ethanol as an additive (oxygenate) in gasoline because of water contamination. Spurred by these policy changes and other market

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[1] These include ethanol derived from sugar or starch (other than corn starch), ethanol derived from waste material (including crop residue, other vegetative waste material, animal waste, and food waste and yard waste), biogas, butanol or other alcohols produced through the conversion of organic matter from renewable biomass.

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developments, corn-based ethanol production in the USA increased from 1.8 billion gallons in 2001 to 10.9 billion gallons in 2010, representing an average annual growth rate of more than 20 percent. In 2010, installed corn-ethanol capacity stood at more than 13 billion gallons per year with another 1.4 billion gallons of capacity reported as under construction or resulting from expansion. The development of advanced biofuels has been slower than anticipated by EISA, leading to changes in the annual cellulosic biofuel target[2] .

The rapid expansion of corn ethanol production in the USA since 2001 has been accompanied by a re-evaluation of the costs and benefits of biofuels because of concerns over the potential indirect impacts. The use of commodities, such as corn, for biofuel production has been cited for rising food prices, generating a vigorous global food-versus-fuel debate (Muller et al., 2008). In addition, the EISA defined life-cycle GHG emissions as “the aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes).” The express directive on land use change in the EISA has led to a considerable amount of research to estimate the global indirect land use change (ILUC) effects of biofuel production and its associated GHG emissions.

The indirect effects of biofuels are not readily evident from the data, and as a result ILUC must be estimated through modeling. Most of the models that have been employed for this purpose can be classified broadly into partial equilibrium (PE) and general equilibrium (GE) categories. The economy-wide framework of GE models makes them suitable for capturing the extensive economic interactions that govern the indirect effects of biofuels production and use. However, their economy-wide scope limits the amount of detail that can be incorporated in such models if they are to remain tractable. PE models concentrate on one or a few sectors of the economy and can incorporate details to capture local-level socioeconomic factors, but tend to overestimate indirect effects because of the absence of economy-wide adjustment mechanisms.

Examples of PE models used for biofuel policy analysis in the literature are FASOM, FAPRI, POLYSYS, AGLINK/COSIMO, IMPACT and GLOBIOM. These models generally focus on the agricultural sectors, but in some cases include forestry.[3] The first three are models of the USA, whereas the others have a global scope. GE models used for biofuel policy evaluation include the USAGE model, various versions of the GTAP model (e.g. GTAP-E, GTAP-EL, GTAP-BIO, GTAP-LEI) and others that generally make use of the GTAP database of the global economy, including DART, MIRAGE, EPPA-MIT, WorldScan, and LEITAP, among others.[4] A number of modeling efforts, including GTAP/IMAGE, GTAP/CLUE, and Land-SHIFT, have begun to merge the PE and GE approaches for biofuel policy analysis to combine their different advantages. Witzke et al. (2008) provide an overview of biofuel modeling in PE models, while Kretschemer and Peterson (2010) focus on GE models. These reviews highlighted a number of crucial factors that drive the land use change estimates attributed to biofuels in the literature, including data availability/quality and modeling choices related to the biofuel production process, land use/supply, biofuel trade, by-product accounting, and the specification of biofuel policy, among others.

Estimates of the potential ILUC impacts of biofuel production in the USA in the literature range from 0.09 to 0.73 ha per 1000 gallons (Tyner et al., 2010; CARD, 2009; Hertel et al., 2010; Oladosu and Kline, 2010; Searchinger et al., 2008). The most recent estimates are generally in the lower end of this range, but differences remain. For example, USEPA (2010) ruled that corn-based ethanol in the USA and sugarcane-based ethanol in Brazil met the emission threshold for conventional biofuels and advanced biofuels, respectively. However, Lapola et al. (2010) suggested that indirect land use change can overcome carbon savings from biofuels in Brazil. Plevin et al. (2010) explored a range of parameters within a reduced-form model and concluded that fuel policies that require narrow bounds around point estimates of life-cycle GHG emissions are incompatible with current and anticipated modeling capabilities. Recent analyses using empirical methods suggest that biofuel production in the USA produced small effects on land use and external markets during the past decade (Kim and Dale, 2011; Oladosu et al., 2011; Gallagher, 2010). Thus, there is a continuing need to improve the modeling and estimation of the land use implications of biofuels to support the development of more sustainable alternatives to fossil fuels.

This paper provides a dynamic evaluation of the global indirect land use change implications of recent biofuel production in the USA. Most simulations of the ILUC effects of biofuels with GE models have employed a static framework. The dynamic model employed here, GTAP-DEPS (GTAP for Dynamic Energy Policy Simulations), is a significant enhancement of the static modeling approach (Oladosu, 2012). It allows the recent evolution of biofuel use in the USA to be simulated explicitly. In addition to dynamics, sub-models of energy resources supply, labor supply and investment in GTAP-DEPS are enhanced to better reflect the role of biofuel production and use in the USA and the global economy. The rest of the paper is organized as follows. The next section presents an overview of the model employed in this study, its data sources, and its calibration. The following section describes the scenarios simulated with the model and the results. A summary section highlights the main results, and the paper ends with a conclusions section.

2. Approach: The GTAP-DEPS model

The model employed in this study is based on the GTAP framework, which is a combined computable general equilibrium (CGE) database and modeling framework developed by the Center for Global Trade Analysis at Purdue University, USA. It combines “bilateral trade, transport and production data characterizing economic linkages among regions, together with individual country input–output databases which account for inter-sectoral linkages within regions” (CGTA, 2008). The standard GTAP model includes only a few sectors and regions. Practical applications generally expand the number of sectors and regions, and incorporate more sophisticated specifications of economic activities than the standard model. GTAP-DEPS is a recursive dynamic model built using version 6 of the GTAP database. It includes 18 world regions and 33 economic sectors, with one of these sectors representing the production of investment goods.

2.1. Overview of the GTAP-DEPS model

The structure of the standard GTAP model is documented in Hertel (1997). As with all CGE models, it solves for the vector of prices that jointly maximize consumer utility from the purchase of goods and services subject to budget constraints, and that minimize the producer costs of production under zero-profit conditions. The model incorporates specifications for bilateral trade

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[2] For the U.S. Environmental Protection Agency USEPA (2010) lowered the cellulosic target from 100 million gallons to 6.5 million gallons.

[3] Forest and Agricultural Sector Optimization Model (FASOM); Food and Agricultural Policy Research Institute (FAPRI); Policy Analysis System (POLYSYS); AGLINK/COSIMO is an agricultural model used by the Organization for Economic Cooperation and Development (OECD); International Policy Analysis of Agricultural Commodities and Trade(IMPACT); Global Biomass Optimization Model (GLOBIOM).

[4] Global Trade Analysis Project (GTAP); Modeling International Relationships in Applied General Equilibrium (MIRAGE); Dynamic Applied Regional Trade (DART); Emissions Prediction and Policy Analysis (EPPA);

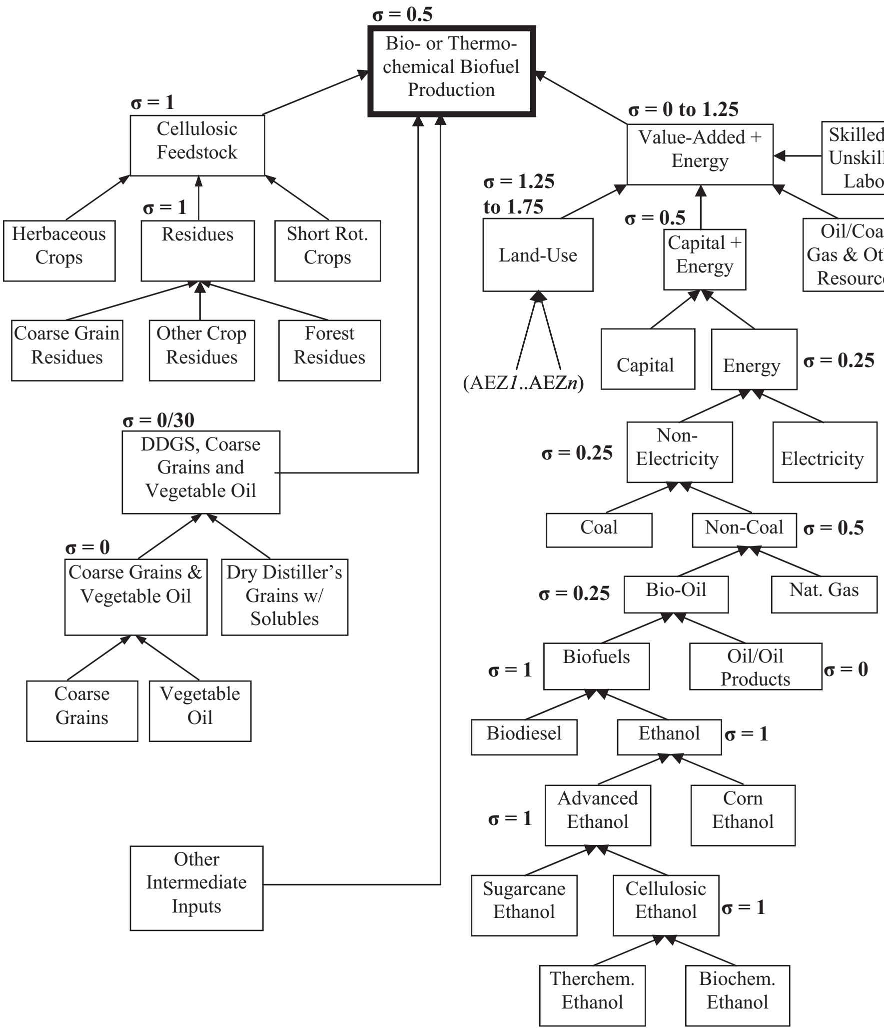

Fig. 1. Structure of production activities in GTAP-DEPS.

relations as well as equations for savings and investments. The starting point for the GTAP-DEPS model is the GTAP-E version (McDougall and Golub, 2009), which has a more sophisticated energy use and substitution structure than the standard model. Regional production in each sector of the economy is modeled with nested constant elasticity of substitution (CES) cost functions that combine primary factor inputs with intermediate inputs. The resulting nested structure for production activities in the GTAP-DEPS model is illustrated in Fig. 1. The symbol, σ, in Fig. 1 represents the elasticity of substitution parameters in the cost functions. Incomes from factor supply, taxes, and other incomes accrue to an aggregate regional household.

