# Linking Natural Resources to the CGE Framework: the Case of Land Use Changes in the EPPA Model

Angelo Gurgel[a], Y.-H. Henry Chen[b], Sergey Paltsev[b] and John Reilly[b]

[a]*Sao Paulo School of Economics, Fundacao Getulio Vargas,*
*Rua Itapeva 474, Sao Paulo SP*
*angelo.gurgel@fgv.br*

[a,b]*Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change,*
*77 Massachusetts Ave, E19-411, Cambridge MA 02139*
*chenyh@mit.edu, paltsev@mit.edu, jreilly@mit.edu*

Incorporating natural resources in large-scale models has been an increasing area of theoretical and empirical development in the CGE literature. The explicit representation of land use and land use conversion in global models has been one of the most recent and challenging examples of such development. We contribute to this literature describing in details one approach to include the natural resource land in a global CGE model and representing its connection to the broader economy through agriculture and forestry production. We apply the model to project future land use trajectories. The simulations highlight the important linkages between environmental services and economic development and the differences in the patterns of land use trajectories among developed and developing countries. The introduction of environmental resources in the model results in some changes in its original microeconomic and macroeconomic results, but does not alter the main response of the model. Finally, we show that parameters defining agricultural yields and population growth are important in projecting future services from land use, but alternative rates of GDP growth have less effect on the main trends in land use trajectories.

## 1. Introduction

Representing environmental linkages in large-scale economic models has become an important frontier in theoretical and empirical studies. A detailed description of the origins and the gradual inclusion of environmental resources in CGE modeling started with consideration of energy issues and evolved to deal with externalities and environmental policies (Bergman, 2005). While climate change and greenhouse gas (GHG) emissions policies have dominated, many other environmental issues have been addressed. These include: the depletion of fossil fuel and mineral resources, over-fishing, deforestation, agriculture and land use, pollution control, and consequences of environmental taxes, among others. In fact, the value of large-scale, economy-wide models with significant sectoral and regional detail is that complex linkages and interactions among environmental and resource issues can be studied. For example, will climate policy drive up food costs, or constrain land available for food production?

In this context, the explicit representation of land use and land conversion in quantitative models dealing with global or continental areas is among one of the most recent and challenging streams of the environmental and natural resource economics. There are several

recent studies combining socioeconomic and ecological systems aiming to investigate land use change and its drivers (Meyfroidt et al., 2013). The importance of these developments is to provide information for decision-makers and the public on the land-use implications of environmental, energy and trade policy and changing consumption patterns and growth. Given linkages among regions through markets and trade, and the long-term nature of environmental issues such as climate change, unintended consequences of policies can be distant in both time and space.

With the still recent, but growing interest, it is perhaps not surprising that several different approaches for representing land use change have been developed. For example, estimations of econometric models to connect land use changes and greenhouse gas emissions (Kerr et al., 2003; Lubowski et al., 2006). Other partial equilibrium approaches represent land use markets drawing on broader literature to provide data and parameter values (Sohngen et al., 2001; Popp, A. et al., 2011; Havlík et al., 2011; Wise et al., 2009; Rosegrant & Zhu, 2009).

An extensive review of the more recent attempts to include land use change in general equilibrium models is briefly summarized here, see Hertel et al. (2009) for more details. They note the pioneering work of Darwin et al. (1995). Many recent studies have been motivated by concerns about the impacts of biofuels on land use and food prices, as these became policy concerns in the US and Europe over the past decade with efforts to expand the use of biofuels and bioenergy (Gurgel et al. 2007; Eickhout et al., 2007; Banse & Meijl, 2008; Melillo et al., 2009; Taheripour et al., 2010; Banse et al., 2011; Tilmisina et al., 2012; Britz et al., 2011; Golub & Hertel, 2010). Another motivation was the effect on land use of international trade, especially with efforts to liberalize trade in agricultural goods under World Trade Organization (WTO) negotiations (Villoria & Hertel, 2011; Schmitz et al., 2012; Golub & Henderson, 2012). Other relevant topics which have helped to develop and incorporate land use changes in the general equilibrium modeling include: climate change and climate policy (Cai et al., 2009; Golub et al., 2009; Sohngen et al., 2009; Gurgel *et al.*, 2011; Reilly, J. *et al.*, 2012; Bosello et al., 2010); the role of environmental services (Antoine et al., 2008) technological progress (Villoria et al., 2014); future of cropland expansion (Schmitz e t al., 2014).

Given the recent interest in land we focus our attention on it as an example of how to include natural resources, and its connection to the broader economy through agriculture and forestry. The next section presents the principles, database and general approaches for representing land use and related environmental services associated with different categories of land use. The third section describes the details of introducing land use changes in a specific CGE formulation, the fourth section presents some model results and sensitivities and the last section concludes the paper.

## 2. Representing natural resources in CGE models: the case of land use

The key elements that need resolution in order to incorporate land use include the underlying data base, the mobility of land across uses, the conversion of natural land to managed uses, technological change and the representation of major land demanding sectors such as crop production, livestock production, forestry and bioenergy (Schmitz et al., 2014). Our point of departure is the MIT Economic Projection and Policy Analysis (EPPA) model, a recursive dynamic CGE model of the world economy. The inclusion of land use change in EPPA has

an extensive history and a variety of applications (Melillo *et al.*, 2009; Cai et al., 2009; Reilly et al., 2012; Antoine et al., 2009; Gurgel et al., 2007; Winchester & Reilly 2015; Winchester et al., 2015). By focusing on a specific application over the next sections, each of key elements identified by Schmitz et al. (2014) are covered with a specific example of how this has been represented in the EPPA model, with a discussion of other possible approaches.

### *2.1 The EPPA model*

The MIT Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic multi-regional computable general equilibrium (CGE) model of the world economy (Chen et al., 2015; Paltsev et al., 2005). The GTAP data set provides the base information on Social Accounting Matrices (SAMs) and the input-output structure for regional economies, including bilateral trade flows, and a representation of energy markets in physical units (Hertel, 1997; Narayanan et al., 2012). The data are aggregated into 18 regions and 14 sectors (Table 1). EPPA also incorporates data on greenhouse gas ($CO_2$, $CH_4$, $N_2O$, HFCs, PFCs, and $SF_6$) and air pollutant emissions ($SO_2$, $NO_x$, black carbon, organic carbon, $NH_3$, CO, VOC), based on the Emissions Database for Global Atmospheric Research (EDGAR).

Natural resources including energy and land resources enter the model as depletable, renewable, or produced factor inputs, as well as conventional produced capital (i.e. structures, machinery, and equipment) and labor. With regard to land, EPPA treats natural forest and grassland as natural capital, and crop-, pasture-, and managed forest- land as "produced" from natural forest and grassland, with the treatment of land described in detail in following sections. EPPA was designed to examine climate policy over a time horizon of up to century. To dramatically reduce GHGs widespread adoption of advanced technologies not widely in use now would be required. As a result, the basic economic data in GTAP is expanded to disaggregates transportation to include household transport (i.e. personal automobile) with additional vehicle options such as electric vehicles. The electricity sector is also further disaggregated from GTAP to delineate fossil energy generation from nuclear and hydro power, and to represent advanced technologies such as wind, solar, and generation with carbon capture and storage. In addition, the model includes technologies to produce fuels from unconventional sources such as liquid fuels from biomass and shale oil resources and gas from coal or unconventional gas resources. To represent such technologies, the model takes into account detailed bottom-up engineering parameters, see Chen et al (2015) and Paltsev et al. (2005) for more details.

The base year of the EPPA version used here (EPPA6) is 2007. EPPA simulates the economy recursively, with 2010 as the initial forecast year and then at 5-year intervals to 2100. Economic growth from the base year to 2015 is calibrated to the actual data on GDP, and through 2015 on data/short-term projections of the IMF. The model is formulated in a series of mixed complementary problems (MCP) including a mix of equations and inequalities, (Mathiesen, 1985; Rutherford, 1995; Ferris & Pang, 1997). It is written and solved using the modeling languages of GAMS and MPSGE, and the latter is now a subsystem of the former (Rutherford, 1999).

Table 1. Regions, Sectors and Primary Factors in the EPPA6 Model

| Region | | Sector | | Primary Factor Inputs |
|---|---|---|---|---|
| United States | USA | ***Production Sectors*** | | ***Depletable Natural Capital*** |
| Canada | CAN | Agriculture – Crops | CROP | Conventional Oil Resources |
| Mexico | MEX | Agriculture - Livestock | LIVE | Shale Oil |
| Japan | JPN | Agriculture - Forestry | FORS | Conventional Gas Resources |
| Australia, New Zealand & Oceania | ANZ | Food Products | FOOD | Unconventional Gas Resources |
| European Union[1] | EUR | Coal | COAL | Coal Resources |
| Eastern Europe and Central Asia | ROE | Crude Oil | OIL | ***Renewable Natural Capital*** |
| Russia | RUS | Refined Oil | ROIL | Solar Resources |
| East Asia | ASI | Gas | GAS | Wind Resources |
| South Korea | KOR | Electricity | ELEC | Hydro Resources |
| Indonesia | IDZ | Energy-Intensive Industries. | EINT | Natural Forest Land |
| China | CHN | Other Industries | OTHR | Natural Grass Land |
| India | IND | Services | SERV | ***Produced Capital*** |
| Brazil | BRA | Transport | TRAN | Conventional Capital (Bldgs & Mach.) |
| Africa | AFR | ***Household Sectors*** | | Cropland* |
| Middle East | MES | Household Transport | HHTRAN | Pasture and Grazing Land* |
| Latin America | LAM | Ownership of Dwellings | DWE | Managed Forest Land* |
| Rest of Asia | REA | Other Household Services | HHOTHR | ***Labor*** |

[1] The European Union (EU-27) plus Croatia, Norway, Switzerland, Iceland and Liechtenstein.

* "produced" from natural lands with further investment and inputs

Future scenarios in EPPA are driven by economic growth that results from savings and investments and exogenously specified productivity improvement in labor, capital, land, and energy. Growth in demand for goods produced from each sector including food and fuel occurs as GDP and income grow. Stocks of depletable resources fall as they are used, driving production to higher cost grades. Sectors that use renewable resources such as land compete for the available flow of services from them, generating rents. These together with policies, such as constraints on the amount of greenhouse gases, change the relative economics of different technologies over time and across scenarios. The timing of entry of advanced technologies, such as cellulosic biofuel, occurs when these technologies become less expensive than the conventional alternatives. Costs of technologies change differentially over time due to economy-wide productivity trends, and resource depletion or competition for renewable resources to the extent a technology uses them, and due to policies that affect costs, such as carbon pricing. A detailed description of the dynamics in EPPA can be found in Chen et al., (2015).

### *2.2 Land use and land use changes*

#### *2.2.1 Database*

A global CGE model dealing with land use requires a database of land cover and land use for the world. A key decision is the number of land use categories to represent, which depends on the detail in underlying databases and the need to retain computational tractability of solving the model. In the case of EPPA, the model considers five land use types: cropland, pasture, forest, natural forest and natural grass. EPPA combines two main land databases. The "GTAP8 Land Use and Land Cover Database" (Baldos & Hertel, 2012) includes crop, pasture, built-up, forest and other lands by agroecological zones (AEZs) for 134 countries and regions of the world, covering the entire globe. The GTAP land use data itself is built from FAOSTAT production data and cropland and pasture land data from previous studies (Ramankutty & Foley, 1999; Ramankutty, 2011). The GTAP8 land database is the main source of cropland and pasture area in EPPA. The other land use categories in EPPA are based on the Terrestrial Ecosystem Model (TEM) (Felzer et al., 2004), which uses historical land use transitions from previous work Hurtt et al., 2006).

The TEM data is integrated with the GTAP data to help identify unmanaged forest and grasslands that can potentially be converted to managed land types. GTAP includes all forest lands in a single land type, regardless of whether it is regularly harvest or not. In this regard, GTAP follows conventional economics and aggregates land on the basis of it value. But this means that very large areas with little economic activity add very little to the current "economic" quantity of land. Because EPPA is designed to simulate over 50 to 100 years, a goal was to assure that physical constraints on the area of land in any country or region are not violated, and that ultimately actual areas of land that remain undisturbed can be recovered from the model simulations, recognizing that these areas may have ecological value (such as, e.g., a store of carbon) not reflected in current market data on land value. The TEM data distinguishes forest areas under regular harvesting or subject to secondary vegetation growth, which are classified in EPPA under the managed forest category. Undisturbed forests and grasslands in TEM database are classified in EPPA as natural forest and natural grass categories, respectively. This also facilitates direct coupling the EPPA and TEM, allowing

productivity changes in TEM due to climate or other environmental changes to be reflected in EPPA and to evaluate how land use change affects carbon storage in vegetation and soils. Recent applications of the linked models can be found in Melillo et al. (2009) and Reilly et al. (2012).

