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 and forest products, increasing non-market demands for ecosystem services, and more stringent 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

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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 use 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 non-market demands for ecosystem services, and more stringent 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]

[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

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 model preferences, and, as society becomes wealthier, places greater value 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 eight sectors producing intermediate and final goods and services. The agrochemical sector converts fossil fuels into fertilizers that are used

policies, efficiency implications of carbon taxes and caps, and endogenous depletion of non-renewable 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).

to boost yields in the agricultural sector. The agricultural sector combines cropland and fertilizers to produce intermediate outputs (food crops and cellulosic feed stocks) that can be used to produce food or biofuels. The food processing sector converts food crops into food products that are used to meet the global food demand. The biofuels sector converts food crops and cellulosic feedstocks into liquid fuels, which substitute imperfectly 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.

2.1 Resource Use

2.1.1 Land

The total land endowment in the model, $\overline{L}$, is fixed, so that the per-capita land endowment, L_t, declines with increases in population. The land in the economy comprises of 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, both of which are expressed in per capita terms. The per-capita land endowment constraint is

$$L_t = \frac{\overline{L}}{\Pi_t} = L_t^N + L_t^M, \tag{1}$$

where Π_t is the predetermined population at time t. Based on 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.

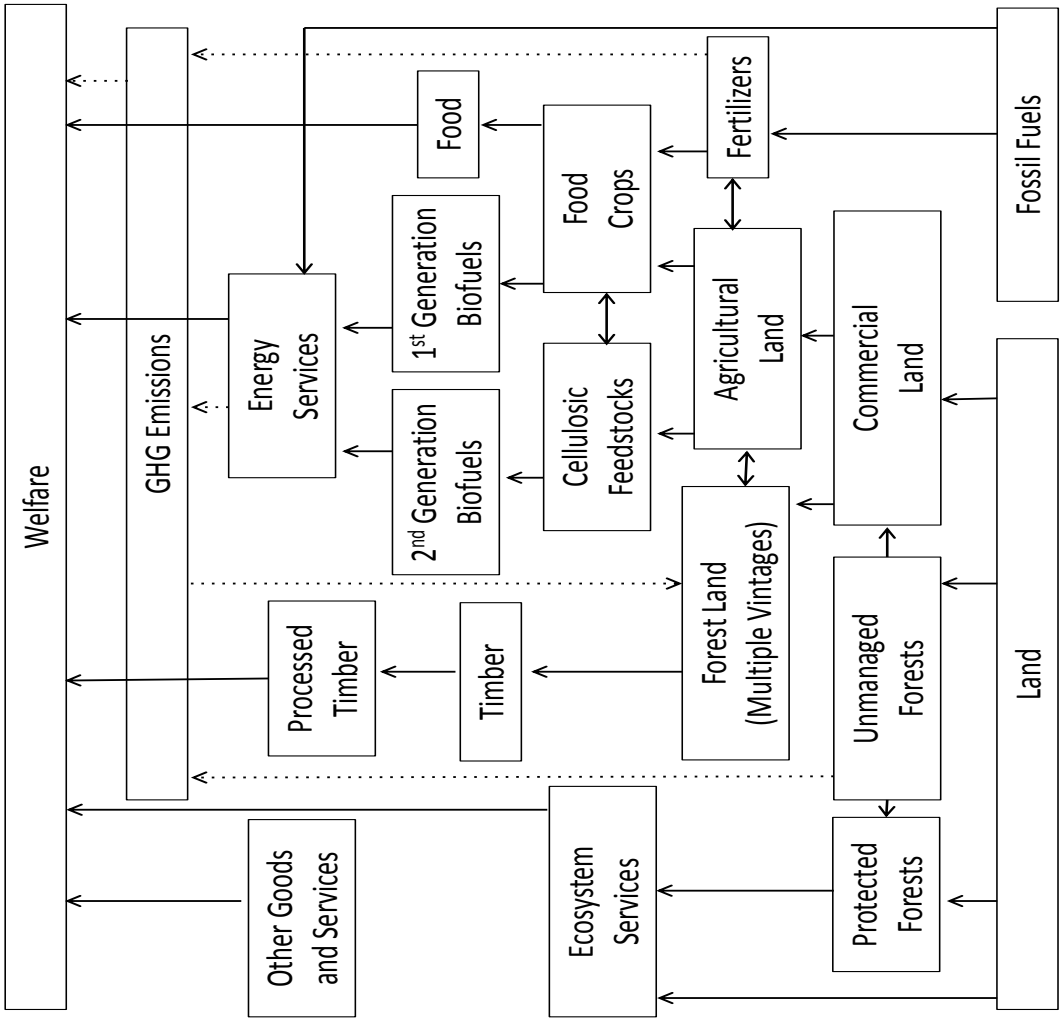

Figure 1: Structure of the Economy

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 as follows, where lower case variables describe flows and upper cases correspond to stocks, and all variables are expressed on a per capita basis:

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

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

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 reserved and non-reserved 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 reserved land entails additional costs, c_t^R, associated with passing legislation to create new natural parks. We assume that these costs are continuous, monotonically increasing, and strictly convex functions of the share of natural land previously accessed. There are no additional costs of natural land conversion to commercial land, as these costs are offset by the revenues from deforestation.

[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 (Nesshöver 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.

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 allocation of commercial land across time and between agriculture and forestry are:

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

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

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

The cost of fossil fuels, c_t^x, 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, denoted by x^n, and converts them into fertilizers that are further used in the agricultural sector. The production of fertilizers, n, is a simple engineering process that can be described by a linear production function:

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

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^ϕ, is constant and scale-invariant.

2.3 Agricultural Sector

The agricultural sector combines the agricultural land and fertilizers to deliver an agricultural products, g^i. In the model, we distinguish between two types of agricultural outputs. Food crops, g^1, can be either consumed as food, f, or converted to first generation biofuels, b^1. Cellulosic feed stocks, g^2, can only be converted to second generation biofuels, b^2. Agricultural land and fertilizers are imperfect substitutes in the production of agricultural products. The output of agricultural products, g^i, is thus determined by the constant elasticity of substitution (CES) function:

$$g_t^i = \theta_t^{g,i} \left[\alpha^g \left(L_t^{A,i} \right)^{\rho_g} + (1 - \alpha^g) (n_t)^{\rho_g} \right]^{\frac{1}{\rho_g}}, \; i = 1, 2, \tag{9}$$

where θ_t^g and α^g are, respectively, the yield of agricultural land and the value share of land in production of agricultural product at the benchmark time 0, and $L_t^{A,i}$ 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 additional costs from use of other production factors (such as e.g. labor or capital), the prices of which are predetermined in our partial equilibrium model. We assume that those costs per ton of agricultural product, c^g, are exogenous and scale-invariant.

2.4 Food Processing Sector

The food processing sector converts an amount of food crops, g^1, into food products and services, f, 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

[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.

following production function:

$$f_t = \theta_t^f g_t^1, \tag{10}$$

where θ_t^f is the total factor productivity (TFP) of the food processing sector, which captures the technological progress in both direct transformation of agricultural product into edible food, and the storage, transportation, and distribution of processed food. We assume that the food processing costs per ton of food products, c^f, are exogenous and scale-invariant.

