Forest, Agriculture, and Biofuels in a Land use Model with Environmental services (FABLE)

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Forest, Agriculture, and Biofuels in a Land use model with Environmental services (FABLE)*

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Abstract

The goal of this paper is to introduce FABLE (Forest, Agriculture, and Biofuels in a Land use model with Environmental services), a dynamic global model, aimed at analyzing the optimal profile for global land use in the context of growing commercial demands for food, bioenergy, and forest products, increasing non-market demands for ecosystem services, and greenhouse gas mitigation targets. The model seeks to determine the optimal allocation of scarce land across competing uses across time. FABLE integrates distinct strands of agronomic, economic and biophysical literatures into a single, intertemporally consistent, analytical framework, at global scale. It is based on a dynamic long-run, forward-looking partial equilibrium framework, in which the societal objective function places value on food production, liquid fuels (including first- and second- generation biofuels), timber production, forest carbon and biodiversity. The forestry sector is characterized by multiple forest vintages, which add considerable computational complexity in the context of this dynamic forward-looking analysis. Our baseline accurately reflects developments in global land use over the years that have already transpired, and determines the optimal path of global land use over the course of next century based on projections of population, income and demand growth from a variety of recognized sources.

JEL: C61, Q15, Q23, Q26, Q40, Q54

Keywords: agriculture, biofuels, climate change, dynamic model, ecosystem services, energy, environment, FABLE, food, forestry, GHG emissions, global land use, livestock

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1 Introduction

The allocation of the world's land resources over the course of the next century has become a pressing research question. Continuing population increases, improving, land-intensive diets amongst the poorest populations in the world, increasing production of biofuels and rapid urbanization in developing countries are all competing for land even as the world looks to land resources to supply more environmental services. The latter include biodiversity and natural lands, as well as forests and grasslands devoted to carbon sequestration. And all of this is taking place in the context of faster than expected climate change which is altering the biophysical environment for land-related activities. This combination of intense competition for land, coupled with highly uncertain future productivities and valuations of environmental services, gives rise to a significant problem of decision-making under uncertainty. The issue is compounded by the inherent irreversibility of many land conversion decisions.

The goal of this paper is to introduce FABLE (Forest, Agriculture, and Biofuels in a Land use model with Environmental services), a dynamic global model, aimed at analyzing the optimal profile for global land use in the context of growing commercial demands for food and forest products, increasing nonmarket demands for ecosystem services, and greenhouse gas (GHG) mitigation targets. The model seeks to determine the optimal allocation of scarce land across competing uses across time. While market failures, including ill-defined property rights, poorly developed land markets, lack of information, and credit constraints preclude such a path from being achieved in reality, this optimal path is a useful point of reference for those seeking to influence patterns of global land use. In addition, due to its forward-looking nature, this model can offer important insights regarding the behavior of forward-looking investors under alternative states of the world. As with most new model developments, introducing this intertemporal dimension into the model is costly; as a consequence we are unable to offer the kind of geographic and sectoral (particularly, energy sector) coverage, which is usual in the land-based integrated assessment models (Bouwman et al. 2006, Paltsev et al. 2005, Wise and Calvin 2011).[1]

FABLE integrates distinct strands of agronomic, economic and biophysical literatures into a single, intertemporally consistent, analytical framework, at global scale. It is based on a dynamic long-run, forward-looking partial equilibrium framework, in which the societal objective function places value on food production, liquid fuels (including first- and second- generation biofuels), timber production, forest carbon and biodiversity. A non-homothetic AIDADS utility function represents consumer preferences, and, as society be-

[1] Because of their complexity most of the integrated assessment models employed to analyze land-use decisions at broad scale are solved recursively rather than as fully inter-temporal forward-looking optimization problems. The forward-looking approach adopted in our paper is uncommon, notwithstanding its better capabilities to address important economic policy issues such as inter-temporal allocation of GHG emission flows from land-use through abatement policies, efficiency implications of carbon taxes and caps, and endogenous depletion of nonrenewable land resources. For a detailed discussion on relative pros and cons of recursive versus forward-looking approaches in climate policy analysis, see Babiker et al. (2009).

comes wealthier, greater value is placed on eco-system services, and smaller value on additional consumption of food, energy and timber products. Given the importance of land-based emissions to any GHG mitigation strategy, as well as the potential impacts of climate change itself on the productivity of land in agriculture, forestry and ecosystem services, FABLE accounts for alternative GHG constraints. The forestry sector is characterized by multiple forest vintages, which add considerable computational complexity in the context of this dynamic forward-looking analysis.

We solve the model over the 200 year period: 2005 - 2204, focusing analysis on the next century. Our baseline accurately reflects developments in global land use over the years that have already transpired, while also incorporating projections of population, income and demand growth from a variety of recognized sources.

2 Model Outline

FABLE is a deterministic, discrete dynamic, finite horizon partial equilibrium model of global land use. Income, population, wages, oil prices, total factor productivity, and other variable input prices are assumed to be exogenous. The model focuses on the optimal allocation of scarce land across competing uses across time.

There are two natural resources in the model: land and fossil fuels. The supply price of fossil fuels is predetermined, and is expected to rise over time. The supply of land is fixed and faces competing uses that are determined endogenously by the model.

We analyze nine sectors producing intermediate and final goods and services. The agrochemical sector converts fossil fuels into fertilizers that are used to boost yields in the agricultural sector. The agricultural sector combines cropland and fertilizers to produce intermediate outputs (food and feed crops, and cellulosic feed stocks) that can be used to produce food, animal feed, or biofuels. The livestock farming sector combines pasture land and animal feed to produce domesticated animals. The food processing sector converts food crops and livestock into processed food products that are used to satisfy the global food demand. The biofuels sector converts food crops and cellulosic feedstocks into liquid fuels, which substitute for petroleum products in final demand. The energy sector combines petroleum products with the biofuels, and the resulting mix is further combusted to satisfy the demand for energy services. The forestry sector produces an intermediate product, which is further used in timber processing. The timber processing sector converts output from the forestry sector into a final timber product, which satisfies commercial demands for lumber and other articles of wood. The ecosystem services sector provides a public good to society in the form of ecosystem services. The production of other goods and services are predetermined.

The societal objective function being maximized places value on processed food, energy services, timber products, and eco-system services. Emissions of greenhouse gases (GHGs) are central to the problem at hand. These are currently treated as a time-varying constraint on the flow of GHGs (emissions target). As the model focuses on the representative agent's behavior, the resource endowments and consumption products are expressed in per-capita terms. Figure 1 below summarizes the model structure.

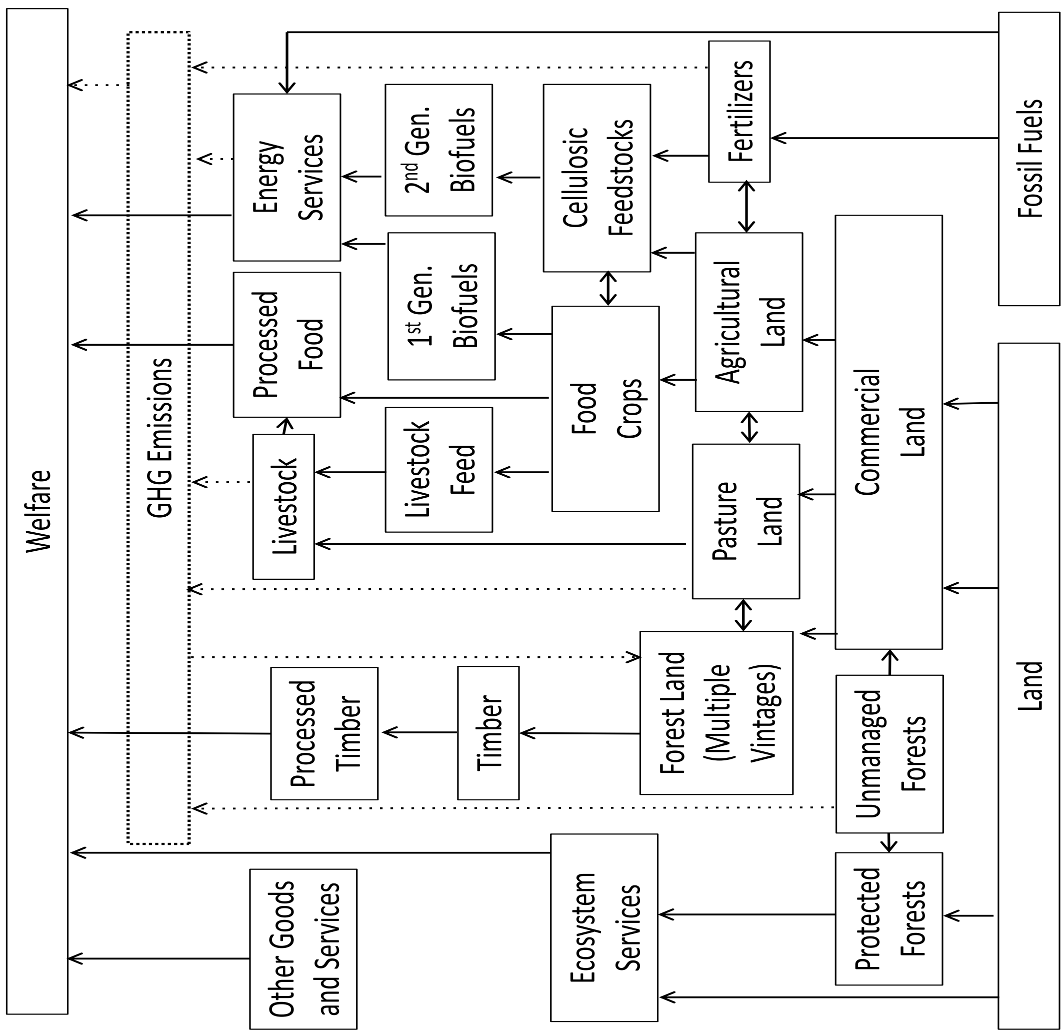

Figure 1: Structure of the Economy

2.1 Resource Use

2.1.1 Land

The total land endowment in the model, $\overline{L}$, is fixed. The land in the economy at any time t comprises natural forest lands - which are in an undisturbed state (e.g., parts of the Amazon), L_t^N, and managed commercial lands, L_t^M. The land endowment constraint is

$$\overline{L} = L_t^N + L_t^M. \tag{1}$$

Following the previous literature on natural land use (Antoine et al. 2008, Gurgel et al. 2011) we assume that the natural land consists of two types. Institutionally protected land, L^R, includes natural parks, biodiversity reserves and other types of protected forests. This land is used to produce ecosystem services for society, and cannot be converted to commercial land. Unmanaged natural land, L^U, can be accessed and either converted to commercial land (deforested) or to protected land. Once the natural land is deforested, its potential to yield ecosystem services is diminished and cannot be restored within the (single century) time frame of the analysis. Thus, the conversion of natural lands for commercial use is an irreversible decision.[2] Equations describing allocation of commercial land across time and different uses are:

$$L_t^N = L_t^U + L_t^R. \tag{2}$$

$$L_{t+1}^U = L_t^U - \Delta L_t^U - \Delta L_t^R,\ L_0^U > 0, \tag{3}$$

and

$$L_{t+1}^R = L_t^R + \Delta L_t^R,\ L_0^R > 0, \tag{4}$$

Equation (2) shows that the total endowment of natural land is a sum of the hectares of protected and unmanaged natural land. Equation (3) shows that at each period of time the area of unmanaged natural land with initial stock, L_0^U, declines by the amounts allocated for conversion to commercial and protected land, ΔL_t^U and ΔL_t^R, where Δ operator denotes a change in variables L_t^U and L_t^R. Equation (4) shows that at each period of time, the total area of reserved land with initial stock of L_0^R increases by the amount of newly protected land, ΔL_t^R.

Accessing the natural lands comes at cost, c_t^U, associated with building roads and other infrastructure (Golub et al. 2009). In addition, converting natural land to protected land entails additional costs, c_t^R, associated with institutional obstacles (such as e.g, passing legislation, creating recreational infrastructure) to create new natural parks. We assume that these costs are continuous, monotonically increasing, and strictly convex functions of the share of natural land

[2] This point requires additional clarification. The biophysical and ecological literature suggests that restoration of forest structure and plant species takes at least 30-40 years and usually many more decades (Chazdon 2008), costs several to ten thousands dollars per hectare (Nesshover et al. 2009), and is only partially successful in achieving reference conditions (Benayas et al. 2009). Modeling restoration of biodiversity under these assumptions introduces greater computational complexity without making significant changes relative to findings presented in this study.

previously accessed. There are no additional costs of natural land conversion to commercial land, as these costs are offset by the revenues from deforestation.

Commercial lands are used in either the agriculture or forestry sectors (we ignore residential, retail, and industrial uses of land in this partial equilibrium model of agriculture and forestry). Equations describing the allocation of commercial land across time and between agriculture and forestry are:

$$L_t^M = L_t^C + L_t^P + L_t^F. \tag{5}$$

and

$$L_{t+1}^M = L_t^M + \Delta L_t^U,\; L_0^M > 0. \tag{6}$$

Equation (5) shows that total endowment of commercial land, L^M, is a sum of the hectares of commercial land dedicated to crop land, L^C, pasture land, L^P, and managed forests, L^F, respectively. Equation (6) shows that at each period of time, the total area of commercial land with initial stock of L_0^M increases by the amount of converted unmanaged natural land, ΔL^U.

2.1.2 Fossil Fuels

The fossil fuels, x^f, have two competing uses in our partial equilibrium model of land-use. A fraction of fossil fuels, $x^{f,n}$, is converted to fertilizers that are further used in the agricultural sector. The remaining amount of fossil fuels, $x^{f,e}$, is combusted to satisfy the demand for energy services. The total supply of fossil fuels is thus given by

$$x_t^f = x_t^{f,n} + x_t^{f,e}. \tag{7}$$

The cost of fossil fuels, c_t^f, is pre-determined, and reflects the expenditures on fossil fuels' extraction, transportation and distribution, as well the costs associated with GHG emissions control (e.g. carbon prices) in the non-land-based economy.

2.2 Agrochemical Sector

The agrochemical sector consumes an amount of fossil fuels, $x^{f,n}$, and converts them into fertilizers that are further used in the agricultural sector. The production of fertilizers, x^n, is a simple engineering process that can be described by a linear production function:

$$x_t^n = \theta^n x_t^{f,n}, \tag{8}$$

where θ^n is the rate of conversion of fossil fuels to fertilizers. We assume that the non-energy cost of conversion of fossil fuels to fertilizers, c^n, is constant and scale-invariant.

