The Optimal Allocation of Global Land Use in the Food-Energy-Environment Trilemma*

Jevgenijs Steinbuks and Thomas W. Hertel
Center for Global Trade Analysis
Purdue University

November 16, 2011

Abstract

This study analyzes the optimal allocation of the world's land resources over the course of the next century in the dynamic forward-looking framework, which brings together distinct strands of economic, agronomic, and biophysical literature and incorporates key drivers affecting global land-use. We show that, while some deforestation is optimal in the near term, the desirability of further deforestation is eliminated by mid-century under the baseline scenario. While the adverse productivity shocks from climate change have a modest effect on global land use, when combined with high growth in energy prices they lead to significant deforestation and higher GHG emissions than in the baseline. Imposition of a GHG emissions constraint further heightens the competition for land, as fertilizer use declines and land-based mitigation strategies expand. However, the effectiveness of such a pre-announced constraint is completely diluted by intertemporal substitution of deforestation which accelerates prior to imposition of the target.

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

Keywords: biofuels, climate change, deforestation, energy, environment, food, forestry, forest vintages, GHG emissions, global land use

*Acknowledgements: We would like to thank Kenneth Judd, Todd Munson, Paul Preckel and Brent Sohngen for their helpful suggestions and comments that resulted in a significant improvement of this paper. We appreciate the financial support from the National Science Foundation, grant 0951576 "DMUU: Center for Robust Decision Making on Climate and Energy Policy".

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 the paper is to determine 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 GHG mitigation targets. We develop a dynamic long-run, forward-looking partial equilibrium framework, in which the societal objective function places value on food production, liquid fuels (including biofuels), timber production, forest carbon and biodiversity. A non-homothetic AIDADS utility function represents model preferences, and, in the long-run, places greater value on eco-system services, and smaller value on 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, we aim to identify the optimal allocation of the world's land resources, over the course of the next century, in the face of 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 between 2005 and 2204, focusing on the first 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. Though we do not explicitly incorporate uncertainty at the optimization stage of the model, we examine the ways in which global land-use responds to changes in factors corresponding to the most important sources of uncertainty associated with this problem. Specifically, we consider three counterfactual scenarios: higher growth in energy prices, lower growth in agricultural productivity, and global GHG emissions regulations.

We show in our model baseline that, in the absence of market imperfections, deforestation associated with cropland expansion, which accounts for a large share of land-use GHG emission, should optimally decline in the medium run. Though adverse productivity shocks from climate change have a modest effect on global land use, consumption of agricultural output declines significantly in the long-run. Energy prices and policies have a considerable effect on the overall amount of land used in agriculture. In a 'perfect storm' of high growth in energy prices and declining agricultural productivity growth, additional demand for cropland leads to significant deforestation and higher GHG emissions than in the baseline. Our model's results confirm the phenomenon of "green paradox" when we expect the world's land base to deliver land-based GHG abatement. The introduction of GHG emissions constraint leads to a significant long-run reduction in GHG emission flows. However, an even greater increase in GHG emissions before such constraint is introduced makes it ineffective over the hundred year term.

2 Literature Review

The economic analysis of land-use is a complex research problem, and therefore, the economic analysis of this issue is primarily based on large-scale computational models. These models can be grouped into two classes. Partial equilibrium models of land-use focus on a detailed representation of narrowly defined sector (e.g. agriculture, forestry or energy) within a particular country or region. These models are typically used in analyzing the effects of agricultural, energy, and climate policies on land-use within a particular sector. Computable general equilibrium (CGE) models capture the effects of macro-economic fundamentals, international trade and capital flows on land-use through changes in relative prices of inputs and outputs. CGE models are widely employed to analyze the economic effects of international climate policy at the macro-economic level. Van Der Werf and Peterson (2009) and Hertel et al. (2009) provide a comprehensive summary of best known computational models applied to land use, bioenergy, and climate policy.

Another important issue in dynamic computational models of land-use refers to their method of solution. Because of their complexity most of the models are solved recursively rather than as fully inter-temporal forward-looking optimization problems. The forward-looking approach adopted in our paper is less common, notwithstanding its better capabilities to address important economic policy issues such as inter-temporal allocation of GHG emission flows from land-use through abatement policies, efficiency implications of carbon taxes and caps, and endogenous depletion of non-renewable land resources.[1]

This section summarizes recent contributions to the literature on economic analysis of land use that are most relevant to our work.

2.1 Agriculture and Food Demand

The bulk of the literature on agriculture and land-use studies how the agricultural system adapts to rising food demand resulting from income and population growth, as well as to changes in agricultural productivity of commercial land. Ianchovichina et al. (2001) analyze the global effects of rising food demand on agricultural and forest resources using a global, dynamic computable general equilibrium model enhanced with natural resource detail (D-FARM). They find that, at least in the short term, the global food shortages and large-scale deforestation are unlikely, although food prices are likely to rise in certain regions. Golub et al. (2009) develop a recursive-dynamic general equilibrium model (GTAP-Dyn) designed explicitly to project patterns of land-use change at the global scale over the long run based on fundamental supply/demand drivers. They find that increasing consumer demand for crops, livestock and forestry products results in substantial deforestation and expansion of global agricultural land, with greatest deforestation occurring in North and Latin America. Choi et al. (2011b) analyze land-use effects resulting from projected changes in total factor productivity for crops and livestock production using forward-looking global, dynamic partial equilibrium model. Their model suggests that in the medium term, changes in agricultural productivity result in significant increases in the area of land devoted to livestock grazing, a comparably large reduction in cropland, and a small reduction in forest land.

[1] For a detailed discussion on relative pros and cons of recursive versus forward-looking approaches in climate policy analysis, see Babiker et al. (2009).

2.2 Renewable Energy

The literature on renewable energy and land-use has focused heavily on the competition for land between biofuels and food production, and the ensuing implications for land-based GHG emissions. Searchinger et al. (2008) use a global recursive partial equilibrium model combined with life-cycle analysis of greenhouse gas emissions model (GREET) to estimate emissions from land use change due to biofuels. They find that corn-based ethanol is a poor instrument for GHG mitigation. Based on Searchinger et al.'s (2008) results, global corn-based ethanol production nearly doubles greenhouse emissions over 30 years, when compared to the petroleum it replaces. This difference is driven largely by land-based emissions associated with expanding global croplands. Gurgel et al. (2007) investigate the potential production and land use implications of a global biofuels industry using a recursive-dynamic multi-regional CGE model of the world economy (MIT-EPPA). Accounting for land conversion from natural areas to agricultural use and introduction second-generation biofuels, they find a modest increase in biofuels production and land-use in the baseline scenario. However, active policies to support the biofuels industry result in considerable expansion in biofuels' production and cropland under their policy scenario. Chakravorty et al. (2011) develop a forward-looking multi-regional partial equilibrium model with endogenous fossil fuel extraction and land allocation decisions to study the effects of biofuels' mandates. They find that, in the long run, biofuel mandates marginally affect aggregate food production and have limited effects on food prices, even though they have a major impact on where the food is produced. Mandates also have almost no effect in reducing global greenhouse gas emissions, and increase it in some cases.