2.5 Biofuels Sector

The biofuels sector consumes the remaining amount of food crops to produce first generation biofuels, b^1. We assume that a ton of food crops, g^1, 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

$$b_t^1 = \theta^{b,1}\left(g_t^1 - \frac{f_t}{\theta^f}\right). \tag{11}$$

The biofuels sector also converts cellulosic feedstocks, g^2, into second generation biofuels, 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 progress, θ_t^ϕ (Acemoglu 1998, van Meijl and van Tongeren 1999). Under this assumptions the production of second generation biofuels, b^2, is determined by the following

CES function

$$b_t^2 = \theta^{b,2} \left[\left(\alpha^b\right)^{\theta_t^\phi} (\phi)^{\rho_b} + \left(1-\alpha^b\right) \left(g_t^2\right)^{\rho_b} \right]^{\frac{1}{\rho b}}, \tag{12}$$

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]

2.6 Energy Sector

The energy sector consumes petroleum products, x^e, and first and second generation biofuels, 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 production of energy services, e_t, is given by CES function:

$$e_t = \theta_t^e \left(\alpha^e \left(b_t^1\right)^{\rho_e} + (1-\alpha^e) \left(x_t^e + b_t^2\right)^{\rho_e} \right)^{\frac{1}{\rho e}}, \tag{13}$$

where the parameter θ^e describes 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

[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 technical appendix, section E.1.

[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.

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.

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

$$c_t^e = \sum_i c^{b,i} + c_t^x, \; i = 1, 2. \tag{14}$$

2.7 Forestry Sector

The forestry sector is characterized by v vintages of trees. At the end of period t each hectare of managed forest land, $L_{v,t}^C$, has an average density of tree vintage age v, with the initial allocation given and denoted by $L_{v,0}^C$. Each period of time the managed forest land can be either planted, harvested or simply left to mature. The newly planted trees occupy $\Delta L^{C,P}$ hectares of land, and reach the average age of the first tree vintage next period. The harvested area occupies $\Delta L_v^{C,H}$ hectares of forest land. If the managed forest land is harvested, it yields θ_v^w tons of forest product (raw timber), w_v, where θ_v^w 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 $\theta_{v_{\max}}^w$. They do not grow further and stay until harvested. In addition, conversion of natural forest land to commercial land (deforestation) yields timber benefits. We assume that natural forest lands are occupied by old trees, so deforested area, ΔL^U, yields $\theta_{v_{\max}}^w$ tons of timber.

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 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 planting costs per hectare of newly forest planted, c^p, are invariant to scale and are the same across all vintages.

The following equations describe the forestry sector:

$$L_t^C = \sum_{v=1}^{v_{\max}} L_{v,t}^C, \tag{15}$$

$$\begin{aligned} L_{v+1,t+1}^C &= L_{v,t}^C - \Delta L_{v,t}^{C,H},\ v < v_{\max} - 1 && (16)\\ L_{v_{\max},t+1}^C &= L_{v_{\max},t}^C - \Delta L_{v_{\max},t}^{C,H} + L_{v_{\max}-1,t}^C - \Delta L_{v_{\max}-1,t}^{C,H} && (17)\\ L_{1,t+1}^C &= \Delta L_t^{C,P}, && (18) \end{aligned}$$

and

$$w_t = \sum_{v=1}^{v_{\max}-1} \theta_{v,t}^w \Delta L_{v,t}^{C,H} + \theta_{v_{\max},t}^w \left(\Delta L_{v_{\max},t}^{C,H} + \Delta L_t^U \right), \tag{19}$$

Equation (15) describes the composition of managed forest area across forest vintages. Equation (16) illustrates the harvesting dynamics of forest areas with the average ages v and $v_{\max}$. Equation (18) shows the transition from planted area, $\Delta L_t^{C,P}$, to new forest vintage area. Equation (19) describes the output of forest product from harvested forest areas of average tree age v and deforested natural lands.

2.8 Timber Processing Sector

The timber processing sector converts harvested forest product, w, into processed timber products, s, 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:

$$s_t = \theta_t^s w_t, \tag{20}$$

where θ^s is the TFP of the timber processing sector, 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^s, are exoge-

[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.

nous and scale-invariant.

2.9 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 output for ecosystem services, r_t, is given by the following CES function of different land inputs:

$$r_t = \theta^r \left[\alpha^{A,r} \left(L_t^A\right)^{\rho_r} + \alpha^{C,r} \left(L_t^C\right)^{\rho_r} + \left(1 - \alpha^{A,r} - \alpha^{C,r}\right) \left(L^U + \theta_t^R L_t^R\right)^{\rho_r} \right]^{\frac{1}{\rho r}}. \tag{21}$$

where the parameter θ^r describes the production "technology" of ecosystem services[7]. The parameters $\alpha^{A,r}$, $\alpha^{C,r}$, and $1 - \alpha^{A,r} - \alpha^{C,r}$ are the value shares of agricultural, managed, and natural 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

[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.

of land in production of ecosystem services, σ_e. By characterizing the production process of ecosystem services using equation (21) 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, 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).

We assume that 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^r, is exogenous and scale-invariant.

2.10 Other Goods and Services

The production of other goods and services, o_t, 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 TFP growth, which is 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.

2.11 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 fertilizers in agricultural production, and (d) 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

[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.

for fossil fuels is pre-determined, whereas the other sources of GHG emissions are endogenous.

We assume that GHG emissions 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 μ^x tons of CO_2 equivalent (tCO_2e). A ton of fertilizer applied to agricultural land emits μ^n tCO_2e.

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. The conversion of natural forest land to commercial land entails emissions of μ^L tCO_2e per hectare of land deforested. 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

$$z_t = \mu^x x_t^e + z_t^L, \tag{22}$$

and

$$z_t^L = \mu^L \Delta L_t^U + \mu^n x_t^n + (1-\varphi)\sum_{v=1}^{V} \mu_v^h \Delta L_{v,t}^{C,H} - \sum_{v=1}^{V} \mu_v^w L_{v,t}^C. \tag{23}$$

Equation (22) describes the composition of GHG emissions flows. Equation (23) shows net GHG emissions from deforestation, agricultural 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

$$z_t^L \leq \overline{z}_t^L = \theta_t^z \left(z_t^L - \left(1 - \frac{\mu^{b,i}}{\mu^x}\right) b_t^i \right), i = 1, 2. \tag{24}$$

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 (24) describes the constraint on non-fossil fuel emissions in the atmosphere, and shows how this constraint is derived.

2.12 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

[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).

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):

$$\sum_{q=f,e,w,r,o} F(q,u) = 1, \tag{25}$$

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

$$F(q,u) = \frac{\alpha_q + \beta_q \exp(u)}{1+\exp(u)} \ln\left(\frac{q-\overline{q}}{A\exp(u)}\right). \tag{26}$$

In equation (26) the parameters α_q and β_q define the varying marginal budget shares of goods and services q in the consumers' total real expenditures. The parameter $\overline{q}$ defines the subsistence level of consumption of goods and services q. The functional form of $F(q,u)$ implies that the consumption of goods and services q is always greater than their subsistence levels, $\overline{q}$. The parameter A affects the curvature of the transformation function $F(q,u)$. 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 $\overline{q}$ 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 (25) subject to the budget identity constraint (26) yields the following system of inverse demand equations:

$$p_q(q) = \frac{\alpha_q + \beta_q \exp(u)}{1+\exp(u)} \frac{y - \sum_q p_q q}{q-\overline{q}}, \tag{27}$$

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

2.13 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 agricultural output, 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 product and timber production, and the scarce fossil fuels and reserved natural forest land to solve the following problem:

$$\max_{f,e,s,r} \Omega = \sum_{t=0}^{T-1} \delta^t \left[\begin{array}{c} \sum\limits_{q=f,e,s,r,o} \int_0^{q^*} \left(p_q\left(q\right) - c_q\left(q\right)\right) dq \\ -c_t^N \Delta L_t^N - c_t^R - c^n n_t - c^g g_t - c^p \Delta L_t^{C,P} - c_t^w \end{array} \right] + \delta^T \Gamma \left(L_T^U, L_T^C\right) \tag{28}$$

s.t. constraints (1)-(27), where Γ is the scrap value function. In technical appendix, section C.1, we discuss the parameter values of scrap value function.

3 Construction of Baseline

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's (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

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

et al. 2009). The values of baseline parameters are summarized in Table A.2 and Figure 2.