2.3 Agricultural Sector

The agricultural sector combines the crop land, L^C, and fertilizers, x^n, to deliver agricultural products. In the model, we distinguish between two types of agricultural outputs. Food crops, $x^{g,c}$, are used as inputs to production of food, animal feed, or first generation biofuels. The equation describing allocation of food crops among these sectors is

$$x_t^{g,c} = x_t^{c,g} + x_t^{l,g} + x_t^{b,g}, \tag{9}$$

where $x_t^{c,g}$, $x_t^{l,g}$, and $x_t^{b,g}$ respectively denote the amounts of food crops used in food processing, animal feed, and first-generation biofuels. Cellulosic feed stocks, $x^{g,b}$, can only be converted to second generation biofuels, $x^{b,2}$.

Agricultural land and fertilizers are imperfect substitutes in the production of agricultural products. The per capita output of agricultural products, $x^{g,i}$, is thus determined by the constant elasticity of substitution (CES) function:

$$x_t^{g,i} = \frac{\theta_t^{g,i}}{\Pi_t} \left[\alpha^g \left(L_t^{C,i} \right)^{\rho_g} + (1 - \alpha^g) \left(x_t^n \right)^{\rho_g} \right]^{\frac{1}{\rho_g}}, \; i = b, c, \tag{10}$$

where Π_t is the predetermined population at time t, θ_t^g and α^g are, respectively, the crop technology (agricultural yield) index and the value share of crop land in production of agricultural product at the benchmark time 0, and $L_t^{C,i}$ are hectares of agricultural land allocated for food crops and cellulosic feed stocks. The parameter $\rho_g = \frac{\sigma_g - 1}{\sigma_g}$ is a CES function parameter proportional to the elasticity of substitution of agricultural land for fertilizers, σ^g. The production of agricultural output is also subject to non-land costs from use of fertilizers and other production factors (such as e.g., labor or capital), $c^{g,i}$, the prices of which are predetermined.

2.4 Livestock Farming Sector

The livestock farming sector combines pasture land, L^P, and animal feed, $x^{l,g}$, to produce domesticated animals, x^l. Pasture land and animal feed are imperfect substitutes in the production of livestock. The per capita output of livestock, x^l, is thus determined by the constant elasticity of substitution (CES) function:

$$x_t^l = \frac{\theta_t^l}{\Pi_t} \left[\alpha^l \left(L_t^P \right)^{\rho_l} + \left(1 - \alpha^l\right) \left(\Pi_t x_t^{l,g} \right)^{\rho_l} \right]^{\frac{1}{\rho_l}}, \tag{11}$$

where θ_t^l and α^l are, respectively, the livestock technology index and the value share of pasture land in production of livestock at the benchmark time 0. The parameter $\rho_l = \frac{\sigma_l - 1}{\sigma_l}$ is a CES function parameter proportional to the elasticity of substitution of pasture land land for animal feed, σ^l. The production of livestock is also subject to non-land costs from use of other production factors (such as e.g., labor or capital), c^l, the prices of which are predetermined.

2.5 Food Processing Sector

The food processing sector converts an amount of food crops, $x^{c,g}$, and livestock, x^l, into processed grains, y^g, and processed animal products (such as meat and dairy), y^l, that are further consumed in final demand. The purpose of this sector in the model is to capture the efficiency gains from technology improvements in food production, which result in lower requirements for agricultural inputs in final demand.[3] The conversion process is represented by the following production functions:

$$y_t^g = \theta_t^{g,y} x_t^{c,g}, \tag{12}$$

$$y_t^l = \theta_t^{l,y} x_t^l, \tag{13}$$

where $\theta_t^{g,y}$ and $\theta_t^{l,y}$ are technology indices of crop and livestock processing, which capture the technological progress in both direct transformation of agricultural products into edible food, and the storage, transportation, and distribution of processed food. We assume that the food processing costs per ton of processed crops, $c^{g,y}$, and livestock, $c^{l,y}$, are exogenous and scale-invariant.

2.6 Biofuels Sector

The biofuels sector consumes the remaining amount of food crops to produce first generation biofuels, $x^{b,1}$. We assume that a ton of food crops, $x^{b,g}$, can be converted to $\theta^{b,1}$ tons of oil equivalent ($toe's$) of first generation biofuels. The output of first generation biofuels is thus given by

$$x_t^{b,1} = \theta_t^{b,1} x^{b,g}. \tag{14}$$

The biofuels sector also converts cellulosic feedstocks, $x^{g,b}$, into second generation biofuels, $x^{b,2}$. Second generation biofuels are a new technology, which is expected to take over a market gradually. The temporal path of the share of the market controlled by this new technology is expected to follow some type of S-shaped function (Geroski 2000). There are many reasons cited for such gradual penetration, including capital adjustment costs, scarcity of specialized engineering resources and the necessary equipment to install new capacity, and slow regulatory approval processes. In this study, the approach for representing the penetration process is based on McFarland et al. (2004), and is similar to that used in MIT-EPPA integrated assessment model (Paltsev et al. 2005). We explicitly introduce in the production function an additional fixed factor specific to the new technology, ϕ, whose endowment in the economy limited. As technology penetrates the market the share of technology fixed factor in the production function declines with the rate of factor-specific technological

[3] For example, technological innovation in food conservation results in fewer losses from spoilage, and, correspondingly, lower amounts of processed food needed to satisfy the commercial demand for food. Correspondingly, input requirements for agricultural product also decrease.

progress, θ_t^{ϕ} (Acemoglu 1998, van Meijl and van Tongeren 1999). Under this assumptions the production of second generation biofuels, $x^{b,2}$, is determined by the following CES function

$$x_t^{b,2} = \theta^{b,2} \left[\left(\alpha^b\right)^{\theta_t^{\phi}} (\phi)^{\rho_b} + \left(1 - \alpha^b\right) \left(x_t^{g,b}\right)^{\rho_b} \right]^{\frac{1}{\rho b}}, \tag{15}$$

where where $\theta_t^{b,2}$ and α^b are, respectively, the technology parameter and the value share of fixed factor in production of second generation biofuels at the benchmark time 0. The parameter $\rho_b = \frac{\sigma_b - 1}{\sigma_b}$ is a CES function parameter proportional to the elasticity of substitution of technology fixed factor for cellulosic feed stocks, σ^b. The agricultural products' conversion to renewable fuel incurs additional non-food processing costs, $c^{b,i}$. We assume these costs are constant and scale-invariant.[4]

2.7 Energy Sector

The energy sector consumes petroleum products, x^e, and first and second generation biofuels, $x^{b,i}$. First generation biofuels (e.g., corn or sugarcane ethanol) blend with petroleum products in different proportions[5], and the resulting mix further combusted to satisfy the demand for energy services. Following the economic literature on biofuels modeling (Hertel, Tyner and Birur 2010) we assume that first-generation biofuels and petroleum products are imperfect substitutes. Second generation biofuels (e.g., cellulosic biomass-to-liquid diesel obtained through Fischer-Tropsch gasification) offer a full 'drop-in' fuel alternative. We therefore assume that petroleum products and second generation biofuels are perfect substitutes. Under these assumptions the per capita production of energy services, y_t^e, is given by CES function:

$$y_t^e = \theta_t^e \left(\alpha^e \left(x_t^{b,1}\right)^{\rho_e} + (1 - \alpha^e) \left(\frac{x_t^{f,e}}{\Pi_t} + x_t^{b,2} \right)^{\rho_e} \right)^{\frac{1}{\rho e}}, \tag{16}$$

where the parameter θ^e describes the energy technology index, or the efficiency of energy production, (i.e., the amount of energy services provided by one *toe* of the energy fuel (Sorrell and Dimitropoulos 2008, p. 639)), α^e is the value share of first-generation biofuels in energy production at the benchmark time 0, and $\rho_e = \frac{\sigma_e - 1}{\sigma_e}$ is a CES function parameter proportional to the elasticity of substitution of petroleum products for first generation biofuels, σ_e.

[4]With introduction of second generation biofuels one would expect these costs to decline, and biofuels conversion rate to increase as the biofuels' production technology improves. We show the model sensitivity to changes in these parameters in section 5 below.

[5]Blends of E10 or less are used in more than twenty countries around the world, led by the United States, where ethanol represented 10% percent of the U.S. gasoline fuel supply in 2011. Blends from E20 to E25 have been used in Brazil since the late 1970s. E85 is commonly used in the U.S. and Europe for flexible-fuel vehicles. Hydrous ethanol or E100 is used in Brazilian neat ethanol vehicles and flex-fuel light vehicles and in hydrous E15 called hE15 for modern petrol cars in Netherlands.

The total non-land cost of energy is a sum of the costs of fossil fuels and biofuels net of land-use costs:

$$c_t^e = \sum_i c^{b,i} + c_t^f,\; i = 1, 2. \tag{17}$$

2.8 Forestry Sector

The forestry sector is characterized by v vintages of trees. At the end of period t each hectare of managed forest land, $L^F_{v,t}$, has an average density of tree vintage age v, with the initial allocation given and denoted by $L^F_{v,0}$. Each period of time the managed forest land can be either planted, harvested or simply left to mature. The newly planted trees occupy $\Delta L^{F,P}$ hectares of land, and reach the average age of the first tree vintage next period. The harvested area occupies $\Delta L^{F,H}_v$ hectares of forest land. If the managed forest land is harvested, it yields θ^w_v tons of forest product (raw timber), x^w_v, where θ^w_v is the merchantable timber yield function, which is monotonically increasing in the average tree density of age v. Forest land becomes eligible for harvest when planted trees reach a minimum age for merchantable timber, $\overline{v}$. Managed forest areas with the average density of oldest trees $v_{\max}$ have the highest yield of $\theta^w_{v_{\max}}$. They do not grow further and remain in this vintage until harvested.

We assume that the average harvesting costs per ton of forest product, are invariant to scale and are the same across all managed forest areas of different age. With a continuous growth up to vintage $v_{\max}$, the average long-run cost of harvesting per hectare of managed forest land, c^w, is therefore a declining function of timber output. Harvest of managed forests and conversion of harvested forest land to agricultural land is subject to additional near term adjustment costs. The average per hectare planting costs per hectare of newly forest planted, c^p, are invariant to scale.

The following equations describe the forestry sector:

$$L_t^F = \sum_{v=1}^{v_{\max}} L^F_{v,t}, \tag{18}$$

$$L^F_{v+1,t+1} = L^F_{v,t} - \Delta L^{F,H}_{v,t},\; v < v_{\max} - 1 \tag{19}$$

$$L^F_{v_{\max},t+1} = L^F_{v_{\max},t} - \Delta L^{F,H}_{v_{\max},t} + L^F_{v_{\max}-1,t} - \Delta L^{F,H}_{v_{\max}-1,t} \tag{20}$$

$$L^F_{1,t+1} = \Delta L^{F,P}_t, \tag{21}$$

and

$$x_t^w = \sum_{v=1}^{v_{\max}} \frac{\theta^w_{v,t}}{\Pi_t} \Delta L^{F,H}_{v,t}. \tag{22}$$

Equation (18) describes the composition of managed forest area across forest vintages. Equation (19) illustrates the harvesting dynamics of forest areas with the average ages v and $v_{\max}$. Equation (21) shows the transition from planted area, $\Delta L^{F,P}_t$, to new forest vintage area. Equation (22) describes the per capita output of forest products.

2.9 Timber Processing Sector

The timber processing sector converts harvested forest product, x^w, into processed timber products, y^w, that are further consumed in final demand. Similar to food processing, the purpose of this sector in the model is to capture the efficiency gains from technology improvements in timber production, which result in lower requirements for forest products in final demand.[6] The conversion process is represented by a linear production function:

$$y_t^w = \theta_t^{w,y} x_t^w, \tag{23}$$

where $\theta^{w,y}$ is the technology index of timber processing, which captures the technological progress in both direct transformation of forest product into processed timber, and the quality improvements and durability of timber products. We assume that the timber processing costs per ton of food products, $c^{w,y}$, are exogenous and scale-invariant.

2.10 Ecosystem Services Sector

The ecosystem services sector combines different types of land to produce terrestrial ecosystem services. It is well known in both economic and ecological literatures that ecosystem services are difficult to define, and it is even more difficult to characterize their production process (National Research Council 2005). This stems in part from the fact that there is a significant heterogeneity in ecosystem services (Costanza et al. 1997, Daily 1997), which include physical products (e.g., subsistence food and lumber) environmental services (e.g., pollination and nutrition cycling), and non-use goods which are valued purely for their continued existence (e.g., some unobserved biodiversity). In many cases the lack of markets and market prices impedes the translation from quantities of ecosystem goods and services to their production values, and requires the application of non-market and experimental valuation techniques (Bateman et al. 2011). And there are significant differences in definitions and modeling approaches in the economic and ecological literatures, which the National Research Council (2005, p.3) refers to "the greatest challenge for successful valuation of ecosystem services". While addressing these limitations is beyond the scope of this study, given their important role in the evolution of the long run demand for land, we incorporate ecosystem services, albeit in a stylized fashion, into the global land use model determining the optimal dynamic path of land-use in the coming century.

We assume that the per capita output of ecosystem services, y_t^r, is given by the following CES function of different land inputs:

$$y_t^r = \frac{\theta^r}{\Pi_t} \left[\sum_{i=C,P,F} \alpha^{i,r} \left(L_t^i\right)^{\rho_r} + \left(1 - \sum_{i=C,P,F} \alpha^{i,r}\right) \left(L_t^U + \theta^R L_t^R\right)^{\rho_r} \right]^{\frac{1}{\rho_r}}. \tag{24}$$

[6]For example, technological innovation in durability of timber products results in their less frequent replacement. Therefore lower amounts of forest product are needed to satisfy the commercial demand for timber products.

where the parameter θ^r describes the technology index of ecosystem services "production"[7]. The parameters $\alpha^{i,r}$ are the value shares of crop, pasture, and managed forest lands in production of ecosystem services at the benchmark time 0. The parameter $\rho_r = \frac{\sigma_r - 1}{\sigma_r}$ is a CES function parameter proportional to the elasticity of substitution of different types of land in production of ecosystem services, σ_r. By characterizing the production process of ecosystem services using equation (24) we assume that agricultural, managed forest, and natural lands substitute imperfectly in production of ecosystem services. Unmanaged and protected natural land produce the same ecosystem services (Costanza et al. 1997). However, protected forest lands are more efficient in delivering many ecosystem services and preserving biodiversity, as they have e.g., better management for reducing degradation of biodiversity, and better infrastructure for providing eco-tourism and recreation services (Hocking et al. 2000, Bruner et al. 2001, Rodrigues et al. 2004). The parameter θ^R captures relative effectiveness of protected land in delivering eco-system services.