To complete the database for land use changes in EPPA, we also consider the agricultural land rents from the GTAP8 database (Narayanan et al., 2012) and data from a global forestry land use model, which provides information to estimate a land use value for natural areas and other inputs required to model the conversion of these to managed uses. These are detailed later.

### *2.2.2 Mobility of land across alternative uses*

The representation of land use change in EPPA is unique among CGE models, as it explicitly converts land from one type to another. The model reflects the observation that with land improvements (draining, tilling, fertilization, fencing), for example, pastureland can become cropland, or forestland can be harvested, cleared and ultimately used as cropland. The opposite direction is also represented: if, for example, demand for cropland does not support continued investments the land can go to pasture or managed forest harvesting, or abandoned completely and returned to natural land.

Integrating land use conversion into the EPPA framework had two key requirements: (1) that we retain consistency between the physical land accounting and the economic accounting in the general equilibrium setting, and (2) that we develop the data in a manner that is consistent with observation as recorded in the CGE data base for the base year. Failure on the first account would mean that we could not consistently insure that the physical accounts "add up.". Failure on the second account would mean that the base year data would not be in equilibrium and so the model would immediately jump from the base year to the equilibrium state consistent with parameterization of land rents and conversion costs.

The first of these conditions is achieved by assuming that one hectare of land of one type is converted to one hectare of another type, and through conversion it takes on the productivity level as the average for that type for that region. It is in that sense that cropland is produced from pasture or forest land. The conversion requires using real inputs through a land transformation function as in Figure 1. The second of these conditions is achieved by observing that in equilibrium the marginal conversion cost of land from one type to another should be equal to or greater than the difference in value of the types.

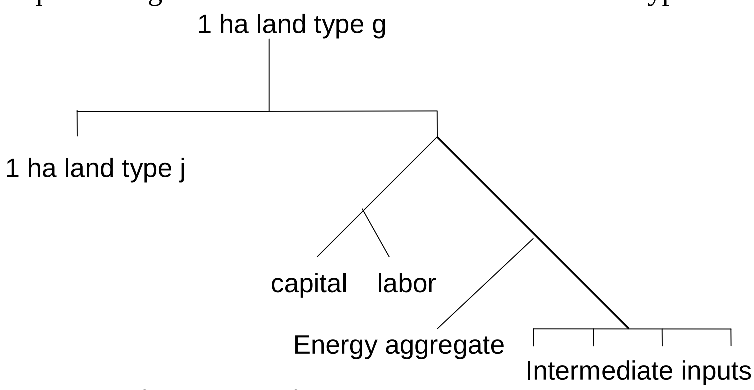


Figure 1. Structure of Land Transformation Functions

The unit cost $C$ for converting land type $j$ to land type $g$, as described by the land transformation function in Figure 1, can be formulated as:[a]

$$C = \left[\alpha\left(\frac{PLRENT_j}{\overline{PLRENT}_j}\right)^{1-\sigma} + (1-\alpha)\left(\frac{PO_j}{\overline{PO}_j}\right)^{1-\sigma}\right]^{1/(1-\sigma)} \quad (1)$$

where $PLRENT_j$ is the index for the rent for land type $j$ with the base year level $\overline{PLRENT}_j$, $PO_j$ is the index for the cost of all other inputs (including capital, labor, energy aggregate, and intermediate inputs) with base year level $\overline{PO}_j$, $\alpha$ is the cost share of the rent, and $\sigma$ is the substitution elasticity between land type $j$ and all other inputs. Land conversion needs to ensure that in each region, as land use changes, total area of land in physical terms is accounted for exactly, neither create nor destroy any land area. As a result, we implement a Leontief cost function for Equation (1) and therefore $\sigma = 0$, which guarantee that land change will be one hectare for one hectare. This is also represented by the top CES nest of Figure 1. While to make the presentation simpler, we use $PO_j$ to represent the cost index of all other inputs, unit costs for other input bundles that constitute $PO_j$ can be written explicitly following the same logic as Equation (1).

Based on Equation (1), the activity level of land conversion from type $j$ to $g$, denoted by $LNDTRAN_g$, is determined by the following MCP problem, which is just the cost-benefit analysis for the land conversion:

$$C \geq \frac{PLRENT_g}{\overline{PLRENT}_g}; LNDTRAN_g \geq 0; \left(C - \frac{PLRENT_g}{\overline{PLRENT}_g}\right) \cdot LNDTRAN_g = 0 \quad (2)$$

The more common land use change approach among CGE models is to use a Constant Elasticity of Transformation (CET) function to represent the allocation of land among different uses. With the CET, a land supply elasticity of each type is implied by the elasticity of substitution. The CET and closely related Constant Elasticity of Substitution (CES) functions are share preserving in the sense that it takes ever-larger absolute prices differences among land types to change the amount of land from one use to another as one moves further from the base shares (Gurgel, 2007). As with the CES, all land types allocated through a single CET have identical substitution elasticies but this limit can be overcome with multiple nests of CET functions. Implicitly, the CET can be seen as reflecting some underlying variation in suitability of land for different uses and/or the cost or willingness of owners to switch land to another use. At the margin there is land that is easily converted from one use to another, but with ever-greater conversions to a use, ever-less suitable land must be converted, meaning higher implicit costs. The share-preserving nature of the CET assures that radical changes in land use do not occur, and for short-term analysis this may reflect well landowners' resistance to convert without significant and sustained economic incentives to do so. However, for longer-term analysis where demand for some uses could expand substantially the CET approach can unrealistically limit land use change. The CET also does not explicitly account for conversion costs associated with clearing and preparing the soil, spreading seeds and managing the creation of a new agricultural system. The CET only limits conversions and so results in different land rents for different types of land and indirectly results in greater cost through substitution of other inputs for a land type as its rent rises.

[a] This is done by using the calibrated share form for CES functions. See Rutherford (1998) for more details.

There are also another problems with the CET approach (Schmitz, C. *et al*., 2014)[b]. Because land enters the CET function aggregated in value terms there is no direct relationship to area in physical units. While such supplementary accounts could be created as we do with EPPA. When a unit of one type of land in value terms is converted to another type of land using the CET there is no way to consistently update the supplemental physical accounts. The CET elasticities are also symmetric, which means that the ease of conversion from forest to cropland is the same as from crop to forestland. Thus, conversion in either direction has the same "cost" when in reality much more effort and input is typically required to create cropland. Simple abandoning cropland that was originally forested with no additional effort or input will generally allow it to return to natural forest.

Given the limitations of the CET approach, we believe the approach developed in EPPA has significant advantages, especially over longer time horizons where retaining consistency of physical accounting is important.[c] However, the EPPA-approach means there are no inherent differences in land that cannot be overcome through investment in conversion. This is a relatively strong assumption, however, it is moderated by other elements of the formulation. First, conversion costs and land availabilities are country/region specific reflecting the differences among land that exist in each region. For example, most cropland in an arid region would be irrigated, and so the conversion costs to cropland already reflect the fact that most land requires irrigation in that region. Second, we assume no possibility of conversion from the "Other" land category, which includes desert, tundra, built areas, and similar land types. Third, when simulated as in a linkage with TEM, we assign changes in land use to specific geographic grids based on the TEM-estimated productivity for that use. If land expansion means going into less productive areas, the effect of that lower yield on the average yield in the region is fed back into EPPA. An alternative would be to sub-divide regional land availability along the AEZ classification in the GTAP land database as the AEZs are an attempt to represent the importance of climate on land suitability for cropping. However, AEZs are based on current climate, and implicitly assume homogeneity of land within each AEZ. The TEM vegetation productivity is based on climate, atmospheric $CO_2$, ozone, and soil, as it varies on a 0.5°x 0.5° latitude-longitude grid, and thus provides a much finer set of gradations that change continuously in simulations where climate and atmospheric composition change.

### *2.2.3 Conversion of natural land to agricultural use*

Among the several challenges in land use modeling, one of the most critical is the representation of the conversion of natural or unused land into agricultural land categories. A main issue is that while there are vast areas of land that could be converted to crops or other uses, that land often has little or no market value. Hence it is a negligible quantity in the value terms assigned it in the CGE framework. One approach creates a land supply schedule that

---

[b] The models identified as Envisage, Farm, GTEM and Magnet use CET functions to represent land allocation among alternative uses (Schmitz et al., 2014).

[c] Other alternative approaches to the CET land use transformation functions exist, besides the one in EPPA, as land use transition matrices at regional level based on census data and satellite image Ferreira Filho, J. de S. & Horridge (2014). However, as this approach was developed only to the case of one country (Brazil), it is not suitable at the moment to be used at the global scale as in EPPA.

allows an increase in the agricultural land area as a function of agricultural land rents (Meijl & Rheenen, 2006). This approach does not allow for representation of the spatial differences in the supply decision, which can be improved by the inclusion of AEZs (Golub & Hertel, 2012).

In the case of the EPPA model, we represent the conversion of natural areas to agricultural use in the same way as other land use conversions, where the costs of conversion are explicitly represented. This allows, for example, cropland increase by clearing natural forestry area and preparing the soil to receive crops. The opposite direction can also be observed, i.e., cropland can be abandoned to re-grow secondary forestry or reorganized to produce livestock or forestry products. However, two relevant additions are made: a) the conversion of natural forests allows the production of timber products that substitutes for forest harvest on managed forest land; b) we consider a fixed factor with limited substitution possibilities in the conversion costs of natural areas, which allows us to represent a land supply response, based on rates of conversion observed over the last two decades. This last feature captures a variety of factors that work to slow land conversion, including increasing costs associated with larger deforestation in a single period and institutional constraints (such as limits on deforestation, public pressures for conservation, or establishment of conservation easements or land trusts). However, these are just reflected implicitly by the elasticity. We can also simply remove from consideration lands that are fully protected such as parks or reserves. In an earlier application we considered explicitly recreational opportunities for land that were a function of income that resulted in demand for forest land and protected forest land (Antoine et al., 2008), but the necessary data are not available globally.

These additions result in some slight changes in Figure 1 for natural land conversion as shown in Figure 2. The dashed line indicates the production structure for natural forest conversion, where a fixed coefficient multiproduct production function also produces timber, a perfect substitute for output of the forestry sector.

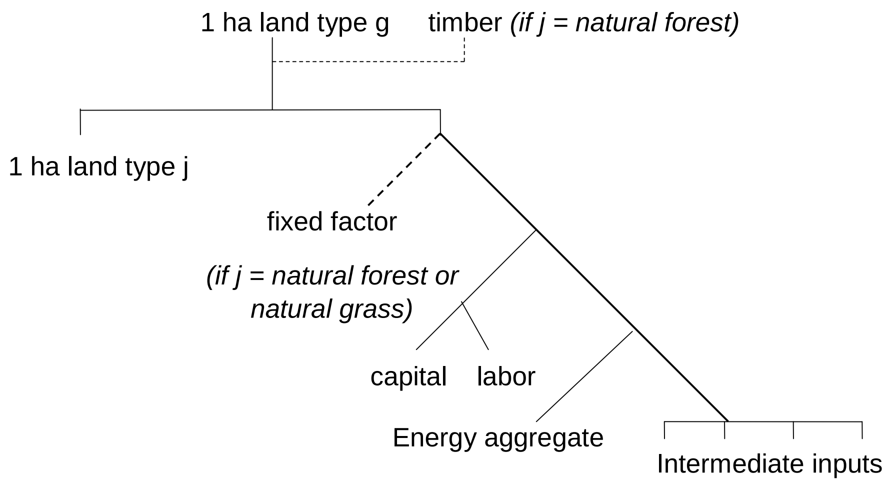


Figure 2. Structure of Land Transformation Functions for Natural Land Use Categories

As noted earlier, data on the value of land are from GTAP8 database (Narayanan et al., 2012) where land rents are an aggregate value for all land of each type. These must be

considered "use" values as they come from national economic statistical agencies that record actual monetary transactions. They thus do not attribute any rental value to land that is not in current use – natural (or unmanaged) forest and grassland, nor do they separate out the physical quantities of these land types. To get per hectare rents, the aggregate rental data are divided by the physical quantity of land. In addition, to be comparable to observed rents, the physical quantity can include only that land that is used on some regular basis. There are many different definition of managed and natural forests that give rise to wide ranges of estimates of the area of each. We separate out unmanaged land that is not producing a regular income flow by using data from TEM (Felzer et al., 2004), which is based on a global land use transition database (Hurtt et al., 2006). We get from this data set, areas of natural grassland, natural forest, managed forest, as well as other land (tundra, built up land, wetlands, and desert).