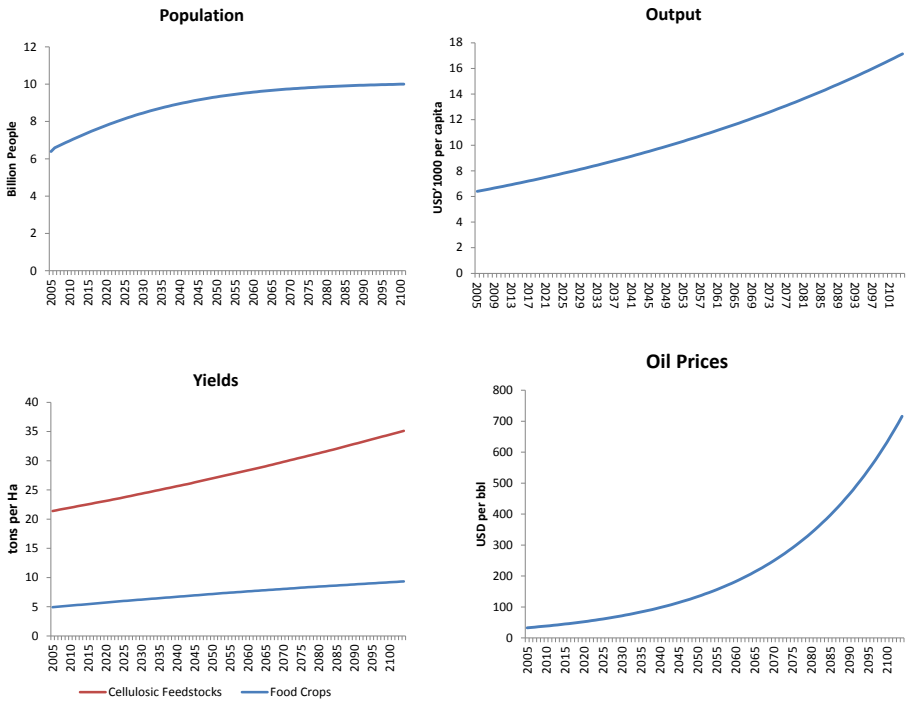

Figure 2: Projections of Exogenous Variables, 2005-2104

3.1 Population

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

$$\Pi_t = \frac{\Pi_T \Pi_0 e^{\pi t}}{\Pi_T + \Pi_0 \left(e^{\pi t} - 1\right)}, \tag{29}$$

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 De-

partment of Economic and Social Affairs Population Division (2011). The logistic growth rate of population is calibrated to match United Nations Department of Economic and Social Affairs Population Division's (2011) demographic projections.

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 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:

$$c_{t+1}^N = \xi_0^N - \xi_1^N \ln\left(\frac{L_{t+1}^N}{L_0^N}\right) + \xi_2^u \left(\frac{\Delta L_t^N}{L_t^N}\right)^2. \tag{30}$$

In equation (30), the parameter ξ_0^N refers to the access costs at time 0, implied by the starting 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

$$c_t^R = \xi_0^R + \xi_1^R \left(\Delta L_t^R\right)^2. \tag{31}$$

In equation (31), 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. The parameter values defining natural land access cost function (30), and natural land protection cost function (31) are calibrated based on

FAO (2010) data to match deforestation rates in 2004 and ensure stable rates of natural land access and protection.

3.3 Fossil Fuels

The primary fossil fuels linked to the economic analysis of land use are petroleum products and the 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 the fertilizers' production. As petroleum products' and the 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. We assume that the cost of fossil fuels is described by the following equation:

$$c^x_{t+1} = \kappa_x c^x_t, \; c^x_0 > 0, \tag{32}$$

where the parameters c^x_0 and κ_x reflect the initial costs and annual growth rate in costs of liquid fossil fuels. We obtain the initial values and the rate of change in oil prices from the U.S. Energy Information Administration reference case scenario for 2035 projections (EIA 2010a, p. 86, Table 10).

3.4 Agrochemical Sector

There are three types of fertilizer used in agricultural production: nitrogen fertilizers, phosphate fertilizers, and potash fertilizers. In our model we consider the nitrogen fertilizers. These fertilizers are particularly important in the climate policy debate, because their production is the most energy- and GHG-intensive.[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

[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/`.

does not vary much across time because fossil fuels' and nitrogen fertilizers' prices are highly correlated and follow the same trend (USGAO 2003).

3.5 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.'s (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.

The agricultural yield 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 et al. 2010) we assume that agricultural yields of both food crops and cellulosic feedstocks grows linearly, adding constant amount of gain per annum:

$$\theta_{t+1}^{g,i} = \theta_t^{g,i} + \kappa_{g,i},\ \theta_0^{g,i} > 0, i = 1, 2 \tag{33}$$

where the parameters $\theta_0^{g,i}$ and $\kappa_{g,i}$ corresponds to the initial level and growth rate in agricultural yields of food crops and 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 non-land costs for food crops and cellulosic feedstocks from GTAP v.7 database. We obtain the parameters for cellulosic feedstocks (*miscanthus giganteus)* from Taheripour and Tyner (2011).

We account for potential impact of climate change on the growth rate of agricultural yields. For food crops, we use Lobell et al.'s (2011) finding that a 1°C rise can lower yields by up to 10%.[17] Following the IPCC's A1B climate change scenario we assume that the global average surface temperature rises linearly by 2.8°C by 2100 (IPCC 2007, Table SPM.3, p.13.). Thus, compared to the baseline scenario, agricultural yield growth of food crops is expected to decline by 28% in 2100. We annualize the decline by assuming that agricultural

[17] Lobell et al. (2011) note that these results are not appropriate for high latitude countries, where in particular rice gains from warming.

yield growth rate of food crops relative to 2005 declines by 10% in 2025, by 20% in 2065, and by 25% in 2085. In contrast, with second generation biofuels feed stocks, higher temperatures favor overall biomass development and yields increase strongly under scenario A (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.

3.6 Food Processing Sector

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

$$\theta^f_{t+1} = \kappa_f \theta^f_t, \ \theta^f_0 > 0, \tag{34}$$

where the parameters θ^f_0 and κ_f reflect the initial level and annual growth rate in the TFP of the food processing sector. We calculate the TFP of the food processing sector in 2004 using GTAP v.7 data, by dividing the output of processed grains and crops (GTAP sectors 21, 23-25) by the output of agricultural product (GTAP sectors 1-8). We set the growth rate of the TFP in the food processing sector to growth rate of the economy's TFP. We obtain the 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.17) 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 fol-

lowing equation:

$$\theta^{\phi}_{t+1} = \kappa_{\phi}\theta^{\phi}_{t},\ \theta^{\phi}_{0} > 0. \tag{35}$$

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's (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:

$$\theta^{e}_{t+1} = \kappa_{e}\theta^{e}_{t},\ \theta^{e}_{0} > 0, \tag{36}$$

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:

$$\begin{aligned} \theta_v^w &= \exp\left(\psi_1 - \frac{\psi_2}{v - \overline{v}}\right), \text{ if } v > \overline{v} \\ \theta_v^w &= 0, \qquad\qquad\qquad\qquad \text{if } v \leq \overline{v}. \end{aligned} \tag{37}$$

In equation (37),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 (37) 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:

$$\theta_{v,t+1}^w = \theta_{v,t}^w + \kappa_v^w, \theta_{v,0}^w > 0, \tag{38}$$

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

$$c_t^w = \xi_0^w \sum\nolimits_v \frac{\Delta L_{v,t}^{C.H}}{\theta_{v,t}^w} + \xi_1^w \left[\sum\nolimits_v \left(\Delta L_{v,t+1}^{C,H} - \Delta L_{v,t}^{C,H}\right)\right]^2 + \xi_2^w \left(\sum\nolimits_v \Delta L_{v,t}^{C.H} - \Delta L_t^{C,P}\right)^2, \tag{39}$$

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:

$$\theta_{t+1}^s = \kappa_s \theta_t^s, \ \theta_0^s > 0, \tag{40}$$

where the parameters θ_0^s and κ_s reflect the initial level and annual growth rate in the TFP of the timber processing sector. We calculate the TFP 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 TFP in the timber processing sector 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 A.31 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. We characterize the growth of productivity in managing protected natural areas by the following equation:

$$\theta_{t+1}^R = \kappa_R \theta_t^R, \ \theta_0^R > 0, \tag{41}$$

where the parameters θ_0^R and κ_R reflect the initial level and annual growth rate in the productivity in managing protected natural areas. We set the initial level of the productivity in managing protected natural areas based on Benayas et al. (2009), and its growth rate equal to the economy's TFP. Following Antoine et al. (2008), we use the GTAP v.7 database to construct outdoor recreation sector, which comprises of hunting and fishing, wildlife viewing in reserves, and other wildlife viewing activities. 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.