We assume that the non-land cost of producing ecosystem services is zero for agricultural and managed forest land, as production of ecosystem services is not their primary function. This cost is also zero for unmanaged natural lands. As regards protected natural lands, we assume that average non-land cost of producing ecosystem services (e.g., maintenance and infrastructure expenditures) per hectare of reserved natural land, c_t^R, is exogenous and scale-invariant.

2.11 Other Goods and Services

The production of other goods and services, y_t^o, in this model is predetermined. The reason we include it in this partial equilibrium model is to complete the demand system (described in a section below), which determines welfare. As the supply of other goods and services is predetermined, we assume that they grow at the overall rate of total factor productivity (TFP) growth, which is roughly equal to the world economy's TFP growth rate[8]. Because the production of other goods and services does not draw on the land resource, we assume without loss of generality that their cost of production is zero.

2.12 GHG Emissions

The GHG emissions flows, z_t, in the model result from a number of sources: (a) combustion of petroleum products, (b) the conversion of unmanaged and managed forests to agricultural land (deforestation), (c) non-CO_2 emissions from use of nitrogen fertilizers in agricultural production, (d) non-CO_2 emissions from the livestock sector (which include emissions from enteric fermentation

[7] We put the term "technology" in quotation terms because, as discussed above, characterizing "true" production process of ecosystem services is beyond the scope of the paper. Here we use the term "technology" as a scalar that maps ecological assets to ecosystem services in reference period 0.

[8] The economy's output has a small fraction of endogenously determined output from land-use. We ignore this complication in this partial-equilibrium model.

and manure management) and (e) net GHG sequestration through forest sinks (which includes the GHG emissions from harvesting forests). We differentiate between the emissions resulting from combustion of petroleum products and the emissions resulting from land-use, z^L, because the price path (and therefore the bulk of the combustion path) for fossil fuels is pre-determined, whereas the other sources of GHG emissions are endogenous.

We assume that GHG emissions from the first three sources are linearly related to the use of fossil fuels, and the allocations of commercial lands. A ton of oil equivalent (*toe)* of fossil fuel combusted emits $\mu^{f,e}$ tons of CO_2 equivalent (tCO_2e). A ton of oil equivalent (*toe)* of fossil fuel converted to fertilizer emits $\mu^{f,n}$ tCO_2e. The conversion of natural forest land to commercial land entails emissions of μ^L tCO_2e per hectare of land deforested. A ton of fertilizer applied to agricultural land emits μ^n tCO_2e.

The livestock emissions are calculated as a sum of emissions per hectare of pasture land (e.g., due to manure left on pastures), μ^P, and emissions per ton of livestock produced (e.g., due to enteric fermentation), μ^l.

GHG's can also be reduced by carbon forest sequestration.[9] A hectare of forest vintage v sequesters μ_v^w tCO_2e. Young forest vintages grow quickly and sequester carbon at a rapid rate. Older vintages grow slowly and eventually cease to sequester carbon. As the unmanaged forest land (both reserved and non-reserved) comprises mainly the older tree vintages, its potential to sequester additional GHGs is small, and may be ignored. However, the potential for GHG releases when these trees are cut down and burned or left as slash (Fearnside 2000, Houghton 2003) is large. Harvesting managed forests results in emissions of $(1-\varphi)\mu_v^h$ tCO_2e per hectare of land harvested, where μ_v^h is the carbon stock associated with harvested tree vintage v, and φ is the share of permanently stored carbon in harvested forest products. We ignore the annual sequestration of carbon by agricultural product, as those crops are harvested and subsequently consumed in the form of food or bioenergy.

Based on the above, the equations describing net GHG flows in the economy are

$$z_t = \mu^{f,e} x_t^{f,e} + \mu^{f,n} x_t^{f,n} + z_t^L, \tag{25}$$

and

$$z_t^L = \mu^L \Delta L_t^U + \mu^P L_t^P + \mu^n x_t^n + \mu^l x_t^l + (1-\varphi) \sum_{v=1}^{v_{\max}} \mu_v^h \Delta L_{v,t}^{F,H} - \sum_{v=1}^{v_{\max}} \mu_v^w L_{v,t}^F. \tag{26}$$

Equation (25) describes the composition of GHG emissions flows. Equation (26) shows net GHG emissions from deforestation, food and livestock production, and forest sequestration.

Finally, we consider institutional control of GHG emissions' flows (e.g. through the Kyoto Protocol), which foresees their gradual reduction and the stabilization of atmospheric carbon stocks. Specifically, we assume that at any point of

[9] GHG emissions flows are also sequestered by atmospheric and ocean sinks. We ignore this complication as our model does not provide comprehensive accounting of all GHG emissions flows, and focuses on understanding emissions from land use and related sectors.

time net GHG emissions from deforestation, application of fertilizers, and forest sequestration cannot exceed the emissions' quota, $\overline{z}^L$. We do not impose the emissions' constraints on GHG emissions from fossil fuels' combustion because they are exogenously determined. Rather we assume that emissions control instruments are reflected in exogenous fossil fuels' prices, which affect the demand for fossil fuels. Finally, because biofuels provide a renewable alternative to fossil fuels, we credit the emissions' quota, $\overline{z}^L$,by the fraction of fossil fuels' emissions displaced by the biofuels.[10] The resulting relationships for emissions control are

$$z_t^L \leq \overline{z}_t^L = \theta_t^z \left(z_t^L - \left(1 - \frac{\mu^{b,i}}{\mu^x} \right) x_t^{b,i} \right), i = 1, 2. \tag{27}$$

where global warming intensity, θ_t^z is a function determining the evolution of the GHG emissions' quota over time, and $\mu^{b,1}$ and $\mu^{b,2}$ are non-land-use emissions of first and second generation biofuels' production. Equation (27) describes the constraint on non-fossil fuel emissions in the atmosphere, and shows how this constraint is derived.

2.13 Preferences

The representative agent's utility, U, is derived from the consumption of food products, energy services, timber products, ecosystem services and other goods and services. The specific functional form for the utility function in this study is based on implicitly directive additive preferences, AIDADS (Rimmer and Powell 1996). Our choice of the utility function based on AIDADS preferences is motivated by its several important advantages over other functional forms underpinning standard models of consumer demand.[11] First, similar to the well-known AIDS demand system (Deaton and Muellbauer 1980) the AIDADS model is flexible in its treatment of Engel effects, i.e. "the model allows the MBS' (Marginal Budget Shares) to vary as a function of total real expenditures" (Rimmer and Powell 1996, p. 1614). Second, the AIDADS has global regularity properties, in contrast to the local properties of AIDS[12]. This is essential for solution of the model over a wide range of quantities. A number of studies (Cranfield et al. 2003, Yu et al. 2004) demonstrated that AIDADS outperforms other popular models of consumer demand in projecting global food demand, which makes it especially well-suited for the economic modelling of land-use.

The utility function for the AIDADS system is the implicitly directly additive function (Hanoch 1975):

$$\sum_{q=g,l,e,w,r,o} F\left(y^q, u\right) = 1, \tag{28}$$

[10] This doesn't necessarily mean that biofuels are 'greener' than fossil fuels. That will depend on the emissions associated with agricultural production and natural land conversion.

[11] The most popular demand systems estimated in recent applied work are the Homothetic Cobb-Douglas System (HCD), the Linear Expenditure System (LES), the Constant Difference of Elasticities Demand System (CDE), and the Almost Ideal Demand System (AIDS).

[12] One of well-known limitations of the AIDS system is that its budget shares fall outside $[0, 1]$ interval. This frequently occurs when AIDS is applied to model the demand for staple food when income growth is large (Yu et al. 2004, p. 102).

where $q = \{g, l, e, w, r, o\}$ is the consumption bundle, u is the utility level obtained from the consumption of goods or services y^q, and $F(y^q, u)$ is a twice-diffirentiable monotonic function that is strictly quasi-concave in y^q. Based on Rimmer and Powell (1996), the functional form for $F(y^q, u)$ is

$$F(y^q, u) = \frac{\alpha_q + \beta_q \exp(u)}{1 + \exp(u)} \ln\left(\frac{y^q - \underline{y}^q}{A \exp(u)}\right). \tag{29}$$

In equation (29) the parameters α_q and β_q define the varying marginal budget shares of goods and services y^q in the consumers' total real expenditures. The parameter $\underline{y}^q$ defines the subsistence level of consumption of goods and services q. The functional form of $F(y^q, u)$ implies that the consumption of goods and services y^q is always greater than their subsistence levels, $\underline{y}^q$. The parameter A affects the curvature of the transformation function $F(\underline{y}^q, u)$. The AIDADS system imposes standard non-negativity and adding-up restrictions based on the economic theory. These restrictions ensure that the consumers' marginal budget shares and minimal consumption level of goods and services $\underline{y}^q$ are greater or equal to zero, and the sum of marginal budget shares in total real expenditures does not exceed one.

Rimmer and Powell (1996, p.1615) demonstrate that maximizing the utility function (28) subject to the budget identity constraint (29) yields the following system of inverse demand equations:

$$p_q(q) = \frac{\alpha_q + \beta_q \exp(u)}{1 + \exp(u)} \frac{y - \sum_q p_q y^q.}{y^q - \underline{y}^q}, \tag{30}$$

where p_q are "prices" - or in this case, the marginal valuation - of goods and services y^q and y is the economy's output per capita.

2.14 Welfare

The objective of the planner is to maximize welfare function, Ω, defined as the sum of net aggregate surplus discounted at the constant rate $\delta > 0$, and the bequest value of unmanaged and commercial forest areas.[13] Net surplus is computed by integrating the marginal valuation of each product, less the land access costs and non-land-based costs of producing each good. Thus, for food and timber products, this represents non-land production costs. For energy, these are non-land biofuels costs and fossil fuel costs. For fertilizers, these are non-energy costs. For forestry, these are harvesting and planting costs. And for recreation, these are the costs of maintaining natural parks. The planner allocates commercial land for agricultural crops, livestock, and timber production, and the scarce fossil fuels and reserved natural forest land to solve the following

[13] We do not consider the bequest value of protected forests, as they cannot be "scrapped" in our model.

problem:

$$\max_{g,l,e,w,r} \Omega = \sum_{t=0}^{T-1} \delta^t \begin{bmatrix} \sum\limits_{q=g,l,e,w,r,o} \int_0^{y^{q*}} \left(p_q\left(y^q\right) - c_q\left(y^q\right)\right) dy^q \\ -c_t^U \left(\Delta L_t^U + \Delta L_t^R\right) - c_t^R \Delta L_t^R - c^n x_t^n \\ -\sum_i c^{g,i} {x^{g,i}}_t - c^l - c^p \Delta L_t^{F,P} - c_t^w \end{bmatrix} + \delta^T \Gamma\left(L_T^U, L_T^F\right) \tag{31}$$

s.t. constraints (1)-(30), where Γ is the scrap value function.

3 Empirical Implementation of FABLE

The model baseline extends for a period of 200 years, with an emphasis on the first century, and the starting point being the world economy in 2004. It is consistent with the IPCC (2000) A1B climate change scenario's storyline that describes a future world of strong economic growth, global population that grows quickly until mid-century and slows thereafter, the rapid introduction of new and more efficient technologies, and balanced energy use across all sources. It also foresees that, as the economy grows, its economic structure changes toward a service economy, including the expansion of ecosystem services sector. The majority of model's baseline parameters are based on the Global Trade Analysis Project (GTAP) v.7 data base (Hertel 1997, Narayanan and Walmsley 2008) and its satellite data for land use and global climate change policy (Hertel et al. 2009). The values of baseline parameters are summarized in Table A.3 and Figure 2.

3.1 Population

We assume that the population, Π_t, follows logistic (Verhulst) model with declining growth rates over time:

$$\Pi_t = \frac{\Pi_T \Pi_0 e^{\pi t}}{\Pi_T + \Pi_0 \left(e^{\pi t} - 1\right)}, \tag{32}$$

where Π_0 is level of population in 2004, Π_T is the limiting population in 2104, and π is the population growth rate. Compared to standard exponential growth assumption the logistic model provides a better fit to demographic projections, and has been recently adapted in the economic literature (Guerrini 2006, Bucci and Guerrini 2009, Guerrini 2010). Data on population in 2004 are from GTAP v.7 database. The estimate of limiting population is from United Nations Department of Economic and Social Affairs Population Division (2012). The logistic growth rate of population is calibrated to match United Nations Department of Economic and Social Affairs Population Division (2012) demographic projections.

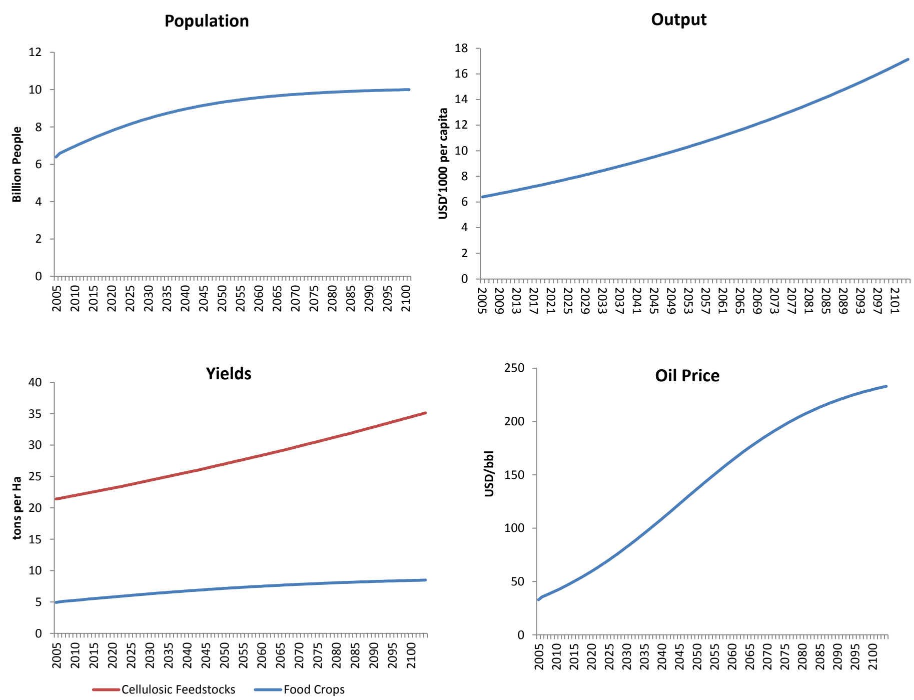

Figure 2: Projections of Exogenous Variables, 2005-2104

3.2 Resource Use

3.2.1 Land

The data for the total land and commercial land endowments come from the GTAP Integrated Global Land Use Data Base (Lee et al. 2009) and GTAP Global Forestry Data Base (Sohngen et al. 2009b). We define the initial amount of commercial land as the sum of crop land, pasture land, and managed (accessible) forest land areas. The initial amount of natural land is defined as the area of unmanaged (inaccessible) forest land. Other land areas, such as built-up lands, pastures, grasslands, savannah, shrublands, desserts, and barren lands, are not included in the current version of the model. The data for initial allocation of natural lands come from Antoine et al. (2008, p.8, Table 3).