2.3 Commercial Forestry

The literature on commercial forestry and land-use studies the allocation of land to the commercial forestry sector in the context of timber production and climate mitigation policies. There is a large number of dynamic models focusing on the commercial forestry sector (Stavins 1999, Sohngen and Mendelsohn 2003, Richards and Stokes 2004, Sohngen and Mendelsohn 2007). However, the research on the commercial forestry sector that accounts for competition across multiple types of land-use has only recently started to appear. Choi et al. (2011a) develop a detailed forward-looking partial equilibrium model of global forests and agricultural land use, which accounts for dynamics of forest management as well as for the economic conditions at the margin between crop, livestock and forest uses. Their modeling approach allows for inter-temporal choice of forest harvests, investments, the unmanaged forest conversion, and forest carbon sequestration as climate, land, and market fundamentals change. Their model predicts an increase in the area of land devoted to livestock grazing, and a reduction in cropland and forestland by 2060. Substantial deforestation occurs, although the rates of deforestation and carbon losses are substantially smaller than those observed historically.

2.4 Ecosystem Services and Biodiversity

The literature on ecosystem services and land-use studies optimal natural land conservation decisions taking into account irreversibility in disruption of biodiversity and significant option values attached to the future stream of benefits from ecosystem services. There are a large number of studies on optimal natural land conversion to commercial agricultural land under uncertainty and irreversibility (Conrad 1997, Conrad 2000, Bulte et al. 2002, Leroux et al. 2009). However, those studies do not differentiate between types of land-use and have limited applications to climate change policies. Recent studies by Antoine et al. (2008) and Gurgel et al. (2011) integrated the demand for recreation services into a broader land-use perspective using recursive-dynamic multi-regional CGE model of the world economy (MIT-EPPA). Antoine et al. (2008) found that increased the demand for ecosystem services raises the cost of climate policies by restricting biofuels production without the offsetting benefit of keeping the land in its natural state. Gurgel et al. (2011) argue that recreational demand for forests is highly complementary with GHG abatement through forest sinks, as forests can provide recreational services while also storing carbon. This should have important implications for GHG emissions pricing in land-use.

2.5 GHG Sequestration

The literature on GHG Sequestration and land-use explores different strategies to manage anthropogenic carbon emissions from terrestrial systems, and their implications for land-use. Wise et al. (2009) employ a dynamic recursive model of energy, economy, agriculture, land use and land cover (MiniCAM) to explore the implication of limiting atmospheric CO2 concentrations at levels ranging from 450 ppm to 550 ppm. They find that comprehensive mitigation strategies that limit fossil fuel, industrial, as well as terrestrial carbon emissions have profound implications for agriculture: unmanaged ecosystems and forests expand, and food crop and livestock prices rise. Wise et al. (2009) argue that future improvement in food crop productivity directly affects land-use change emissions, making the technology for growing crops potentially important for limiting atmospheric CO2 concentrations. Burney et al. (2010) make a similar argument and suggest that investment in yield improvements compare favorably with other commonly proposed mitigation strategies. Their estimates suggest that each dollar invested in agricultural yields has resulted in 68 fewer kgC (249 kgCO_2e) emissions relative to 1961 technology, thereby avoiding 3.6 GtC (13.1 GtCO_2e) in emissions per year.

3 Model Outline

The model which we develop seeks to integrate these five, rather distinct strands of literature into a single, intertemporally consistent, analytical framework, at global scale. It is a discrete dynamic, finite horizon partial equilibrium model with no uncertainty. 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 to boost yields in the agricultural sector. The agricultural sector combines cropland and fertilizers to produce intermediate output that can be used to produce food or biofuels. The food processing sector converts agricultural output into food products that are used to meet the global food demand. The biofuels sector converts agricultural products into liquid fuels, which substitute imperfectly for fossil fuels in final demand. The energy sector combines fossil fuels 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 recreation sector provides a public good - ecosystem services - to society.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. The model's structure, equations, variables, and parameters are summarized in technical appendix.

3.1 Resource Use

3.1.1 Land

The total land endowment in the model, $\overline{\Lambda}$, is fixed, so that the per-capita land endowment, Λ_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), N_t, and commercial lands, L_t, both of which are expressed in per capita terms. The per-capita land endowment constraint is

$$\Lambda_t = \frac{\overline{\Lambda}}{\Pi_t} = N_t + L_t, \tag{1}$$

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. Reserved land, N^R, with initial stock N_0^R, is institutionally protected and cannot be converted to commercial land. This includes natural parks, biodiversity reserves and other types of protected forests. The reserved natural land is used to produce ecosystem services for society. Non-reserved natural land, N^N, can be accessed and either converted to commercial land (deforested) or to reserved natural land. Once the natural land is deforested, its potential to yield ecosystem services is interrupted 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. 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:

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

$$N_{t+1}^N = N_t^N - \Delta L_t - \Delta N_t^R, \; N_0 > 0, \tag{3}$$

and

$$N_{t+1}^R = N_t^R + \Delta N_t^R, \; N_0^R > 0, \tag{4}$$

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 non-reserved natural land with initial stock, N_0, declines by the amounts allocated for conversion to commercial and reserved natural land, ΔL_t and ΔN_t^R, where Δ operator denotes a change in variables L_t and N_t^R. Equation (4) shows that at each period of time, the total area of reserved land with initial stock of N_0^R increases by the amount of newly protected natural land, ΔN_t^R.

Following past literature on land access modelling (Gouel and Hertel 2006, Golub et al. 2009) we assume that the marginal natural land access cost function, c^N is a continuous, monotonically increasing, and strictly convex function of the share of natural land previously accessed:

$$c_{t+1}^N = \xi_0^n - \xi_1^n \ln\left(\frac{N_{t+1}^N}{N_0^N}\right) + \xi_2^n \left(\frac{N_{t+1}^N - N_t^N}{N_t^N}\right)^2. \tag{5}$$

In equation (5), 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. In addition, we assume that converting natural land to reserved land entails additional costs, c^R, associated with passing legislation to create new natural parks. These costs are given by

$$c_t^R = \xi_0^R + \xi_1^R \left(N_{t+1}^R - N_t^R\right)^2. \tag{6}$$

In equation (6), 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. There are no additional costs of natural land conversion to commercial land, as these costs are offset by the revenues from deforestation.

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

$$L_t = G_t + W_t. \tag{7}$$

and

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

Equation (7) shows that total endowment of commercial land, L, is a sum of the hectares of commercial land dedicated to agriculture, G, and managed forest, W, respectively. Equation (8) shows that at each period of time, the total area of commercial land with initial stock of L_0 increases by the amount of converted non-reserved natural land, ΔL.