[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.

3.12 Other Goods and Services

The growth of TFP is described by the following equation:

$$\theta^o_{t+1} = \kappa_o \theta^o_t,\ \theta^o_0 > 0, \tag{42}$$

where the parameters θ^o_0 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's (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[19]. The GHG emission coefficient from production of ammonia from fossil fuels comes from IPCC's (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's (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 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 lifecycle 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

[19] See `http://www.eia.doe.gov/oiaf/1605/coefficients.html#tbl3`, last checked in April, 2011.

stock per hectare of harvested forest vintage v, μ_v^h, is given by:

$$\mu_v^h = \overline{\mu}^w \exp\left(\psi_1 - \frac{\psi_2}{v}\right). \tag{43}$$

In equation (43) 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 (37).[20] Then the amount of GHG sequestered by a hectare of forest land of tree vintage v is

$$\mu_v^w = \mu_v^h - \mu_{v-1}^h. \tag{44}$$

We obtain the carbon conversion factor and yield function (37) 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 (26) 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.[21] We parameterize the scrap value function as

$$\Gamma\left(N_T^N, W_T\right) = \varpi_1 L_T^U + \varpi_2 \sum_{v=1}^{V} \frac{L_{v,T}^C}{\delta^{T-v}}, \quad (\varpi_1 > 0, \varpi_2 > 0), \tag{45}$$

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

[20] Note that the minimum age parameter, $\overline{v}$, is not included in equation (44). This is because at young ages, stands may have substantial carbon, but little merchantable timber (Sohngen et al. 2009b).

[21] 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`

natural lands are not depleted over 50 percent of their initial amount during the time horizon of the problem.[22]

4 Model Baseline

This section describes the results of simulations 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.

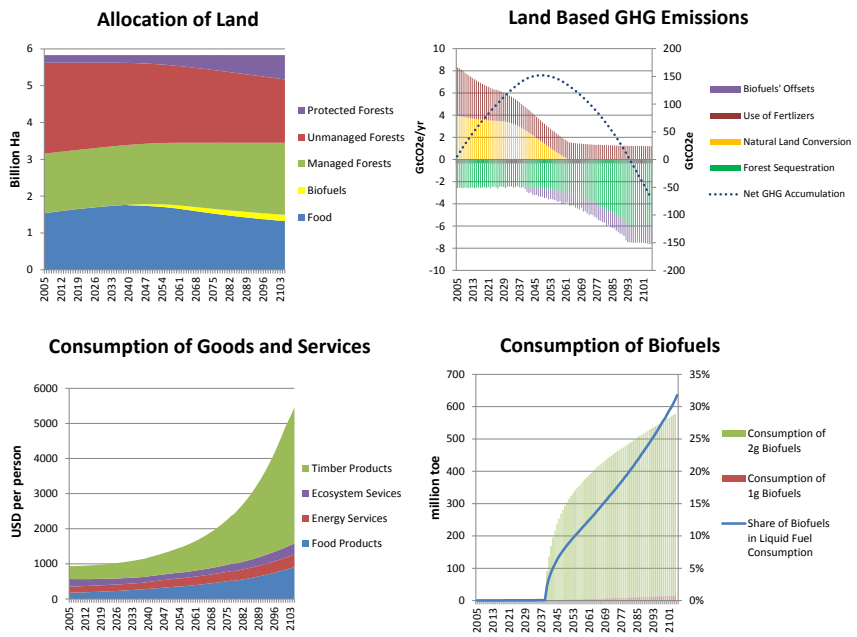

Figure 3: Model Baseline

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 increases by 14 percent compared to 2004, reaching its maximum of 1.75 billion hectares in 2040. Managed forest area remains practically unchanged at 1.63 billion hectares (1 percent larger compared to 2004). Changes in areas dedicated to biofuels feedstocks and protected

[22] 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.

natural forests remain insignificant. By mid-century, slower population growth, rising real income, agricultural yields, and improvements in food processing, storage and transportation technologies result in a decline in demand for food crops and an increase in demand for managed forests. By 2100 cropland area declines to 1.35 billion hectares, or 12 percent lower than 2004. Managed forest area increases to 1.93 billion hectares, which is 19 percent larger than 2004. Growing energy prices result in significant growth in the land area dedicated to biofuels, which reaches 0.17 billion hectares by 2100. 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 sharply to 0.62 billion hectares (about 3 times compared to 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.[23] Positive bars in this panel denote emissions, whereas negative bars denote GHG abatement 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 3.5 $GtCO_2e$/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. In 2050 GHG emissions from deforestation decrease by 64 percent compared to 2004, and amount to 1.43 $GtCO_2e$/yr. They cease entirely by mid 2060s along this optimal global path of land use. GHG emissions from application of fertilizers decline steadily as prices of natural gas increase and pressure on croplands diminishes in the face of slowing global population growth and improving crop technology. In 2100 annual flows of GHG emissions from use of fertilizers amount to 1.22 $GtCO_2e$/yr, which is 72 percent smaller than 2004. GHG emissions sequestration from managed forests does not change significantly by mid-century. In the long term the amount of sequestered GHG emissions increases with the growth in managed forest area. In 2100 sequestered GHG emissions amount to 6 $GtCO_2e$/yr, which is about 2 times larger 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

[23] 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. These emissions are reported separately in technical appendix, tables D.1 and D.2.

offsets account for 1.55 $GtCO_2e$/yr. Overall, accumulation of land based GHG emissions flows increases in the first part of this century, reaching its maximum of 150 $GtCO_2e$ around 2050. It then declines in the second part of the century, turning negative around 2095, and abating 40 $GtCO_2e$ by 2100. As explained above, higher oil prices, expansion of biofuels, declining deforestation, and forest growth are the main reasons for rising GHG abatement 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 all goods and services increases in absolute terms. The growth in per capita consumption is fueled by productivity growth across the board, while population growth declines over the baseline. In 2100 the per capita consumption of services from processed food, energy, processed timber, and ecosystems is considerably higher compared to their levels in 2004. Of course, this does not translate into an equivalent increase in consumption of the bulk agriculture and timber products. Rather most of this rise in real consumption is due to efficiency gains in the processing sectors, as well as increases in the use of non-primary inputs in the production process.

The lower right-hand panel of Figure 3 describes the results for consumption of biofuels.[24] The consumption of first generation biofuels grows slowly as oil 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 14 Mtoe, considerably higher than in 2004, but still small in relative terms. Second generation biofuels become competitive around 2040 and rapidly expand reaching 300 million toe in 2050, and 550 million toe in 2100. The share of biofuels in total liquid fuel consumption accounts for 8.5 percent in 2050, and for 29 percent in 2100. This baseline result is of comparable magnitude to findings in recent economic studies on bioenergy and land use (Gurgel et al. 2007, Chakravorty et al. 2011, Popp et al. 2011).[25]

[24] 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 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.