TEM carries a long history of gridded land use data going back centuries. In heavily developed areas such as the US and Europe very little land has never been disturbed. We classify forestland that has not been harvested beyond the typical rotation age for that area as "natural forest" even though they are not pristine "old growth" forest stands. Hence such areas may have been harvested regularly at one point, but not recently. "Managed forests" thus include forests that have been harvested in recent decades whether left to regrow naturally or highly managed. Data on pasture and cropland is obtained from the GTAP8 Land Use database (Baldos & Hertel, 2012). Table 2 presents the land cover data for each EPPA region, measured in MHa. Because the definition of natural and managed forest is unique to our approach these areas, in particular, are not necessarily consistent with sources that use a different categorization.

While conversion costs from managed forest to cropland and pasture, or from pasture to cropland, is by our equilibrium assumption, equal or greater than the difference in value of these types, we have no information on the "value" of land not currently in use, or the cost of conversion. So, an important step to represent natural land categories and their conversion to other uses is to determine a meaningful reservation or non-use value for them. To do so, we use data from the Global Timber Market and Forestry data Project at Ohio State (Sohngen, 2007).

This database assumes that, at the margin, the cost of access to remote timber land must equal the value of the standing timber stock plus that of future harvests as the forest regrows. With this assumption the net present value of the land and timber is calculated using an optimal timber harvest model for each region of the world and for different timber types. Setting the access costs to this value establishes the equilibrium condition that observed current income flow (i.e rent and returns) from currently unaccessed land is zero because the timber there now and in the future can only be obtained by bearing costs to access it equal to its discounted present value.

Table 2 – Land Cover by EPPA Regions (MHa)

| | Pasture | Cropland | Managed Forest | Natural Grass | Natural Forest | TOTAL |
|---|---|---|---|---|---|---|
| USA | 167,088 | 229,111 | 53,512 | 132,816 | 196,827 | 779,354 |
| CAN | 37,463 | 63,042 | 24,842 | - | 332,869 | 458,216 |
| MEX | 37,662 | 62,726 | 4,534 | 52,952 | 41,270 | 199,144 |
| JPN | 3,630 | 413 | 4,233 | 200 | 32,288 | 40,764 |
| ANZ | 31,132 | 264,420 | 1,154 | 396,858 | 131,110 | 824,674 |
| EUR | 124,522 | 60,524 | 34,971 | 33,964 | 132,706 | 386,687 |
| ROE | 109,716 | 279,561 | 8,182 | 107,440 | 39,140 | 544,039 |
| RUS | 123,952 | 78,637 | 60,327 | 217,682 | 633,601 | 1,114,199 |
| ASI | 36,281 | 6,645 | 4,788 | - | 66,160 | 113,874 |
| CHN | 139,869 | 277,030 | 22,977 | 86,214 | 93,487 | 619,577 |
| IND | 171,259 | 22,793 | 2,515 | - | 69,596 | 266,163 |
| BRA | 59,578 | 173,665 | 31,324 | 42,576 | 477,077 | 784,220 |
| AFR | 240,759 | 790,383 | 31,216 | 484,806 | 523,580 | 2,070,744 |
| MES | 32,812 | 70,904 | 295 | 260,657 | 30,246 | 394,914 |
| LAM | 79,346 | 275,710 | 27,167 | 130,797 | 334,637 | 847,657 |
| REA | 79,097 | 118,599 | 15,553 | 129,136 | 118,822 | 461,207 |
| KOR | 1,104 | 100 | 839 | - | 7,849 | 9,892 |
| IDZ | 60,859 | 2,075 | 4,631 | 3,217 | 142,685 | 213,467 |
| TOTAL | 1,536,129 | 2,776,338 | 333,060 | 2,079,315 | 3,403,950 | 10,128,792 |

Source: Felzer et al. (2004) and Baldos& Hertel (2012), here summarized by EPPA regions.

We make use of this data and some simplifying assumptions to calculate an average standing stock of timber for each of our regions and the value of the land. In particular, we observe that:

$$NPV\ of\ Virgin\ Forest = X_0 + \sum_{t=1}^{\infty} \frac{X_t}{(1+r)^t} \qquad (3)$$

where $X_0$ is the value of the standing timber stock on the virgin forest today and $X_t$ is the value of future harvests. The second part of this sum in (3) is the discounted value of future harvest. We take that to be the value of land once the timber stock is gone, assuming that the value of the land rests in its ability to produce future harvests. We assume that future harvests are some fraction, θ, of $X_0$.[d] The database also provides the optimal rotation length for these lands.

Assuming optimal rotation once the virgin forest is harvested means that $X_t$=0 in every year except when there is a harvest. Recognizing this fact allows us to rewrite equation (3) where we define the time period length, *t*, to be to the optimal rotation length. For example, for an optimal rotation of 30 years, *t*=1 will occur when 30 years have passed, and *t*=2 when 60 years have passed, etc. Assuming an interest rate of 5% per annum means that $r= 1.05^{30}-1= 3.32$. This allows us to rewrite equation 1 as:

[d] In our current formulation we assume θ=1.

$$NPV\ of\ Virgin\ Forest = X_0 + \sum_{t'=1}^{\infty} \frac{X_0}{(1+r)^{t'}} \quad (4)$$

where *t'* is the time index where a period is of length equal to the optimal rotation for the forest which varies by region. With future harvests kept constant (independent of *t*) and recognizing that the infinite discount factor is just 1/*r*, Equation 4 can be solved for $X_0$:

$$\frac{NPV\ of\ Virgin\ Forest}{1+{}^{1}/_{r}} = X_0 \quad (5)$$

This allows us to deduce the value of the stock of timber in virgin forests, and for the purposes of CGE applications, the quantity, in value terms, of timber when it is harvested. The database also provides the area in each type of forest, the NPV, and the optimal rotation. Since we have only one "unmanaged" forest type, we calculate a weighted average among different types for each of EPPA regions. We do not have similar data for natural grassland, which obviously does not have a timber stock on it. We assume that natural grassland rent relative to pasture is the same as natural forest relative to managed forest. The resulting regional land rents by land class are shown in Table 3.

Table 3 – Land Rents per hectare at Regional Level (2007 US$/ha)

| | Cropland | Pasture | Managed Forest | Natural Grass | Natural Forest |
|---|---|---|---|---|---|
| USA | 161.31 | 37.62 | 25.74 | 6.02 | 4.12 |
| CAN | 37.07 | 21.78 | 36.96 | - | 5.91 |
| MEX | 164.13 | 30.00 | 53.04 | 5.40 | 9.55 |
| JPN | 1,702.50 | 9,218.91 | 94.64 | 32.37 | 34.07 |
| ANZ | 82.06 | 15.25 | 337.23 | 6.86 | 151.75 |
| EUR | 217.85 | 331.11 | 106.99 | 6.62 | 2.14 |
| ROE | 91.81 | 21.02 | 43.73 | 0.42 | 0.87 |
| RUS | 106.48 | 69.34 | 14.71 | 13.87 | 2.94 |
| ASI | 389.90 | 1,050.55 | 88.19 | - | 57.33 |
| CHN | 451.12 | 165.90 | 96.11 | 9.95 | 5.77 |
| IND | 318.03 | 1,043.80 | 316.07 | - | 69.54 |
| BRA | 120.26 | 24.50 | 13.66 | 4.66 | 2.59 |
| AFR | 67.05 | 7.69 | 30.23 | 2.58 | 10.13 |
| MES | 79.27 | 23.77 | 315.91 | 20.44 | 271.68 |
| LAM | 234.83 | 38.55 | 22.79 | 18.12 | 10.71 |
| REA | 231.90 | 99.62 | 33.54 | 22.62 | 23.81 |
| KOR | 8,581.89 | 18,869.82 | 109.45 | - | 54.72 |
| IDZ | 314.74 | 2,523.18 | 70.09 | 39.29 | 41.36 |

Once we have priced natural forest and natural grass areas, these are incorporated in the model as part of the initial endowments of households in each region. The areas may be converted to other uses or conserved in their natural state. The reservation value of natural lands enter each regional representative agent welfare function with an elasticity of substitution with other consumption goods and services. Hence, the value the agent derives from natural land, itself, is a deterrent to conversion. Thus, if for example, current timber demand rises and puts pressure to harvest more land that creates a partly offsetting demand to

conserve forest area because, implicitly, the agent sees it as more valuable in the future. In a fully forward looking model these expectations could be consistently modeled. In the recursive dynamic structure of EPPA, introducing the natural forest value into the representative agents welfare function approximates this behavior.

To calibrate the land conversion function of natural to managed forests in the base year we need to split the forestry output and their land requirements in two: the value of production from harvested forestry and the value of production from clearing natural forests. The database (Sohngen, 2007), provides data on total hectares occupied by forestry plantations, annual forest area harvested and changes in the area of forests (plantation and natural) by region. Using these and our previous calculation of the value of the timber stock in virgin forests, we determine the share of total timber production in each region due to the clearing of natural forests, as also the natural harvesting share of the total area producing timber. We use those shares to re-benchmark the output of the forestry sector and its land requirements, and also to assign the value of timber production in the land transformation function and the natural forest being converted to managed forests in the benchmark data.

Another key feature in our formulation is the representation of the land supply response, which enters as the substitution elasticity between the fixed factor and other inputs as shown in Figure 2. We estimate a simple crop land supply elasticity, $\varepsilon_s$, and recognize the approximate relationship of the supply elasticity to the substitution elasticity between the fixed factor and other inputs $\sigma$, following Rutherford (2002), as:

$$\varepsilon_S = \frac{\sigma(1-\alpha)}{\alpha} \tag{6}$$

where $\alpha$ is the cost share of the fixed factor.

To estimate $\varepsilon_s$ we used data for 1990 to 2010 on land price changes in the US (Economic Report of the President, 2013). Global land price data are not easily available but because of global commodity trade we expect similar price movements of land globally. Beyond this theoretical argument, evidence that land prices move in parallel internationally are avaliable (Sutton & Webb, 1988). Average annual conversion rates of land in the historical period are derived from the land cover database (Hurtt et al., 2006). Table 4 presents the parameters associated with the natural forest land parameterization.

These elasticities appear to compare reasonably well with other estimates. For example, Kooten & Sohngen (2007) conduct sensitivity analysis considering land supply elasticities of 0.13 and 0.38 for all regions in their forest modeling, arguing that these are representative of the range in the literature. Given the observation that conversion rates vary strongly by region, we believe the case for trying to represent this variation is compelling, even if the data for exact calibration is lacking.[e]

### *2.2.4 Technological change*

Technological change in EPPA can come about through three different channels: (1) Exogenous productivity growth assumptions in factor inputs; (2) different choices of technique or technology implied by the different mix of inputs allowed through substitution in the production function in each sector and induced by changes in relative prices; and (3),

---

[e] Those regions with virtually no conversion in the historical data were assigned an elasticity of 0.02.

explicit choice of new technologies whose input requirements, and production function are specified in the model data set. Essentially we specify blueprints for the possible future technologies available at different times in the future that may be used in place of the conventional technology if input prices change to make them competitive. All three forms of technoloigical change are relevant in the land use modeling, as described below.

Table 4 – Parameters to model natural land use transformation functions

| | Share of forestry output from natural forest cleared | Share of natural forest land being cleared from total land used to produce forestry output | Elasticity of land supply | Elasticity of substitution among fixed factor and other inputs |
|---|---|---|---|---|
| USA | 0.10 | 0.004 | 0.02 | 0.00004 |
| CAN | 0.01 | 0.000 | 0.02 | 0.00002 |
| MEX | 0.34 | 0.106 | 0.14 | 0.00300 |
| JPN | 0.01 | 0.002 | 0.01 | 0.00007 |
| ANZ | 0.09 | 0.045 | 0.06 | 0.00100 |
| EUR | 0.01 | 0.001 | 0.02 | 0.00018 |
| ROE | 0.01 | 0.002 | 0.02 | 0.00028 |
| RUS | 0.01 | 0.000 | 0.02 | 0.00002 |
| ASI | 0.57 | 0.095 | 0.39 | 0.00200 |
| CHN | 0.01 | 0.001 | 0.02 | 0.00007 |
| IND | 0.07 | 0.023 | 0.02 | 0.00037 |
| BRA | 0.21 | 0.068 | 0.16 | 0.00300 |
| AFR | 0.48 | 0.454 | 0.18 | 0.00800 |
| MES | 0.01 | 0.008 | 0.02 | 0.00015 |
| LAM | 0.01 | 0.007 | 0.10 | 0.00200 |
| REA | 0.30 | 0.101 | 0.22 | 0.00100 |
| KOR | 0.01 | 0.503 | 0.02 | 0.01300 |
| IDZ | 0.68 | 0.249 | 0.35 | 0.00400 |
| USA | 0.10 | 0.004 | 0.02 | 0.00004 |

Quantities of each land type in EPPA can be altered through conversion to another type or abandonment to a non-use category. Land is also subject to an exogenous productivity improvement set at 1% per year for each land type, reflecting assessment of potential productivity improvements (Reilly & Fuglie, 1998; Gitiaux et al., 2011; Ray et al., 2013) that show historical crop yields growing near this rate, although the range among regions and crops is wide and varies over time.