Taxes/subsidies include those on output, domestic and intermediate inputs, primary factors, household income, government and private consumption, as well as tariffs on international trade. Incomes received by the aggregate regional household are distributed to a private household, a government, and a capital account (savings) with fixed shares. Government income is allocated to goods and services according to a Cobb–Douglas utility function. Purchases of goods and services by the private household are based on the constant differences in elasticities (CDE) expenditure system (Liu et al.,1998). International trade in goods/services is modeled with a two-level nest of CES functions based on the Armington assumption of imperfect substitution among traded goods and services. The demand for each good or service is modeled for each type of buyer (private household, government, and producer) as a composite of purchases from domestic and foreign markets. In turn, the aggregate import demand for each good or service is an Armington composite of supplies from different foreign markets. The total export of a good or service from each region is calculated as the sum of demand over all importing regions. A market-clearing condition ensures that total domestic production is equal to the sum of domestic and export sales.

2.2. *Specifications for biofuel policy analyses*

2.2.1. *Modeling of biofuel production and use*

The model allows biofuels to substitute for oil/oil products to approximate the blending of biofuel and oil products at refineries or product terminals. In addition, households can purchase biofuels as direct substitutes for petroleum products. The ease of substitution in the latter case can be used to distinguish between a largely biofuel-blending supply system, such as the existing biofuel supply/use chain in the USA, and one in which consumers can choose between petroleum and biofuels at the pump, such as in Brazil. In both cases, the final product to the consumer is modeled as a bio-oil mix. As illustrated in Fig. 1, the aggregate biofuel commodity is modeled as a hierarchical nest of the different categories of biofuels similar to those specified in the RFS2 policy. On the top level of the bio-oil nest, biodiesel and ethanol are combined into the aggregate biofuel commodity.

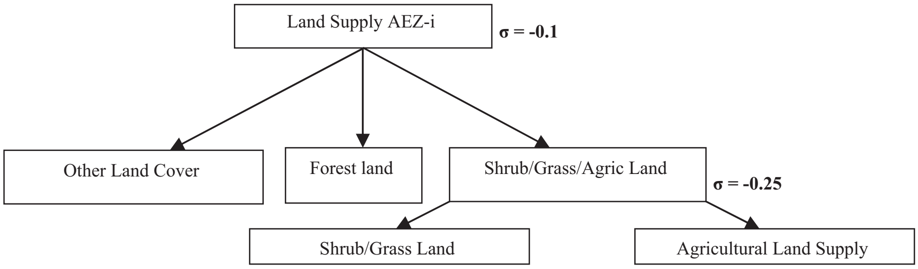

Fig. 2. Agro-ecological zone land supply sub-model.

Ethanol is then a combination of conventional ethanol (corn ethanol produced from coarse grains in the model) and advanced ethanol, with the latter including sugarcane and cellulosic ethanol. Finally, cellulosic ethanol is produced from biochemical and thermochemical processes. Cellulosic feedstock includes crop residues, forest residues, short-rotation forestry, and herbaceous energy crops. This nesting structure is designed to provide a flexible representation of the evolution of different biofuel categories as they respond to policy, technology, and other changes over time.

2.2.2. *Land-supply modeling*

Fig. 1 shows that land input into each crop, forestry and pasture activity is a combination of land from different agro-ecological zones or AEZ (Lee et al., 2007).[5] The total demand for agricultural land in each AEZ is calculated as the sum of allocations to crops, forestry and pasture activities. Fig. 2 illustrates the land-supply sub-model which incorporates four primary land cover categories, forestland, shrub/grass land, agricultural land and other land. Total land cover in each AEZ is allocated to three aggregate cover types (forest, composite shrub/grass/agricultural land, and other land cover) in the top nest of Fig. 2. The composite shrub/grass/agricultural land in turn is the combination of shrub/grass and agricultural lands. This two-level nesting structure attempts to capture the fact that shrubland/grassland can be brought into agricultural production more easily than forest and represents the main transition pathway between standing forests and other land cover. Supply prices for the non-agricultural land-cover categories were set and held at 1. This procedure allows us to keep quantities in the land supply sub-model in physical terms (i.e., hectares) while the land use sub-nest in Fig. 1 is based on economic data (dollars).[6] Constant prices for these land-cover categories also mean that only changes in agricultural land prices drive the allocation of land. Agricultural land prices and quantities in the land use and land-supply sub-models are linked by equating their percentage changes, implying that the translation factor between the physical and economic measures of agricultural land is constant. The intersection of the upward sloping land supply curve (from the land supply sub-model) with the land demand curve (from the land use sub-model) produces equilibrium prices for agricultural land in each regional AEZ.

The yield implications of changes in the size and distribution of agricultural land occur on the land use side of the model, but the effects are transmitted to the supply sub-model through percentage changes in quantities and prices. Changes in the relative prices of agricultural inputs lead to shifts in the relative use of land and other inputs per unit of agricultural production. This captures the yield effects of changes in the intensity of agricultural land use, such as changes in fertilization rates per unit land area. The model also includes separate non-intensive yield functions with both non-price (trend) and price-driven components. The price-driven component captures yield changes that are not directly associated with the substitution of other inputs for land but may be motivated by increases in the price of agricultural commodities, such as changes in rotation and double-cropping, among others. In the model, this component responds to the price of the value-added/energy composite input in Fig. 2, where land enters the production structure.

2.2.3. *Corn ethanol by-product modeling*

By-products of corn ethanol production, mainly distillers' dry grains with solubles (DDGS), are crucial to evaluating its land use effects. DDGS is a substitute for corn and soymeal in livestock feed. The production of DDGS in the USA was estimated at about 38 million tons in 2009, with exports growing from under 1 million tons in 2004 to more than 8 million tons (Wisner, 2010). In order to capture this substitution, the coarse grains and vegetable oil commodities in the model are included in a separate intermediate input sub-nest as shown in Fig. 1. Soymeal purchases by livestock sectors are in the input–output intersection of these sectors with the vegetable oil sector. Composite purchases of coarse grains and soymeal are substitutes for DDGS in another sub-nest. Production of DDGS is included as a sector of the economy that purchases inputs mainly from the corn ethanol sector, but also from other sectors. Output of the DDGS sector is a fixed coefficient function of corn ethanol production.

2.2.4. *Labor and natural resource supply modeling*

Supplies of labor and natural resources are modeled as functions of the regional wage rate and resource rents, respectively. For skilled and unskilled labor this is a constant-elasticity function, with an intercept that is specified exogenously to represent the population-driven change in the labor force. Similarly, supply functions for each of the four natural resources in the model (oil, coal, natural gas, and other resources) are specified separately as exclusive endowments for the crude oil production, coal production, natural gas production, and other industry/services sectors, respectively. Representation of energy-resource costs is important for capturing the interaction between fossil and biofuel energy markets, which in turn is an important ingredient in measuring the indirect effects of biofuel policy.

2.3. *Model dynamics*

The model structure described above is entirely static. The GTAP-DEPS model incorporates explicit dynamics of regional capital stock accumulation, international assets/liabilities, international investment/

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[5] Agro-ecological zones are mappings of global land based on agro-ecological characteristics, such as precipitation, temperature, soil type, etc. In the land data complementing the GTAP economic database, there are 18 AEZs representing the combination of six lengths of growing period categories and three climatic regimes.