3.1.2 Fossil Fuels

The fossil fuels, x, have two competing uses in our partial equilibrium model of land-use. A fraction of fossil fuels, x^ϕ, 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

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

The cost of fossil fuels 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. It is described by the following equation:

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

where the parameter c_0^x and κ_x reflect the initial costs and annual growth rate in costs of liquid fossil fuels.

3.2 Agrochemical Sector

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

$$\phi_t = \theta^{\phi} x_t^{\phi}, \tag{11}$$

where θ^{ϕ} 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.

3.3 Agricultural Sector

The agricultural sector combines the agricultural land and fertilizers to deliver an output, g, that can be either converted to food, f, or biofuels, b. Agricultural land and fertilizers are imperfect substitutes in the production of agricultural products. The output of the agricultural product, g, is thus determined by the constant elasticity of substitution (CES) function:

$$g_t = \theta_t^g \left[\alpha^g \left(G_t\right)^{\rho_g} + \left(1 - \alpha^g\right)\left(\phi_t\right)^{\rho_g}\right]^{\frac{1}{\rho_g}}, \tag{12}$$

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. Based on the agronomic literature (Cassman et al. 2010) we assume that agricultural yield grows linearly, adding constant amount of gain per annum:

$$\theta_{t+1}^g = \theta_t^g + \kappa_g,\ \theta_0^g > 0, \tag{13}$$

where the parameters θ_0^g and $\kappa_g$corresponds to the initial level and growth rate in agricultural yield. 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.

3.4 Food Processing Sector

The food processing sector converts an amount of agricultural product, g, into food products, f, that are further consumed in final demand. The conversion process is represented by the following production function:

$$f_t = \theta_t^f g_t, \tag{14}$$

where θ_t^f is the total factor productivity (TFP) of the food processing sector. Equation (15) describes the growth of TFP in the food processing sector:

$$\theta_{t+1}^f = \kappa_f \theta_t^f, \ \theta_0^f > 0, \tag{15}$$

where the parameters θ_0^f and κ_f reflect the initial level and annual growth rate in the TFP of the food processing sector. This growth captures the technological progress in both direct transformation of agricultural product into edible food, and the storage, transportation, and distribution of processed food. The efficiency gain from technology improvements in food processing sector result in lower requirements for both processed food and agricultural product in final demand.[2] We assume that the food processing costs per ton of food products, c^f, are exogenous and scale-invariant.

3.5 Biofuels Sector

The biofuels sector consumes the remaining amount of agricultural product to produce biofuels, b. We assume that a ton of agricultural product, g, can be converted to θ^b tons of oil equivalent $(toe's)$ of biofuels. The output of biofuels is thus given by

$$b_t = \theta^b \left(g_t - \frac{f_t}{\theta^f} \right). \tag{16}$$

The agricultural product's conversion to renewable fuel incurs additional non-food cost[3], c^b. In the current version of the model we assume this cost is constant

[2] For example, technological innovation in food conservation results in fewer food losses from spoilage, and, correspondingly, lower amounts of processed food needed to satisfy the commercial demand for food. It follows from equation (14) that input requirements for agricultural product also decrease.

[3] This cost can be non-trivial, for example, in processing agricultural products for producing second generation of biofuels.

and scale-invariant.[4]

3.6 Energy Sector

The energy sector consumes fossil fuels, x^e, and biofuels, b, that are further combusted to satisfy the demand for energy services. Biofuel and fossil fuels are assumed to be imperfect substitutes, because of different technological requirements for using each type of fuel. Total production of fuel input, e_t^f, is given by the constant elasticity of substitution (CES) function:

$$e_t^f = \gamma^e \left(\alpha^b \left(b_t\right)^{\rho_b} + \left(1 - \alpha^b\right) \left(x_t^e\right)^{\rho_b}\right)^{\frac{1}{\rho_b}}, \tag{17}$$

where the parameter γ^e describes the technology of energy production, α^b is the value share of biofuels in energy production at the benchmark time 0, and $\rho_b = \frac{\sigma_b - 1}{\sigma_b}$ is a CES function parameter proportional to the elasticity of substitution of fossil fuels for biofuels, σ_b.

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

$$c_t^e = c^b + c_t^x. \tag{18}$$

We allow for the possibility of efficient use of fuel inputs. One *toe* of energy from fossil fuel or biofuel combusted yield θ_t^e *toe's* of energy services, e :

$$e_t = \theta_t^e e_t^f, \tag{19}$$

where the function θ_t^e reflects the energy efficiency, i.e. the amount of energy services provided by one *toe* of the energy fuel (Sorrell and Dimitropoulos 2008, p. 639). Equation (20) describes the growth of the energy efficiency:

$$\theta_{t+1}^e = \kappa_e \theta_t^e,\ \theta_0^e > 0, \tag{20}$$

where the parameters θ_0^e and κ_e reflect the initial level and annual growth rate in the energy efficiency.

[4] In further versions we will allow this cost to decline as the biofuels' production technology improves.

3.7 Forestry Sector

The forestry sector is characterized by V vintages of forest trees. At the end of period t each hectare of managed forest land, $W_{v,t}$, has an average density of tree vintage age v, with the initial allocation given and denoted by $W_{v,0}$. Each period of time the managed forest land can be either planted, harvested or simply left to mature. The newly planted trees occupy W^p hectares of land, and reach the average age of the first tree vintage next period. The harvested area occupies H_v 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. The yield of a newly planted forest area is always zero (i.e. $\theta_0^w = 0$). 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. 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 have the highest yield of θ_V^w and do not grow further. They 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, yields θ_V^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, 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 short-run 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:

$$W_t = \sum_{v=1}^{V} W_{v,t}, \tag{21}$$

$$W_{v+1,t+1} = W_{v,t} - H_{v,t},\ v < V \tag{22}$$
$$W_{V,t+1} = \sum_{V-1}^{V} W_{v,t} - H_{v,t}$$

$$W_{1,t+1} = W_t^p, \tag{23}$$

$$w_t = \sum_{v=1}^{V-1} \theta_{v,t}^w H_{v,t} + \theta_{V,t}^w \left(H_{V,t} + \Delta L_t\right), \tag{24}$$

$$\theta_{v,t+1}^w = \theta_{v,t}^w + \kappa_v^w, \theta_{v,0}^w > 0, \tag{25}$$

and

$$c_t^w = \xi_0^w \sum\nolimits_v \frac{H_{v,t}}{\theta_{v,t}^w} + \xi_1^w \left(\sum\nolimits_v H_{v,t+1} - \sum\nolimits_v H_{v,t}\right)^2 + \xi_2^w \left(\sum\nolimits_v H_{v,t} - W_t^p\right)^2. \tag{26}$$

Equation (21) describes the composition of managed forest area across forest vintages.Equation (22) illustrates the harvesting dynamics of forest areas with the average age v. Equation (23) shows the transition from planted area, W^p, to new forest vintage area. Equation (24) describes the output of forest product from harvested forest areas of average tree age v and deforested natural lands. Equation (25) describes the growth in the merchantable timber yield, 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. Equation (26) shows forest harvesting costs, 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.