Besides exogenous yield change, it is possible to further intensify conventional agricultural production in the EPPA model as land can be partially substituted by inputs and other primary factors in the agricultural production functions as relative prices change over time. The ability to intensify production is controlled primarily by two substitution elasticities in the crop, livestock and forestry production nests. The elasticity $\sigma_{ER}$ is the substitution between energy/materials and land and $\sigma_{EVRA}$ is the substitution between the energy/materials/land input bundle and the value added bundle that combines capital and labor (Paltsev et al., 2005). These elasticities are set as 0.3 and 0.7, respectively. It means that

higher prices for land can be overcome by substituting in the lower nest toward energy, fertilizer, and other materials, and in the upper nest toward capital. The actual simulated output of agricultural product per hectare of land in a scenario in each agricultural sector in EPPA is a combination of the exogenous productivity trend and the endogenous intensification possibilities that depend on relative prices of inputs. Economists also define a concept of total factor productivity. In this regard, EPPA also includes exogenous economy-wide productivity improvement in labor and capital that contribute with the exogenous productivity in land to determine changes in total factor productivity for these sectors.

The representation of new technologies is also a key feature of CGE models dealing with natural resources and environmental goods and services. In the case of land use modeling, bioenergy technologies, and biofuels have motivated several developments and improvements in CGE models. Different versions of the EPPA model have been used to address a variety of aspects of bioenergy, from commercial potential of second generation biofuels (Gurgel et al., 2007; Reilly & Paltsev, 2009), to the role of first generation biofuels to meet near term mandates Winchester et al., 2015; Gitiaux & Rausch, 2012), to a detailed investigation of multiple first- and second-generation bioenergy pathway (Winchester & Reilly, 2015) and linking of the model to a terrestrial vegetation model to study land use change and environmental impacts of climate on crop, pasture, and forests (Melillo et al., 2009; Reilly *et al.*, 2012; Gurgel et al., 2011). These studies have shown the details and importance of the parameterization of the bioenergy technologies, including their potential productivity by region, the policies and market aspects affecting their demand, the by-products, their price mark-up compared to their fossil fuel energy substitute, among others. Because of this extensive previous work, here we simply calibrate the model to represent current levels of bioenergy production, but do not explore future policy scenarios that further spur bioenergy use. Readers interested in more details on incorporating advanced biofuel technologies can consult references cited above. As a result, in the scenarios we present in Section 3 bioenergy and biofuels production remains a small contributor to energy and, in terms of land use, is one more (relatively small) demand by cropland area.

There are some important differences in the EPPA approach to biofuels introduction and other modeling efforts. We introduce advanced technologies as a perfect substitute for conventional technologies, subject to adjustment costs as the industry scales up (Morris et al., 2014). Since there is some ethanol production in some regions, another approach used to explicitly introduce biofuels is to use a CES production nest where biofuel and conventional fuel are imperfects substitutes. Indeed given blend wall limits on current vehicles, ethanol is an imperfect substitute for gasoline. However, for longer term analysis were the fleet can change the CES, imperfect substitute, assumption severely limits the potential share of the market biofuels can ever take, and doesn't consider the potential production of "drop-in" fuels that are perfect substitutes. Other approaches that are more explicit about blend walls, new vehicle penetration and the characteristics of particular biofuels are thus needed. For applications and approaches see, in particular, Winchester & Reilly (2015), Winchester et al., (2015), Gitiaux & Rausch (2012) and Rausch et al. (2009).

### *2.3 Agricultural and Food Consumption*

The sectoral breakdown in Table 1 includes agriculture, crop, livestock, forestry and bioenergy production sectors. These are linked together through the input-output structure of

each regional economy. Hence, output of these sectors end up in the food, energy, and other sectors of the economy. For example, much of crop sector output ends up as an animal feed input to the livestock sector. By definition, the crop and bioenergy sector use cropland, the livestock uses managed grassland, and the forest sectors harvests from managed and natural forestland. This is "by definition" because, for example, before managed forest or grassland can be used for growing crops, it must be converted to cropland and so this "definition" does not restrict what land is used in each sector. Each of the agriculture and food sectors also use intermediates goods from other sectors, including energy, as reflected in the I-O data for each region, and all require investment.

How much food and agriculture products is produced, and hence how much land is use is strongly influenced by the growth in population and incomes. While constant returns to scale (CRTS) CES functions often used in CGE modeling make solving the model easier, it implies an income elasticity of one for all commodities in any period. However, most studies find that, for instance, as income grows, the expenditure shares on food will decrease although food consumption levels may increase (Zhou et al., 2012; Haque 2006), and this suggests an income elasticity of less than unity. Similar observations can be found for the consumption of agricultural products. As a result, CGE applications based on CES functions tend to overestimate food consumption growth as income increases.

CES functions are also used throughout EPPA to model consumption and production activities. To account for the lower income elasticities for food in earlier versions of EPPA, the consumption shares in the expenditure function were adjusted between periods, exogenously taking into account the growth in income in a reference projection. While adjusting the consumer expenditure shares generated a growth in food demand over time consistent with the reference income projection, the approach retained the CRTS property within each period, and if GDP growth was changing with different scenarios of productivity growth or as a result of strong policy measures, the change in food demand would need to be recalibrated with additional adjustments to consumption shares over time.

In the current version of EPPA, we take a further step toward a within-period non-homothetic preference. Our strategy is to adopt the approach described in Markusen (2006), where a Stone-Geary preference system is incorporated into a CGE model written in MPSGE (Rutherford, 1999). In particular, instead of changing the expenditure shares, we create shift parameters for the nested CES expenditure function. Each shift parameter changes the reference point of consumption from zero (as in the CES case). The shift parameter, sometimes referred to as the subsistence consumption level, is calibrated to match estimated regional income elasticities. Note that the Stone-Geary preference is a Linear Expenditure System (LES), which has a constant marginal budget share for each commodity. As a result, for a given set of shift parameters, the limit property of Stone-Geary is still CRTS, and therefore when income increases significantly, the realized income elasticities of demand calculated from the model response will converge to one. To overcome this limitation, our strategy is to recalibrate shift parameters of later periods so the realized income elasticities can at least approximate the empirically observed levels, even as income grows.

Although the focus here is on the final consumption of food, crop, and livestock products, the Stone-Geary adjustment is also applied to the final consumption of other commodities. This symmetric treatment makes it possible to incorporate all commodities' income elasticities—although due to sectorial mapping considerations, currently we only incorporate

income elasticity estimates for food, crop, and livestock products from Reimer & Hertel (2004), and calculate an average income elasticity for other commodities based on Engel's aggregation. With these elasticities, the shift parameters can be calibrated accordingly. To explain this, let us consider a utility function $U$ with preference over $N$ commodities indexed by $i$, and use $c_i$, $c_i^*$, and $w$ to represent the base year consumption of commodity $i$, shift parameter for the consumption of $i$, and the budget, respectively:

$$u = U(c_1 - c_1^*, c_2 - c_2^*, \dots, c_N - c_N^*) \quad (7)$$

The income elasticity for commodity $i$ can be written as:[f]

$$\eta_i = \left(\frac{c_i - c_i^*}{c_i}\right) / \left(\frac{w - \sum_{i=1}^{N} c_i^*}{w}\right) \quad (8)$$

The solution for the base year shift parameter is $c_i^* = (1 - \eta_i)c_i$ (Chen et al., 2015). To illustrate how the shift parameter is recalibrated over time, let us consider two products $x$ and $y$, where $x$ represents commodity $i$ (and so in the following we will drop the notation $i$), $y$ is the aggregation of all commodities other than $i$, and use $t$ for the time period ($t = 0, 1, 2, \dots, N$). As shown in Figure 3, with the base year consumption bundle $A_0: (x_0, y_0)$ and $\eta_x$ (the income elasticity for $x$), one can derive the base year shift parameter for $x$ as $c_0 = (1 - \eta_x)x_0$. Now, given $\eta_x$, let us consider the consumption bundles $A_1^T: (x_1^T, y_1^T)$ and $A_2^T: (x_2^T, y_2^T)$, respectively, where $A_1^T$ is the consumption bundle of $t = 1$ with: 1) income level $w = w_1$; 2) the base year relative price; and 3) the income elasticities $\eta_x$ and $\eta_y$, and while $A_2^T$ is for $t = 2$ and is under a different income level $w = w_2$, it faces the same base year relative price and income elasticities. In this case, the desired income-consumption path is $A_0 A_1^T A_2^T$.

In the usual Stone-Geary preference setting, the shift parameters are kept at their base year levels, and the resulting income-consumption curve is $A_0 A_1 A_2^S$, which is indeed a straight line since the underlying marginal budget shares are constant.

To approximate $A_0 A_1^T A_2^T$, rather than using $A_0 A_1 A_2^S$, our strategy is to find $A_0 A_1 A_2$, where $A_1$ is the consumption bundle with: 1) income level $w = w_1$; 2) the base year relative price; and 3) the shift parameter $c = c_o$, and $A_2$ is the consumption bundle with 1) $w = w_2$; 2) the base year relative price; and 3) the shift parameter $c = c_1$. Note that one cannot update the shift parameter $c$ until the third period ($t = 2$), when previous income levels ($t = 1; 0$) become available and allow us to derive $c_1$, the shift parameter for $t = 2$. The same procedure is applied to derive $c_2$ for $t = 3$ (based on income levels of $t = 2$ and $t = 0$) up to $c_{N-1}$ for $t = N$ (based on income levels of $t = N - 1$ and $t = 0$). More precisely, to calibrate $c_1$, we solve for $A_1^T: (x_1^T, y_1^T)$ when $w_1$ is available, and then together with the given $A_0: (x_0, y_0)$, use the line $\overleftrightarrow{A_0 A_1^T}$ to find $c_1$. Similarly, when $w_2$ is available so $A_2^T$ is determined, $c_2$ (for $t = 3$) can be found by the intersection of $\overleftrightarrow{A_0 A_2^T}$ and the $x$-axis, and so on.

[f] Rigorously, the right side of Equation (8) is an approximation to the point elasticity $\eta_i$.

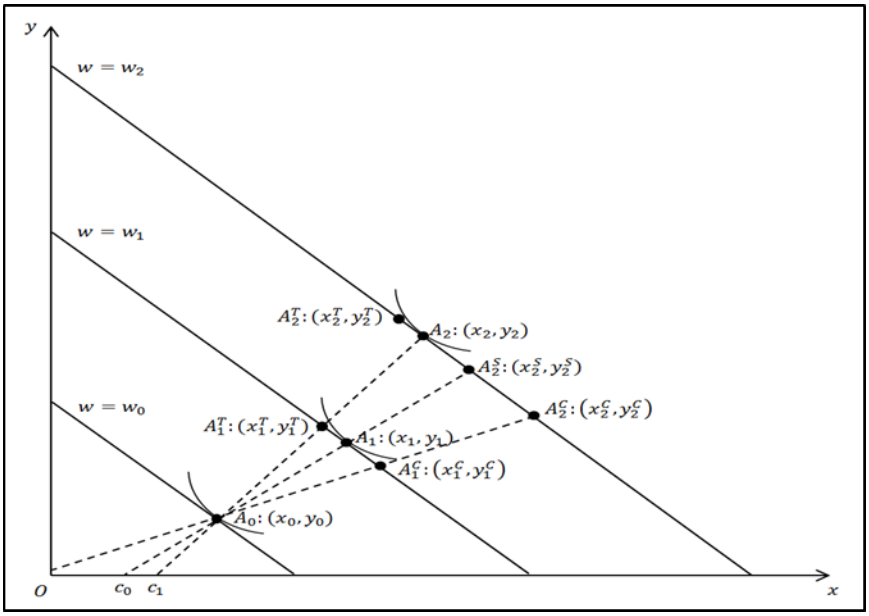

Figure 3. Consumption bundles with various income elasticities.
Source: Chen et al., 2015.

Note that one adjustment is needed to incorporate the income elasticities information. In EPPA, since the labor endowment of the representative consumer increases over time proportional to population growth, the model's representative consumer should be interpreted as an aggregated consumer. If we denote $\eta_i^0$, $\eta_i$, $w$, and $pop$ as the given (or observed) income elasticity of commodity $i$ for each individual, the income elasticity of $i$ for the model's representative consumer, the individual's budget for final consumption, and the population index, respectively, then after taking total derivatives on aggregate consumption and aggregated budget to decompose changes and rearranging terms, we have:

$$\eta_i = \frac{\eta_i^0 \frac{dw}{w} + \frac{dpop}{pop}}{\frac{dw}{w} + \frac{dpop}{pop}} \qquad (9)$$

$\eta_i$ in Equation (9) characterizes the behavior of the model's representative (aggregate) consumer. Note that while the budget for each individual is $w$, the aggregated budget for the representative consumer is $w \cdot pop$. The adjustment done by Equation (9) ensures that the given income elasticities information is correctly translated and implemented.