[6] Initial prices are usually set to a value of 1 in CGE models so that all quantities can be denominated in comparable monetary terms. However, because all quantities in the land-supply sub-model are in hectares, this unitary valuation allows us to specify this sub-model in physical rather than monetary terms. This practice is particularly useful since these land-cover categories are not part of the existing economic accounts but are potential resources for economic production.

income flows, and financial assets as described in Ianchovichina and McDougall (2001). Letting *1* and *0* represent current and previous periods, respectively, this investment decision framework can be described by the following equations:

$$I_1 = K_1\left[g_{nk,1} - \left(\frac{eg_{i,1}}{\varepsilon_{i,k}}\right)\right] \tag{1}$$

$$g_{nk,1} = g_{nk,0} + \mu_k\left[\frac{g_{ia,1}}{\varepsilon_{i,k}} + g_{k,1} - g_{nk,0}\right] \tag{2}$$

$$g_{ia,1} = [g_{rk,1} - g_{pi,1}] \tag{3}$$

$$g_{k,1} = \frac{I_0}{K_0} \tag{4}$$

$$K_1 = g_{k,1}K_0 \tag{5}$$

$$eg_{i,1} = \mu_f[g_{if,1} - g_{ie,1}] \tag{6}$$

$$g_{ie,1} = -\varepsilon_{i,k}[g_{k,1} - g_{nk,0}] - \mu_e[\ln(ie_0) - \ln(if_0)] \tag{7}$$

where, I=investment, net of depreciation, K=capital stock, i=rate of return on capital (ROR), eg_i=expected change in the growth rate of the ROR on capital, g_{nk}=normal or long-run growth rate of the capital stock, g_k=actual growth rate of the capital stock, g_{rk}=growth rate of the rental rate on capital, g_{pi}=growth rate in the price of investment goods, *ia*, *ie*, *if*=actual ROR, expected ROR, target ROR, g_{ia}, g_{ie}, g_{if}=growth rate of the actual, expected, and target ROR, $\varepsilon_{i,k}$=negative of the elasticity of expected ROR with respect to the capital stock, μ_f=adjustment factor for the expected change in the growth rate of the ROR on capital, μ_k=adjustment factor for the normal growth rate of capital, μ_e=adjustment factor for the expected ROR.

Eq. (1) can be recognized as a modified form of the long-run equilibrium investment function. A long-run equilibrium is found when the first term ($g_{nk,1}$) is constant, and the second term ($eg_{i,1}$) is zero, and requires that: (a) actual, expected and target rate of ROR on capital are equal; and (b) actual and normal growth rate of the capital stock are equal. The denominator ($\varepsilon_{i,k}$) in the second term of Eq. (1) is the elasticity of the ROR to changes in the capital stock, and serves to convert the expected growth rate in the ROR to the equivalent change in investment.

Eqs. (2)–(5) govern adjustments in the normal growth rate of the capital stock towards the long-run equilibrium. Eq. (2) adjusts the normal growth rate of the capital stock as a function of changes in the actual ROR, and the gap between the actual and previous normal growth rate of the capital stock. Eq. (3) defines the growth rate of actual ROR as the difference between the growth rate of the rental rate on capital ($g_{rk,1}$) and the growth rate in the price of investment goods ($g_{pi,1}$). Eq. (4) computes the growth rate in the capital stock ($g_{k,1}$) based on investments in the previous period (I_0), which determines the current capital stock as in Eq. (5).

Eq. (6) defines the expected growth rate of the ROR as a function of the gap between the growth of the target ROR ($g_{if,1}$) and the growth in the expected ROR ($g_{ie,1}$), with an adjustment factor, μ_f. The expected ROR adjusts to two gaps. First, the gap between the actual and previous normal rate growth of the capital stock is converted into an equivalent change in the expected ROR using the parameter, $\varepsilon_{i,k}$. Second, the expected ROR adjusts to the gap between the expected and targeted ROR in the previous period or the error in expectations about the ROR in the previous period, with an adjustment factor, μ_e.

The above dynamic specification gradually moves the economy towards a long-run stable equilibrium by penalizing gaps between the actual and normal or long-run capital stock, and between actual, expected and target ROR. In addition, the long-run capital stock is allowed to systematically adjust over time, rather than exogenously specified. The adjustment process is governed by the elasticity parameter, $\varepsilon_{i,k}$, and the three adjustment factors, μ_f, μ_k, and μ_e. Golub and McDougall (2011) show that parameter $\varepsilon_{i,k}$ is equal to the inverse of the elasticity of substitution in a CES function with labor and capital inputs. The adjustment factors can also be interpreted as elasticity parameters. This investment decision formulation is complemented with equations tracing changes in the distribution of regional household wealth between domestic and foreign equity, and changes in the distribution of the assets of a global trust among regional firms. In lieu of a full bilateral investment and equity matrix, the global trust serves as an intermediary that "manages" foreign investments on behalf of all regions. Incomes from regional firms, consisting of capital earnings, are distributed to regional households and to the global trust in proportion to their equity shares. In turn, the income received by the global trust is distributed to regional households in proportion to their shares in the global trust.

The above dynamics of capital and international investment/income flows have been incorporated in the GTAP-DEPS model with a number of changes. In the original formulation, the allocation of household wealth and international investments is based on an atheoretic cross-entropy portfolio-optimization approach. In the GTAP-DEPS implementation, the associated model equation has been replaced by a function in which the ratio of household assets in local equity to household assets in the global trust responds to the ratio of the asset prices of local firms and the global trust according to a given elasticity parameter. In addition, the distribution of net regional capital earnings and global trust income are based on initial, rather than final, domestic and foreign wealth/equity shares. Thus, while regional households and the global trust re-optimize the allocation of their equity/wealth during the current period, the changes do not affect income allocation until the next period. This matches the fact that new investments in capital, which are determined by the wealth allocation decisions of regional households and the global trust, are not productive until the following period. Changes in the equity value of regional firms are explicitly specified as equal to the value of new investments. In addition, the regional capital stock in the current period, consisting of the sum of capital stock and investment from the previous period (net of depreciation), is held fixed in the GTAP-DEPS model. Finally, the allocation of regional capital stock among firms is determined using a constant elasticity of transformation (CET) function according to the ratio of sectoral capital rental rates to the regional average rate. The elasticity parameter of the CET function can be set to make the movement of regional capital among firms sluggish or mobile, rather than perfectly mobile as in the standard GTAP model.

2.4. Model data and parameters

The model is based on a modified version of the GTAP-6 database (Taheripour et al., 2007), which added corn ethanol, sugarcane ethanol and biodiesel to the original global economic data. The database contains complete global data on production, consumption, trade, and investment, and this version of the data includes 57 economic sectors and 87 world regions. In addition, it includes default values for the expansion and substitution parameters of the household-expenditure system, input factor substitution, and Armington elasticities for domestic and import substitution. The database was aggregated and further modified in accordance with the model structure presented above. See Oladosu et al. (2012) for a detailed discussion of modifications to the social accounting matrix and generation of a baseline forecast of exogenous dynamic variables for the GTAP-DEPS model.

Parameters for the production and land supply sub-models are as shown in Figs. 1 and 2. These elasticities are comparable to values used in similar studies (Bouët et al., 2010). The elasticity parameters for the labor, coal, oil, natural gas, and other natural resource supply curves were chosen as follows. The supply elasticity for labor was assigned a value of 0.2. Parameters for oil, coal, and natural gas supplies were estimated by fitting the available supply data to global prices. The estimated supply elasticities range from 0 to 0.61 with an average of 0.16 for oil, 0 to 1.10 with an average of 0.26 for coal, and 0 to 1.27 with an average of 0.48 for natural gas. Parameters for the dynamic components of the model were set based on discussions in Golub and McDougall (2011). In particular, the parameters $\varepsilon_{i,k}$, μ_k, μ_f, and μ_e in Eqs. (1)–(7) were set to 1, 0.2, 0.4 and 0.4, respectively. In addition, the elasticity of transformation in the CET function for capital stock allocation to sectors was set to -2, allowing for a less than perfectly mobile movement of capital among sectors of the economy in response to relative changes in capital rental rates.

The price-induced components of the non-intensive yield functions are turned off initially by setting the yield elasticities to zero for the calibration and baseline runs of the model. The chosen values are discussed under the relevant simulation scenarios below. The intercept parameters for the yield curves are used to include trend increases in yield. Values for the three main crop groups (coarse grains, oilseeds and other grains) are set as two-thirds of the average percentage increases in yield from 2001 to 2009 in each region and are calculated from the Production, Supply, and Distribution Database (USDA, 2010). This assumption keeps the trend rate in coarse grains in the USA close to the empirically estimated rate for corn in Tannura et al. (2008). For the USA, these values were 1.86 percent for coarse grains, 1.65 percent for oilseeds, and 0.79 percent for other grains. Most of the estimates for all regions were between 1 and 2.5 percent, with only Japan having negative values of between -0.8 and -0.08 percent.