3.8 Timber Processing Sector

The timber processing sector converts harvested forest product, w, into processed timber products, s, that are further consumed in final demand. The conversion process is represented by a linear production function:

$$s_t = \theta_t^s w_t, \tag{27}$$

where θ^s is the TFP of the timber processing sector. Equation (15) describes the growth of TFP in the timber processing sector:

$$\theta_{t+1}^s = \kappa_s \theta_t^s,\ \theta_0^s > 0, \tag{28}$$

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. This growth captures the technological progress in both direct transformation of forest product into processed timber, and the quality improvements and durability of timber products. The efficiency gain from technology improvements in timber processing sector result in lower requirements for both processed timber and forest product in final demand.[5] We assume that the timber processing costs per ton of food products, c^s, are exogenous and scale-invariant.

3.9 Recreation Sector

The recreation sector uses the reserved natural land to produce ecosystem services, such as hunting, fishing, and wildlife viewing. The output for ecosystem services, r_t, is given by

$$r_t = \theta_t^r N_t^R, \tag{29}$$

where θ_t^r is the TFP of the recreation sector. Equation (30) describes the growth of TFP in the recreation sector:

$$\theta_{t+1}^r = \kappa_r \theta_t^r,\ \theta_0^r > 0, \tag{30}$$

where the parameters θ_0^r and κ_r reflect the initial level and annual growth rate in the TFP of the recreation sector. The average cost of producing ecosystem services (expenditures to maintain protected natural lands) per hectare of reserved natural land, c^r, is exogenous and scale-invariant.

3.10 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

[5] 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.

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[6]. Equations (31) and (32) below describe the production of other goods and services:

$$o_t = \theta_t^o o_0, \tag{31}$$

and

$$\theta_{t+1}^o = \kappa_o \theta_t^o,\ \theta_0^o > 0. \tag{32}$$

where the parameters θ_0^o and κ_o reflect the initial level and annual growth rate in the TFP of the economy. As production of other goods and services is predetermined and does not draw on land resource, we assume without loss of generality that their cost of production is zero.

3.11 GHG Emissions

The GHG emissions flows, z_t, in the model result from a number of sources: (a) the use of fossil fuels, (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 the use of fossil fuels, z^x, and the emissions resulting from land-use, z^L, because the price path for fossil fuels is pre-determined, whereas the other sources of GHG emissions are fully endogenous in the model.

We assume that GHG emissions are linearly related to the use of fossil fuels, and the allocations of commercial lands. A *toe* of fossil fuel combusted emits μ^x tons of CO_2 equivalent (tCO_2e). Fertilizer production process emits μ^ϕ tCO_2e per ton of fertilizer produced. A ton of fertilizer applied to agricultural land emits μ^g tCO_2e.

GHG's can also be reduced by carbon forest sequestration. 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 even-

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

tually 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. The annual sequestration of carbon by agricultural product is ignored, as those crops are either consumed or combusted in the form of bioenergy.

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

$$z_t = z_t^x + z_t^L, \tag{33}$$

$$z_t^x = \mu^x x_t^e + \mu^\phi x_t^\phi, \tag{34}$$

and

$$z_t^L = \mu^L \Delta L_t + \mu^\phi x_t^\phi + (1-\varphi)\sum_{v=1}^{V} \mu_v^h H_{v,t} - \sum_{v=1}^{V} \mu_v^w W_{v,t}. \tag{35}$$

Equation (33) describes the composition of GHG emissions flows. Equation (34) describes the GHG emissions from the use of fossil fuels. Equation (35) 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 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 and fertilizers' production 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 amount of fossil fuels' emissions displaced by the biofuels.[7] The resulting relationships for emissions control are

$$z_t^L \leq \overline{z}_t^L, \tag{36}$$

and

$$\overline{z}_t^L = \theta_t^z \left(z_t^L - \left(1 - \frac{\mu^b}{\mu^x}\right) b_t \right). \tag{37}$$

where global warming intensity, θ_t^z is a function determining the evolution of the GHG emissions' quota over time, and μ^b are non-land-use emissions of biofuels' production. Equation (36) describes the constraint on non-fossil fuel emissions in the atmosphere. Equation (37) shows how this constraint is derived.

3.12 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.[8] 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 better regularity properties than AIDS[9], which is essential for solution of the model over a wide range of quantities. A number of studies (Cranfield et al. 2003, Yu et al. 2004) demonstrated that AIDADS outperforms other popular models of consumer demand in projecting global food demand, which makes it especially well-suited for the economic modelling of land-use.

[7] 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.

[8] 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).

[9] 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).

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

$$\sum_{q=f,e_s,w,r,o} F(q,u) = 1, \tag{38}$$

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

$$F(q,u) = \frac{\alpha_q + \beta_q \exp(u)}{1+\exp(u)} \ln\left(\frac{q-\overline{q}}{A\exp(u)}\right). \tag{39}$$

In equation (39) 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

$$q > \overline{q}, \tag{40}$$

i.e. 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 restrictions of the economic theory on the value of parameters α_q, β_q and $\overline{q}$:

$$\alpha_q \geq 0, \beta_q \geq 0, \overline{q} \geq 0, \tag{41}$$

$$\alpha_q \leq 1, \beta_q \leq 1, \tag{42}$$

and

$$\sum_q \alpha_q \leq 1, \sum_q \beta_q \leq 1. \tag{43}$$

Inequalities defined by formula (41) are non-negativity constraints that ensure that the consumers' marginal budget shares and minimal consumption level of goods and services q are greater or equal to zero. Inequalities defined by formulas (42) and (43) are the adding-up restrictions that ensure that the consumers' marginal budget shares in total real expenditures do not exceed one.

Rimmer and Powell (1996, p. 1615) demonstrate that maximizing the utility function (38) subject to the budget identity and the constraints (39) - (43) yields the following system of inverse demand equations:

$$p_q(q) = \frac{\alpha_q + \beta_q \exp(u)}{1 + \exp(u)} \frac{y - \sum_q p_q q}{q - \overline{q}}, \tag{44}$$

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.

3.13 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.[10] Net surplus is computed by integrating the marginal valuation of each product, less the 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:

$$\max_{f,e,s,r} \Omega = \sum_{t=0}^{T-1} \delta^t \left[\begin{array}{c} \sum_{q=f,e,s,r,o} \int_0^{q^*} \left(p_q(q) - c_q(q)\right) dq \\ -c_t^N - c_t^R - c^\phi \phi_t - c^g g_t - c^p W_t^p - c_t^w \end{array} \right] + \delta^T \Gamma\left(N_T^N, W_T\right) \tag{45}$$

s.t. constraints (1)-(44), where Γ is the scrap value function.