Additional modification beyond final consumption is done to model the food sector. In EPPA, intermediate inputs of the food sector are modeled by a Leontief structure, which means that without further adjustments, crops and livestock inputs to food sector will grow proportionally as the food sector expands, despite the observation that other food sector inputs such as those from service sectors tend to have increasing shares. To account for this, we update the food sector input shares in a way such that the percentage changes of crop and livestock inputs are represented by the percentage changes of crops and livestock final consumption levels.

## 3. Sample Applications and Land Use Scenarios in the EPPA Model

Modeling natural resources in the CGE framework allows investigation of the use of these resources as inputs to economic activities and at least some aspects of the environmental consequences of using them. In the case of land use and land use change, future land use trajectories will be driven not only by increasing demand for food, fuel and fiber and concerns related to the conservancy of natural environment, but also by the availability of new agricultural areas and willingness to convert them. We present in this section some long run projections of global land use changes using the EPPA model and compare how results differ between versions with and without the explicit modeling of land use changes. We then provide sensitivity scenarios illustrating how population, GDP and land productivity growth assumptions alter future land use trajectories. For simplicity of presentation, most of the results aggregated in two regional groups, developed and developing countries. [g]

### *3.1 Land use in the baseline*

The land use distribution among agricultural and natural vegetation areas in the EPPA database in the year 2010 is displayed in Figure 4. It shows the total world area in use to produce crops, livestock and forestry products, as also the forestland and grassland areas. Natural forest is the largest land cover in the world in 2010, occupying 3.39 billion ha. The second largest is the pasture area (2.82 billion ha) , followed by natural grasslands (2.03 billion ha). Land use for crop production covers 1.55 billion ha, and managed forest areas are 0.33 billion ha. The same order of importance follows in the developed and developing countries. Developing countries have greater areas in all land use categories, except in the case of managed forests. However, the shares of each land use type are different: developed countries have higher shares of natural forest and natural grasslands, while developing countries contribute with higher shares of cropland and pasture. Other land use covers and categories (as build-up, deserts, tundra), are fixed in the model, so we do not represent them in the following figures.

Table 5 displays the evolution of global land use from 2010 to 2050. EPPA projects an increase of 58 million ha of cropland in the first half of this century, while natural forests will decline by 36 million ha until 2040, and then grow back after that, reaching an area slightly higher in 2050 than in 2010. The opposite trend is observed in the case of pasture areas, which increase by 27 million ha from 2010 to 2030, and decrease after that. Natural grasslands are the only land cover decreasing along all the period, losing 93 million ha. Managed forest areas follow the cropland trend, increasing in all years. These trends at global level reflect an increase demand for crops and wood products, and a preference to convert natural grassland rather than forests to agricultural use. A variety of factors contribute to these trends, including gradually slowing population growth and GDP growth, changing food demand as economies become wealthier, assumptions about exogenous land productivity growth, and the relative ability to substitute other inputs for land in each sector's production function. For example, the greater of land in the production in livestock combined with substitution elasticity contributes to considerable "intensification" of the livestock sector, using considerably less

---

[g] Developed countries includes the following EPPA countries and regions: USA, CAN, JPN, ANZ, EUR, ROE and RUS. Developing countries are: ASI, KOR, IDZ, CHN, IND, BRA, AFR, MES, LAM, REA.

land and more of other inputs to produce the same amount of livestock output. Since all of these and other factors jointly play a role, it is not possible to disentangle them, but the sensitivity analysis conducted later helps to show importance of each of several factors.

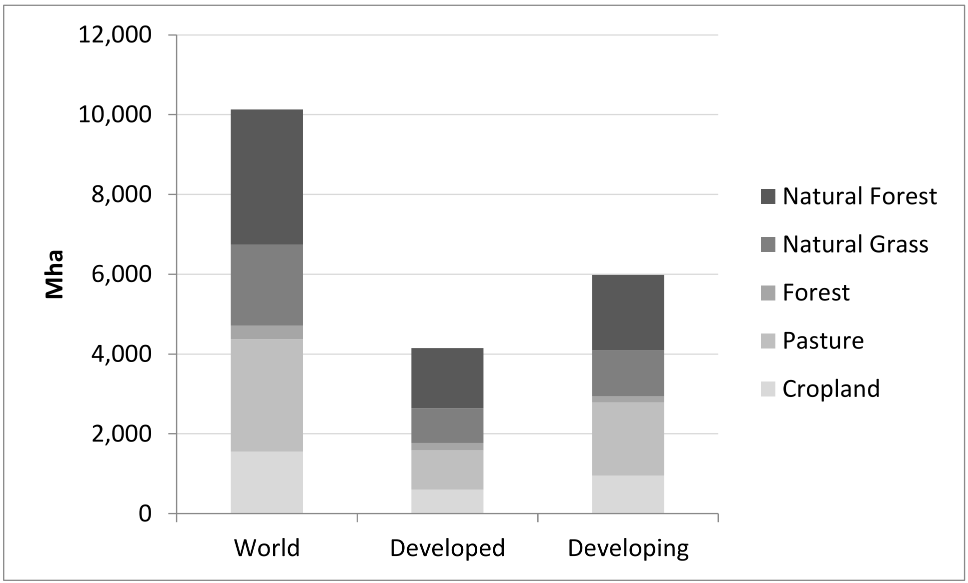


Figure 4. Land use in the base year (2010), Mha.

Table 5. Global land use, Mha.

| | Cropland | Pasture | Forest | Natural Grass | Natural Forest |
|---|---|---|---|---|---|
| 2010 | 1555 | 2822 | 335 | 2028 | 3389 |
| 2015 | 1551 | 2841 | 347 | 2011 | 3378 |
| 2020 | 1564 | 2848 | 357 | 1993 | 3367 |
| 2025 | 1569 | 2849 | 366 | 1986 | 3359 |
| 2030 | 1573 | 2848 | 372 | 1979 | 3356 |
| 2035 | 1578 | 2846 | 377 | 1974 | 3354 |
| 2040 | 1589 | 2841 | 381 | 1965 | 3353 |
| 2045 | 1601 | 2819 | 388 | 1949 | 3371 |
| 2050 | 1613 | 2795 | 394 | 1935 | 3391 |

The global land use trends are not homogeneous between the two country groups considered here. Figure 5 presents the cumulative land use changes in developed and developing countries compared to 2010 land use patterns. The changes in land use move in opposite directions in these two groups of countries, and changes are much larger in developing countries. While cropland reduces by 10 billion ha by 2050 in developed countries, developing countries expand it by 68 billion ha. Natural forests increase by 4.5 billion ha in the developed world, but decreases by 40 billion ha in developing countries until 2040. This trend reverts to only 2 billion ha reduction in 2050. Managed forest areas increase

by 63 billion ha from 2010 to 2050 in developing countries, but these countries lose 97 billion ha of natural grassland in the same period.

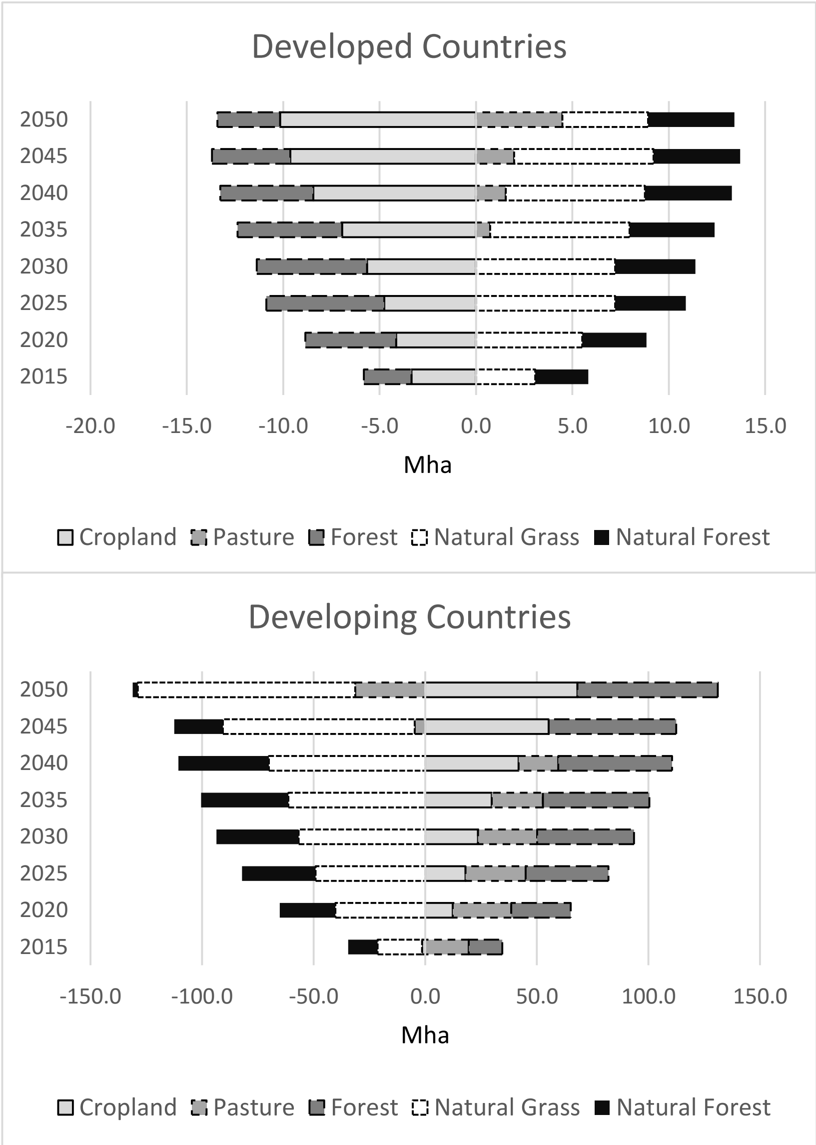


Figure 5. Land use dynamics in developed and developing countries, changes from 2010 land cover, Mha.

These results show very different trends and preferences by alternative environmental services from land. Developed nations have a much more consolidated land use pattern, with relatively small changes in the land use allocation, while developing countries continue to expand agricultural and forestry areas, increasing their shares of food and other raw materials production in the world and decreasing the stock of natural vegetation. With stronger population growth in developing countries and availability of suitable land, the expansion of agricultural areas is an expected result in these countries. EPPA captures this possibility by the elasticities governing the land supply response. In addition, food and other product demand growth is more rapid in developing countries because of population and income

growth. The Armington trade assumption in the model reflects a preference for domestic consumption over imports, and hence more of that increasing demand is met through consumption in these regions than through imports.

An interesting result in terms of land use is the preferable conversion of natural grassland areas in the developing world and the reversion of the deforestation process at the end of the model horizon in such countries. These results are consequence of relatively lower costs to convert natural grasslands to agricultural use than converting forest. The increasing productivity in the managed forest sector, which reduces the importance of deforestation to supply timber products, also helps to decrease deforestation in the last periods. Another factor influencing the decreasing rate of expansion of agricultural areas has to do with the gradual reduction in the population growth approaching 2050, diminishing the pressure on food demand, even as we assume a constant 1 percent increase in land productivity.

Finally, as the non-use value of natural vegetation areas enters the welfare function, the model balances the marginal benefits from agricultural and forestry production from a new ha of agricultural area against the marginal costs of converting the natural vegetation, which includes the explicit costs of conversion as also as the opportunity costs of losing the reservation value of this land in the welfare function. The reversed trend in deforestation in developing countries in the last periods indicates that the net benefits from the conversion of one ha of natural grass to agriculture are getting higher than the net benefits from deforesting one ha of natural forest for the same purpose.

### *3.2 Comparing the model with and without land use changes*

The explicitly representation of land use changes in the EPPA model is an advance in the modeling of global economic and environmental phenomena. However, we might expect the introduction of this feature to alter some of the sectorial and macroeconomic results of the original model. It is worth, then, to compare key results of the model before and after the introduction of land use changes.

Figure 6 shows the differences on sectorial output between the two versions of the model. The largest deviation occur in those sectors using land as a required input and in developing countries. In the developed countries, the EPPA version with land use changes gives higher levels of output from the crop, livestock, and food products, and mixed picture for forestry—less in the near term and more forestry output in 2030 and beyond. The changes are on the order of -3 to +9 percent. The opposite is observed for developing countries, where output of all four of these sectors decline on the order of 1 to 16 percent. Effects on other sectors are an order of magnitude smaller (< +/-0.4%), and generally of the same sign in the developed countries. In developing regions, impacts on other sectors are somewhat bigger than in developed regions (< +/-4.0%) and generally of opposite sign.