[25] Direct comparison of model predictions of biofuels penetration is difficult due to consider-

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.3 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. Greater ease of natural land conversion results in a decline in unmanaged forest land, which decreases by 85 million Ha in 2100. Agricultural land dedicated to food crops expands in near decades 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 30 $GtCO_2e$ in the medium term, and declines slightly thereafter. The consumption of all land-based goods and services, and biofuels increase in the long term.

able uncertainty in variety of factors, such as, e.g., evolution of biofuels' production technologies, land access costs, yield growth rates, and energy demand projections. We show model sensitivity to these factors in counterfactual simulations below, and in technical appendix, section E.1.

[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.

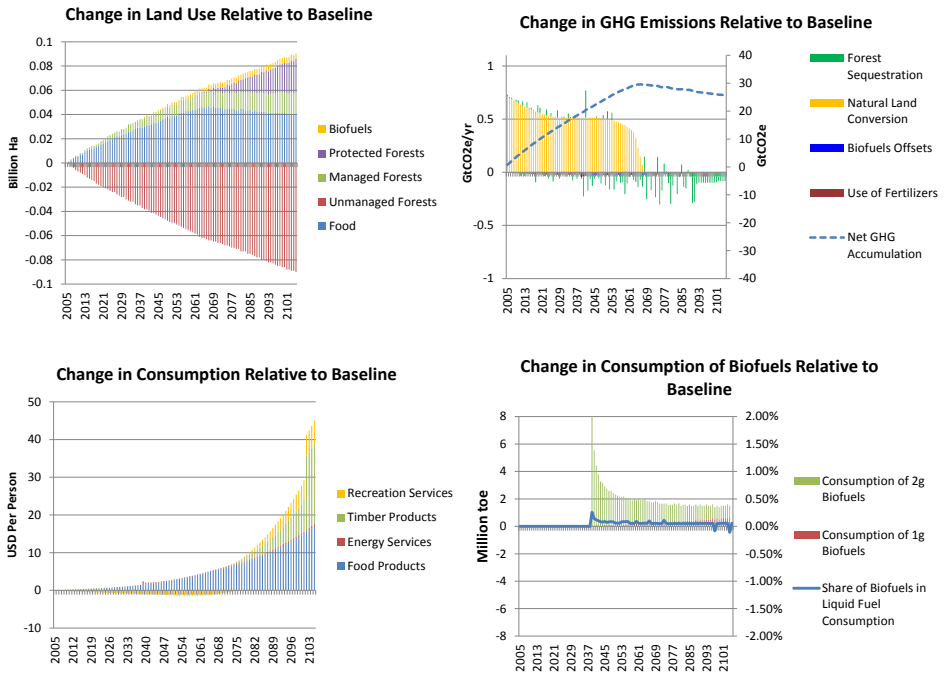

Figure 4: Sensitivity Analysis: 50% Decline in Short Term Adjustment Costs of Natural Land Conversion

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 other land 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 in near decades and the medium- term, and net GHG accumulation increases by 26 $GtCO_2e$ in 2060. In the long term, the effect of the decline in fertilizers' use becomes more significant, and net GHG accumulation declines slightly to reach 24 $GtCO_2e$ in 2100. The consumption of food products and services increases, and the consumption of timber products and recreation services declines. There is a small increase in the consumption of biofuels.

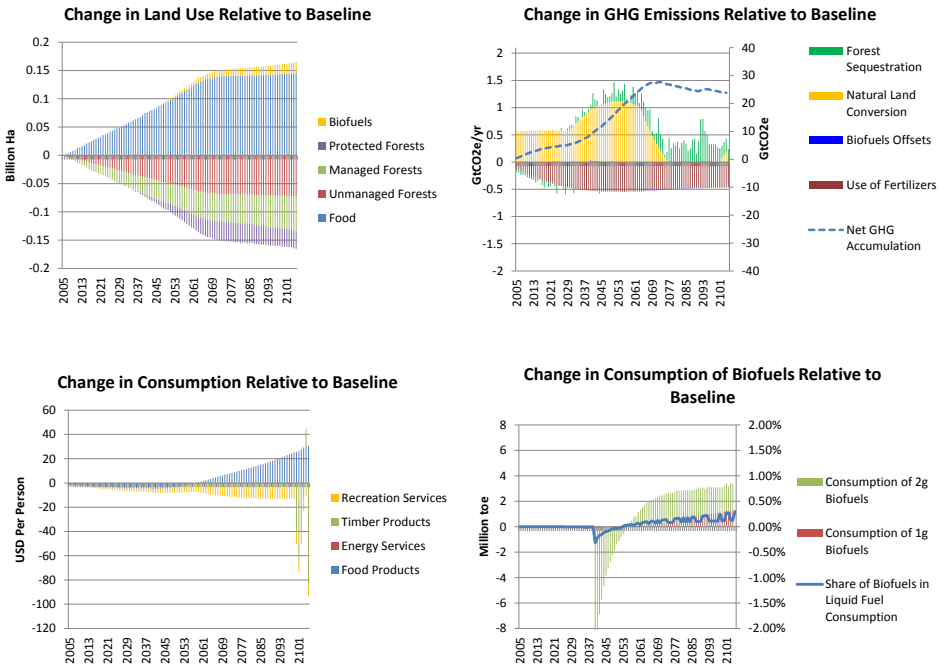

Figure 5: Sensitivity Analysis: 50% Increase in Elasticity of Substitution between Agricultural Land and Fertilizers

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. After arrival of second generation biofuels, their production increases by 300 million toe, and the biofuels share in liquid fuel production increases to reach 44% in 2100. Agricultural area dedicated to cellulosic feedstocks increases by additional 32 million Ha in 2100, whereas areas dedicated to food crops and natural forests decline. GHG flows increase with the additional conversion of natural lands, and 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.

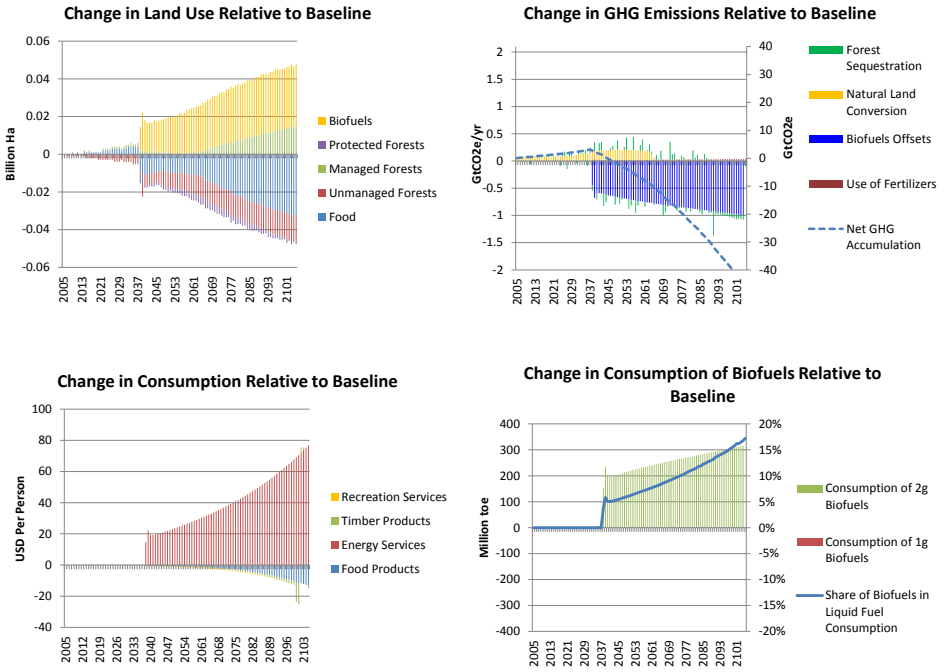

Figure 6: Sensitivity Analysis: 50% Increase in Biofuels' Conversion Rate

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 160 million toe, and the biofuels share in liquid fuel production increases to reach 37% in 2100. Agricultural area dedicated to cellulosic feedstocks increases by additional 45 million Ha in 2100, whereas areas dedicated to food crops and

natural forests decline. GHG flows increase with the additional conversion of natural lands, and decline with biofuels' offsets. The former effect dominates in the long run, and net GHG accumulation increases by 8 $GtCO_2e$ in 2100. The consumption of energy services increases, and the consumption of food and ecosystem services declines.