Following past literature on land access modelling (Gouel and Hertel 2006, Golub et al. 2009) we assume that marginal natural land access cost per hectare is given by:

$$c_{t+1}^{U} = c_t^u - \xi_1^u \ln\left(\frac{L_{t+1}^N}{L_0^N}\right) + \xi_2^u \left(\frac{\Delta L_t^U + \Delta L_t^R}{L_t^N}\right)^2. \tag{33}$$

In equation (33), the variable c_t^u refers to the marginal access cost, implied by the marginal valuation of non-reserved natural land. The parameter ξ_1^N determines the long-run elasticity of natural land access costs with respect to cumulatively accessed hectares, which eventually becomes infinite as the remaining non-reserved natural land is exhausted. The parameter ξ_2^N governs the size of the short-term adjustment costs. We assume that additional costs per hectare of converting natural land to protected land are given by

$$c_t^R = \xi_0^R + \xi_1^R \Delta L_t^R. \tag{34}$$

In equation (34), the parameter ξ_0^R refers to the long-run time-invariant costs of protecting land. The parameter ξ_1^R governs the size of the short-term adjustment costs. We set the value of the marginal access cost, c_t^u, equal to the shadow price of agricultural lands dedicated to food crops (see equation 39 below). The parameter values defining natural land access cost function (33), and natural land protection cost function (34) are calibrated based on FAO (2010) data to match deforestation rates in 2004 and ensure stable rates of natural land access and protection.

3.2.2 Fossil Fuels

The primary fossil fuels linked to the economic analysis of land use are petroleum products and natural gas. Biofuels substitute for petroleum products and, to lesser extent, natural gas, in energy demand for transportation services. The natural gas is also the key input in nitrogen fertilizers' production. As petroleum products' and natural gas prices are closely related in the long run (Hartley et al. 2008), we use the crude oil price as a reference cost of fossil fuels. Following the U.S. Energy Information Administration (EIA) projections (EIA 2010a)we assume that the cost of fossil fuels is logistic function with declining growth over time:

$$c_t^f = \frac{c_T^f c_0^f e^{\kappa_f t}}{c_T^f + c_0^f \left(e^{\kappa_f t} - 1\right)},\ c_0^f > 0, \tag{35}$$

where the parameters c_0^f, and c_T^f, reflect the oil prices in the beginning and in the end of this century, and κ_f is the growth rate in costs of liquid fossil fuels. We obtain the value of the oil price in 2004 from the EIA, and calibrate the values of terminal oil price and the growth rate to match projections of the U.S. Energy Information Administration reference case scenario for 2035 (EIA 2010a, p. 86, Table 10).

3.3 Agrochemical Sector

There are three types of fertilizer used in agricultural production: nitrogen fertilizers, phosphate fertilizers, and potash fertilizers. In our model we focus on nitrogen fertilizers. These fertilizers are particularly important in the climate policy debate, because their production is the most energy- and GHG- intensive. They are also critical to boosting yields in response to scarcity of land.[14] We use the FAOSTAT database[15] to obtain the global production of nitrogen fertilizers in 2004. For fertilizers' production costs and conversion rates we consider anhydrous ammonia (NH_3), which is one of the most common nitrogen fertilizers. We use USDA ERS fertilizer use and price dataset[16] to obtain the fertilizers' price. We then subtract the fossil fuels' price from the fertilizers' price to obtain non-energy cost of fertilizers' production. This cost does not vary much across time because fossil fuels' and nitrogen fertilizers' prices are highly correlated and follow the same trend (USGAO 2003).

3.4 Agricultural Sector

The initial amount of food crops (measured as the global physical production of agricultural crops) and global expenditures on food crops in 2004 come from the FAOSTAT database. We set the production of cellulosic feedstocks close to zero, as the production of second generation biofuels was practically non existent in 2004. The elasticity of substitution of nitrogen fertilizers for agricultural land is based on Hertel et al. (1996) estimates for the US corn production over the 1976-1990 period. We obtain the economic rent of global cropland from GTAP v.7 database.

[14]Note that by von Liebig's Law of the Minimum (yield is proportional to the amount of the most limiting nutrient, whichever nutrient it may be) the production of other two types of fertilizers will follow the path of nitrogen fertilizers.

[15]Thorough description of the FAOSTAT database is available from the following website: `http://faostat.fao.org/`.

[16]Thorough description of the dataset is available from the following website: `http://www.ers.usda.gov/Data/FertilizerUse/`.

The crop technology index and value shares of agricultural land and fertilizers in 2004 are calibrated from known values of agricultural output, fertilizers, and the agricultural land as described in Rutherford (2002). Based on the agronomic literature (Cassman 1999, Cassman et al. 2010) we assume that crop technology index, $\theta^{g,c}$ is a logistic function with declining growth over time:

$$\theta_t^{g,c} = \frac{\theta_T^{g,c}\theta_0^{g,c}e^{\kappa_{g,c}t}}{\theta_T^{g,c} + \theta_0\left(e^{\kappa_{g,c}t} - 1\right)}, \tag{36}$$

where $\theta_0^{g,c}$ is the initial value of crop technology index, $\theta_T^{g,c}$ is crop yield potential, i.e., "the yield an adapted crop cultivar can achieve when crop management alleviates all abiotic and biotic stresses through optimal crop and soil management" (Evans and Fischer 1999), and $\kappa_{g,c}$ is the logistic growth rate. In a comprehensive study Lobell et al. (2009) report a significant variation in the ratios of actual to potential yields for major food crops across the world, ranging from 0.16 for tropical lowland maize in Sub-Saharan Africa to 0.95 for wheat in Haryana, India. Following global estimates of Licker et al. (2010) we assume the average ratio of 0.53. We calibrate the value of the logistic growth rate $\kappa_{g,c}$ to match recent crop yield dynamics, and allow for yield plateau when they reach 70–80% of the potential yield, $\theta_T^{g,c}$.

As regards the cellulosic feedstocks, we assume that their yield grows linearly across time, adding a constant amount of technology gain per annum

$$\theta_{t+1}^{g,b} = \theta_t^{g,b} + \kappa_{g,b},\ \theta_0^{g,b} > 0, \tag{37}$$

where the parameters $\theta_0^{g,i}$ and $\kappa_{g,i}$ corresponds to the initial level and growth rate in agricultural yield of cellulosic feedstocks. We obtain the agricultural yield growth rate based on production-weighted average of econometric estimates of Cassman et al. (2010) for major grain yields using global data over 1966 - 2009 period. We obtain the yield data for cellulosic feedstocks (*miscanthus giganteus)* from Taheripour and Tyner (2011).

We also account for the potential impact of climate change on the growth rate of agricultural yields. In the baseline we assume moderate temperature increase by the end of the century following Representative Concentration Pathways (RCP) 2.6 GHG forcing scenario (Moss et al. 2008). We assume that potential crop yields remain unchanged by the end of the century, as a decline in yields due to moderate increase in temperature is likely to be offset by CO_2 fertilization effect (Long et al. 2006). In contrast, second generation biofuels feed stocks benefit from higher temperatures and yields increase strongly (Brown et al. 2000). Based on the simulation results for switchgrass yields in the upper Midwest of the United States (Brown et al. 2000), agricultural yield growth for cellulosic feedstocks is expected to increase by 50% in 2100. We annualize the growth by assuming that agricultural yield growth rate of cellulosic feed stocks relative to 2005 increases by 10% every twenty years until 2100.

It can be shown (see, e.g., Rutherford (2002) for complete derivation) that non-land costs per ton of agricultural product, $c^{g,i}$, are given by

$$c_t^{g,i} = \frac{1}{\theta_t^{g,i}} \left((\alpha^g)^{\sigma_g} \left(c_t^{C,i} \right)^{1-\sigma_{g,i}} + (1-\alpha^g)^{\sigma_g} \left(c_t^f \right)^{1-\sigma_g} \right)^{\frac{1}{1-\sigma_g}}, \quad (38)$$

where $c_t^{C,i}$ are endogenous shadow prices (rents) of agricultural lands dedicated to food crops and cellulosic feedstocks. These prices are determined from a conditional input demand function for agricultural lands:

$$L_t^{C,i} = \frac{x_t^{g,i}}{\theta_t^{g,i}} \left(\frac{\alpha^g}{c_t^{C,i}} \right)^{\sigma_g} \left(\alpha^{\sigma_g} \left(c_t^{C,i} \right)^{1-\sigma_g} + (1-\alpha^g)^{\sigma_g} \left(c_t^f \right)^{1-\sigma_g} \right)^{\frac{\sigma_g}{1-\sigma_g}}. \quad (39)$$

3.5 Livestock Farming Sector

The initial output of livestock products (measured as the global physical production of meat, diary and eggs) in 2004 come from the FAOSTAT database. We obtain the economic rent of global pasture land and the expenditures on animal feed, from GTAP v.7 database. The initial amount of animal feed comes from the USDA FAS PSD database.[17] The elasticity of substitution of animal feed for pasture land is taken from Golub et al. (2009). The livestock technology index and value shares of agricultural land and fertilizers in 2004 are calibrated from known values of livestock output, animal feed, and the pasture land as described in Rutherford (2002). Non land livestock farming costs are given by

$$c_t^l = c_0^l x_t^l + \xi_0^l \left(\Delta L_t^P \right)^2. \quad (40)$$

where c_0^l captures the non-land cost per ton of livestock, and ξ_0^l captures the adjustment costs of pasture land conversion. We obtain the non-land cost of livestock farming from GTAP v.7 database, and calibrate the adjustment cost parameter to match recent trends in grain and livestock production (Taheripour et al. 2013).

3.6 Food Processing Sector

The growth of technology indices in the food processing sector is described by the following equation:

$$\theta_{t+1}^{i,y} = \kappa_{i,y} \theta_t^{i,y},\ \theta_0^{i,y} > 0,\ i = g, l, \quad (41)$$

where the parameters $\theta_0^{i,y}$ and $\kappa_{i,y}$ reflect the initial level and annual growth rate in technologies of the food processing sector. We calculate the level of technology index of the grain and livestock processing in 2004 using GTAP v.7 database. For grains, we dividing the output of processed grains and crops (GTAP sectors 21, 23-25) by the output of grains and cereals (GTAP sectors 1-8). For livestock, we dividing the output of processed livestock and diary

[17] see `http://www.fas.usda.gov/psdonline`, last accessed in August 2013.

(GTAP sectors 19-20, 22) by the output of livestock products (GTAP sectors 9-11). We set the growth rate of the technology in the food processing sector equal to the economy's TFP. We obtain the non-land food processing costs from GTAP v.7 database.

3.7 Biofuels Sector

In the model baseline we define the first-generation biofuels as a grain-based ethanol and the second generation biofuels as cellulosic biomass-to-liquid diesel obtained through Fischer-Tropsch gasification. The values for biofuels conversion rate and cost for ethanol and biomass-to-liquid diesel are taken from Taheripour and Tyner (2011). Following Winston (2009) we adjust the quantity of first generation biofuels produced by 0.7 to match the energy content of liquid fossil fuels. The elasticity of substitution of second generation biofuels feedstocks for fixed factor technology and their value shares in CES function (A.24) are calculated based on MIT-EPPA model (Paltsev et al. 2005, Tables 12 and 13, p.40).

The change in factor-specific technological progress is described by the following equation:

$$\theta^{\phi}_{t+1} = \kappa_{\phi}\theta^{\phi}_{t},\ \theta^{\phi}_{0} > 0. \tag{42}$$

The rate of factor-specific technological change, κ_{ϕ}, is highly uncertain and is an important contribution to the uncertainty in projected deployment in second generation biofuels (Creutzig et al. 2012). Following the economic literature on biofuels modeling (Popp et al. 2011, Wise and Calvin 2011) we set the rate to 0.5 percent. In section 5 we perform a sensitivity analysis with respect to a higher value of the rate of factor-specific technological change.

3.8 Energy Sector

We obtain the initial values for total consumption of liquid fossil fuels and first generation biofuels from EIA (2010b, p. 24, Table 3). We set the initial consumption of second generation biofuels close to zero. The elasticity of substitution of fossil fuels for first generation biofuels is based on Hertel, Tyner and Birur (2010) econometric estimates for the US biofuel industry over the 2001-2008 period. The technology of energy production, and the value shares of biofuels and fossil fuels in energy production in 2004 are calibrated as described in Rutherford (2002).

The growth in the energy efficiency is described by the following equation:

$$\theta^{e}_{t+1} = \kappa_{e}\theta^{e}_{t},\ \theta^{e}_{0} > 0, \tag{43}$$

where the parameters θ^{e}_{0} and κ_{e} reflect the initial level and annual growth rate in the energy efficiency. We set the energy efficiency in 2004 equal to one, and obtain the growth rate in the energy efficiency from World Energy Council (2008).

3.9 Forestry Sector

We set the number of forest tree vintages to 100 and assume that average densities of managed forest land corresponding to different tree ages are uniformly distributed. Following the literature on the economic analysis of managed forests (Sohngen and Mendelsohn 2007, Sohngen et al. 2009b) we assume that the merchantable timber yield function is given by the following equation:

$$
\begin{aligned}
\theta_v^w &= \exp\left(\psi_1 - \frac{\psi_2}{v - \overline{v}}\right),\ if\ v > \overline{v} \\
\theta_v^w &= 0,\ if\ v \le \overline{v}.
\end{aligned} \tag{44}
$$

In equation (44),the parameters ψ_1 and ψ_2 are growth parameters determining the support and the slope of the timber yield function, and $\overline{v}$ is a minimum age for merchantable timber. The yield function (44) parameters, the minimum age for merchantable timber, and the average planting and harvesting costs come from GTAP Global Forestry Data Base (Sohngen et al. 2009b). Similar to the agricultural sector, we assume that the merchantable timber yield per hectare of forest land with the average tree age v grows linearly across time, adding a constant amount of technology gain per annum:

$$\theta_{v,t+1}^w = \theta_{v,t}^w + \kappa_v^w, \theta_{v,0}^w > 0, \tag{45}$$

where the parameters $\theta_{v,0}^w$ and κ_v^w correspond to the initial levels and technology gains to the merchantable timber yield of vintage v. We obtain the data for yield growth in the commercial forestry sector by annualizing the difference in the average yields from global forest studies of Sedjo (1983) and Cubbage et al. (2010).