2.5. Model calibration and baseline simulation

The model was calibrated by exogenizing the regional gross domestic growth rates and setting them to the forecasted levels while making the average regional productivity of primary factors (excluding capital) endogenous to re-balance the model. Economic forecasts for the current analysis were based on data from the *World Development Indicators* (WDI) database (World Bank, 2010) and the *World Economic Outlook* (WEO) database (International Monetary Fund, 2010). After the calibration, a baseline run of the model was conducted by holding the regional productivity parameters at the calculated levels and endogenizing the regional gross domestic product once again. Fig. 3 shows two variables from the baseline run of the model. Fig. 3a is the baseline forecast of regional GDP growth rates with the crash in global growth rates in 2009 particularly notable. The USA economy grows at a rate of 2 to 3 percent after slowing to almost zero in 2008 and turning negative in 2009. Fig. 3b displays the pattern of investment

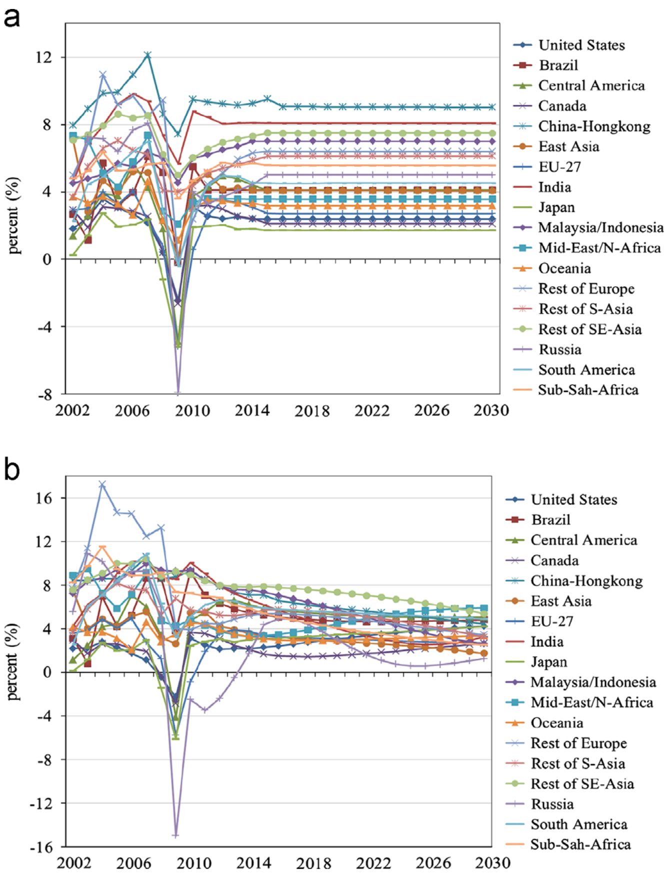

Fig. 3. (a) Regional GDP growth rates in the baseline, (b) regional investment growth rates in the baseline.

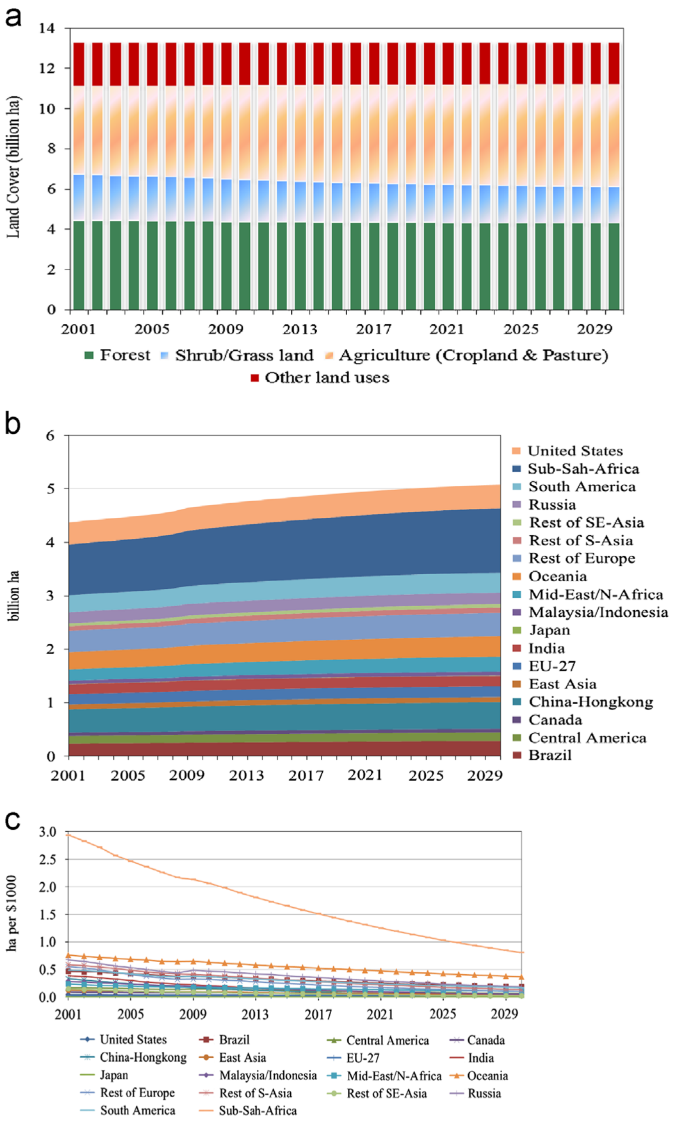

Fig. 4. (a) Global land cover in the baseline, (b) regional distribution of agricultural land in the baseline, (c) regional agricultural land area per $1000 of GDP in the baseline.

growth rates in all regions in the baseline run and shows its convergence over time as expected from the model dynamics and the real GDP growth rates shown in Fig. 3a.

Figs. 4a and 4b presents the baseline results for global land cover and the regional distribution of agricultural land. Fig. 4a shows that forest land area declines by about 130 million ha, from 4.45 billion ha in 2001 to about 4.32 billion ha (about 3 percent) by 2030, shrub/grassland declines by about 500 million ha or about 21 percent, and other land declines by about 100 million ha or about 5 percent. Agricultural land area in the baseline run of the model is projected to reach 5.1 billion ha by 2030, which is an increase of a little over 700 million ha or about 16 percent. Fig. 4b shows that the regional distribution of agricultural land did not change much over the time horizon. Sub-Saharan Africa accounts for one-fifth of the global total because of the large portion of its agricultural land that is in pasture, and its share increases slightly over the period. Other regions with increases in their shares of global agricultural land in the baseline simulation include Brazil, Oceania, and South America. Most of the remaining regions, including the United States, have slight decreases in their shares of global agricultural land. Fig. 4c displays the agricultural land area per $1000 of the real regional GDP in the baseline, showing a wide range from less than 0.03 (USA) to almost 3 (Sub-Saharan Africa). However, these values decline over the period from 2001 to 2030, reflecting the yield trends in the baseline as well as potential changes in the structure of the economy over time. For example, the agricultural land area per $1000 of real GDP for Sub-Saharan Africa falls from about 3 in 2001 to less than 1 in 2030.

Fig. 5 shows that the increase in biofuel production in the USA from 2001 to 2030 in the baseline simulation, assuming no RFS mandates, is small. Corn ethanol production grows from about 1.7 billion gallons in 2001 to almost 3 billion gallons in 2030. All other categories of biofuels remain largely flat. The changes in biofuel production in the baseline case are driven mainly by economic growth and the potential of the economy to consume biofuels without policy intervention. The low fuel flexibility of vehicles in the USA means that the elasticity of substitution between petroleum and biofuels is small. Thus, in the baseline simulation, increases in the real price of crude oil, from about $25 to $125 per barrel between 2001 and 2030, lead to minimal price-motivated substitution of petroleum with biofuels in the USA.

3. Biofuel policy simulations and results

The fulcrum of current USA biofuel policy, the RFS2 under EISA, is a hybrid technology mandate and performance standard. The biofuel blending requirements represent a technology mandate, while the emission thresholds set for each fuel type are performance standards. The additive (oxygenate) requirement in USA gasoline consumption, as well as recent rules that eliminated MTBE as an additive, can also be interpreted as hybrid technology and performance standards. These policies work in conjunction with other subsidy- and tax-based policies at federal and state levels, but these price-based incentives did not change significantly from 2001 to 2010. The specification of biofuel policy in the following simulations attempts to capture the implementation of the RFS2 mandates as described below.

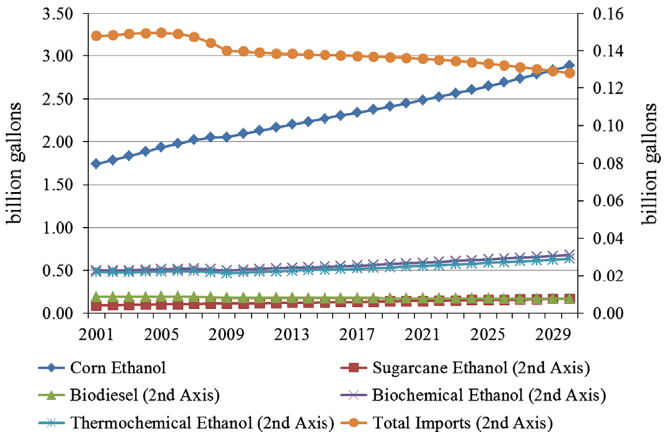

Fig. 5. Production of biofuels by type in the baseline.

3.1. Biofuel policy specification in the GTAP-DEPS model

Given the use of a CES function to model the blending of ethanol and petroleum products, the demand function for ethanol can be written as

$$\frac{Q_e}{Q} = A_e\left(\frac{P}{P_e}\right)^{\sigma} \tag{8}$$

where, Q_e, P_e=ethanol use and price, respectively, Q, P=total liquid fuel use and price, respectively, A_e=CES share parameter, σ=elasticity of substitution between biofuels and petroleum products.

In percentage change form, Eq. (8) can be equivalently written as

$$q_e = q + a_e - \sigma(p_e - p), \tag{9}$$

where a_e, q_e, q, p_e, and p represent the percentage change counterparts to A_e, Q_e, Q, P_e, and P, respectively.