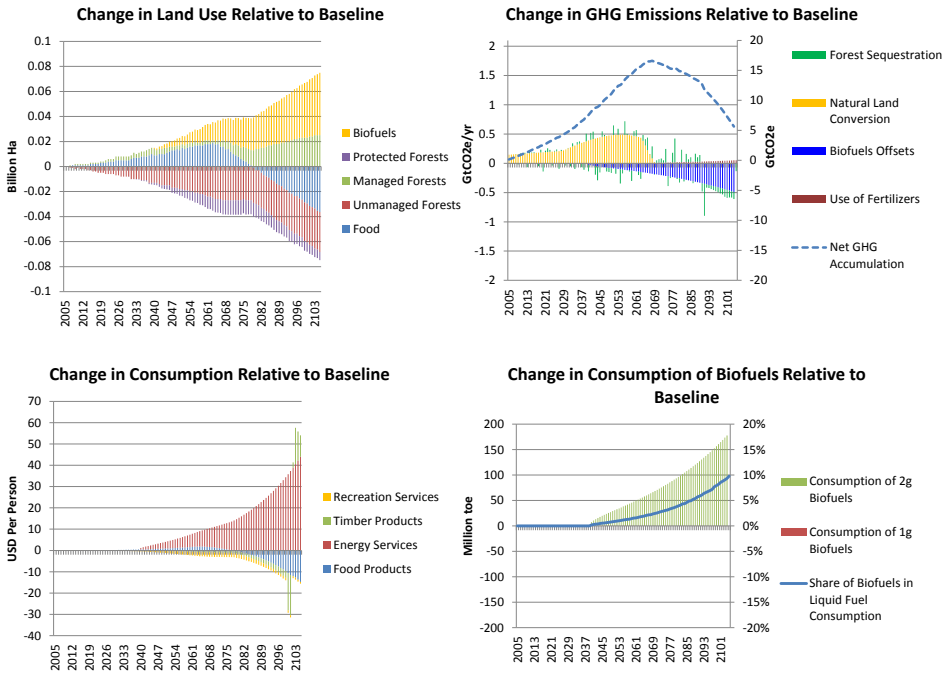

Figure 7: Sensitivity Analysis: 50% Increase in Fixed Factor Specific Technological Change

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 food crops and biofuels feedstocks add 21 and 12 million Ha, whereas managed and protected forest areas decline by 54 and 11 million Ha in 2100. The GHG emissions flows from land use decline slightly in the medium term because of avoided deforestation. In the long term there is an increase in GHG emissions flows from land use as decline in managed forest area leads to smaller GHG sequestration. Net GHG accumulation declines by 2

$GtCO_2e$ in 2100. The consumption of biofuels increase, although their share in liquid fuel consumption declines because of even greater increase in demand for petroleum products. The income effect of increased requirements for petroleum products propagates into significant decline in consumption of processed timber services. The consumption of energy services declines considerably.

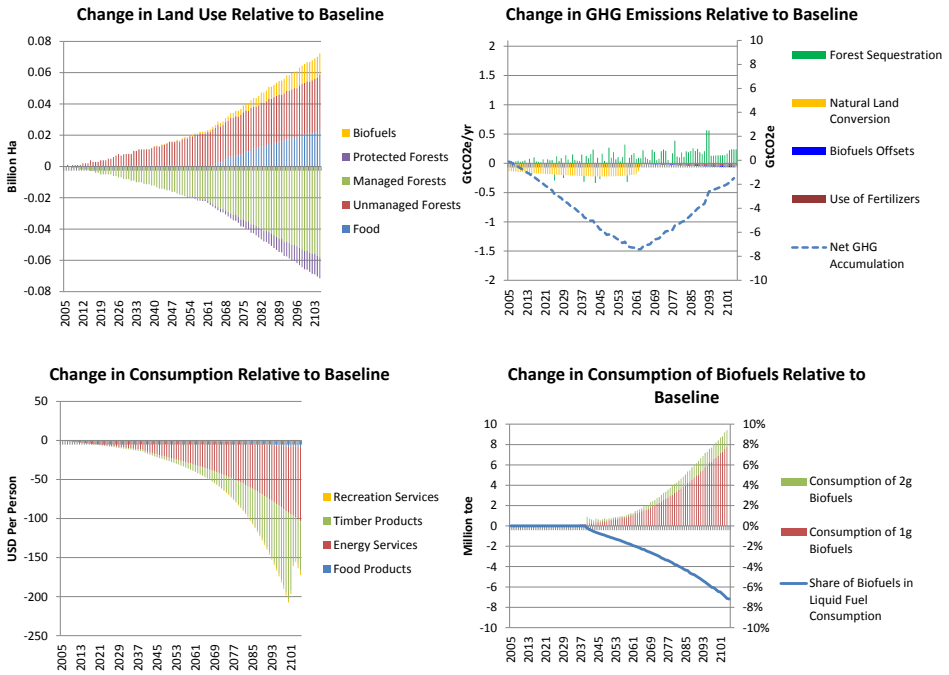

Figure 8: Sensitivity Analysis: 50% Decline in Energy Efficiency Growth Rate per annum

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 main effect of the increase in demand for energy services is an increase in agricultural land area. Areas dedicated to food crops and biofuels feedstocks add 27 and 16 million Ha, whereas managed and protected forest areas decline by 79 and 21 million Ha in 2100. The GHG emissions flows from land use decline in the medium term because of avoided deforestation. In the long term there is an increase in GHG emissions

flows from land use as decline in managed forest area leads to smaller GHG sequestration. Net GHG accumulation declines by 3 $GtCO_2e$ in 2100. The consumption of biofuels increase, although their share in liquid fuel consumption declines because of even greater increase in demand for petroleum products. The income and substitution effects of increased demand for energy services propagates into decline in consumption of processed food, timber, and ecosystem services. The consumption of energy services however increases in response to exogenous increase in demand parameters.

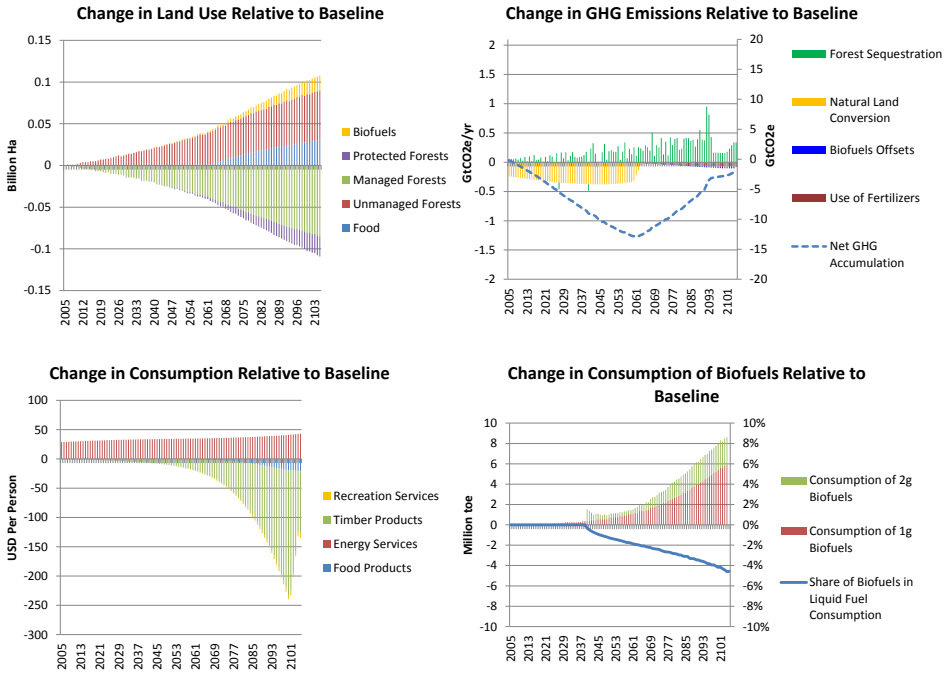

Figure 9: Sensitivity Analysis: 50% Increase in AIDADS Marginal Budget Shares for Energy Services