Forest harvesting costs are given by

$$
\begin{aligned}
c_t^w = {} & \xi_0^w \sum\nolimits_v \theta_{v,0}^w \Delta L_{v,t}^{F.H} + \xi_1^w \left[\sum\nolimits_v \left(\Delta L_{v,t}^{F,H} - \Delta L_{v,t-1}^{F,H}\right)\right]^2 \\
& + \xi_2^w \left(\sum\nolimits_v \Delta L_{v,t}^{F.H} - \Delta L_t^{F,P}\right)^2,
\end{aligned} \tag{46}
$$

where the parameters ξ_0^w, ξ_1^w, and ξ_2^w correspond to long-run forest harvesting costs and short-run adjustment costs of harvesting and harvested land conversion to agricultural land. We calibrate short-run adjustment costs of harvesting and conversion of harvested forest land to agricultural land to match recent dynamics in commercial land-use.

3.10 Timber Processing Sector

The growth of TFP in the timber processing sector is described by the following equation:

$$\theta_{t+1}^{w,y} = \kappa_{w,y} \theta_t^{w,y},\ \theta_0^{w,y} > 0, \tag{47}$$

where the parameters $\theta_0^{w,y}$ and $\kappa_{w,y}$ reflect the initial level and annual growth rate in the technology of the timber processing sector. We calculate the technology index of the timber processing sector in 2004 using GTAP v.7 data, by dividing the output of timber products (GTAP sectors 30-31) by the output of commercial forestry sector (GTAP sector 13). We set the growth rate of the technology in the timber processing sector equal to growth rate of the economy's TFP. We obtain the timber processing costs from GTAP v.7 database.

3.11 Ecosystem Services Sector

The parameters for production of ecosystem services in production function 24 are based on the estimates of Costanza et al. (1997), who estimated values for 17 ecosystem services from 16 ecosystem types at global scale.[18] We exclude the services from the production of food and timber, as well as from based climate abatement, as those are determined endogenously in the model. We also exclude the production of ecosystem services from ecosystems not represented in the model (e.g., marine, grasslands and deserts). We use agroecological zone (AEZ) representation of GTAP land use database to differentiate between tropical and temperate/boreal forest land. Based on ecological literature (Ehrlich and Mooney 1983) we assume that there is a limited substitution between different land types in production of ecosystem services. Because effectiveness of protected land areas is very difficult to quantify (Chape et al. 2005), we set the parameter θ^R large enough to make sure new protected areas are established.

We measure the non-land costs of managing protected natural areas based on GTAP v.7 database as public expenditures on outdoor recreation services per hectare of protected land.[19] We assume that the non-land cost of managing protected natural areas declines over time with technological improvements in non-land inputs. We characterize the change in non-land costs of managing protected natural areas by the following equation:

$$c_t^R = \frac{c_0^R,}{(1+\kappa_R)^t}\ c_0^R > 0, \tag{48}$$

where the parameters κ_R reflect the annual rate of decline in the non-land cost of managing protected natural areas.

3.12 Other Goods and Services

The growth of TFP is described by the following equation:

$$\theta_{t+1}^o = \kappa_o \theta_t^o, \theta > 0, \tag{49}$$

[18] We are familiar with multiple criticisms of this approach National Research Council (2005, p. 188-189). However, there have been very few attempts to evaluate production of ecosystem services at global scale, and the work of Costanza et al. (1997) still remains most influential.

[19] Following Antoine et al. (2008), we define outdoor recreation services sector based on GTAP v.7 database. This sector comprises of hunting and fishing, wildlife viewing in reserves, and other wildlife viewing activities.

where the parameters θ_0^o and κ_o reflect the initial level and annual growth rate in the TFP of the economy. The initial values for the production of other goods and services and economy's output per capita are based on the value of output at agents' prices from GTAP v.7 database. The production of other goods and services is obtained from GTAP v.7 sectors 9-12, 14-15, 18-20, 22, 26-29, 33-42, 45, 47-54 and 56-57. We set total factor productivity growth rate using Jorgenson and Vu (2010) projections based on econometric estimates for 122 economies over the 1990 - 2008 period.

3.13 GHG Emissions

The value of the GHG emission coefficient from combustion of liquid fossil fuels comes from the US Energy Information Administration (EIA) website[20]. The GHG emission coefficient from production of ammonia from fossil fuels comes from IPCC (2006a) Tier 1 estimates. We compute GHG emissions per ton of anhydrous ammonia applied to crop lands as follows. First, we calculate the nitrogen equivalent mass of anhydrous ammonia using conversion factor of $\frac{17}{28}$. We then use IPCC (2006b) Tier 1 estimates to compute the amount of nitrogen released to the atmosphere from ammonia application. We then convert the amount of nitrogen released to the atmosphere to nitrogen dioxide (NO_2) using conversion factor of $\frac{44}{28}$. Finally, we find the carbon dioxide equivalent of the nitrogen dioxide using global warming potential of NO_2.

The GHG emissions coefficients from livestock are taken from FAOSTAT database. These include the emissions from enteric fermentation, and manure management (per ton of livestock) and the manure left on pasture land (per hectare of land). The GHG emissions factor per hectare of converted non-reserved natural land is based on the estimates of Hertel, Golub, Jones, O'Hare, Plevin and Kammen (2010) using methodology from Searchinger et al. (2008). The non-land-use emissions of biofuels' production are taken from GREET life-cycle model (Searchinger et al. 2008, Dunn et al. 2011). We do not impose any regulation for land-use emissions in the baseline scenario, and consider it in the following sections of this study.

Following the literature on forest carbon sequestration in economic analysis of land-use (Sohngen and Mendelsohn 2007, Sohngen et al. 2009a) the carbon stock per hectare of harvested forest vintage v, μ_v^h, is given by:

$$\mu_v^h = \overline{\mu}^w \exp\left(\psi_1 - \frac{\psi_2}{v}\right). \tag{50}$$

In equation (50) the parameter $\overline{\mu}^w$ is the carbon conversion factor, that accounts for the stocking density of specific timber types, whole tree factors, and forest floor carbon, and ψ_1 and ψ_2 are the parameters defining merchantable timber yield function from equation (44).[21] Then the amount of GHG sequestered by a hectare of forest land of tree vintage v is

[20] See `http://www.eia.doe.gov/oiaf/1605/coefficients.html`, last checked in August, 2013.

[21] Note that the minimum age parameter, $\overline{v}$, is not included in equation (51). This is because

$$\mu_v^w = \mu_v^h - \mu_{v-1}^h. \quad (51)$$

We obtain the carbon conversion factor and yield function (44) parameters from GTAP Global Forestry Data Base (Sohngen et al. 2009b). The share of permanently stored carbon in harvested forest products is from Sohngen and Mendelsohn (2007).

3.14 Preferences and Welfare

The parameters α_q and β_q defining the varying marginal budget shares of goods and services q in the consumers' total real expenditures in equation (29) are estimated by maximum likelihood as described in Cranfield et al. (2003) and Yu et al. (2004). The parameters $\overline{q}$ define the subsistence level of consumption of goods and services q were calibrated to match the initial allocation of land resources. The social discount rate is the same as in the Dynamic Integrated model of Climate and the Economy (DICE), version 2007.[22] We parameterize the scrap value function as

$$\Gamma\left(L_T^U, L_T^F\right) = \varpi_1 L_T^U + \varpi_2 \sum_{v=1}^{v_{max}} \frac{L_{v,T}^F}{\delta^{T-v}}, \ (\varpi_1 > 0, \varpi_2 > 0), \quad (52)$$

where the parameters ϖ_1 and ϖ_2 denote the scrap prices of unmanaged and commercial forests at the beginning of period T. We calibrate the values of ϖ_1 and ϖ_2, so that forest replanting rates are stable over time and unmanaged natural lands are not depleted over 50 percent of their initial amount during the time horizon of the problem.[23]

4 Model Baseline

This section describes the results of the model baseline. We solve the model over the period 2005 - 2204, and present the results for the first 100 years to minimize the effect of terminal period conditions on our analysis.

Figure 3 depicts the optimal allocation of global land-use, land based GHG emissions, consumption of goods and services that draw on land resources, and consumption of biofuels in the model baseline over the course of next century. Beginning with the upper left-hand panel of Figure 3, we see that, in the near term decades, area dedicated to food crops increase by 10 percent compared to 2004, reaching its maximum of 1.55 billion hectares in 2035. Area dedicated to animal feed expands rapidly, adding 150 million hectares, whereas the pasture

at young ages, stands may have substantial carbon, but little merchantable timber Sohngen et al. (2009b).

[22]For a detailed description of the DICE model see Nordhaus (2008). DICE 2007 model parameters can be accessed at the following website: `http://nordhaus.econ.yale.edu/DICE2007.htm`

[23]We have tried setting different values of ϖ_1, and the optimal path of natural land conversion was not significantly affected over the first 100 years.

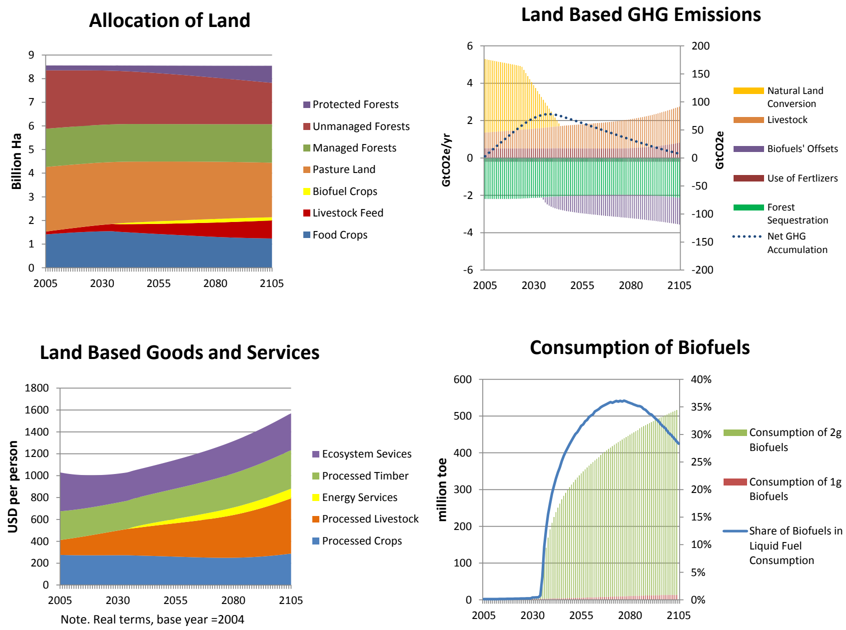

Figure 3: Model Baseline

land declines, losing 120 million hectares by 2035. Managed and unmanaged forest areas decline by 205 and 3 million hectares. Changes in areas dedicated to biofuels feedstocks and protected natural forests remain insignificant. By mid-century, slower population growth, rising real income, shifting diets, and technology improvements in food processing, storage and transportation result in a decline in demand for food crops. By 2100 area dedicated to food crops falls to 1.25 billion hectares, which is 12 percent lower than in 2004. Improvements in crop technology and agricultural yield result in greater intensification of livestock production. Pasture land continues to decline, reaching 2.33 billion hectares, which is 15 percent smaller than 2004. Area dedicated to animal feed increases significantly to reach 0.73 billion hectares, which is nearly 6 times greater than 2004. Growing energy prices result in significant growth in the land area dedicated to biofuels, which reaches 0.14 billion hectares by 2100. Managed forest area is little changed. Rising real incomes, growing demand for ecosystem services, and improvements in management of natural forest lands result in strong growth in protected natural land area, which increases significantly to 0.68 billion hectares (about 3 times greater than 2004) in 2100.

The upper right-hand panel in Figure 3 reports gross land based annual GHG emissions flows and their net accumulation over time.[24] Positive bars in this panel denote emissions, whereas negative bars denote GHG abatement

[24] As this study focuses on optimal path of land based GHG emissions, the emissions from combustion of petroleum products are not shown in Figure 3.

through forest sinks and biofuels offsets. Conversion of natural forest lands is a significant driver of land-based GHG emissions in the near term, which amounts to 3.2 $GtCO_2e$/yr in 2025. By mid-century, increasing access costs of natural land combined with declining demand for commercial land, results in a sharp decline in deforestation. GHG emissions from deforestation are eliminated by 2050 along this optimal global path of land use. GHG emissions from application of fertilizers remain stable for the most of the century, and increase closer to the end of the century along with continued expansion of animal feed. In 2100 annual flows of GHG emissions from use of fertilizers amount to 0.73 $GtCO_2e$/yr, which is 40 percent larger than 2004. Continued growth in consumption of meat and dairy products results in a significant increase in GHG emissions from livestock. In 2100 annual flows of GHG emissions from livestock amount to 1.84 $GtCO_2e$/yr, which is 2.2 times larger than 2004. GHG emissions sequestration from managed forests does not change significantly. In 2100 sequestered GHG emissions amount to 2.1 $GtCO_2e$/yr, which is about 5 percent smaller than 2004. GHG emissions offsets from biofuels are insignificant in the near term. With the arrival of second generation biofuels technology, biofuels become a significant source of land based GHG abatement due to their low emissions intensity relative to petroleum Dunn et al. (2011). In 2100 annual biofuels offsets account for 1.4 $GtCO_2e$/yr. Overall, accumulation of land based GHG emissions flows increases in the first part of this century, reaching its maximum of 80 $GtCO_2e$ around 2040. It then declines in the second part of the century reaching 12 $GtCO_2e$ by 2100. As explained above, higher oil prices, expansion of biofuels, and declining deforestation are the main reasons for falling GHG emissions of land based sectors.

The lower left-hand panel in Figure 3 illustrates the results for per-capita consumption of goods and services that draw on land resources. The consumption of livestock products, timber products, and biofuels grow in absolute terms. This growth is driven by changing preferences, decline in population growth, and rising energy prices. In 2100 the per capita consumption of livestock and land-based energy services is considerably higher compared to their levels in 2004, whereas the increase in timber products consumption is more moderate. The per capita consumption of processed food crops remain unchanged over the course of this century. The consumption of ecosystem services declines in near decades as a result of deforestation. However, the consumption of ecosystem services subsequently increases with greater demand for recreation and continued growth in protected forest areas. Nonetheless, the consumption of ecosystem services in 2100 is still lower than their corresponding levels in 2004.