The CES share parameter, A_e, is a structural or technology factor that determines the initial quantity ratio of ethanol to total liquid fuel before price effects are taken into consideration. It is also equal to the quantity share during model simulations if: (a) $\sigma=0$. This is the fixed coefficient Leontief production function in which ethanol and petroleum products are blended in fixed proportions or (b) $\sigma > 0$ and the price ratio in Eq. (8) is equal to (1).

Thus, the main role of σ is to determine how rapidly the quantity ratio changes from the initial calibration of Eqs. (8) and (9) in response to price changes. The share parameter is usually assumed to be constant in simulations with the CES function. In that case, the percentage change in a_e is zero. However, the elimination of MTBE from U.S. gasoline (driven by the loss of liability protection against water contamination) and the RFS2 ethanol blending requirements (a hybrid technology and performance mandate) are best represented as changes in the technology parameter, A_e, in this context. In essence, given the forecasted consumption of liquid fuels at the beginning of the year, the USEPA essentially specifies the required A_e parameter that would meet the RFS2 requirement. Given that these share parameters must sum to one, the share parameter for petroleum must decline in relation to the increase in the share of biofuels. Thus, a gallon of the petroleum–biofuel mix would require a larger amount of biofuels and a smaller amount of petroleum after the change, with or without changes in the relative price of petroleum and biofuels. This captures the nature of the RFS2 design and implementation in the USA. The ultimate consumption of ethanol during the year is then determined by a combination of the specified blending requirement, the elasticity of substitution, price changes, and total liquid fuel consumption, with the last two factors depending on market conditions and economic growth, among other factors. Once the implied change in a_e caused by the policy is accounted for in Eq. (9), the estimated/calibrated elasticity of substitution between petroleum products and ethanol in the U.S. economy would reflect the ability of the ethanol supply infrastructure and consumers to respond to relative gasoline and biofuel prices. For the current study, the elasticity of substitution

Table 1
Percentage changes in biofuel demand by category.

	Corn ethanol	Cellulosic ethanol	Other advanced ethanol	Biodiesel
2001 (billion gallons)	1.74	0.04	0.15	0.01
Percentage changes				
2002	19.10	0.01	25.97	22.24
2003	36.32	0.01	23.34	35.53
2004	25.70	0.01	27.03	96.39
2005	14.26	0.01	33.33	225.34
2006	35.05	0.01	25.00	175.85
2007	25.63	0.01	20.00	95.59
2008	40.62	0.01	16.67	38.06
2009	13.98	0.01	14.29	−25.35
2010	19.50	33.33	10.00	18.85

between petroleum products and ethanol was set at 0.25 in the United States and the rest of the world, except Brazil. In the case of Brazil, a value of 0.25 was also used on the production side of the economy to represent blending requirements, while a value of 2 was used for Brazilian households. The latter is appropriate because Brazil's vehicle stock and ethanol supply infrastructure enable a large proportion of consumers to exercise flexible price-based fuel choice at the pump.

3.2. *Biofuel policy simulation scenarios*

Four scenarios to examine the domestic and global land use implications of policy-motivated changes in biofuel production and use in the USA were simulated in this study. In Case 1, percentage increases in biofuel consumption in the USA were imposed on the baseline case for each year from 2002 to 2010 (see Table 1) and then held constant at the 2010 level from 2011 to 2030. We held the use of biofuels constant after 2010 to examine the implications for land use change from biofuel production between 2001 and 2010 over the entire simulation period. Exogenous parameters to represent policy-motivated changes in the petroleum-biofuel mix were added to the CES functions in the model. For total biofuel, biodiesel, corn ethanol and sugarcane ethanol these parameters are endogenous in the policy simulations, and the demands for biodiesel, sugarcane ethanol, corn ethanol and cellulosic ethanol are exogenous. Thus, the share of each component in each bio-oil/biofuel category shifts in response to the mandated percentage changes given in Table 1, even without changes in relative prices. However, the final solution represents the composite effects of the non-price shifts and changes in relative prices.

Case 2 added crop yield parameters to Case 1 through the price-responsive component of the non-intensive yield function as discussed in the second paragraph of Section (2.2) on land supply modeling. Estimates of crop yield elasticity with respect to price for the USA were derived for coarse grains (corn), oilseeds (soybeans) and other grains (wheat) from Huang and Khanna (2010) at 0.15, 0.06 and 0.43, respectively. Lacking reliable data on which to base crop yield elasticities, the remaining 17 regions of the model were assigned half of the values used for the USA. The resulting elasticities for other grains were also applied to the other land-using sectors (i.e., sugarcane, other agriculture, and the three livestock sectors).

Case 3 evaluates the sensitivity of simulation results to increases in the magnitude of land-supply elasticity parameters relative to Case 2. In Case 3, the slope of the land supply curves was reduced, lowering the equilibrium price for a given quantity of agricultural land in each AEZ. The magnitudes of the elasticities of transformation in Fig. 2 were doubled, changing the values from −0.1 and −0.25 to −0.2 and −0.5, respectively. Overall, this would be expected to lead to increases in the use of land relative to other factors of production in land-using sectors of the economy.

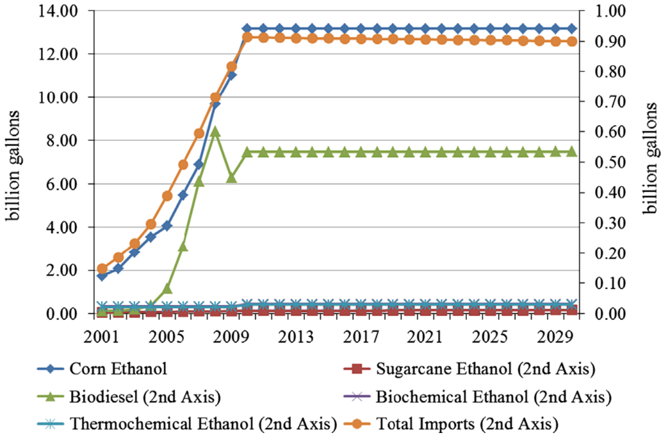

Fig. 6. Biofuels supply in the USA under Case 1.

Case 4 evaluates the impact of doubling the regional fossil resources supply elasticities. The reduced slope of these supply curves would be expected to reduce the price implications of a given change in oil sales and the attendant income effects.

3.3. *Case 1 results: Ethanol consumption in the USA from 2001 to 2010*

Fig. 6 displays the change in biofuel production in the USA under Case 1. It shows that the increases in biofuel supply are almost entirely from corn ethanol, accounting for almost 13.2 billion gallons in 2010. Biodiesel production is about 0.5 billion gallons, whereas the other advanced biofuels and imports remain small. The results are discussed below in terms of the LUC associated with all biofuels but the effects are largely driven by corn ethanol production.

The regional agricultural LUC implications under Case 1 are illustrated in Fig. 7.[7] It shows that agricultural land area increases in most countries, but the increase in the USA is the largest throughout the simulation period. Four regions, Sub-Saharan Africa, Mid-East/North Africa, Russia, and the Rest of Europe, show decreases in agricultural land area relative to the baseline. Brazil, Rest of South America, and Oceania also had contractions in agricultural land area starting in different years between 2010

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[7] Recall that in this study indirect land-use change (ILUC) is the net increase in agriculture land area in response to biofuel policy. In the simulation results, this corresponds to the change in total agricultural land cover, which nets out intercrop transfers.

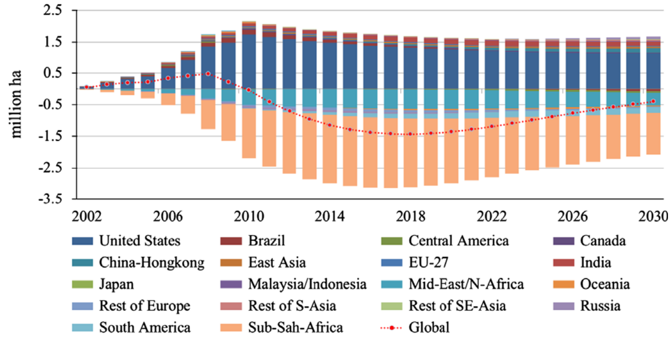

Fig. 7. Changes in agricultural land area under Case 1 relative to the baseline.