Although the higher agricultural production in developed countries and the lower in developing countries under the land use version of EPPA seems counterintuitive, the results reflect an important feature of the modeling. Without an explicit representation of land use changes, the assumptions about future exogenous land productivity improvements were lower in developed countries, capturing their current higher yields and the existing agricultural technological gap in developing countries. In the land use version of EPPA, the productivity trend is the same in all countries and regions, which allows the model to better capture the trade-offs between land intensification and land expansion to new agricultural areas. As

consequence, the exogenous land productivity growth will favor agricultural production in developed countries, while developing countries will prefer to convert natural areas to agricultural production. Developed countries benefit from higher output and relatively higher productivity in the land use version of the model, which benefits all sectors, where as in developing countries there is a reallocation of activity from agricultural sectors to other sectors. As agricultural sectors in developing countries account for a higher share of GDP than in developed, there is a larger expansion in other sectors in developing than in developed countries.

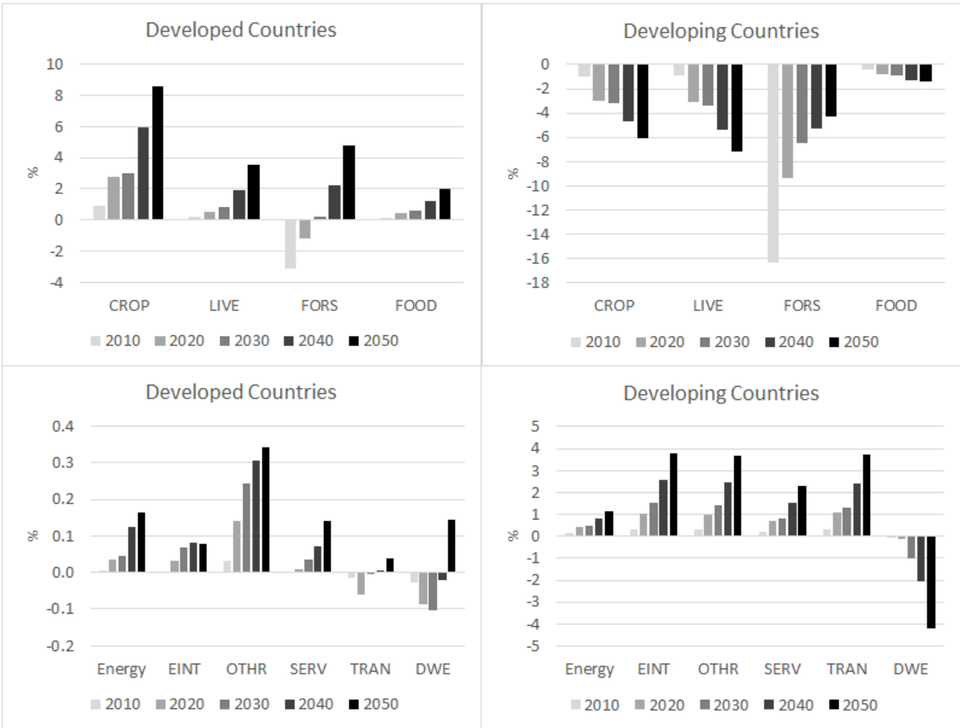


Figure 6. Differences in sectorial output between models with land use and without land use (%)

Another evidence from Figure 6 is the lower output level in the forestry sector in the land use version of EPPA, in both developed and developing countries. This is just consequence of the model calibration regarding recent levels of observed deforestation. As some share of timber products are produced by the conversion of natural forests to other agricultural land, this output is not included in the production level of the forestry sector anymore. Since the deforestation process reduces over time, the share of timber coming from deforestation reduces, and the output level from the forestry sector becomes similar in the two versions of the model.

The macroeconomic results are also slightly different between the two versions of the model. Figure 7 shows the deviation in aggregated consumption, investment and government spending levels projected by both versions. The differences are lower than 2% in the case of consumption and investments. Consumption and investments in developed countries are slightly higher in the land use version of EPPA, while consumption is higher and investments and government spending are lower in developing countries. Since the level of GDP is

exogenously determined as a target and is the same in both versions, the results in Figure 7 mean that aggregated trade balance in developed countries becomes smaller (more negative) in the land use version of EPPA, and more positive in developing countries. In this way, the land use model generates higher agricultural and food output in developed countries, which reflects in higher aggregated consumption and investments, and more negative trade balance of these goods. In the case of developing countries, lower agricultural and food production decrease their investments, but as population growth is higher than in developed countries, primary resources are employed in other sectors of the economy and overall consumption still grows. To compensate such growth, investments and government spending must decrease. In fact, these together more than compensate the higher consumption, which means that net exports increase in order to achieve the same GDP in the version of EPPA without land use changes. It keeps the consistency with a more negative net exports in developed countries.

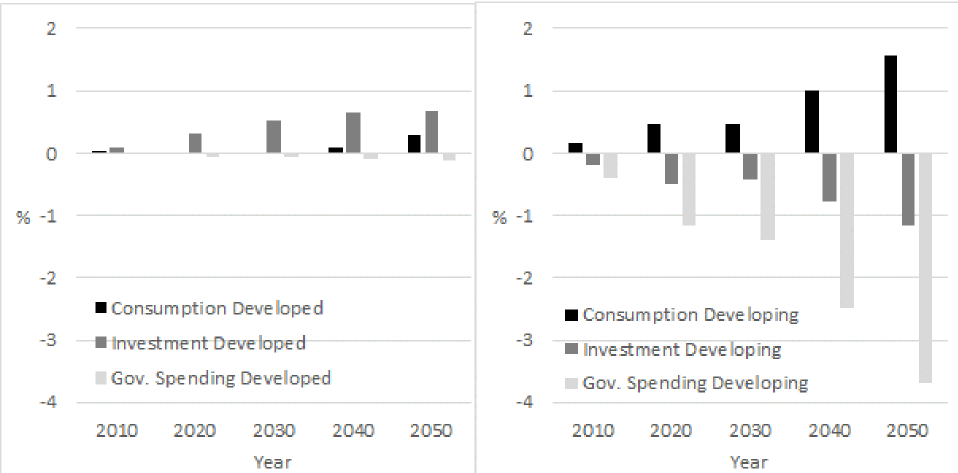


Figure 7. Differences in aggregated consumption and investments between models with land use and without land use (%)

***3.3 Land use changes under alternative assumptions***

Projections about future global land use change may be affected by several assumptions regarding model assumptions and structure, economic growth, population, land productivity, environmental legislation and climate change policies, bioenergy production, among others. In this section we test some of these key aspects to illustrate how they may impact the results from land use modeling in the EPPA model.

We choose to test alternative assumptions regarding GDP growth, land yields and population growth. For all three aspects we test a higher and lower level for these. In the case of GDP, we test GDP targets higher and lower by 20% compared to the base projections in EPPA[h]. In the case of land yields, we reduce and increase the exogenous land productivity index from its base value of 1% per year to 0.5% per year and 1.5% per year, respectively. Finally, we test higher and lower population growth rates, increasing and decreasing it by 1

[h] The detailed description of the baseline GDP assumptions and projections in EPPA6 and a similar sensitivity exercise about alternative GDP growth rates can be found at Chen et al. (2015).

percentage point per year (i.e. if the base population is growing at 1% in a region, then the sensitivities are 0% and 2%).

Figure 8 shows the trajectories of cropland expansion under the reference set up of EPPA, discussed in the last sections, and under the alternative assumptions about GDP, yields and population growth. The trajectories are very similar under all assumptions for the group of developed countries, except in the case of low growth in land productivity and high population growth. Both impose the need for a larger amount of cropland toward the end of the period. The cropland area in these countries ranges from 0.59 billion ha to 0.64 billion ha. In the case of developing countries, population and yield assumptions also have a strong effect on the trajectory of cropland area. High population and low yields require larger cropland areas, as expected. The cropland area in 2050 ranges from 0.95 billion ha to 1.12 billion in developing countries, evidence of the importance of yields in reducing or increasing the pressure on food production and cropland expansion.

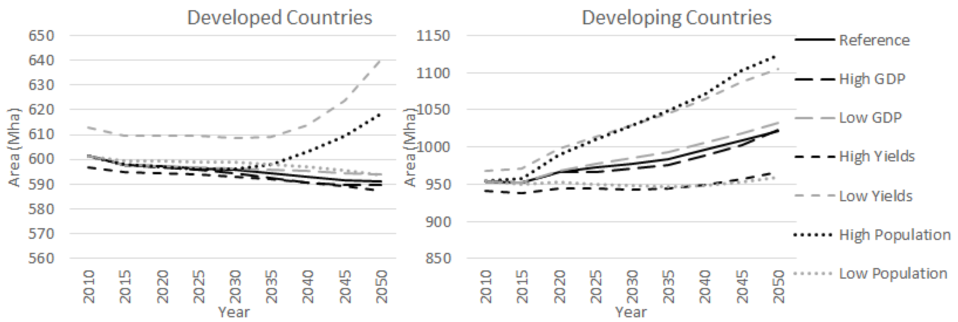


Figure 8. Cropland trajectories under alternative assumptions (%)

In the case of pasturelands, Figure 9 shows land productivity and higher population growth as the most relevant assumptions in changing the reference trajectory in developed countries. The GDP growth rate and lower population growth has little effect on pasture area in this region. However, in the case of developing countries, lower yields and higher population growth rates affect pasture area in different ways along the model horizon. Initially, they push for more extensive pasture areas, but after 2025 there is a strong decrease in pastureland compared to the reference case. This result is a combination of demand for livestock (and hence pasture land), the ability to intensify livestock production on pasture, and the demand for cropland, converted from pasture. The intensification of livestock production occurs strongly in the developing countries, especially in the cases of higher pressures to feed more people or with lower increases in agricultural productivity. Since livestock production uses land much more extensively in developing countries, this is perhaps not a surprising result, and it suggests that livestock production may move toward that of production in the developed countries—with more feedlots and the like as substitute for pasture.

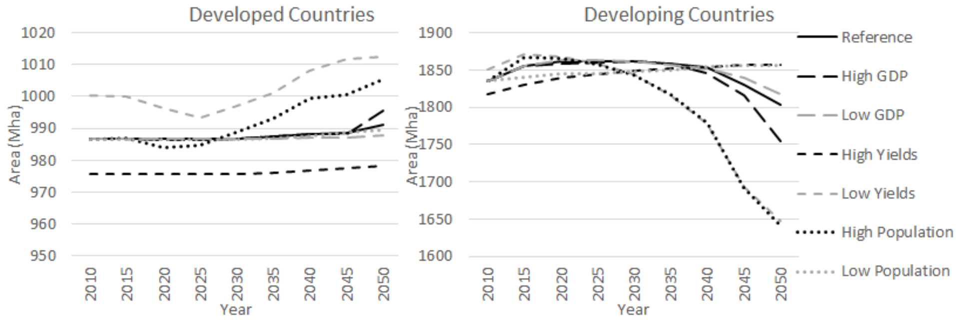


Figure 9. Pasture land trajectories under alternative assumptions (%)

Figure 10 presents the alternative land trajectories for managed forests. Again, assumptions about yields and population are the most relevant in altering the trajectory in the reference case. Larger managed forest areas are required in the group of developed countries under lower land productivity and higher population. The land under managed forest in developing countries, however, follows closely the reference case. It means the expansion in area required to grow wood and forestry products in developing countries in the first half of the century is relatively stable and is largely unaffected by alternative assumptions of GDP levels, population or yields.