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

4 Model Baseline

4.1 Baseline Construction

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 et al. 2009). The values of calibrated baseline parameters are summarized in technical appendix.

4.1.1 Population

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

$$\Pi_t = \frac{\Pi_T \Pi_0 e^{\pi t}}{\Pi_T + \Pi_T \left(e^{\pi t} - 1\right)}, \tag{46}$$

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

4.1.2 Resource Use

Land The data for the total land and commercial land endowment constraints defined by the equations (46) and (7) comes 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 land defined by the equation (2) comes from Antoine et al. (2008, p.8, Table 3). The parameter values defining natural land access cost function (5), and natural land protection cost function (6) are calibrated based on FAO (2010) data to match deforestation rates in 2004 and ensure stable rates of natural land access and protection.

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 price for fossil fuels. We obtain the initial values and the rate of change in energy prices from the U.S. Energy Information Administration reference case scenario for 2035 projections (EIA 2010a, p. 86, Table 10).

4.1.3 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. We use the FAOSTAT database[11] 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 ni-

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

trogen fertilizers. We use USDA ERS fertilizer use and price dataset[12] to obtain the fertilizers' price. We then subtract the fossil fuels' price from the fertilizers' price to obtain non-energy cost of fertilizers' production. This cost does not vary much across time because fossil fuels' and nitrogen fertilizers' prices are highly correlated and follow the same trend (USGAO 2003).

4.1.4 Agricultural Sector

We compute the consumption of agricultural products based on production function (12). The initial amount of agricultural product (measured as the global physical production of agricultural crops) and global agricultural expenditures in 2004 come from the FAOSTAT database. 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 crop land and fertilizers in 2004 are calibrated from known values of agricultural product, fertilizers, and the crop land as described in Rutherford (2002). 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 cost of agricultural product from GTAP v.7 database.

4.1.5 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.

4.1.6 Biofuels Sector

In the model baseline we define the biofuels as a first-generation grain-based ethanol. The values for biofuels conversion rate and cost for equation (16) are for ethanol and are taken from Taheripour and Tyner (2011). Following Winston (2009) we adjust the quantity of biofuels produced by 0.7 to match the energy content of liquid fossil fuels.

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

4.1.7 Energy sector

We compute the energy fuel input based on production function (17). We obtain the initial values for total consumption of liquid fossil fuels and biofuels from EIA (2010b, p. 24, Table 3.). The elasticity of substitution of fossil fuels for biofuels is based on Hertel et al.'s (2010b) 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). We set the energy efficiency in 2004 equal to one, and obtain the growth rate in the energy efficiency from World Energy Council (2008).

4.1.8 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:

$$\begin{aligned} \theta_v^w &= \exp\left(\psi_1 - \frac{\psi_2}{v - \overline{v}}\right), \text{ if } v > \overline{v} \\ \theta_v^w &= 0, \qquad\qquad\qquad\quad \text{ if } v \leq \overline{v}. \end{aligned} \tag{47}$$

In equation (47),the parameters ψ_1 and ψ_2 are growth parameters determining the support and the slope of the timber yield function. The yield function (47) 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). 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. 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). Similar to agricultural sector, we assume that the yield growth in the commercial forestry sector is characterized by a linear trend.

4.1.9 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.

4.1.10 Recreation Sector

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 compute the initial values of the productivity of the reserved natural land for equation (29) by dividing the output from recreation sector by initial endowment of reserved natural land. We set the growth rate of the TFP in the recreation sector to growth rate of the economy's TFP. We measure the non-land costs of producing recreation services based on GTAP v.7 database as public expenditures on outdoor recreation services per hectare of protected land.

4.1.11 Other Goods and Services

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.

4.1.12 GHG Emissions

The value of the GHG emission coefficient from combustion of liquid fossil fuels comes from the US Energy Information Administration (EIA) website[13]. 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

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

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 et al. (2010a) using methodology from Searchinger et al. (2008). The non-land-use emissions of biofuels' production are from Farrell et al. (2006). We do not impose institutional controls for land-use emissions in the baseline scenario, and consider them in the following sections of this study.

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

$$\mu_v^h = \overline{\mu}^w \exp\left(\psi_1 - \frac{\psi_2}{v}\right). \tag{48}$$

In equation (48) 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 (47).[14] Then the amount of GHG sequestered by a hectare of forest land of tree vintage v is

$$\mu_v^w = \mu_v^h - \mu_{v-1}^h. \tag{49}$$

We obtain the carbon conversion factor and yield function (47) 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).

4.1.13 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 (39) 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

[14] Note that the minimum age parameter, $\overline{v}$, is not included in equation (49). This is because at young ages, stands may have substantial carbon, but little merchantable timber (Sohngen et al. 2009b).

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.[15] We parameterize the scap value function as

$$\Gamma\left(N_T^N, W_T\right) = \varpi_1 N_T^N + \varpi_2 \sum_{v=1}^{V} \frac{W_{v,T}}{\delta^{T-v}}, \quad (\varpi_1 > 0, \varpi_2 > 0), \tag{50}$$

where the parameters ϖ_1 and ϖ_2 denote the scrap prices of unmanaged and 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 umanaged natural lands are not depleted over 50 percent of their initial amount during the time horizon of the problem.[16]

4.2 Model Baseline Results

This section describes the results of simulations of the model baseline described above. We solve model over the period 2005 – 2204, and present the results for the first 100 years to minimize terminal period effects.

Figure 1 depicts the optimal allocation of global land-use, GHG emissions, consumption of goods and services that draw on land resources, and consumption of biofuels in the model baseline. Beginning with the upper left-hand panel of Figure 1, we see that, in the short-run cropland area increases, reaching its maximum of 1.75 billion hectares in 2050 (14 percent larger compared to 2004), whereas managed forest area remains practically unchanged at 1.64 billion hectares (1 percent larger compared to 2004). In the medium- and long-run, slower population growth, rising real income and agricultural productivity, and energy efficiency improvements result in a decline in demand for cropland and an increase in demand for managed forests. By 2100 cropland area declines to 1.44 billion hectares (6 percent smaller compared to 2004), whereas managed forest area increases to 1.96 billion hectares (21 percent larger compared to 2004). Protected natural land area increases moderately in the short- an medium- run, and in 2050 amounts to 0.25 billion hectares (22 percent larger compared to 2004). In the long-run, the area of protected natural land increases sharply to