The lower right-hand panel of Figure 3 describes the results for consumption of biofuels.[25] The consumption of first generation biofuels grows slowly as oil

[25] In our baseline, biofuels expansion is driven solely by oil prices. Of course there are government mandates which have played an important role in biofuel expansion in the US and the EU, in particular. However, in the long run, we believe that the fare of biofuels will be largely determined by oil prices. In our baseline, oil prices are rising steadily such that we expect the US mandates for first generation biofuels will not be binding (Meyer et al. 2011). As regards second generation biofuels, recent evidence suggests that US-RFS2 mandate for

prices and agricultural yields increase. However, along this optimal path, first generation biofuels do not become a significant source of energy consumption. In 2100 the consumption of first generation biofuels is 13 Mtoe, considerably higher than in 2004, but still small in relative terms. Second generation biofuels become competitive around 2035 and rapidly expand reaching 300 million toe in 2050, and 500 million toe in 2100. The share of biofuels in total liquid fuel consumption steadily increases, reaching its maximum of 36 percent in 2075. Further expansion of biofuels is crowded by even greater expansion of animal feed, and the share of biofuels in total liquid fuel consumption declines to about 30 percent in 2100.

5 Model Sensitivity to Parameter Values

This section explores the model sensitivity to the values of several important parameters used in the empirical analysis. These include the conversion cost of natural lands, substitutability between agricultural lands and fertilizers in production of agricultural output, the costs and efficiency of biofuels' production, energy efficiency, and the demand for energy services. We show model baseline sensitivities with respect to the following changes[26]:

- a 50% decline in short-term adjustment costs of natural land conversion;
- a 50% increase in elasticity of substitution between agricultural land and fertilizers,
- a 50% improvement in second generation biofuels' production technology,
- a 50% increase in fixed factor specific technological change,
- a 50% decline in energy efficiency growth rate, and
- a 50% increase in AIDADS marginal budget shares for energy services.

Table A.4 summarizes the changes in parameters values under consideration.[27]

Figure 4 shows the effects of a 50% decline in short-term adjustment costs of natural land conversion (all of the figures in this section report changes, relative to the baseline). Greater ease of natural land conversion results in a decline in unmanaged forest land, which decreases further by 65 million Ha in 2100. Agricultural land dedicated to food crops and animal feed expands in near decades

cellulosic biofuels will unlikely be met (National Research Council 2011). More generally, we expect that budgetary pressures will limit the extent to which governments will be willing to subsidize biofuels in the coming decades. This leaves oil prices as the primary driver of biofuels expansion.

[26]Because of a lack of space, we are unable to show sensitivity results across all parameters and scenarios. In this section we concentrate on the parameters subject to largest uncertainties. The additional results are available from authors upon request.

[27]The magnitudes of parameter changes in model sensitivity analysis are not based on projections from other studies. Rather these magnitudes represent a simple attempt to construct confidence intervals for baseline predictions.

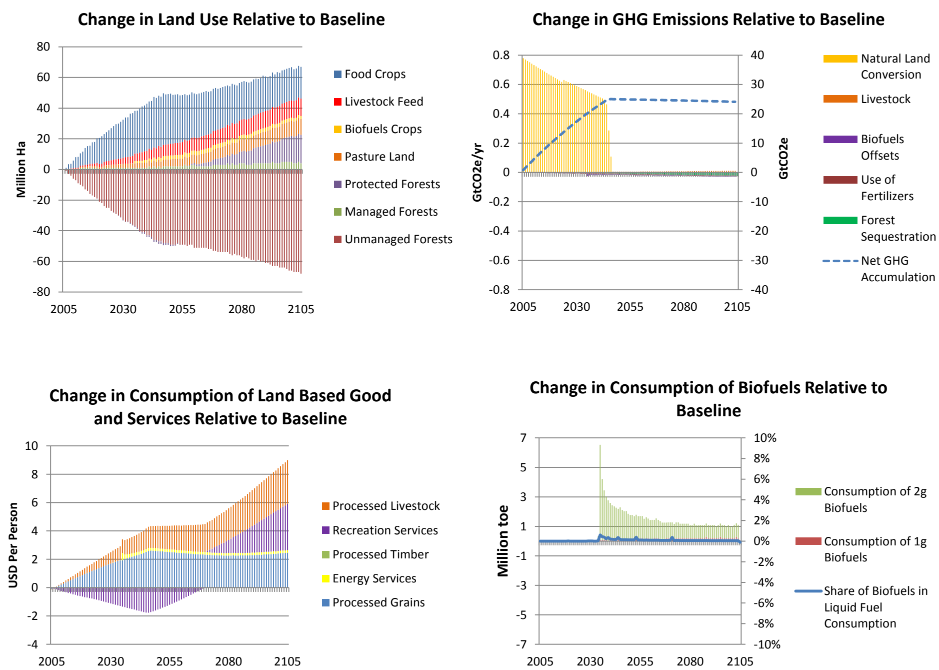

Figure 4: Sensitivity Analysis: 50% Decline in Short Term Adjustment Costs of Natural Land Conversion

and the medium term. In the long term, there is also an increase in managed and protected forest areas and the area dedicated to biofuels feedstocks. The additional conversion of natural lands results in increased GHG flows, and net GHG accumulation increases by 25 $GtCO_2e$ in mid-century, and remains constant thereafter. The consumption of ecosystem services declines in the mid term as a result of additional deforestation, but increases thereafter with the increase in protected lands. The consumption of all other land-based goods and services, and biofuels increase modestly in the long term.

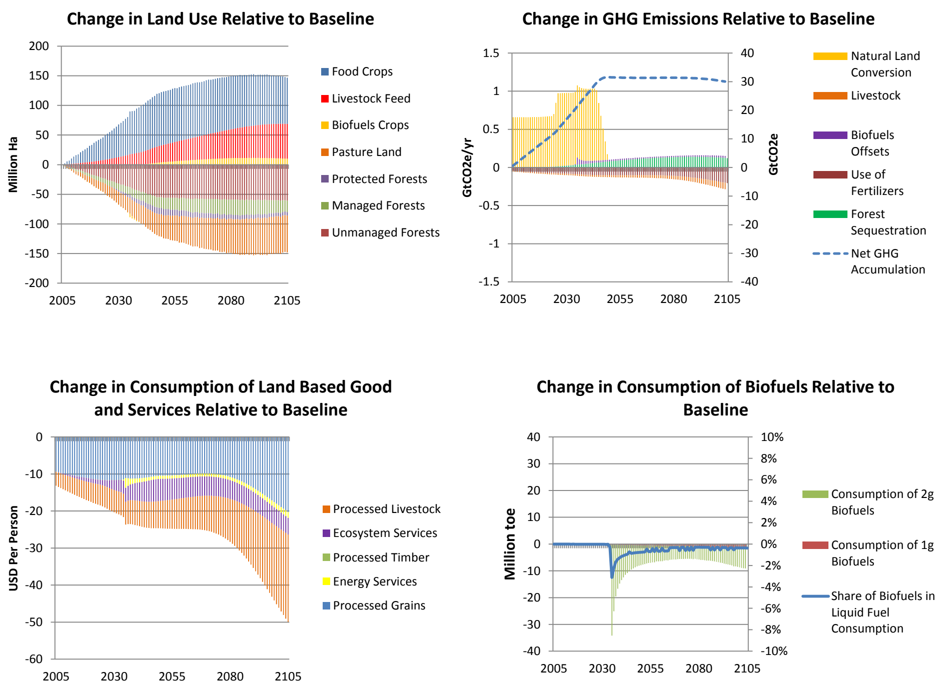

Figure 5: Sensitivity Analysis: 50% Increase in Elasticity of Substitution between Agricultural Land and Fertilizers

Figure 5 shows the effects of a 50% increase in elasticity of substitution between agricultural land and fertilizers. Given the increase in fertilizers' costs in baseline scenario, better substitution between agricultural land and fertilizers implies additional demand for agricultural land, which increases by about 150 million Ha in 2100. All forest areas decline. GHG flows increase with the additional conversion of natural lands. However, the decline in fertilizers' use results in smaller GHG flows. The former effect dominates, and net GHG accumulation increases by 30 $GtCO_2e$ in 2100. The consumption of all land based goods and services declines. There is also a small decrease in the consumption of biofuels.

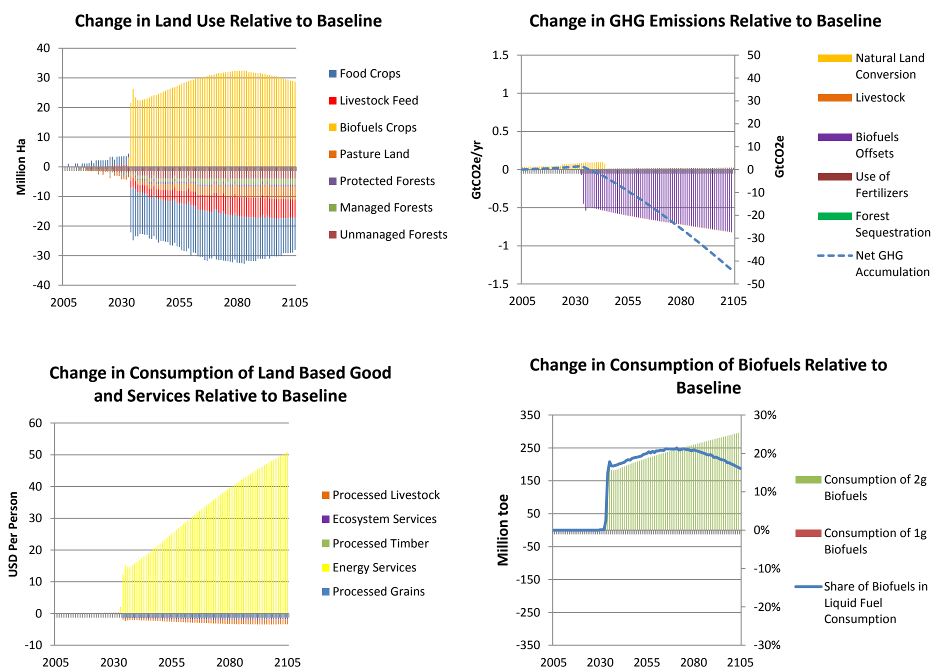

Figure 6: Sensitivity Analysis: 50% Increase in Biofuels' Conversion Rate

Figure 6 shows the effects of a 50% improvement in second generation biofuels production technology. This improvement makes second generation biofuels a more competitive alternative to petroleum products, and they enter large scale commercial production considerably earlier. After arrival of second generation biofuels, their production increases by 300 million toe, and the biofuels share in liquid fuel production increases to reach 47% in 2100. Agricultural area dedicated to cellulosic feedstocks increases by additional 30 million Ha in 2100, whereas areas dedicated to food crops, animal feed and natural forests decline. GHG flows increase with the additional conversion of natural lands, and later decline with biofuels' offsets. The latter effect dominates in the long run, and net GHG accumulation declines by 40 $GtCO_2e$ in 2100. The consumption of energy services increases, and the consumption of other land based goods and services declines.

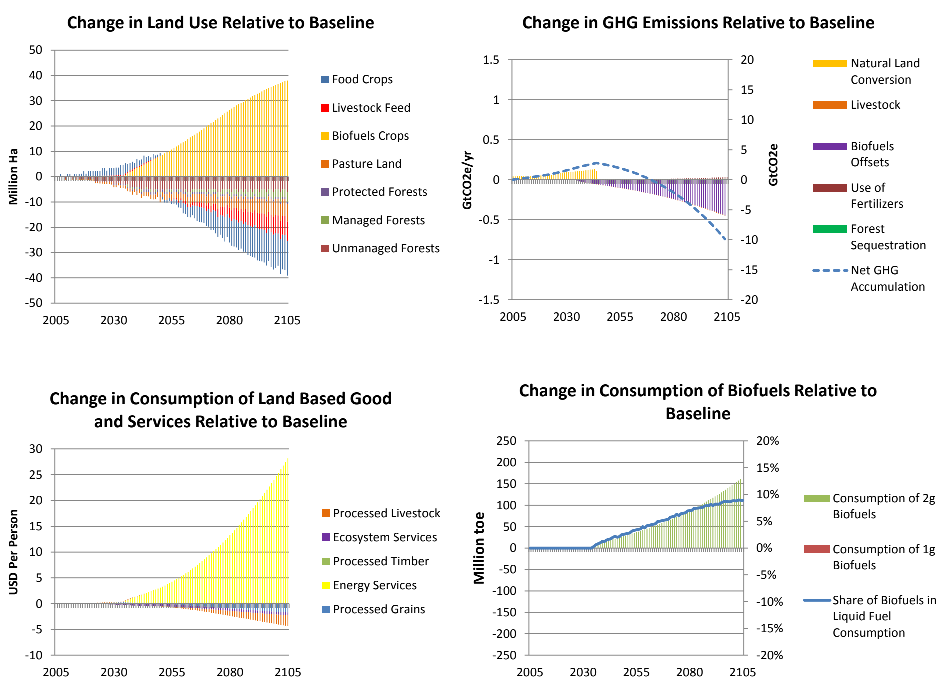

Figure 7: Sensitivity Analysis: 50% Increase in Fixed Factor Specific Technological Change

Figure 7 shows the effects of a 50% increase in fixed factor specific technological change. Similar to the improvements in biofuels' production technology, faster technological progress in biofuels penetration make biofuels a more competitive alternative to petroleum products. Biofuels production increases by 150 million toe, and the biofuels share in liquid fuel production increases to reach

39% in 2100. Agricultural area dedicated to cellulosic feedstocks increases by additional 36 million Ha in 2100. All other areas decline. GHG flows increase because of additional conversion of natural lands, and decline due to greater biofuels' offsets. The latter effect dominates in the long run, and net GHG accumulation declines by 10 $GtCO_2e$ in 2100. The consumption of energy services increases, and the consumption of other land based goods and services declines.