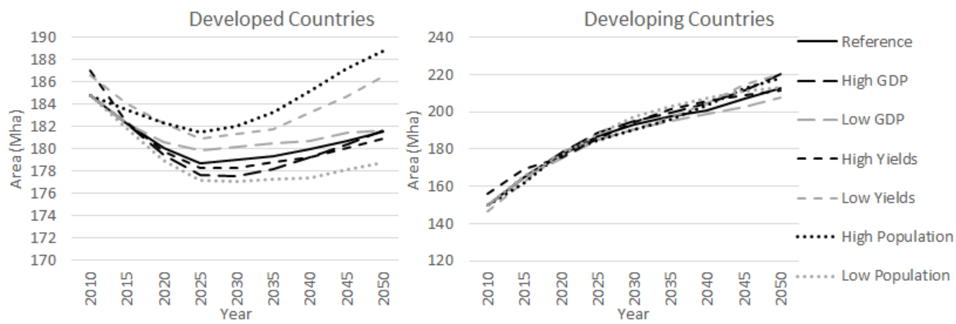


Figure 10. Managed forest land trajectories under alternative assumptions (%)

The opposite happens to the area of natural forest (Figure 11). Its trajectory strongly depends on assumptions about GDP, yields and population growth, especially in developing countries. Low yields and higher population growth push for higher areas of natural forest in both groups of countries. This result appears counterintuitive reasoning.  To explain the result we also must refer Figure 12, which shows the trajectories of natural grasslands. As discussed in section 3.1, we observe in the reference scenario a reversion in the deforestation process at the end of the model horizon in developing countries, associated with the decrease of pasture areas and to the lower costs to convert natural grasslands to agricultural use. The scenarios with slow increase in yields and faster growth in population intensify such things, since they trigger a strong intensification process in livestock production, freeing pasture areas to other uses, as crop production. As the conversion of natural grass areas in other uses brings higher net benefits than the conversion of natural forests, the "reservation value" of natural grass in

the welfare function is gradually replaced by the non-use value of natural forests, stimulating their increase in developed countries and their recovery in developing ones. In developed countries, the importance of the non-use value of natural forest in the household gross welfare is evident from the early periods, while in developing countries the deforestation trend is reversed only after 2030, when the strong pasture intensification starts under the low yields and high population growth scenarios.

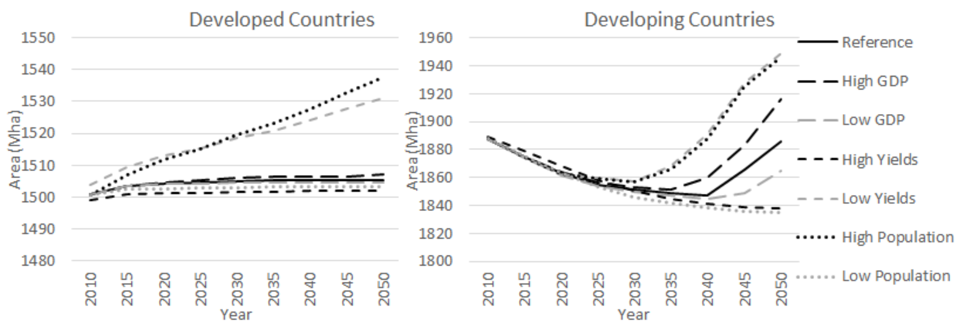


Figure 11. Natural forest land trajectories under alternative assumptions (%)

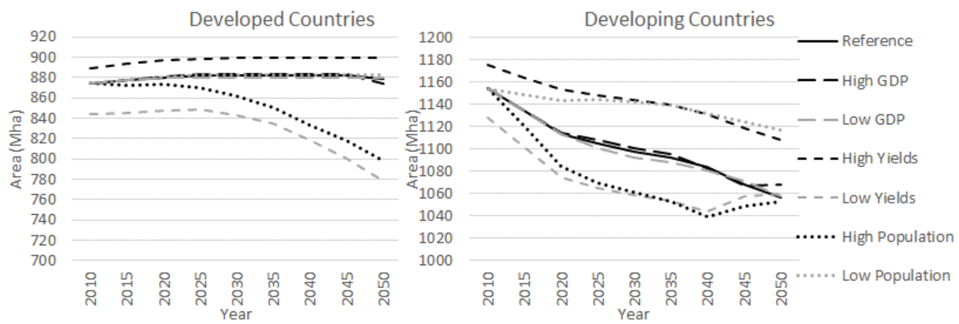


Figure 12. Natural grass land trajectories under alternative assumptions (%)

The alternative assumptions about yields, GDP and population growth highlight some relevant uncertainties in the land use modeling. Larger yield improvements and low population growth imply in lower and smoother land use transitions through time, more conservation of natural environments and less pressure to expand agricultural land. The opposite tends to happen if land productivity does not grow as fast enough or population increases faster, causing more intense land use changes in developing countries and less willingness to preserve natural grasslands. Although the low yield improvements of only 0.5% per year and the higher population growth tested here are arbitrary and may have lower chances to happen in the future, they illustrate how alternative demands for environmental services from land, including food and natural conservation, may change over time. In this way, they call the attention to the need of public and private investments on agricultural and forestry technological improvements.

## 4. Conclusions and Policy Implications

The representation of environmental resources in large-scale CGE models is a growing and challenging branch of the economic and scientific literature, necessitated by increasing competition for scarce natural resources and the policy implications that implies. The policy questions demand new techniques that link traditional general equilibrium models where quantities of inputs and output are aggregated together in value terms to physical quantities of natural resources. In this regard, one of the topics in this literature receiving large attention and several contributions in the last years has been the explicit representation of land use and land conversion in global models. However, several challenges and caveats still exist, since data, behavioral parameters and assumptions about the future need further developments.

We contribute to this literature describing in detail one approach to include land and land use as a natural resource in CGE models, considering its connection to the broader economy through agriculture and forestry. We discuss the most relevant aspects to consider and the steps to incorporate the land use changes in an existing model. We also use the model to project future land use trajectories and compare the results with and without the explicit representation of land use changes. Finally, we implement some illustrative scenarios under alternative assumptions about GDP, yields and population growth to verify how the model responds to each of these factors.

The simulations performed highlights the important linkages between the environment and economy in terms of land use change, deforestation, and potential reforestation at the global scale. The patterns of land use trajectories in developed countries differ in signs and intensity from those expected for developing countries. While we project developing countries to expand their agricultural land, our projections have developed regions increasing natural vegetation areas. However, developing countries tend to attribute higher values to natural forests latter on, when they become scarcer. The same does not happen in the case of natural grassland areas. These are similar to other major projections of land use change, such as those by the FAO in both the differences between developed and developing regions, and in the general magnitude of the changes.

Parameters defining agricultural yields and population growth are relevant to project future services from land use, while we find that alternative GDP growth does not impact much the outputs. Alternative demands for environmental services from land, including agricultural goods and natural conservation, will change over time, and stronger pressures on food demand or on agricultural productivity may change the perception about different natural landscapes, determining the protection of some but the conversion of others.

These new techniques and models are being applied to a wide range of policy questions. We have the traditional agricultural policy questions: What will it take to feed a growing population with higher incomes? How important is international trade in balancing supply and demand in different regions of the world, and ultimately the role of trade policy in distorting comparative advantage or contributing to spikes in the prices of commodities? But the new focus on natural resources stems from environmental policy questions. Will climate change undermine agricultural productivity and shift comparative advantage? Will proposed solutions to climate change, such as large-scale biomass energy or carbon sequestration through reforestation demand compete with land resources and drive up food prices? Is it a case of the rich, who are able to pay for biomass fuels, depriving low-income people of food?

Or is there enough land in the world to double or triple cropland, but in doing so, will that destroy natural ecosystems and contribute to carbon emissions? Or can agricultural intensification be done in such a way as to actually improve soils and sequester carbon, while providing adequate food, fiber, and forest products? The advantage of the full economy, general equilibrium approach in these policy questions is that the model are naturally constructed to investigate the interactions among sectors, and make a comprehensive accounting of resources.

Partial equilibrium models in food agriculture, energy, or forestry typically assume some supply of new land, without tracing where it comes from and whether another use might compete for it. These methods may be adequate for short-term analyses where no big changes in resource use are imagined. But as we move to consider long-term climate change, fueling the world with bioenergy, or solving climate problem through reforestation we move well beyond marginal changes. Much biomass energy or reforestation analysis totals up some version of "marginal" land that is "not being used" and assumes it will be available for biomass energy or reforestation, and imagines some process that will restrict those uses to only that land. In a market economy, natural resources go to the highest bidder, and that reflects the demands of people who have money to pay for the goods produced. Positive models of the economy of natural resource use need to reflect such market forces, and in doing so they can help to identify where corrective policies are needed, and whether those policies will be in terms of having income and food assistance for lower income people, extending pricing to protect unpriced ecosystem services, promoting trade in a way to ease pressure on natural resources in places where resources are overused, motivating R&D to advance productivity and efficiency in the use of resources, etc.

This paper focused on some of the methods needed to investigate such policy questions, and in so doing, referred to some of the burgeoning policy analysis literature in the area. That said, in results we presented in this paper, two main policy messages arise. First, future conservation and protection of natural biomes require strong investments in technological improvements in crop, livestock and timber production. Second, natural grasslands tends to be more endangered than natural forest areas in the future, since the current concerns are mostly focused on the more biodiverse forestlands. This may imply a large loss of grassland environments in the case of larger population growth or weak increases in agricultural yields.

**Acknowledgments**

The authors gratefully acknowledge the financial support for this work provided by the National Council for Research of Brazil (CNPq), the U.S. Department of Energy, Office of Science under DE-FG02-94ER61937 and other government, industry, and foundation sponsors of the Joint Program on the Science and Policy of Global Change. For a complete list of sponsors, please visit http://globalchange.mit.edu/sponsors/all.

**References**


Antoine, B., Gurgel, A. & Reilly, J. M. Will Recreation Demand for Land Limit Biofuels Production? J. Agric. Food Ind. Organ. 6, Article 5 (2008).

Baldos, U. & Hertel, T. Development of a GTAP 8 Land Use and Land Cover Data Base for Years 2004 and 2007. (2012). at <https://www.gtap.agecon.purdue.edu/resources/download/6048.pdf>

Baldos, U. L. C. & Hertel, T. W. Development of a GTAP 8 Land Use and Land Cover Data Base for Years 2004 and 2007. (2012). at <https://www.gtap.agecon.purdue.edu/resources/download/6048.pdf>

Banse, M. & Meijl, H. Van. Will EU biofuel policies affect global agricultural markets? Eur. Rev. Agric. Econ. 35, 117-141 … (2008). at <http://erae.oxfordjournals.org/content/35/2/117.short>

Banse, M., Meijl, H. Van & Tabeau, A. Impact of EU biofuel policies on world agricultural production and land use. Biomass and Bioenergy 35, 2385-2390 … (2011). at <http://www.sciencedirect.com/science/article/pii/S0961953410003235>

Bergman, L. CGE modeling of environmental policy and resource management. Handb. Environ. Econ. 3, 1273-1306 (2005). at <http://www.sciencedirect.com/science/article/pii/S157400990503024X>

Bosello, F., Eboli, F., Parrado, R. & Rosa, R. REDD in the Carbon Market: A General Equilibrium Analysis. Fond. Eni Enrico Mattei Work. Pap. 530 (2010). doi:10.1007/s10666-014-9419-1

Britz, W. & Hertel, T. W. Impacts of EU biofuels directives on global markets and EU environmental quality: An integrated PE, global CGE analysis. Agric. Ecosyst. Environ. 142, 102-109 (2011).

Cai, Y. et al. Green House Gas Mitigation Policy , Bio-fuels and Land-use Change - a Dynamic Analysis. 2009 (2009).

Chen, Y., Paltsev, S., Reilly, J. & Morris, J. The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. MIT Joint Program on the Science and Policy of Global Change. Report 278 (2015). at < http://globalchange.mit.edu/research/publications/2892>

Darwin, R., Tsigas, M., Lewandrowski, J. & Raneses, A. World agriculture and climate change: Economic adaptations. (1995). at <https://ideas.repec.org/p/ags/uerser/33933.html>

Economic Report of the President. (2013). at <https://www.whitehouse.gov/administration/eop/cea/economic-report-of-the-President/2013>

Eickhout, B., Meijl, H. van, Tabeau, A. & Rheenen, T. Van. Economic and ecological consequences of four European land use scenarios. Land use policy 24, 562-575 (2007). at <http://www.sciencedirect.com/science/article/pii/S0264837706000664>

Felzer, B., Kicklighter, D., Melillo, J. & Wang, C. Effects of ozone on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. Tellus B 56, 230-248 (2004). at <http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0889.2004.00097.x/full>

Ferreira Filho, J. de S. & Horridge, M. Ethanol expansion and indirect land use change in Brazil. Land use policy 36, 595-604 (2014). at <http://www.sciencedirect.com/science/article/pii/S026483771300210X>

Ferris, M. & Pang, J. Engineering and economic applications of complementarity problems. Siam Rev. 39, 669-713 (1997). at <http://epubs.siam.org/doi/abs/10.1137/S0036144595285963>

Gitiaux, X. & Rausch, S. Biofuels, climate policy, and the European vehicle fleet. J. Transp. Econ. Policy 46, 1-23 (2012). at <http://www.ingentaconnect.com/content/lse/jtep/2012/00000046/00000001/art00001>

Gitiaux, X., Reilly, J. & Paltsev, S. Future Yield Growth: What Evidence from Historical Data? MIT Joint Program on the Science and Policy of Global Change, Report 199. (2011). at <http://18.7.29.232/handle/1721.1/66297>

Golub, A. & Henderson, B. Global climate policy impacts on livestock, land use, livelihoods, and food security. P. Natl. Acad. Sci. USA. 110, 20894-20899 (2012). at <http://www.pnas.org/content/early/2012/09/26/1108772109.short>

Golub, A. & Hertel, T. Modeling land-use change impacts of biofuels in the GTAP-BIO framework. Clim. Chang. Econ. 3, 1250015 (2012). at <http://www.worldscientific.com/doi/abs/10.1142/S2010007812500157>

Golub, A. & Hertel, T. New Developments in Computable General Equilibrium Analysis for Trade Policy, ed. Gilbert, J., Chapter 6 "Modeling biofuels policies in general equilibrium: insights, pitfalls, and opportunities" (Emerald, Bingley, 2010). pp. 153-187. at <https://books.google.com.br/books?hl=pt-BR&lr=&id=WOCE8SpEk1wC&oi=fnd&pg=PA153&dq=villoria+hertel&ots=SsSKUgvyUt&sig=uumakD7ucq_rASjHXOsTM8DCCvo>

Golub, A., Hertel, T., Lee, H.-L., Rose, S. & Sohngen, B. The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. Resour. Energy Econ. 31, 299-319 (2009).