[15] 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

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

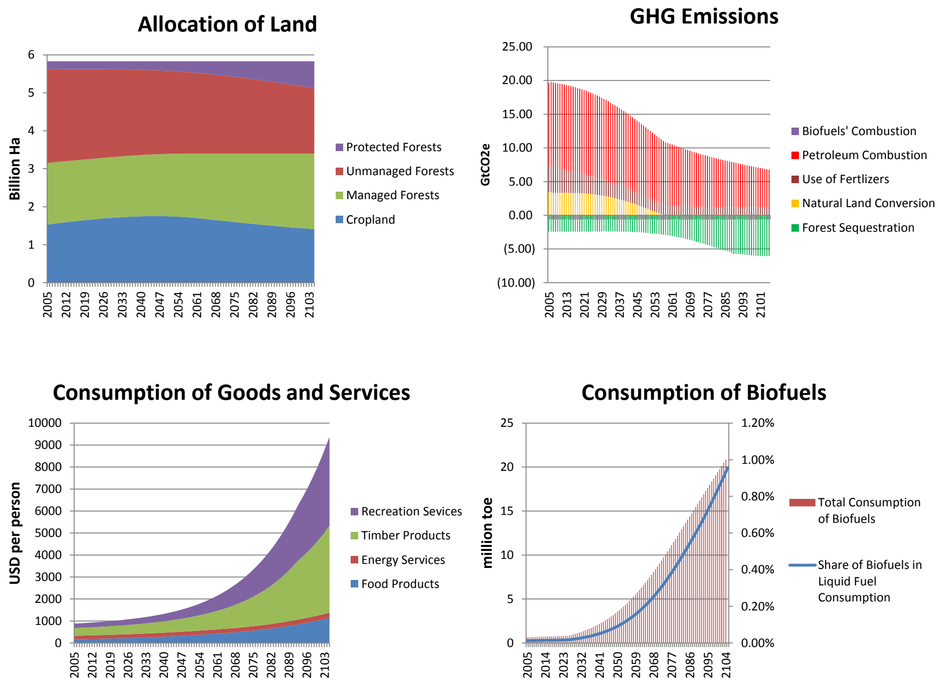

Figure 1: Model Baseline

0.65 billion hectares in 2100 (216 percent larger compared to 2004), with most of the increase taking place after 2050.

The upper right-hand panel in Figure 1 shows the results for gross GHG emissions. Positive bars in this panel denote emissions, whereas negative bars denote carbon sequestration through forests. Petroleum combustion is the major source of GHG emissions in the model, which amount to 13.5 GtCO_2e in 2004. In the long-run the demand for petroleum declines due to higher oil prices and energy efficiency improvements, and GHG emissions from petroleum combustion decline by 52% relative to 2004, reaching 5.9 GtCO_2e in 2104. GHG emissions from conversion of natural land remain significant in short- run, and amount to 3.1 GtCO_2e in 2025 (10 percent smaller compared to 2004). In the medium run, increasing access costs of natural land combined with declining demand for commercial land, results in a sharp decline in deforestation. GHG emissions from deforestation decrease to 0.95 GtCO_2e in 2050 (72 percent smaller compared to 2004) and cease entirely by 2060, along this optimal global path of land use. GHG emissions from production and 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 rising cropland yields. In 2100 GHG emissions from production and application of fertilizers amount to 1.15 GtCO_2e (71 percent smaller compared to 2004). GHG emissions' sequestration from managed forests increases in the short run with the removal of older tree vintages and regrowth of new forest. In 2050 annual sequestration of GHG emissions by the global forestry sector amounts to 2.6 GtCO_2e (7.5 percent larger compared to 2004). In the medium-run and the long-run sequestered GHG emissions continue to increase faster with the increase in managed forest area. In 2100 sequestered GHG emissions amount to 6 GtCO_2e (147 percent larger compared to 2004). The gross emissions from biofuels' consumption (excluding indirect land use effects, which are reported separately) are quite modest, amounting to just 6 MtCO_2e in 2050 and 33.5 MtCO_2e in 2100.

The lower left-hand panel in Figure 1 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 occurs because population growth declines whereas crop and forest yields, productivity growth in all sectors of the economy (and hence per capita income) remains relatively strong. In 2100 the per capita consumption of services from processed food, energy, processed timber, and recreation are respectively higher by a factor of 6, 1.5, 10.5 and 20 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. In relative terms, in 2100 the budget share of recreation services increase, budget shares of food and energy services decline, and the budget share of timber products remains unchanged compared to their levels in 2004. This result is consistent with calibrated structure of AIDADS preferences.

The lower right-hand panel of Figure 1 describes the results for consumption of biofuels. The consumption of biofuels grows in short-, medium-, and long-run as oil prices and agricultural yields increase. In 2100 the per capita consumption of biofuels is 20 Mtoe, considerably higher than in 2004, but still small in relative terms (0.9 percent of total consumption of liquid fuels).

5 Counterfactual Scenarios

In practice, private and public land allocation decisions must be made despite significant uncertainty about the future productivity of land in different uses, as well as the future valuation of environmental services from this land, including biodiversity and carbon sequestration. This uncertainty is particularly problematic in light of the fact that some of the decisions are irreversible (e.g., cutting down natural forests, extraction and combustion of fossil fuels) and others take considerable time to reverse (e.g., harvesting a mature forest). Though we do not explicitly incorporate uncertainty in the model's optimization stage, we do examine the ways in which global land-use responds to changes in factors corresponding to the most important sources of uncertainty associated with this problem. These sources include (but are not limited to) variations in agricultural yield, θ^g, liquid fossil fuels' costs, p_x, and the future valuation of GHG abatement, expressed through the stringency of the GHG emissions constraint, $\overline{z}^L$.To do this, we utilize the model to simulate the effects of the following scenarios, each of which has the potential to put greater pressure on the world's land resources:

scenario A: the rate of growth agricultural yield permanently declines due to adverse effects of climate change;

scenario E: the rate of growth in liquid fossil fuel costs permanently increases because of rising extraction costs and (or) more stringent climate policies, aimed specifically at fossil fuels;

scenario T: the land based GHG emissions constraint is introduced, and becomes more stringent over time, as land-use climate mitigation strategies become more agressive;

We also consider the combinations of scenarios A and E (scenario AE) and scenarios A, E, and T (scenario AET).

We assume that all of these alternative scenarios are realized after 20 years from the 2005 starting period, i.e. 2025. We assume that the above mentioned "events" are fully anticipated, and simulate the model for the entire time horizon, focusing our analysis on the next 100 years.

5.1 Construction of Counterfactual Scenarios

The values of the model parameters corresponding to the three counterfactual scenarios are summarized in the technical appendix. For scenario A, the change in growth rate of agricultural yield due to adverse effects of the climate change, 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 is expected to decline by 28% by 2100. We annualize the decline by assuming that agricultural yield growth relative to 2005 declines by 10% in 2025, by 20% in 2065, and by 25% in 2085.

For scenario E, the steeper growth rate of liquid fossil fuels costs is taken from the U.S. Energy Information Administration High Oil Price case scenario for 2035 projections (EIA 2010a, p. 86, Table 10).