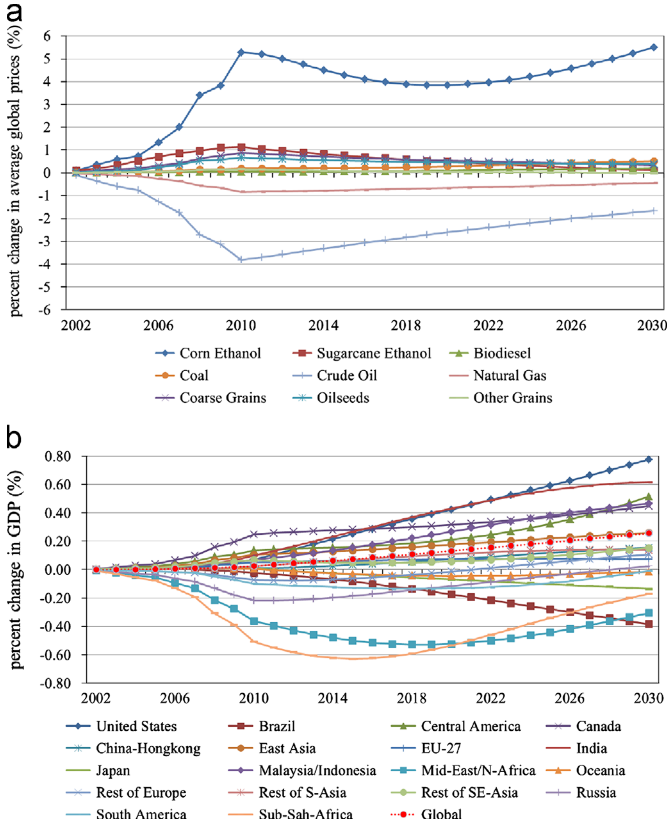

Fig. 8. (a) Changes in average global agricultural and energy prices under Case 1, (b). Changes in regional GDP under Case 1.

and 2030. In the rest of this paper, regions with net increases in agricultural land area are referred to as land use-increasing (LUI) regions, while those with net contractions in agricultural land area are referred to as land use-decreasing (LUD) regions. Fig. 7 also shows that increases in the LUI regions accelerated until 2010 when the biofuel mandates were held constant in the simulation, whereas the decreases in LUD regions continued to accelerate until 2018. The magnitude of the total decrease in LUD regions remained below the total increase in LUI regions until 2010 as reflected by the “global” line in Fig. 7. The annual net change in global agricultural land area under Case 1 peaked at about 480,000 ha in 2008 and then began to decline to a minimum of about −1.43 million ha in 2018.

The increases in agricultural land area in most regions are consistent with the general narrative on the expected land use change implications of biofuel policy. This theory suggests that agricultural land area would increase to compensate for land used to support ethanol production and any shortfalls in exports by the USA. However, the size and location of expected LUC is uncertain (Plevin et al., 2010). Fig. 7 suggests that most of the agricultural land expansion occur in the USA.

Decreases in agricultural land area for the LUD regions in Fig. 7 result from mechanisms directly related to the original objectives of biofuel policy. However, these mechanisms have rarely been accounted for in LUC modeling (Oladosu, 2012). The primary purpose of biofuel policies is to promote energy security by diversifying liquid-fuel consumption away from crude oil. Such policies, if effective, are likely to reduce the incomes received by oil suppliers through reduced prices and/or sales. In turn, the declines in income relative to the baseline would lead to reductions in purchases and production of goods and services by oil suppliers. This mechanism is reflected by the simulation results in Fig. 7 showing that three of the four regions accounting for most of the decreases in land use are Sub-Saharan Africa, Russia, and Mid-East/North Africa. These three regions are among the top 10 suppliers of oil to the USA and fossil-fuel exports represent a large source of revenues. As seen from Fig. 4c, agricultural land area per unit of output of the Sub-Saharan Africa economy is very high, magnifying the LUC effects in this region.

The changes in agricultural and energy prices (Fig. 8a), and changes in regional GDP (Fig. 8b) over the period from 2001 to 2030 corroborate this explanation. Fig. 8a shows that agricultural prices increase by less than 1 percent over the simulation period under Case 1. In contrast, crude oil and natural gas prices decline, whereas the corn ethanol price increases. The crude oil price declines by almost 4 percent in 2010, and by about 2 percent in 2030. The corn ethanol price increases by almost 6 percent in 2010, and by 4 to 6 percent during the period from 2011 to 2030. Fig. 8b shows that Sub-Saharan Africa, Mid-East/North Africa, Russia, Rest of South America, and Rest of Europe have the largest reductions in GDP relative to their baselines under Case 1, with most of the remaining regions showing increases in GDP. The largest percentage decrease in GDP, in Sub-Saharan Africa, is about six-tenths of 1 percent in 2015, which amounts to about $4 billion, given that the region is projected to reach a GDP of about $665 billion in that year under the baseline run.

Overall, the change in global GDP under the policy is positive, with a net increase of around one-fourth of 1 percent in 2030. The increases in GDP growth rates observed for most countries in Fig. 8b imply that their agricultural land use changes also incorporate an income-driven, albeit positive, component. The small, but positive, increase in global GDP reflects the net effect of interacting factors that drive the economic impacts of biofuel policy. The USA benefits from the replacement of oil imports with domestic biofuels, reduction in the average price of crude oil, and expansion of agricultural production to meet the demand for biofuels. For other oil importing economies, reductions in oil prices represent savings on imported oil that can be spent on goods and services, including offsetting the increases in agricultural prices. As noted above, oil exporters see a small reduction in revenue and GDP. The combination of these shifts in production activities and differences among regions in the efficiency of productive activities lead to the net positive global economic benefits. Note that the net GDP effect in most regions turned positive only after 2010, when the production of biofuels in the USA were held constant in the simulation. Thus, the costs and benefits of the biofuel policy largely offset each other during its active implementation from 2001 to 2010, but the cumulative effects of the reduction in oil prices continue after 2010 to generate the changes in GDP in different regions (Fig. 8b).

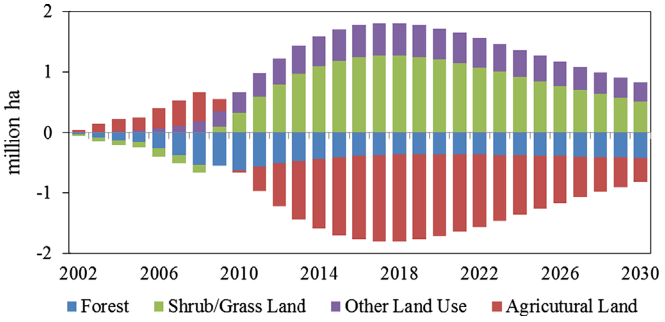

Fig. 9. Annual global land cover changes under Case 1.

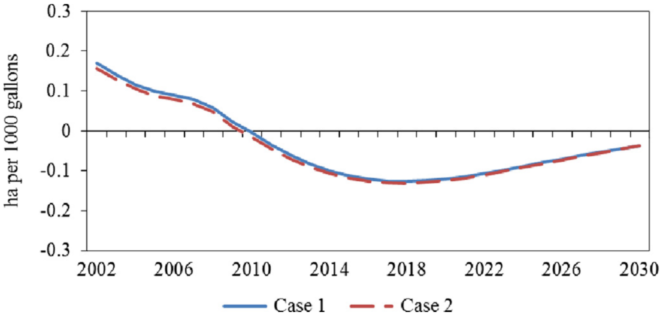

Fig. 11. Global agricultural land area change under Cases 1 and 2.

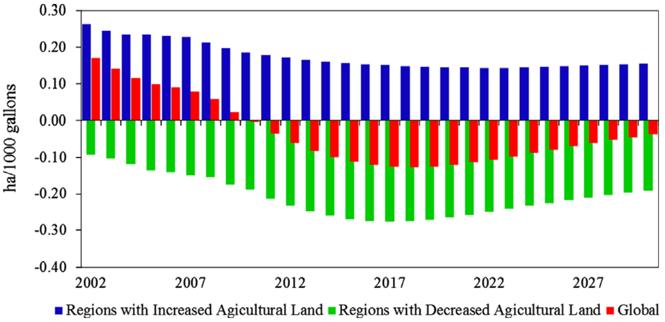

Fig. 10. Expansion/contraction of agricultural land per gallon of biofuel produced in the USA under Case 1.

Fig. 9 illustrates the global changes in agriculture land area disaggregated by land cover type: forest, shrub/grassland, and other land-cover under Case 1. Note that Fig. 9 accounts for only the annual movement of land in or out of agricultural production and does not track vegetation growth over time. As such, most of the changes are in the shrub/grassland category, which is the main transitional path between agricultural and other land-cover types in the model. In reality, over the 30-year period, some of the land moving to shrub/grassland would be expected to transition to forest and other uses. The net global decrease in shrub/grassland is much smaller than the decrease in forest land between 2001 and 2010 given the expansion of land to produce biofuels in the USA. After 2010, biofuels production in the USA is constant and changes in land cover are then dominated by the release of agricultural land in the oil-exporting economies most directly affected by the income effects of the biofuel policy. The change in forest land cover slowed after 2010 in accordance with Fig. 7.

Fig. 10 is a summary of the above land use change results in terms of hectares per 1000 gallons of biofuel produced in the USA. The combined effects of net agricultural land expansion/contraction (release) in different regions produce a negative net global LUC by 2010. Fig. 10 also shows the rate of agricultural land expansion per gallon for LUI and LUD regions separately. In the LUI regions (primarily the USA), the rate of agricultural land expansion declines from 0.263 ha per 1000 gallons in 2002 to 0.143 ha per 1000 gallons in 2023. The declining trend is due to a combination of the cumulative effects of yield changes and the end of increases in the simulated ethanol mandate in 2010. In the LUD regions, the decreases first accelerated from −0.094 ha per 1000 gallons in 2002 to −0.276 in 2017 and then returned to −0.192 in 2030. This pattern again reflects the initial increases in biofuel use in the USA, which once held constant after 2010 allowed the income-driven effects in the affected countries to recover gradually over time. The peak net global LUC rate under this scenario is 0.170 ha per 1000 gallons in 2002, whereas the lowest value is −0.126 ha per 1000 gallons in 2018.