Gurgel, A. et al. Food, fuel, forests, and the pricing of ecosystem services. Am. J. Agric. Econ. 93, 342-348 (2011).

Gurgel, A. et al. Food, fuel, forests, and the pricing of ecosystem services. in American Journal of Agricultural Economics 93, 342-348 (2011).

Gurgel, A., Reilly, J. M. & Paltsev, S. Potential Land Use Implications of a Global Biofuels Industry. J. Agric. Food Ind. Organ. 5, Article 9 (2007).

Gurgel, A., Reilly, J. M. & Paltsev, S. Potential Land Use Implications of a Global Biofuels Industry. Journal of Agricultural & Food Industrial Organization 5, (2007).

Haque, M. O. Income elasticity and economic development: Methods and applications. Vol. 42, (Springer Science & Business Media, 2006). at <https://books.google.com/books?hl=pt-BR&lr=&id=OCNH9ifMIvAC&oi=fnd&pg=PA1&dq=haque+income+elasticity&ots=l_0IFWjRET&sig=v35qGIEr_zW5_3SWdRgk1gzN27U>

Havlík, P., Schneider, U., Schmid, E. & Böttcher, H. Global land-use implications of first and second generation biofuel targets. Energy Policy 39, 5690-5702 (2011). at <http://www.sciencedirect.com/science/article/pii/S030142151000193X>

Hertel, T. Global trade analysis: modeling and applications. (Cambridge University Press, Cambridge, 1997). at <https://scholar.google.com.br/scholar?q=Hertel+GTAP&btnG=&hl=pt-BR&as_sdt=0%2C5#6>

Hertel, T., Rose, S. & Tol, R. Economic analysis of land use in global climate change policy. (Routledge, New York, 2009). at <https://books.google.com.br/books?hl=pt-BR&lr=&id=z16SAgAAQBAJ&oi=fnd&pg=PP1&dq=hertel+land+use+modeling&ots=BG2qNTKwZ6&sig=OJcUqDIYqtsAGl-pSqV0b7kgvME>

Hurtt, G., Frolking, S. & Fearon, M. The underpinnings of land?use history: Three centuries of global gridded land?use transitions, wood?harvest activity, and resulting secondary lands. Glob. Chang. Biol. 12, 1208-1229 … (2006). at <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2006.01150.x/full>

Kerr, S., Liu, S., Pfaff, A. & Hughes, R. Carbon dynamics and land-use choices: building a regional-scale multidisciplinary model. J. Environ. Manag. 69, 25-37(2003). at <http://www.sciencedirect.com/science/article/pii/S0301479703001063>

Kooten, G. Van & Sohngen, B. Economics of forest ecosystem carbon sinks: a review. Department of Economics University of Victoria Working Paper 2007-02. (2007). at <http://www.web.uvic.ca/~repa/publications/REPA working papers/WorkingPaper2007-02.pdf>

Lubowski, R., Plantinga, A. & Stavins, R. Land-use change and carbon sinks: econometric estimation of the carbon sequestration supply function. J. Environ. Econ. Manag. 51, 135-152 (2006). at <http://www.sciencedirect.com/science/article/pii/S0095069605000744>

Markusen, J. Extension of the Simple Model. (2006). at <http://spot.colorado.edu/~markusen/teaching_files/applied_general_equilibrium/GAMS/ch2.pdf>

Mathiesen, L. Computation of economic equilibria by a sequence of linear complementarity problems. Econ. Equilib. Model Formul. Solut. 23, 144-162 (1985). at <http://link.springer.com/chapter/10.1007/BFb0121030>

Meijl, H. van & Rheenen, T. Van. The impact of different policy environments on agricultural land use in Europe. Agric. Ecosyst. Environ. 114, 21-38 (2006). at <http://www.sciencedirect.com/science/article/pii/S0167880905005323>

Melillo, J. M. et al. Indirect emissions from biofuels: how important? Science 326, 1397-1399 (2009).

Meyfroidt, P., Lambin, E. F., Erb, K. H. & Hertel, T. W. Globalization of land use: Distant drivers of land change and geographic displacement of land use. Curr. Opin. Environ. Sustain. 5, 438-444 (2013).

Morris, J. F., Reilly, J. M. & Chen, Y. H. Advanced Technologies in Energy-Economy Models for Climate Change Assessment. MIT Joint Program on the Science and Policy of Global Change, Report 272. (2014). at < http://dspace.mit.edu/handle/1721.1/92404>

Narayanan, B. G., Aguiar, A. & McDougall, R. Global Trade, Assistance, and Production: The GTAP 8 Data Base. (2012). at <https://www.gtap.agecon.purdue.edu/databases/v8/v8_doco.asp>

Paltsev, S., Reilly, J., Jacoby, H. Eckaus, R. S., McFarland, J. R., Sarofim, M. C., Asadoorian, M. O., Babiker, M. H. M. The MIT emissions prediction and policy analysis (EPPA) model: version 4. MIT Joint Program on the Science and Policy of Global Change. Report 125 (2005). at <http://dspace.mit.edu/handle/1721.1/29790>

Popp, A. et al. On sustainability of bioenergy production: Integrating co-emissions from agricultural intensification. Biomass and Bioenergy 35, 4770-4780 (2011).

Ramankutty, N. & Foley, J. Estimating historical changes in global land cover: Croplands from 1700 to 1992. Global Biogeochem. Cycles 13, 997-1027 (1999). at <http://onlinelibrary.wiley.com/doi/10.1029/1999GB900046/full>

Ramankutty, N. Global Cropland and Pasture Data: 1700-2007. (2011). at < http://www.ramankuttylab.com/data.html>

Rausch, S., Reilly, J., Paltsev, S. & Gitiaux, X. Biofuels, Climate Policy and the European Vehicle Fleet. MIT Joint Program on the Science and Policy of Global Change, Report 176 (2009). at <http://18.7.29.232/handle/1721.1/49856>

Ray, D. K., Mueller, N. D., West, P. C. & Foley, J. A. Yield Trends Are Insufficient to Double Global Crop Production by 2050. PLoS One 8, e66428 (2013).

Reilly, J. & Fuglie, K. Future yield growth in field crops: what evidence exists? Soil Tillage Res. 47, 275-290 (1998). at <http://www.sciencedirect.com/science/article/pii/S0167198798001160>

Reilly, J. & Paltsev, S. Economic Analysis of Land Use in Global Climate Change Policy, eds. Hertel, T. W., Rose, S. K., and Tol, R. S. J. Chapter 8 "Biomass energy and competition for land". (Routledge, New Yourk, 2009) at <https://books.google.com.br/books?hl=pt-BR&lr=lang_en&id=z16SAgAAQBAJ&oi=fnd&pg=PA182&dq=paltsev+eppa&ots=BG2qOTNuY4&sig=Brk8lFv6siY0STqpZq9Xr_APXIg>

Reilly, J. et al. Using land to mitigate climate change: Hitting the target, recognizing the trade-offs. Environ. Sci. Technol. 46, 5672-5679 (2012).

Reimer, J. & Hertel, T. Estimation of international demand behaviour for use with input-output based data. Econ. Syst. Res. 16, 347-366 (2004). at <http://www.tandfonline.com/doi/abs/10.1080/0953531042000304245>

Rosegrant, M. & Zhu, T. Global scenarios for biofuels: impacts and implications. Appl. Econ. Perspect. and Policy 30, 495-505 (2008). at <http://aepp.oxfordjournals.org/content/30/3/495.short>

Rutherford, T. Applied general equilibrium modeling with MPSGE as a GAMS subsystem: An overview of the modeling framework and syntax. Comput. Econ. 14, 1-46 (1999). at <http://link.springer.com/article/10.1023/A:1008655831209>

Rutherford, T. CES Preferences and Technology: A Practical Introduction. Economic Equilibrium Modeling with GAMS: An Introduction to GAMS/MCP and GAMS/MPSGE (GAMS/MPSGE Solver Manual), 89-115. (1998).

Rutherford, T. Extension of GAMS for complementarity problems arising in applied economic analysis. J. Econ. Dyn. Control. 19, 1299-1324 (1995). at <http://www.sciencedirect.com/science/article/pii/0165188994008312>

Rutherford, T. Lecture notes on constant elasticity functions. Univ. Color. (2002). at <http://www.gamsworld.eu/mpsge/debreu/ces.pdf>

Schmitz, C. et al. Land-use change trajectories up to 2050: Insights from a global agro-economic model comparison. Agric. Econ. (United Kingdom) 45, 69-84 (2014).

Schmitz, C., Biewald, A. & Lotze-Campen, H. Trading more food: Implications for land use, greenhouse gas emissions, and the food system. Glob. Environ. Chang. 22, 189-209 (2012). at <http://www.sciencedirect.com/science/article/pii/S0959378011001488>

Sohngen, B. Global Timber Market and Forestry data Project. (2007). at <http://aede.osu.edu/research/forests-and-land-use/global-timber-market-and-forestry-data-project>

Sohngen, B., Golub, A. & Hertel, T. Economic Analysis of Land Use in Global Climate Change Policy, eds. Hertel, T. W., Rose, S. K., and Tol, R. S. J. Chapter 11 "The role of forestry in carbon sequestration in general equilibrium models", (Routledge, New York, 2009). at <https://books.google.com.br/books?hl=pt-BR&lr=&id=z16SAgAAQBAJ&oi=fnd&pg=PA279&dq=golub+hertel&ots=BG2qMXPyTa&sig=fvf4paf18Bn0MIwpMsFKNmQMqQg>

Sohngen, B., Mendelsohn, R. & Sedjo, R. A global model of climate change impacts on timber markets. J. Agric. Resour. Econ. 26, 326-346… (2001). at <http://www.jstor.org/stable/40987113>

Sutton, J. & Webb, A. Agricultural trade and natural resources, ed. Sutton, J. D., chapter "Trade policies and the use and value of natural resources". (Lynne Riener, London, 1988). pp. 157-186. at <http://agris.fao.org/agris-search/search.do?recordID=US8844785>

Taheripour, F., Hertel, T. W., Tyner, W. E., Beckman, J. F. & Birur, D. K. Biofuels and their by-products: Global economic and environmental implications. Biomass and Bioenergy 34, 278-289 (2010).

Timilsina, G., Beghin, J. C., Der, D. Van & Mevel, S. The Impacts of Biofuels Targets on Land-Use Change and Food Supply?: A Global Cge Assessment. Agr. Econ. 43, 315-332 (2012).

Villoria, N. B. & Hertel, T. W. Geography matters: International trade patterns and the indirect land use effects of biofuels. Am. J. Agric. Econ. 93, 919-935 (2011).

Villoria, N. B., Byerlee, D. & Stevenson, J. The effects of agricultural technological progress on deforestation: What do we really know? Appl. Econ. Perspect. Policy 36, 211-237 (2014).

Winchester, N. & Reilly, J. M. The Contribution of Biomass to Emissions Mitigation under a Global Climate Policy. MIT Joint Program on the Science and Policy of Global Change, Report 273 (2015). at <http://globalchange.mit.edu/research/publications/2865>

Winchester, N., Malina, R., Staples, M. & Barrett, S. The impact of advanced biofuels on aviation emissions and operations in the US. Energy Econ. 49, 482-491 (2015). at <http://www.sciencedirect.com/science/article/pii/S0140988315001164>

Wise, M., Calvin, K. & Thomson, A. Implications of limiting CO2 concentrations for land use and energy. Science 324, 1183-1186. (2009). at <http://www.sciencemag.org/content/324/5931/1183.short>

Zhou, Z., Tian, W., Wang, J., Liu, H. & Cao, L. Food consumption trends in china. Australian Government, Department of Agriculture, Fisheries and Forestry (2012).