Designing the global emissions target scenario, T, is difficult, because no country currently has a comprehensive scheme for regulating aggregate land-use emissions, although some countries will likely implement such schemes in the near future.[18] We set the land-use emissions' target in 2100 to 50% less

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

[18] In 2008 New Zealand passed legislation to include commercial forestry sector in the emissions trading scheme. Regulation of other land-use emissions is expected to take place in 2015 (Source: the New Zealand's Ministry of Agriculture and Forestry website: `www.maf.govt.nz`). In 2010 the European Commission launched a public consultation on whether emissions and removals of greenhouse gases related to land use, land use change and forestry (LULUCF) should be covered by the EU's target of cutting GHG emissions to 30% below 1990 levels by 2020 (Source: the European Commission's website: `http://ec.europa.eu/commission\_2010-2014/hedegaard/headlines/news/2010-09-10\_01\_en.htm`).

compared to 2004. Its stringency increases rapidly after 2025 when the target is introduced, with larger GHG emissions' reductions taking place by 2050. This approach is consistent with the European Commission's projections to achieve a competitive low-carbon economy by 2050 (European Commission 2011).[19] The global warming intensity, $\theta_{zt}(z_{L0}, t)$ defining the land-use GHG emissions' target is a logistic function:

$$\theta_t^z = \frac{z_T^L z_\tau^L e^{\zeta t}}{z_T^L + z_\tau^L (e^{\zeta t} - 1)}, \tag{51}$$

where z_τ^L are land-use emissions in 2025, z_T^L is the land-use emissions cap in 2104, and ζ is the targeted rate of decline in land-use GHG emissions. We calculate GHG emissions from land-use in 2005 based on equation (35) using GHG emissions coefficients discussed in section 4.10.[20]

5.2 Results of Counterfactual Scenarios

Figures 2, 3, and 4 describe the results of simulations of changes in the optimal allocation of global land-use, GHG emissions, consumption of goods and services that draw on land resources, and consumption of biofuels for scenarios A, AE, and AET. For scenario A, we report changes, which are incremental to the model baseline. For scenario AE, we report incremental changes to scenario A. For scenario AET, we report incremental changes to scenario AE. The results for scenarios E and T are not described in this section, as they are numerically close to reported incremental changes for scenarios AE and AET. We show the results for scenarios E and T in the technical appendix (Tables 4 and 5).

5.2.1 Scenario A: Declining Growth of Agricultural Yield

Figure 2 describes the results of simulations of changes relative to the model baseline for the counterfactual scenario A corresponding to the gradual decline in the rate of growth of agricultural yield starting in 2025. The upper left-hand panel in Figure 2 shows the results for changes in allocation of land use relative to the baseline scenario. Declining agricultural productivity results in greater requirements for cropland and fertilizers to produce agricultural output used in

[19] Specifically, the European Commission's analysis shows that by 2050 the European agriculture sector can reduce non-CO2 emissions by between 42 and 49% compared to 1990 (European Commission 2011, p. 9.).

[20] The targeted rate of decline in land-use GHG emissions is calculated based on equations (37) and (51), and calibrated to represent rapid introduction of the emissions target.

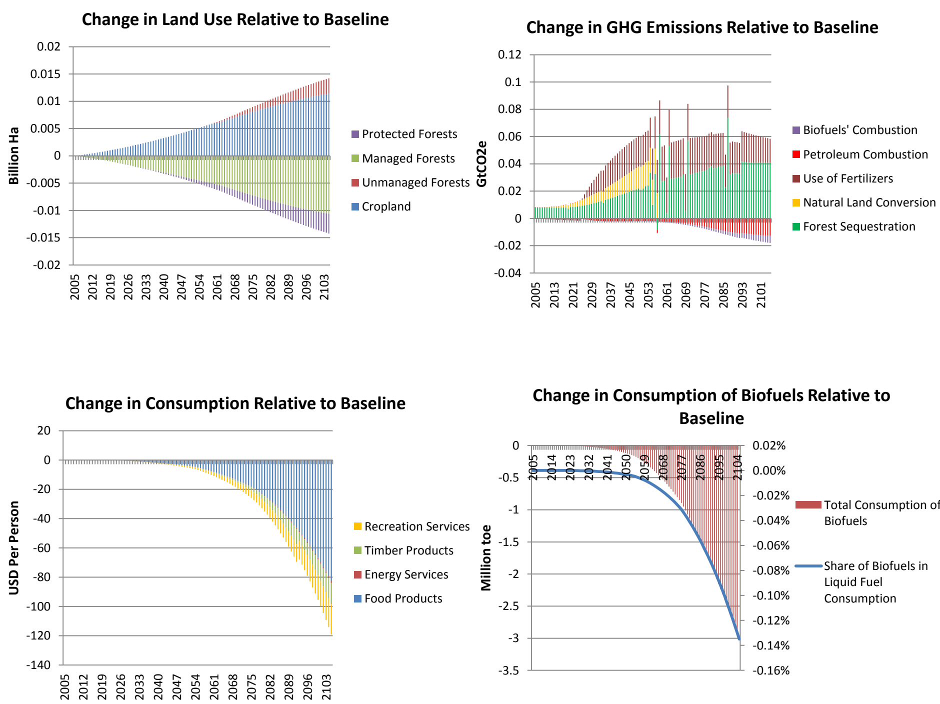

Figure 2: Scenario A: Declining Agricultural Yield

production of food and energy services. However, the expansion of cropland is relatively small. Compared to the baseline scenario, the cropland area expands further by 4.5 million hectares (0.25 percent) in 2050 and by 11 million hectares (0.75 percent) in 2100. Managed forest area declines by 4 million hectares in 2050 and by 10 million hectares in 2104. In addition, protected forest area declines by 0.5 million hectares in 2050 and by 3 million hectares in 2100. Modest increase in use of cropland relative to the baseline scenario is explained by a significant decline in agricultural output and an increased use of fertilizers (see Tables 4 and 5, technical appendix). In 2100 the production of agricultural output falls by 46 million tons (7 percent), whereas application of fertilizers increases by 13 million tons (2 percent).

The upper right-hand panel in Figure 2 shows the results for changes in gross GHG emissions relative to the baseline scenario. The effect of declining agricultural productivity results in an increase in GHG emissions from more use of fertilizers, natural land conversion, and reduced forest sequestration. In the short- and medium- run, the increase in GHG emissions comes from the natural land conversion, which occurs in response to an anticipated decline in agricultural yield. In 2050 the GHG emissions from the natural land conversion are 17 $MtCO_2e$ (2 percent) larger relative to the baseline scenario. In the medium- and long-run the increase in GHG emissions also comes from expansion in fertilizers' use and reduced forest sequestration. Compared to the baseline scenario, the GHG emissions from fertilizers' use and forest sequestration increase by 22 and 21 $MtCO_2e$ in 2050, and by 20 and 41 $MtCO_2e$ (2 and 1 percent) in 2100. There is also a small decline in long run GHG emissions from the reduced demand for energy services.