3.4. Case 2: Ethanol consumption in the USA from 2001 to 2010 with price-responsive non-intensive yield changes

Two new simulations were performed to evaluate the land use change implications under this scenario. First, the baseline simulation was repeated but with the price-responsive non-intensive yield parameters set to values for Case 2. This approach is necessary for the policy simulation results to be comparable across scenarios. The yield function alters the pattern of land use in the affected sectors relative to the original baseline, but the overall economic aggregates (e.g. GDP) are similar. The policy simulation for Case 2 then imposes the increase in ethanol consumption in the USA between 2001 and 2010 on this new baseline, as given in Table 1. Fig. 11 shows that the pattern of land use effects under Case 2 is similar to that for Case 1, but the LUC effects are smaller. The peak per-gallon agricultural land expansion rate dropped from 0.170 to 0.156 ha per 1000 gallons, while its lowest value changed from −0.126 to −0.131 ha per 1000 gallons. The peak change in global agricultural land area under Case 2 is 387,000 ha in 2008 compared with 480,000 ha under Case 1, and declines to −1.49 million ha in 2018 versus −1.43 million ha under Case 1. Thus, the price-responsive component of non-intensive yield change is seen to reduce the land use change impacts of the policy by up to 93,000 ha relative to Case 1 in 2030.

3.5. Sensitivity cases: Increases in price elasticities of land (Case 3) and fossil resources (Case 4) supply

Cases 3 and 4 were each evaluated by performing two new simulations as under Case 2, using the parameters set for each scenarios. Case 3 is expected to increase global LUC in response to biofuel production in the USA because land becomes cheaper relative to other production inputs. Case 4 is also likely to increase global LUC because the higher elasticities of supply for fossil fuels mute the income effects of changes in oil sales under biofuel policy.

Fig. 12 shows the land use change results for Cases 2, 3 and 4. Under Case 3 the peak rate of land expansion rises from 0.156 to 0.26 ha per 1000 gallons, but its lowest value also decreases from −0.131 to −0.219 ha per 1000 gallons compared with Case 2. The associated global peak change in annual agricultural land area under Case 3 is 704,000 ha in 2008 compared with 387,000 ha under Case 2, and the lowest value is −2.49 million ha in 2018 versus −1.45 million ha under Case 2. Thus, a doubling of the land-supply elasticities under Case 3 leads to almost a doubling of the peak rates of land (and land-release) per gallon relative to Case 2. Differences between Case 2 and Case 3 are greatest at the two extremes of the curves (i.e., in the first year when the highest positive LUC values per 1000 gallons occur in the simulations and in year 2018 when the largest negative LUC values occur). This implies that more land area is affected in both the LUI and

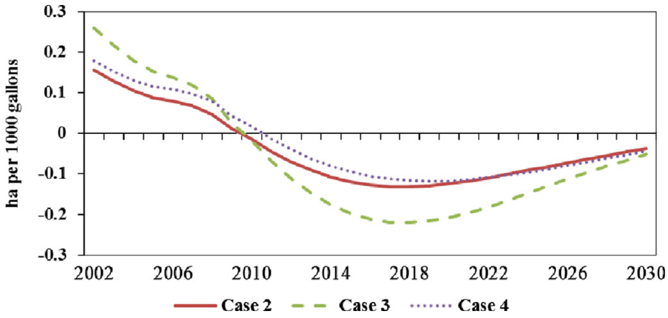

Fig. 12. Global land rates under Cases 2–4.

LUD regions when land becomes cheaper relative to other production inputs.

The results for Case 4 are also as expected. The peak net global rate of land change increases to 0.179 ha per 1000 gallons compared with 0.156 ha per 1000 gallons under Case 2. The curve for Case 4 remained above its Case 2 counterpart until 2023, which contrasts sharply with Case 3. In addition, the zero crossing for Case 4 was delayed by one year to 2011 instead of 2010 as observed under all other cases. Thus, the magnitudes of the land use effects under Case 4 are smaller than for Case 3, but are more persistent. The associated peak change in agricultural land use under Case 4 is about 653,000 ha in 2008, and its lowest level is −1.32 million ha in 2019.

4. Summary

This study employed a dynamic CGE model (GTAP-DEPS) to evaluate the land use change implications of recent increases in biofuel production in the USA. The model includes several enhancements, such as model dynamics and improved characterization of fossil energy resources supply, to support a robust simulation of the effects of biofuel policy. The simulation results suggest that the global LUC implications of biofuel production in the USA between 2001 and 2010 may be lower than prior estimates found in the literature. The modeling approach in this study highlights several other aspects of the land use change implications of biofuels:

1. Two equally important but counteracting mechanisms are found to determine the global net land use change effects of biofuel policy, and demonstrate that the ability to simultaneously consider multiple responses to policy changes is a distinct advantage of general equilibrium models in estimating the indirect effects of biofuels (Van Stappen et al., 2011).
2. The first mechanism is in line with the general narrative about the impacts of biofuel production on land use. The theory suggests that using crops, such as corn to produce biofuels in the USA would lead to increases in global agricultural land use because of the land required to supply the feedstock and to replace shortfalls in crop exports by the USA. Consistent with this mechanism, simulation results show expansion of agricultural land area in most regions, with the USA accounting for the largest increase by far. This result is important because it suggests that, even with the increased use of corn for ethanol production, agricultural production in the USA remains competitive.
3. The second mechanism is directly related to a main objective of USA biofuel policy which is to reduce the imports of crude oil. This mechanism has received little attention in terms of its land use implications. The results of this study suggest that the effects of biofuel policy on real incomes (reductions in oil-producing economies and increases in other regions) are important when assessing the land use change effects of biofuel policy. This mechanism generates net reductions in agricultural land area in the oil-export dependent economies that supply significant amounts of petroleum to the USA. The agricultural output per unit of land influences the magnitude of both positive and negative LUC, contributing to the significant reductions in agricultural land in some regions.
4. Estimates of the net global effects of biofuel policy on LUC fluctuate over the period from 2002 to 2030, driven by the above two mechanisms. Under Case 2, the annual LUC range from 0.14 to 0.25 ha per 1000 gallons of ethanol produced if decreases associated with the second mechanism were ignored (as is the case in many previously published LUC simulations). When both increases and decreases are considered, the annual LUC rate ranges from −0.13 to +0.16 ha per 1000 gallons of biofuel produced.
5. The effect of considering price-responsive, non-intensive yield changes is estimated to reduce peak net global land use implications by about 0.013 ha per 1000 gallons. Although this effect is small in absolute terms, it is more than 5 percent of the peak LUC land conversion rate under Case 1, and represents nearly a reduction of 100,000 ha in the estimated LUC reduction.
6. The cost of land supply exerts a significant influence on the estimated LUC effects of biofuels. Doubling the land-supply elasticity parameters (Case 3) leads to almost a doubling of the peak net rate of global agricultural land area expansion from 0.156 ha per 1000 gallons under Case 2 to 0.260 ha per 1000 gallons. Reductions in agricultural land use in later years are also larger, so the effect of the higher land supply elasticity nets out over the long-run.
7. Oil supply elasticities are also found to influence the LUC estimates through effects on oil-producer revenues. The magnitudes of the effects from doubling these elasticities are smaller than those from doubling the land supply elasticities, but are more persistent.
8. Estimates of the global LUC for year 2002 under the four cases simulated in this study (0.17, 0.16, 0.26 and 0.18 ha per 1000 gallons) are within the range of estimates from previous simulations with static variants of the GTAP model (Tyner et al., 2010; Hertel et al., 2010; Oladosu and Kline, 2010). By comparison the average LUC under Case 2 of this study over the period from 2001 to 2030 is about +0.15 ha per 1000 gallons in the LUI regions and −0.23 ha per 1000 gallons in the LUD regions, with a net global average of about −0.07 ha per 1000 gallons. Although these average estimates mask the associated fluctuations over time, they reflect the cumulative effects of investment response, oil exporter income changes, crop yield changes, and other factors that produce the dynamic pattern of land use change observed under this study.

5. Conclusions

The simulation results in this study provide additional insights into the potential sources of indirect land use change from biofuel policy. In particular, the study identifies a significant, but hitherto unexplored aspect of biofuel policy that has significant potential indirect land use change implications: Agricultural land use is estimated to decline in some regions because of the income effects of reductions in oil imports by the USA under biofuel policy. This negative LUC is driven by a similar economic mechanism that produces positive LUC in other regions.

Estimates of LUC under this study are consistent with the lower end of recent values in the literature, further corroborating that the LUC implications of biofuel production in the USA during the past decade are most likely small. The LUC results also display a pattern over time and regions that becomes apparent only within the type of dynamic global framework employed in this study. Still, several important aspects of LUC modeling and research remain to be addressed. As with previous efforts, modeling of land supply at a detailed spatial scale to produce accurate supply costs of agricultural land remains a daunting task. Land use changes at the local scale are driven by complex social and political drivers that need to be assessed (Kline and Dale 2008, 2011; Kline et al., 2009, 2011). The current study shows that changes in the parameters of reduced-form functions used to represent land supply in these studies can produce significant changes in estimates of indirect land use change. There is also a need for a greenhouse gas accounting framework that adequately accounts for the time pattern of LUC revealed in the results of the current study. Similarly, the income-driven effects observed in the current study depend in large part on the future path of fossil-fuel prices, and its effects on oil-exporting economies and their land use decisions. The resource-supply elasticities in this study are based on a fit of the empirical data for the past two decades and are shown to have significant implications for land use change under biofuel policy. It would be important to account for future changes in energy-resource supply including new discoveries, depletions and reserve development. In addition, the sensitivity of the LUC estimates to the production function parameters of the model should be explored. These and other items are important subjects for future analyses.