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 there is a significant expansion of the forestry sector, and the area of protected natural lands, which deliver eco-system services, increases drastically. The consumption of biofuels increases rapidly after second generation biofuels become competitive around 2040, 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

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

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

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

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

$$c_{t+1}^U = \xi_0^u - \xi_1^u \ln\left(\frac{L_{t+1}^U}{L_0^U}\right) + \xi_2^u \left(\frac{\Delta L_t^U}{L_t^U}\right)^2 \tag{A.5}$$

$$c_t^R = \xi_0^R + \xi_1^R \left(\Delta L_t^R\right)^2 \tag{A.6}$$

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

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

Fossil Fuels

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

$$c_{t+1}^x = \kappa_x c_t^x,\ c_0^x > 0 \tag{A.10}$$

Agrochemical Sector

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

Agricultural Sector

$$g_t^i = \theta_t^{g,i} \left[\alpha^g \left(L_t^{A,i}\right)^{\rho_g} + (1-\alpha^g)\left(n_t\right)^{\rho_g}\right]^{\frac{1}{\rho_g}},\ i = 1,2 \tag{A.12}$$

$$\theta_{t+1}^{g,i} = \theta_t^{g,i} + \kappa_{g,i},\ \theta_0^{g,i} > 0,\ i = 1,2 \tag{A.13}$$

Food Processing Sector

$$f_t = \theta^f g_t^1, \tag{A.14}$$

$$\theta^f_{t+1} = \kappa_f \theta^f_t,\ \theta^f_0 > 0 \tag{A.15}$$

Biofuels Sector

$$b^1_t = \theta^{b,1}\left(g^1_t - \frac{f_t}{\theta^f}\right) \tag{A.16}$$

$$b^2_t = \theta^{b,2}\left[\left(\alpha^b\right)^{\theta^\phi_t}(\phi)^{\rho_b} + \left(1-\alpha^b\right)\left(g^2_t\right)^{\rho_b}\right]^{\frac{1}{\rho^b}} \tag{A.17}$$

$$\theta^\phi_{t+1} = \kappa_\phi \theta^\phi_t,\ \theta^\phi_0 > 0 \tag{A.18}$$

Energy Sector

$$e_t = \theta^e_t\left(\alpha^e\left(b^1_t\right)^{\rho_e} + (1-\alpha^e)\left(x^e_t + b^2_t\right)^{\rho_e}\right)^{\frac{1}{\rho^e}} \tag{A.19}$$

$$\theta^e_{t+1} = \kappa_e \theta^e_t,\ \theta^e_0 > 0 \tag{A.20}$$

$$c^e_t = \sum_i c^{b,i} + c^x_t,\ i = 1,2 \tag{A.21}$$

Forestry Sector

$$L^C_t = \sum_{v=1}^{v_{\max}} L^C_{v,t}, \tag{A.22}$$

$$L^C_{v+1,t+1} = L^C_{v,t} - \Delta L^{C.H}_{v,t},\ v < v_{\max} - 1 \tag{A.23}$$

$$L^C_{v_{\max},t+1} = L^C_{v_{\max},t} - \Delta L^{C.H}_{v_{\max},t} + L^C_{v_{\max}-1,t} - \Delta L^{C.H}_{v_{\max}-1,t} \tag{A.24}$$

$$L^C_{1,t+1} = \Delta L^{C,P}_t, \tag{A.25}$$

$$w_t = \sum_{v=1}^{v_{\max}-1} \theta^w_{v,t}\Delta L^{C,H}_{v,t} + \theta^w_{v_{\max},t}\left(\Delta L^{C,H}_{v_{\max},t} + \Delta L^U_t\right), \tag{A.26}$$

$$\theta^w_{v,t+1} = \theta^w_{v,t} + \kappa^w_v, \theta^w_{v,0} > 0 \tag{A.27}$$

$$\begin{aligned} c^w_t &= \xi^w_0 \sum\nolimits_v \frac{\Delta L^{C.H}_{v,t}}{\theta^w_{v,t}} + \xi^w_1\left[\sum\nolimits_v\left(\Delta L^{C,H}_{v,t+1} - \Delta L^{C,H}_{v,t}\right)\right]^2 \\ &\quad + \xi^w_2\left(\sum\nolimits_v \Delta L^{C.H}_{v,t} - \Delta L^{C,P}_t\right)^2 \end{aligned} \tag{A.28}$$

Timber Processing Sector

$$s_t = \theta_t^s w_t \tag{A.29}$$

$$\theta_{t+1}^s = \kappa_s \theta_t^s,\ \theta_0^s > 0 \tag{A.30}$$

Ecosystem Services Sector

$$r_t = \theta^r \left[\begin{array}{c} \alpha^{A,r} \left(L^A\right)^{\rho_r} + \alpha^{C,r} \left(L^C\right)^{\rho_r} + \\ \left(1 - \alpha^{A,r} - \alpha^{C,r}\right) \left(L^U + \theta_t^R L^R\right)^{\rho_r} \end{array} \right]^{\frac{1}{\rho r}} \tag{A.31}$$

$$\theta_{t+1}^R = \kappa_R \theta_t^R,\ \theta_0^R > 0 \tag{A.32}$$

Other Goods and Services Sector

$$\theta_{t+1}^o = \kappa_o \theta_t^o, \theta_0^o > 0 \tag{A.33}$$

GHG Emissions

$$z_t = \mu^x x_t^e + z_t^L, \tag{A.34}$$

$$z_t^L = \mu^L \Delta L_t^U + \mu^n x_t^n + (1-\varphi) \sum_{v=1}^{V} \mu_v^h \Delta L_{v,t}^{C,H} - \sum_{v=1}^{V} \mu_v^w L_{v,t}^C \tag{A.35}$$

$$z_t^L \leq \overline{z}_t^L = \theta_t^z \left(z_t^L - \left(1 - \frac{\mu^{b,i}}{\mu^x}\right) b_t^i \right), i = 1, 2 \tag{A.36}$$

Preferences

$$p_q\left(q\right) = \frac{\alpha_q + \beta_q \exp(u)}{1 + \exp(u)} \frac{y - \sum_q p_q q}{q - \overline{q}},\ 0 \leq \alpha_q, \beta_q \leq 1 \tag{A.37}$$

$$F\left(q, u\right) = \frac{\alpha_q + \beta_q \exp(u)}{1 + \exp(u)} \ln\left(\frac{q - \overline{q}}{A \exp(u)}\right),\ 0 \leq \overline{q} < q \tag{A.38}$$

Welfare

$$\max_{f,e,s,r} \Omega = \sum_{t=0}^{T-1} \delta^t \left[\begin{array}{c} \sum_{q=f,e,s,r,o} \int_0^{q^*} \left(p_q\left(q\right) - c_q\left(q\right)\right) dq \\ -c_t^N \Delta L_t^N - c_t^R - c^n n_t - c^g g_t - c^p \Delta L_t^{C,P} - c_t^w \end{array} \right] + \delta^T \Gamma\left(L_T^U, L_T^C\right) \tag{A.39}$$