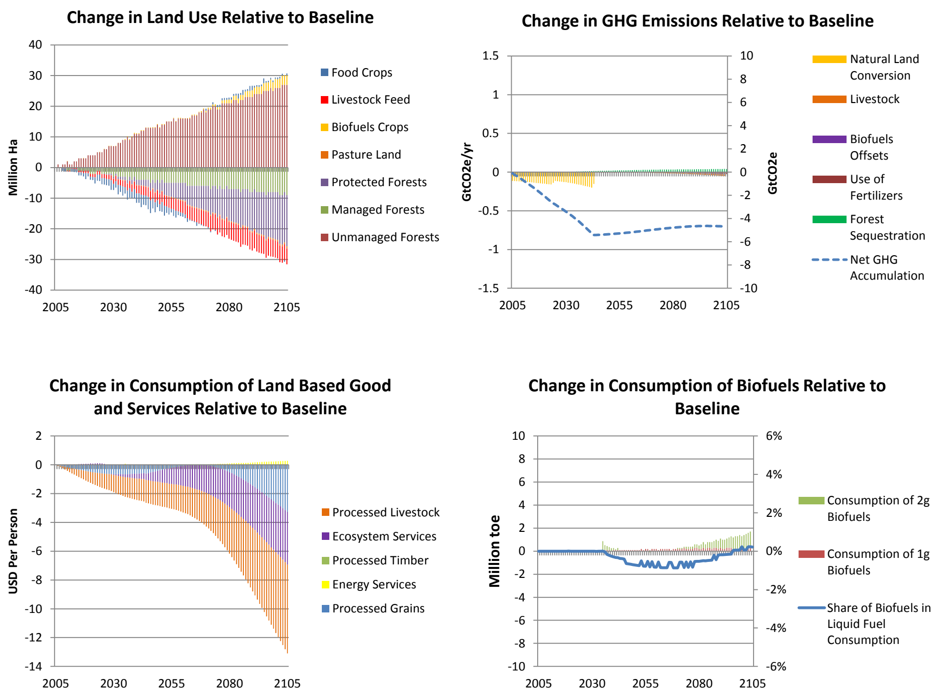

Figure 8: Sensitivity Analysis: 50% Decline in Energy Efficiency Growth Rate per annum

Figure 8 shows the effects a 50% decline in energy efficiency growth rate. Smaller energy efficiency implies increased requirements for energy fuels (here petroleum products and biofuels) to satisfy the demand for energy services. The increased consumption of petroleum and biofuels results in a greater demand for agricultural land. Areas dedicated to biofuels feedstocks add 3 million Ha. All other areas dedicated to commercial land decline in response to demand reduction for land based goods and services due to higher energy prices. Unmanaged forest lands increase by additional 26 million Ha in 2100. The GHG emissions flows from land use decline slightly in the medium term because of avoided deforestation. The consumption of biofuels increase by a small amount, although their share in liquid fuel consumption modestly declines because of even greater increase in demand for petroleum products. The income effect of increased requirements for petroleum products propagates into decline in consumption of all land based goods and services, except for energy services.

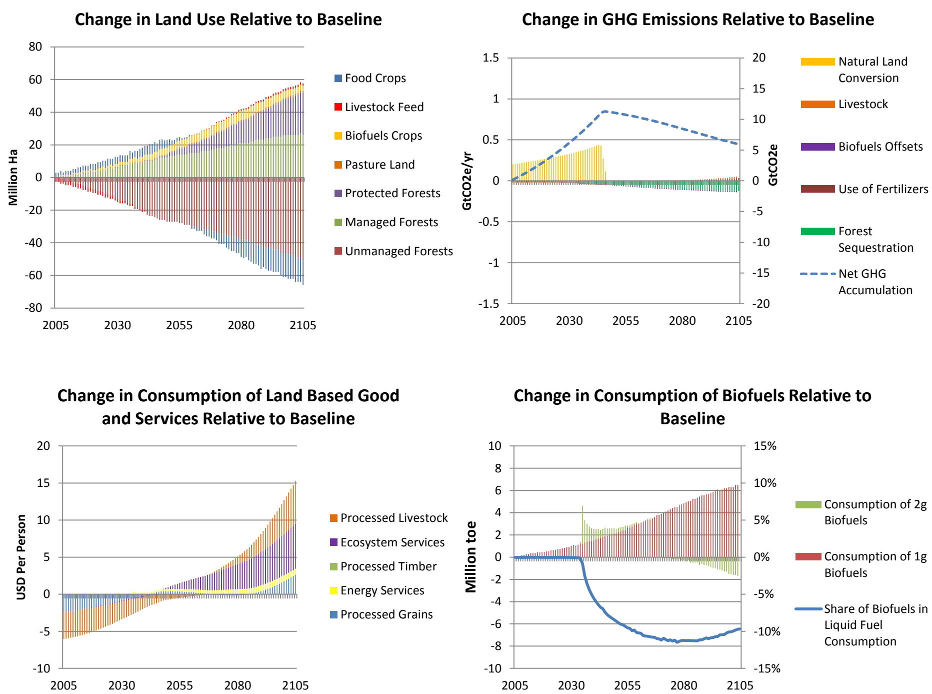

Figure 9: Sensitivity Analysis: 50% Increase in AIDADS Marginal Budget Shares for Energy Services

Figure 9 shows the effects of a 50% increase in AIDADS marginal budget shares for energy services, holding the budget shares of other land-based goods and services constant. Similar to the reduction in energy efficiency, the increase in demand for energy services implies greater requirements for petroleum products and biofuels. As in the previous case, the there is an increase in area dedicated to biofuels feedstocks. This area grows by additional add 4 million Ha, whereas area dedicated to food crops declines by 15 million Ha in 2100. Changes in preference structure also result in additional conversion of unmanaged forests, which decline by 47 million hectares. Areas dedicated to unmanaged and protected forests increase. The GHG emissions flows from land use increase by a small amount because of increased deforestation and decline thereafter as managed forests expand. Net GHG accumulation increases by 5 $GtCO_2e$ in 2100. The consumption of biofuels increases by a small amount, and their share in liquid fuel consumption declines significantly because of even greater increase in demand for petroleum products. The consumption of all land-based goods and services increase in the long term.

6 Conclusions

This paper introduces FABLE, a dynamic global model, aimed at analyzing the optimal profile for global land use in the context of growing commercial demands for food and forest products, increasing non-market demands for ecosystem services, and more GHG mitigation targets. This long-run, forward-looking partial equilibrium model covers key sectors drawing on the world's land resources, and incorporates growing demands for food, renewable energy, and forest products, and increasing non-market demands for ecosystem services. The model accounts for alternative GHG constraints, as well as the potential impacts of climate change itself on the productivity of land in agriculture, forestry and ecosystem services.

Our baseline accurately reflects developments in global land use over the 10 years that have already transpired, while also incorporating long-run projections of population, income and demand growth from a variety of international agencies. The model baseline demonstrates that, in the absence of market imperfections, deforestation associated with cropland expansion, which accounts for a large share of land-use GHG emission, declines along the optimal land-use trajectory in the medium term. In the long term an expansion of the livestock sector, and intensification of livestock production results in a significant increase in the land dedicated to animal feed. The area of protected natural lands, which deliver eco-system services, also increases drastically. The consumption of biofuels increases rapidly after second generation biofuels become competitive around 2035, and takes about a third of a total liquid fuel consumption by the end of this century. In summary, we find that different elements of land use change explored in this paper are in fact closely inter-related. By examining them within a single, intertemporally consistent framework, we are able to offer new insights into the competition for the world's land resources over the coming century.

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A. FABLE Model Equations, Variables and Parameters

Equations

Land Use

$$\overline{L} = L_t^N + L_t^M, \tag{A.1}$$

$$L_t^N = L_t^U + L_t^R, \tag{A.2}$$

$$L_{t+1}^U = L_t^U - \Delta L_t^U - \Delta L_t^R,\ L_0^U > 0, \tag{A.3}$$

$$L_{t+1}^R = L_t^R + \Delta L_t^R,\ L_0^R > 0, \tag{A.4}$$

$$c_{t+1}^U = c_t^u - \xi_1^u \ln\left(\frac{L_{t+1}^N}{L_0^N}\right) + \xi_2^u \left(\frac{\Delta L_t^U + \Delta L_t^R}{L_t^N}\right)^2, \tag{A.5}$$

$$c_t^R = \xi_0^R + \xi_1^R \Delta L_t^R, \tag{A.6}$$

$$L_t^M = L_t^C + L_t^P + L_t^F, \tag{A.7}$$

$$L_{t+1}^M = L_t^M + \Delta L_t^U,\ L_0^M > 0, \tag{A.8}$$

Fossil Fuels

$$x_t^f = x_t^{f,n} + x_t^{f,e}, \tag{A.9}$$

$$c_t^f = \frac{c_T^f c_0^f e^{\kappa_f t}}{c_T^f + c_0^f \left(e^{\kappa_f t} - 1\right)},\ c_0^f > 0, \tag{A.10}$$

Agrochemical Sector

$$x_t^n = \theta^n x_t^{f,n}, \tag{A.11}$$

Agricultural Sector

$$x_t^{g,c} = x_t^{c,g} + x_t^{l,g} + x_t^{b,g}, \tag{A.12}$$

$$x_t^{g,i} = \frac{\theta_t^{g,i}}{\Pi_t} \left[\alpha^g \left(L_t^{C,i}\right)^{\rho_g} + (1-\alpha^g)\left(x_t^n\right)^{\rho_g}\right]^{\frac{1}{\rho_g}},\ i = b, c, \tag{A.13}$$

$$L_t^{C,i} = \frac{x_t^{g,i}}{\theta_t^{g,i}} \left(\frac{\alpha^g}{c_t^{C,i}}\right)^{\sigma_g} \left(\alpha^{\sigma_g} \left(c_t^{C,i}\right)^{1-\sigma_g} + (1-\alpha^g)^{\sigma_g} \left(c_t^f\right)^{1-\sigma_g}\right)^{\frac{\sigma_g}{1-\sigma_g}}, \tag{A.14}$$

$$c_t^{g,i} = \frac{1}{\theta_t^{g,i}} \left(\left(\alpha^g\right)^{\sigma_g} \left(c_t^{C,i}\right)^{1-\sigma_{g,i}} + (1-\alpha^g)^{\sigma_g} \left(c_t^f\right)^{1-\sigma_g}\right)^{\frac{1}{1-\sigma_g}}, \tag{A.15}$$

$$\theta_t^{g,c} = \frac{\theta_T^{g,c} \theta_0^{g,c} e^{\kappa_{g,c} t}}{\theta_T^{g,c} + \theta_0 \left(e^{\kappa_{g,c} t} - 1\right)}, \tag{A.16}$$

$$\theta_{t+1}^{g,b} = \theta_t^{g,b} + \kappa_{g,b},\ \theta_0^{g,b} > 0, \tag{A.17}$$

Livestock Farming Sector

$$x_t^l = \frac{\theta_t^l}{\Pi_t}\left[\alpha^l \left(L_t^P\right)^{\rho_l} + \left(1-\alpha^l\right)\left(\Pi_t x_t^{l,g}\right)^{\rho_l}\right]^{\frac{1}{\rho_l}}, \tag{A.18}$$

$$c_t^l = c_0^l x_t^l + \xi_0^l \left(\Delta L_t^P\right)^2, \tag{A.19}$$

Food Processing Sector

$$y_t^g = \theta_t^{g,y} x_t^{c,g}, \tag{A.20}$$

$$y_t^l = \theta_t^{l,y} x_t^l, \tag{A.21}$$

$$\theta_{t+1}^{i,y} = \kappa_{i,y}\theta_t^{i,y},\ \theta_0^{i,y} > 0,\ i = g, l, \tag{A.22}$$

Biofuels Sector

$$x_t^{b,1} = \theta_t^{b,1} x^{b,g} \tag{A.23}$$

$$x_t^{b,2} = \theta^{b,2}\left[\left(\alpha^b\right)^{\theta_t^\phi}(\phi)^{\rho_b} + \left(1-\alpha^b\right)\left(x_t^{g,b}\right)^{\rho_b}\right]^{\frac{1}{\rho b}} \tag{A.24}$$

$$\theta_{t+1}^\phi = \kappa_\phi \theta_t^\phi,\ \theta_0^\phi > 0 \tag{A.25}$$

Energy Sector

$$y_t^e = \theta_t^e \left(\alpha^e \left(x_t^{b,1}\right)^{\rho_e} + (1-\alpha^e)\left(\frac{x_t^{f,e}}{\Pi_t} + x_t^{b,2}\right)^{\rho_e}\right)^{\frac{1}{\rho e}}, \tag{A.26}$$

$$\theta_{t+1}^e = \kappa_e \theta_t^e,\ \theta_0^e > 0 \tag{A.27}$$

$$c_t^e = \sum_i c^{b,i} + c_t^f,\ i = 1, 2. \tag{A.28}$$

Forestry Sector

$$L_t^F = \sum_{v=1}^{v_{\max}} L_{v,t}^F, \tag{A.29}$$

$$L_{v+1,t+1}^F = L_{v,t}^F - \Delta L_{v,t}^{F,H},\ v < v_{\max} - 1, \tag{A.30}$$

$$L_{v_{\max},t+1}^F = L_{v_{\max},t}^F - \Delta L_{v_{\max},t}^{F,H} + L_{v_{\max}-1,t}^F - \Delta L_{v_{\max}-1,t}^{F,H}, \tag{A.31}$$

$$L_{1,t+1}^F = \Delta L_t^{F,P}, \tag{A.32}$$

$$x_t^w = \sum_{v=1}^{v_{\max}} \frac{\theta_{v,t}^w}{\Pi_t}\Delta L_{v,t}^{F,H}, \tag{A.33}$$

$$\theta_{v,t+1}^w = \theta_{v,t}^w + \kappa_v^w, \theta_{v,0}^w > 0 \tag{A.34}$$

$$c_t^w = \xi_0^w \sum\nolimits_v \theta_{v,0}^w \Delta L_{v,t}^{F.H} + \xi_1^w \left[\sum\nolimits_v \left(\Delta L_{v,t}^{F,H} - \Delta L_{v,t-1}^{F,H}\right)\right]^2 + \xi_2^w \left(\sum\nolimits_v \Delta L_{v,t}^{F.H} - \Delta L_t^{F,P}\right)^2, \tag{A.35}$$

Timber Processing Sector

$$y_t^w = \theta_t^{w,y} x_t^w, \tag{A.36}$$

$$\theta_{t+1}^{w,y} = \kappa_{w,y} \theta_t^{w,y},\ \theta_0^{w,y} > 0, \tag{A.37}$$