Acknowledgements

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References

Bouët, A., Dimaranan, B.V., Valin, H., 2010. Modeling the Global Trade and Environmental Impacts of Biofuel Policies, IFPRI Discussion Paper 01018, Markets, Trade and Institutions Division, International Food and Policy Research Institute.

CARD, 2009. An Analysis of EPA Renewable Fuel Scenarios with the FAPRI-CARD International Models, Center for Agricultural and Rural Development. Iowa State University, Ames, Iowa.

CGTA, 2008. Global trade, assistance and production: the GTAP 7 database. In: Narayanan, B.G., Walmsely, T.L. (Eds.), Center for Global Trade Analysis. Purdue University, West Lafayette, Ind..

Gallagher, P.W., 2010. Corn ethanol growth in the USA without adverse foreign land use change: defining limits and devising policies. Biofuels, Bioproducts, and Biorefining 4 (3), 296–309.

Golub, A., McDougall, R., 2011. Behavioral and entropy parameters of the dynamic GTAP model, Chapter 3. In: Ianchovichina, E., Wamsley, T. (Eds.), Global Economic Analysis: Dynamic Modeling and Application. Cambridge University Press, Cambridge, UK.

Hertel, T.W., Golub, A.A., Jones, A.D., O'Hare, M., Plevin, R.J., Kammen, D.M., 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.W. (Ed.), 1997. Global Trade Analysis: Modeling and Applications. Cambridge University Press, Cambridge, UK.

Huang, H., Khanna, M., 2010.An Econometric Analysis of U.S. Crop Yield and Cropland Acreage: Implications for the Impact of Climate Change, Presentation at the Agricultural & Applied Economics Association, AAEA, CAES, & WAEA Joint Annual Meeting, Denver, Colorado, July 25–27, 2010. Available at ⟨http://papers.ssrn.com/sol3/Delivery.cfm/SSRN_ID1700707_code610295.pdf?abstractid=1700707&mirid=2⟩ 2 (viewed March 18 2011).

Ianchovichina, E., McDougall, R., 2001.Theoretical Structure of Dynamic GTAP, Technical Paper No. 17, Center for Global Trade Analysis, Purdue University, Lafayette, Ind. Available at ⟨https://www.gtap.agecon.purdue.edu/resources/download/1582.pdf⟩.

International Monetary Fund, 2010. World Economic Outlook Database, International Monetary Fund, Washington, D.C. Available at ⟨http://www.imf.org/external/pubs/ft/weo/2010/02/weodata/index.aspx⟩.

Kim, S., Dale, B.E., 2011. Indirect land use change for biofuels: testing predictions and improving analytical methodologies. Biomass and Bioenergy 35 (7), 3235–3240.

Kline, K.L., Dale, V.H., 2008. Biofuels, causes of land use change, and the role of fire in greenhouse gas emissions. Science 321, 199.

Kline, K.L., Dale, V.H., Lee, R., Leiby, P., 2009. In defense of biofuels, done right. Issues in Science and Technology 25 (3), 75–84.

Kline, K.L., Oladosu, G.A., Dale, V.H., McBride, A.C., 2011. Scientific analysis is essential to assess biofuel policy effects: in response to the paper by Kim and Dale on—indirect land use change for biofuels: testing predictions and improving analytical methodologies. Biomass and Bioenergy 35 (2011), 4488–4491.

Kretschemer, B., Peterson, S., 2010. Integrating bioenergy into computable general equilibrium models—a survey. Energy Economics 32 (3), 673–686.

Lapola, D.M., Schadach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., Priess, J., 2010. Indirect land use changes can overcome carbon savings from biofuels in Brazil. Proceedings of the National Academy of the United States of America 107 (8), 3388–3393.

Lee, H., Hertel, T., Sohngen, B., Ramankutty, N., 2007. Towards An Integrated Land Use Database for Assessing the Potential for Greenhouse Gas Mitigation, GTAP Resource #1900, Center for Global Trade Analysis. Purdue University, West Lafayette, Ind., Available at: ⟨https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=1900⟩.

Liu, J., Surry, Y., Dimaranan, B., Hertel, T., 1998. CDE calibration, in global trade assistance and protection: GTAP 4 data base documentation. In: McDougall, R. A., Elbehri, A., Truong, T.P. (Eds.), Center for Global Trade Analysis. Purdue University, West Lafayette, Ind., Available at: ⟨https://www.gtap.agecon.purdue.edu/resources/download/291.pdf⟩.

McDougall, R., Golub, A., 2009. GTAP-E: A Revised Energy-Environmental Version of the GTAP Model, GTAP Research Memorandum No. 15, Center for Global Trade Analysis. Purdue University, West Lafayette, Ind. Avaliable at: ⟨https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2959⟩.

Muller, M., Yelden, T., Schoonover, H., 2008. Food versus Fuel in the United States: Can Both Win in the Era of Ethanol. Institute for Agriculture and Trade Policy Avaliable at: ⟨http://www.iatp.org/iatp/publications.cfm?accountID=258&refID=100001⟩.

Oladosu, G., 2012. Estimates of the global indirect energy-use emission impacts of USA biofuel policy. Applied Energy 99, 85–96, http://dx.doi.org/10.1016/j.bbr.2011.03.031.

Oladosu, G., Kline, K., Uria-Martinez, R., Eaton, L., 2011. Sources of corn for ethanol production in the United States: a review and decomposition analysis of the empirical data. Biofuels, Bioproducts, and Biorefining , http://dx.doi.org/10.1002/bbb.305.

Oladosu, G.A., Kline, K.L., 2010. The role of modeling assumptions and policy instruments in evaluating the global implications of US biofuel policies. In: Proceedings of the 33rd International Conference of the International Association for Energy Economics on The Future of Energy: Global Challenges, Diverse Solutions. 2010 June 6–9; Rio de Janeiro, Brazil. IAEE. Available at ⟨https://www.iaee.org/en/publications/proceedings.aspx#iaeerio⟩.

Oladosu, G., Kline, K., Leiby, P., Uria-Martinez, R., Davis, M., Downing, M., Eaton, L., 2012. Global economic effects of USA biofuel policy and the potential contribution from advanced biofuels. Forthcoming in Future Science—Biofuels 3, 6.

Plevin, R.J., O'Hare, M., Jones, A.D., Torn, M.S., Gibbs, H.K., 2010. Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. Environmental Science and Technology 44 (21), 8015–8021, http://dx.doi.org/10.1021/es101946t.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T., 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. Science 319 (5867), 1238–1240.

Taheripour, F., Birur, D.K., Hertel, T.W., Tyner, W.E., 2007. Introducing Liquid Biofuels into the GTAP Database, GTAP Research Memorandum No. 11,Department of Agricultural Economics. Purdue University, West Lafayette, Ind..

Tannura, M., Irwin, S., Good, D., 2008. Are Corn Trend Yields Increasing at a Faster Rate?, MOBR 08-2, Marketing and Outlook Briefs, Department of Agricultural and Consumer Economics, University of Illinois, Urbana, Ill. Available online at ⟨http://ageconsearch.umn.edu/bitstream/37500/2/mobr_08-02.pdf⟩ (viewed March 18 2011).

Tyner, W.E., Taheripour, F., Zhuang, Q., Birur, D., Baldos, U., 2010. Land use changes and Consequent CO_2 Emissions due to US Corn Ethanol Production: A Comprehensive Analysis, Department of Agricultural Economics. Purdue University, Lafayette, Ind..

USDA, 2010. Production, Supply, and Distribution Online, United States Department of Agriculture, ⟨http://www.fas.usda.gov/psdonline⟩/.

USEPA, 2010. EPA Finalizes Regulations for the National Renewable Fuel Standard Program for 2010 and Beyond, EPA-420-F-10-007, Office of Transportation and Air Quality. United States Environmental Protection Agency, Washington, D.C..

Van Stappen, F., Brose, I., Schenkel, Y., 2011. Direct and indirect land use changes issues in European sustainability initiatives: state-of-the-art, open issues and future developments. Biomass and Bioenergy 35, 4824–4834.

Wisner, R., 2010. Estimated U.S. Dried Distiller's Grains with Solubles (DDGS) Production and Use, Agricultural Marketing Resource Center. Iowa State University, Ames, Iowa.

Witzke, P., Banse, M., Gömann, H., Heckelei, T.,Breuer, T., Mann, S., Kempen, M., Adenäuer, M., Zintl, A., 2008. Modeling of Energy-Crops in Agricultural Sector Models—A Review of Existing Methodologies, EUR 23355 ENG, JRC Scientific and Technical Reports, Ignacio Pérez Domínguez, and Marc Müller (editors), European Commission Joint Research Centre, Brussels, Belgium. Available at 〈http://ftp.jrc.es/pub/EURdoc/JRC42597.pdf〉.

World Bank, 2010. World Development Indicators Database. World Bank, Washington, D.C. Available at: http://databank.worldbank.org/databank/download/WDIandGDF_excel.zip.