Table A.1: Model Variables

Parameter	Description	Units
Exogenous Variables		
Π_t	Population	Billion People
c_t^e	Total Energy Costs	USD'1000 per toe
c_t^x	Fossil Fuels' Costs	USD'1000 per toe
$\theta_t^{g,i}$	Agricultural Yield of Crop i	tons per Ha
θ_t^f	Food Processing Productivity Index	
θ_t^e	Energy Efficiency Index	Energy Services per toe
$\theta_{v,t}^w$	Merchantable Timber Yield	tons per Ha
c_t^w	Forest Harvesting Costs	tons per Ha
θ_t^s	Timber Processing Productivity Index	
θ_t^R	Protected Lands' Management Productivity Index	
θ_t^o	Total Factor Productivity Index	
o_t	Other Goods and Services	USD Trillion
μ_v^w	Carbon Sequestration by Forest Vintage v	tCO_2e per Ha
θ_t^z	Land-Use GHG Emissions Quota	$GtCO_2e$
Endogenous Variables		
$L_t^{A,i}$	Agricultural Land Area of Crop i	GHa
L_t^C	Commercial Forest Land Area	GHa
L_t^U	Unmanaged Natural Lands	GHa
ΔL_t^U	Converted Natural Lands per annum	GHa
L_t^R	Protected Natural Lands	GHa
ΔL_t^R	Flow of Protected Natural Lands per annum	GHa
$\Delta L_t^{C,P}$	Replanted Forest Land Area	GHa
$\Delta L_{v,t}^{C,H}$	Harvested Forest Land Area of Vintage v	GHa
x_t	Fossil Fuels	Gtoe
x_t^e	Petroleum Combusted	Gtoe
x_t^n	Fossil Fuels Allocated to Fertilizers	Gtoe
n_t	Fertilizers Produced	Gton
g_t^i	Agricultural Output of Crop i	Gton
f_t	Processed Food Products	Gton
b_t^i	First ($i = 1$) and Second ($i = 2$) Generation Biofuels	Gtoe
e_t	Energy Services	
w_t	Forest Product	
s_t	Timber Products	
r_t	Eco-system Services	
z^L	GHG Emissions from Land Use	$GtCO_2e$
z^x	GHG Emissions from Fossil Fuels	$GtCO_2e$

Table A.2: 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
$L_0^{A,1}$	Area of Agricultural Land in 2004	Billion Ha	1.533
$L_0^{A,2}$	Area of Cellulosic Feedstocks in 2004	Billion Ha	0.0001
L_0^C	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_0^N	Natural Land Access Cost Function Parameter		0.264
ξ_1^N	Natural Land Access Cost Function Parameter		0.264
ξ_2^N	Natural Land Access Cost Function Parameter		120,000
ξ_0^R	Protection Cost Function Parameter		0.7
ξ_1^R	Protection Cost Function Parameter		50,000
Fossil Fuels			
x_0	Fossil Fuels' Total Consumption in 2004	Billion toe	5.08
x_0^n	Fossil Fuels Converted to Fertilizers in 2004	Billion toe	0.875
x_0^e	Fossil Fuels Combusted in 2004	Billion toe	4.21
c_0^x	Fossil Fuel's Price in 2004	1000USD/toe	0.242
κ_x	Fossil Fuels' Costs Growth Rate per annum		0.032
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

Table A.1: Baseline Parameters (continued)

Parameter	Description	Units	Value
Agricultural Sector			
$\theta_0^{g,1}$	Food Crop Yield in 2004	tons / Ha	4.93
$\kappa_{g,1}$	Food Crop Yield Growth Rate per annum		0.053
$c^{g,1}$	Non Land Cost of Producing Food Crops	1000USD/ton	0.118
$\theta_0^{g,2}$	Cellulosic Feedstocks Yield in 2004	tons / Ha	21.4
$\kappa_{g,2}$	Cellulosic Feedstocks Yield Growth Rate p.a.		0.115
$c^{g,2}$	Non Land Cost of Cellulosic Feedstocks	1000USD/ton	0.161
a^g	Share of Agricultural Land in CES function		0.53
ρ_g	CES Parameter for Agricultural Land and Fertilizers		0.123
Food Processing Sector			
θ_0^f	Food Processing Technology Index in 2004		1.5
κ_f	Food Processing Technology Growth Rate p.a.		0.022
c^f	Food Processing Cost	1000USD/ton	0.081
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		0.048
θ_0^e	Energy Efficiency in 2004		1.102
κ_e	Energy Efficiency Growth Rate p.a.		0.016

Table A.1: Baseline Parameters (continued)

Parameter	Description	Units	Value
Forestry Sector			
ξ_0^w	Forest Harvesting Cost	1000USD/ton	0.067
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			
θ_0^s	Timber Processing Technology Index in 2004		15.2
κ_s	Timber Processing Technology Growth Rate p.a.		0.022
c^s	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
$\alpha^{A,r}$	Share of Agricultural Lands in CES Function		0.07
$\alpha^{C,r}$	Share of Managed Forest Lands in CES Function		0.34
θ_0^R	Productivity of Protected Land in 2004		1.25
κ_R	Productivity Growth of Protected Land p.a.		0.023
c^r	Cost of Managing Protected Land	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
μ^b	GHG Emissions from Production of Biofuels	tCO_2e per toe	1.729
μ^x	GHG Emissions from Petroleum Combustion	tCO_2e per toe	2.902

Table A.1: Baseline Parameters (continued)

Parameter	Description	Units	Value
$\overline{\mu}^w$	Forest Carbon Stocking Density	MgC per m^3	1.1
φ	Share of Stored Carbon in Harvested Forest Products		0.5
Preferences and Welfare Parameters			
α_f	AIDADS Marginal Budget Share at Subsistence Income for Food Products		0.32
α_e	AIDADS Marginal Budget Share at Subsistence Income for Energy Services		0.13
α_s	AIDADS Marginal Budget Share at Subsistence Income for Timber Products		0.14
α_r	AIDADS Marginal Budget Share at Subsistence Income for Ecosystem Services		0.01
α_o	AIDADS Marginal Budget Share at Subsistence Income for Other Goods and Services		0.4
β_f	AIDADS Marginal Budget Share at High Income for Food Products		0.05
β_e	AIDADS Marginal Budget Share at High Income for Energy Services		0.07
β_s	AIDADS Marginal Budget Share at High Income for Timber Products		0.10
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		0.73
$\overline{f}$	AIDADS Subsistence Parameter for Food Products		1.2
$\overline{e}$	AIDADS Subsistence Parameter for Energy Services		0.48
$\overline{s}$	AIDADS Subsistence Parameter for Timber Products		4.8
$\overline{r}$	AIDADS Subsistence Parameter for Ecosystem Services		0.1
$\overline{o}$	AIDADS Subsistence Parameter For Other Goods and Services		0
A	AIDADS Utility Function parameter		1
δ	Social Discount Rate		0.015
ϖ_1	Scrap Price of Unmanaged Forests		90
ϖ_2	Scrap Price of Commercial Forests		10
δ	Social Discount Rate		0.015

Table A.3: Parameter Changes in Model Sensitivity Analysis

Parameter	Description	Baseline Value	New Value
ξ_2^N	Natural Land Access Cost Function Parameter	120,000	80,000
σ_g	Elasticity of Substitution between Land and Fertilizers	1.14	1.71
θ^b	2G Biofuels' Conversion Technology	0.467	0.71
c^b	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	0.13	0.195
β_e	AIDADS Marginal Budget Share at High Income for Energy Services	0.07	0.098