Ecosystem Services Sector

$$y_t^r = \frac{\theta^r}{\Pi_t} \left[\sum_{i=C,P,F} \alpha^{i,r} \left(L_t^i\right)^{\rho_r} + \left(1 - \sum_{i=C,P,F} \alpha^{i,r}\right) \left(L_t^U + \theta^R L_t^R\right)^{\rho_r} \right]^{\frac{1}{\rho_r}} \tag{A.38}$$

$$c_t^R = \frac{c_0^R,}{(1+\kappa_R)^t}\ c_0^R > 0 \tag{A.39}$$

Other Goods and Services Sector

$$\theta_{t+1}^o = \kappa_o \theta_t^o,\ \theta_0^o > 0 \tag{A.40}$$

GHG Emissions

$$z_t = \mu^{f,e} x_t^{f,e} + \mu^{f,n} x_t^{f,n} + z_t^L, \tag{A.41}$$

$$z_t^L = \mu^L \Delta L_t^U + \mu^P L_t^P + \mu^n x_t^n + \mu^l x_t^l + (1-\varphi) \sum_{v=1}^{v_{\max}} \mu_v^h \Delta L_{v,t}^{F,H} - \sum_{v=1}^{v_{\max}} \mu_v^w L_{v,t}^F. \tag{A.42}$$

$$z_t^L \leq \overline{z}_t^L = \theta_t^z \left(z_t^L - \left(1 - \frac{\mu^{b,i}}{\mu^x}\right) x_t^{b,i} \right),\ i = 1,2 \tag{A.43}$$

Preferences

$$p_q(q) = \frac{\alpha_q + \beta_q \exp(u)}{1+\exp(u)} \frac{y - \sum\limits_q p_q y^q.}{y^q - \underline{y}^q},\ 0 \leq \alpha_q, \beta_q \leq 1 \tag{A.44}$$

$$F(y^q, u) = \frac{\alpha_q + \beta_q \exp(u)}{1+\exp(u)} \ln\left(\frac{y^q - \underline{y}^q}{A\exp(u)}\right),\ 0 \leq \underline{q} < q \tag{A.45}$$

Welfare

$$\max_{g,l,e,w,r} \sum_{t=0}^{T-1} \delta^t \left[\begin{array}{c} \sum\limits_{q=g,l,e,w,r,o} \int_0^{y^{q*}} \left(p_q(y^q) - c_q(y^q)\right) dy^q \\ -c_t^U \left(\Delta L_t^U + \Delta L_t^R\right) - c_t^R \Delta L_t^R - c^n x_t^n \\ -\sum_i c^{g,i} x^{g,i}{}_t - c^l - c^p \Delta L_t^{F,P} - c_t^w \end{array} \right] + \delta^T \Gamma\left(L_T^U, L_T^F\right) \tag{A.46}$$

Table A.1: Model Exogenous Variables

Parameter	Description	Units
Exogenous Variables		
Π_t	Population	Billion People
c^e_t	Total Energy Costs	USD'1000 per toe
c^f_t	Fossil Fuels' Costs	USD'1000 per toe
$\theta^{g,i}_t$	Agricultural Yield of Crop i	tons per Ha
θ^f_t	Food Processing Technology Index	
θ^e_t	Energy Efficiency Index	
$\theta^w_{v,t}$	Merchantable Timber Yield	tons per Ha
c^w_t	Forest Harvesting Costs	tons per Ha
$\theta^{g,y}_t$	Timber Processing Technology Index	
c^R_t	Protected Lands' Management Costs	
θ^o_t	Total Factor Productivity Index	
y^o_t	Other Goods and Services	USD Trillion
μ^w_v	Carbon Sequestration by Forest Vintage v	tCO_2e per Ha
θ^z_t	Land-Use GHG Emissions Quota	$GtCO_2e$

Table A.2: Model Endogenous Variables

Parameter	Description	Units
$L_t^{C,i}$	Agricultural Land Area of Crop i	GHa
L_t^P	Pasture Land Area	GHa
L_t^F	Commercial Forest Land Area	GHa
L_t^U	Unmanaged Natural Lands	GHa
ΔL_t^U	Flow of Deforested Natural Lands per annum	GHa
L_t^R	Protected Natural Lands	GHa
ΔL_t^R	Flow of Protected Natural Lands per annum	GHa
$\Delta L_t^{F,P}$	Replanted Forest Land Area	GHa
$\Delta L_{v,t}^{F,H}$	Harvested Forest Land Area of Vintage v	GHa
$c_t^{C,i}$	Shadow Prices of Agricultural Areas	GHa
x_t^f	Fossil Fuels	Gtoe
$x_t^{f,e}$	Petroleum Combusted	Gtoe
$x_t^{f,n}$	Fossil Fuels Allocated to Fertilizers	Gtoe
x_t^n	Fertilizers Produced	Gton
$x_t^{g,i}$	Agricultural Output of Crop i	Gton
$x_t^{l,g}$	Animal Feed	Gton
x_t^l	Livestock Product	Gton
y_t^f	Services from Processed Grains	
y_t^l	Services from Processed Livestock	
$x_t^{b,i}$	First ($i = 1$) and Second ($i = 2$) Generation Biofuels	Gtoe
y_t^e	Energy Services	
x_t^w	Forest Product	Gton
y_t^w	Services from Processed Timber	
y_t^r	Eco-system Services	
z_t^L	GHG Emissions from Land Use	$GtCO_2e$
z_t	GHG Emissions	$GtCO_2e$

Table A.3: Baseline Parameters

Parameter	Description	Units	Value
Population			
Π_0	Population in 2004	Billion People	6.39
Π_T	Population in time T	Billion People	10.1
π	Logistic Population Growth Rate		0.042
Land Use			
$\overline{L}$	Total Land Area	Billion Ha	5.83
$L_0^{C,1}$	Area of Agricultural Land in 2004	Billion Ha	1.533
$L_0^{C,2}$	Area of Cellulosic Feedstocks in 2004	Billion Ha	0.0001
L_0^P	Area of Pasture Land in 2004	Billion Ha	2.73
L_0^F	Area of Commercial Forest Land in 2004	Billion Ha	1.62
L_0^U	Area of Unmanaged Natural Land in 2004	Billion Ha	2.47
L_0^R	Area of Protected Natural Land in 2004	Billion Ha	0.207
ξ_1^u	Natural Land Access Cost Function Parameter		0.264
ξ_2^u	Natural Land Access Cost Function Parameter		42,000
ξ_0^R	Protection Cost Function Parameter		5
ξ_1^R	Protection Cost Function Parameter		300
Fossil Fuels			
c_0^f	Oil Price in 2004	1000USD/toe	0.242
c_T^f	Oil Price in time T	1000USD/toe	1.84
κ_f	Logistic Oil Price Growth Rate		0.045
Agrochemical Sector			
c^n	Non-Energy Fertilizer Costs	1000USD/ton	0.137
x_0^n	Fertilizers' Consumption in 2004	Billion ton	0.937
θ_t^n	Fertilizer's Conversion rate	ton/toe	1.07
Agricultural Sector			
$\theta_0^{g,c}$	Food Crop Yield in 2004	tons / Ha	4.89
$\theta_T^{g,c}$	Food Crop Yield in time T	tons / Ha	9.29
$\kappa_{g,c}$	Logistic Food Crop Yield Growth Rate		0.025
$\theta_0^{g,b}$	Cellulosic Feedstocks Yield in 2004	tons / Ha	21.4
$\kappa_{g,b}$	Cellulosic Feedstocks Yield Growth Rate p.a.		0.115
$c^{g,b}$	Non Land Cost of Cellulosic Feedstocks	1000USD/ton	0.161

Table A.3: Baseline Parameters (continued)

Parameter	Description	Units	Value
a^g	Share of Agricultural Land in CES function		0.55
ρ_g	CES Parameter for Agricultural Land and Fertilizers		0.123
Livestock Farming Sector			
θ^l	Livestock Technology Index		0.69
a^l	Share of Pasture Land in CES function		0.35
ρ_l	CES Parameter for Pasture Land and Animal Feed		-0.33
c_0^l	Livestock Processing Cost	1000USD/ton	0.21
ξ_0^l	Adjustment Cost Function Parameter		300
Food Processing Sector			
$\theta_0^{g,y}$	Crop Processing Technology Index in 2004		1.5
$\kappa_{g,y}$	Crop Processing Technology Growth Rate p.a.		0.022
$c^{g,y}$	Crop Processing Cost	1000USD/ton	0.081
$\theta_0^{l,y}$	Livestock Processing Technology Index in 2004		1.7
$\kappa_{l,y}$	Livestock Processing Technology Growth Rate		0.022
$c^{l,y}$	Livestock Processing Cost	1000USD/ton	0.27
Biofuels Sector			
$\theta^{b,1}$	1G Biofuels' Conversion Rate	toe/ton	0.283
$c^{b,1}$	Non Land Cost of 1G Biofuels	1000USD/ton	0.442
$\theta^{b,2}$	2G Biofuels' CES Production Technology		0.467
$c^{b,2}$	Non Land Cost of 2G Biofuels	1000USD/ton	0.577
a^b	Share of Fixed Factor in CES function		0.4
ρ_b	CES Parameter for Cellulosic Feedstocks and Fixed Factor		-1.5
ϕ_0	Fixed Factor Endowment in 2004		0.05
κ^ϕ	Growth of Factor Specific Tech. Change p.a.		1.005
Energy Sector			
ρ_e	CES Parameter for Drop-in Fuels and 1G Biofuels		0.5
α^e	Share of 1G Biofuels in CES Function		0.09
θ_0^e	Energy Efficiency Index in 2004		1.195
κ_e	Energy Efficiency Growth Rate p.a.		0.016

Table A.3: Baseline Parameters (continued)

Parameter	Description	Units	Value
Forestry Sector			
ξ_0^w	Forest Harvesting Cost	1000USD/ton	0.019
ξ_1^w	Forest Harvesting Adjustment Cost	1000USD/Ha	150,000
ξ_2^w	Forest Conversion Adjustment Cost	1000USD/Ha	300
c^p	Forest Regeneration Cost	1000USD/Ha	0.036
κ_v^w	Yield Gains per annum of Vintage v	Share of Yield 0	0.011
ψ_1	Merchantable Timber Yield Parameter 1		5.75
ψ_2	Merchantable Timber Yield Parameter 2		75
$\overline{v}$	Minimum Age for Merchantable Timber	Years	11
Timber Processing Sector			
$\theta_0^{w,y}$	Timber Processing Technology Index in 2004		15.2
$\kappa_{w,y}$	Timber Processing Technology Growth Rate p.a.		0.022
$c^{w,y}$	Timber Processing Cost	1000USD/ton	1.74
Ecosystem Services Sector			
ρ_e	CES Parameter for Ecosystem Services		0.123
θ^r	Technology Parameter for Ecosystem Services		0.64
$\alpha^{C,r}$	Share of Agricultural Lands in CES Function		0.02
$\alpha^{P,r}$	Share of Pasture Lands in CES Function		0.14
$\alpha^{F,r}$	Share of Managed Forest Lands in CES Function		0.26
θ^R	Effectiveness of Protected Lands		10
κ_R	Decline in Costs of Managing Protected Lands p.a.		0.022
c_0^R	Cost of Managing Protected Land in 2004	1000USD/Ha	0.175
Other Goods and Services			
o_0	Output of Other Goods and Services in 2004	10000USD	0.95
θ_0^o	TFP in 2004		1
κ_o	TFP growth rate per annum		0.022
GHG Emissions			
μ^L	GHG Emissions from Natural Land Conversion	tCO_2e per Ha	515
μ^g	GHG Emissions from Fertilizers	tCO_2e per ton	4.066

Table A.3: Baseline Parameters (continued)

Parameter	Description	Units	Value
$\mu^{b,1}$	GHG Emissions from Combustion of 1G Biofuels	tCO_2e per toe	1.729
$\mu^{b,2}$	GHG Emissions from Combustion of 2G Biofuels	tCO_2e per toe	0.609
μ^{x}	GHG Emissions from Petroleum Combustion	tCO_2e per toe	2.902
μ^{P}	GHG Emissions from Manure on Pasture Land	tCO_2e per Ha	0.208
μ^{l}	GHG Emissions from Livestock	tCO_2e per ton	4.641
$\overline{\mu}^{w}$	Forest Carbon Stocking Density	MgC per m^3	1.1
φ	Share of Stored Carbon in Harvested Forest Products		0.3
Preferences and Welfare Parameters			
α_g	AIDADS Marginal Budget Share at Subsistence Income for Processed Grain Products		0.21
α_l	AIDADS Marginal Budget Share at Subsistence Income for Processed Livestock Products		0.14
α_e	AIDADS Marginal Budget Share at Subsistence Income for Energy Services		0.11
α_w	AIDADS Marginal Budget Share at Subsistence Income for Processed Timber Products		0.03
α_r	AIDADS Marginal Budget Share at Subsistence Income for Ecosystem Services		0.02
α_o	AIDADS Marginal Budget Share at Subsistence Income for Other Goods and Services		0.49
β_g	AIDADS Marginal Budget Share at High Income for Processed Grain Products		0.03
β_l	AIDADS Marginal Budget Share at High Income for Processed Livestock Products		0.04
β_e	AIDADS Marginal Budget Share at High Income for Energy Services		0.05
β_w	AIDADS Marginal Budget Share at High Income for Processed Timber Products		0.02
β_r	AIDADS Marginal Budget Share at High Income for Ecosystem Services		0.05
β_o	AIDADS Marginal Budget Share at High Income for Other Goods and Services		0.81

Table A.3: Baseline Parameters (continued)

Parameter	Description	Units	Value
$\underline{y}^g$	AIDADS Subsistence Parameter for Processed Grain Products		0.33
$\underline{y}^l$	AIDADS Subsistence Parameter for Processed Livestock Products		0.003
$\underline{y}^e$	AIDADS Subsistence Parameter for Energy Services		0.03
$\underline{y}^w$	AIDADS Subsistence Parameter for Processed Timber Products		0.03
$\underline{y}^r$	AIDADS Subsistence Parameter for Ecosystem Services		0.03
$\underline{y}^o$	AIDADS Subsistence Parameter For Other Goods and Services		0.35
A	AIDADS Utility Function parameter		1
δ	Social Discount Rate		0.015
ϖ_1	Scrap Price of Unmanaged Forests		50
ϖ_2	Scrap Price of Commercial Forests		10
δ	Social Discount Rate		0.015

Table A.4: Parameter Changes in Model Sensitivity Analysis

Parameter	Description	Baseline Value	New Value
ξ_2^u	Natural Land Access Cost Function Parameter	42,000	28,000
σ_g	Elasticity of Substitution between Land and Fertilizers	1.14	1.71
$\theta^{b,2}$	2G Biofuels' Conversion Technology	0.467	0.71
κ_ϕ	Factor Specific Tech. Change Growth p.a.	1.005	1.0075
κ_e	Energy Efficiency Growth Rate p.a.	0.016	0.011
α_e	AIDADS Marginal Budget Share at Subsistence Income for Energy Services	0.11	0.165
β_e	AIDADS Marginal Budget Share at High Income for Energy Services	0.05	0.075