The lower left-hand panel in Figure 2 shows the results for changes in per-capita consumption of goods and services that draw on land resources. Compared to the baseline scenario consumption of all goods and services decreases. There is a significant decline in the consumption of processed food services. In 2100 their per capita consumption is about 7 percent lower than in the baseline scenario. The reduction in consumption of services of energy, timber products, and recreation is small. Compared to the baseline scenario they decline by less than 1 percent.

The lower right-hand panel in Figure 2 shows the results for changes in biofuels. Declining agricultural productivity depresses production of biofuels. In 2100 the total consumption of biofuels decreases by 2.5 million toe (13 percent) compared to the baseline scenario. The share of biofuels in liquid fuel consumption declines, and amounts to 0.8 percent of total liquid fuel consumption in 2100.

5.2.2 Scenario AE: Declining Growth of Agricultural Yield *and* Rising Fossil Fuel Costs

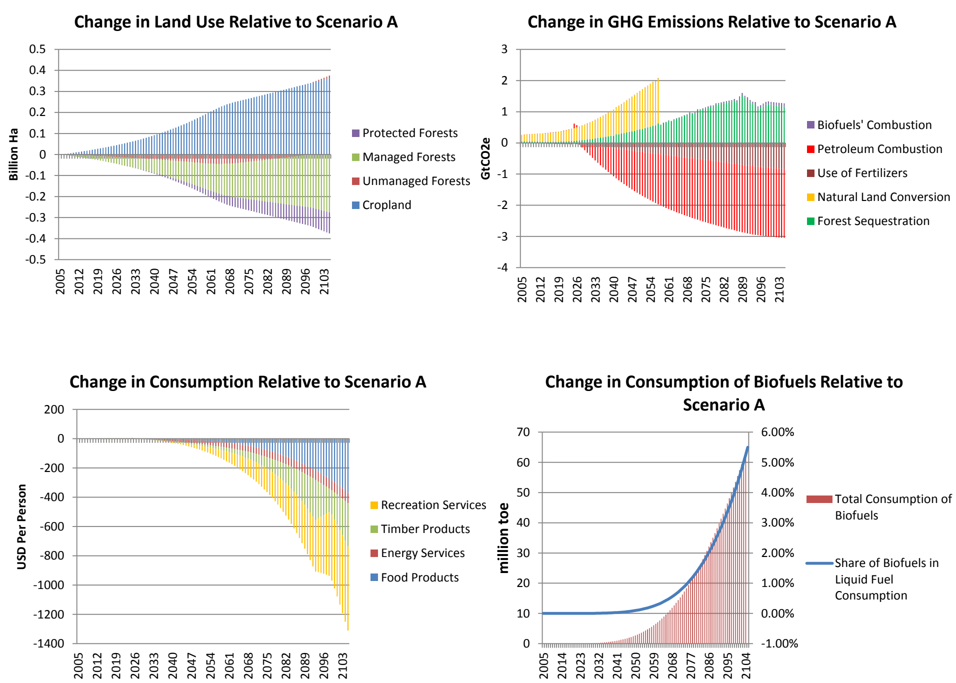

Figure 3: Scenario AE: Declining Agricultural Yield and Rising Fossil Fuel Costs

Figure 3 describes the results of simulations of changes for the counterfactual scenario AE relative to the scenario A. This adds the effect of permanent increase in the rate of growth in liquid fossil fuel costs to the effect of a permanent decline in the rate of growth of agricultural yield starting in 2025. The upper left-hand panel in Figure 3 shows the results for changes in allocation of land use relative to the scenario A. Rising oil and natural gas prices increase the costs of fertilizers and petroleum consumption. As biofuels substitute for fossil fuels in demand for energy services, the demand for biofuels increases. This, in turn, increases the demand for cropland needed to produce the feedstock. Cropland requirements also rise due to the increased cost of fertilizer – a key ingredient in the intensification of agricultural production. Compared to the scenario A, the cropland area expands by additional 138 million hectares (8 percent) in 2050. The expansion of cropland comes at the expense of forest area. Managed forest area declines by 91 million hectares (5.5 percent), and the unmanaged and protected forest areas decline by respectively 32 and 15 million hectares (1.5 and 6 percent). In the long run, the cropland area continues to expand, adding 347 million hectares (24 percent) more relative to scenario A in 2104. Managed and protected forests continue to decline in the long-run, losing additional 258, and 92 million hectares (13 and 14 percent), whereas unmanaged forest area increases by 3 million hectares (less than 1 percent) relative to scenario A in 2100.

The upper right-hand panel in Figure 3 shows the results for changes in gross GHG emissions. Preceding the anticipated increase in energy prices the increase GHG emissions comes mainly from deforestation, caused by conversion of natural and managed forest areas to cropland. In 2025 the GHG emissions from natural land conversion increase by 0.41 $GtCO_2e$ (13 percent) compared to the scenario A. In the medium run, GHG emissions from deforestation continue to increase, whereas GHG emissions from petroleum and fertilizer consumption decline. In 2050 the GHG emission flows from natural land conversion and reduced forest sequestration increase by 1.22 and 0.43 $GtCO_2e$ (127 and 17 percent) compared to the scenario A. GHG emissions from petroleum combustion, and fertilizers' use reduce by 1.37, and 0.28 $GtCO_2e$ (13.5 and 16 percent) compared to baseline scenario. In the long run, as natural land conversion ceases, the increase in GHG comes from reduced forest sequestration and combustion of biofuels. In 2100 these emissions account for an additional 1.22 $GtCO_2e$ and 96 $MtCO_2e$ (20 and 329 percent) compared to the scenario A. GHG emissions from petroleum combustion, and fertilizers' production and application fall by 2.2 and 0.8 $GtCO_2e$ (37 and 68 percent) compared to the scenario A.

The lower left-hand panel in Figure 3 shows the results for changes in per-capita consumption of goods and services that draw on land resources. Compared to the scenario A consumption of all goods and services decrease. In 2100 the most significant decline is in consumption of services from processed food products and energy. Consumption of both declines by 31 percent, compared to the scenario A. Consumption of recreation services falls by 14%, whereas the consumption of services of timber products decreases by 5.5% compared to the scenario A.

The lower right-hand panel in Figure 3 shows the results for changes in biofuels. Higher oil prices increase the demand for biofuels, and by 2100 their total consumption increases drastically by additional 55 million toe (329 percent) compared to the scenario A. The share of biofuels in liquid fuel consumption raises significantly, and accounts to 5 percent of total liquid fuel consumption.

5.2.3 Scenario AET: Declining Growth of Agricultural Yield *and* Rising Fossil Fuel Costs *and* Land-Use Emissions Target

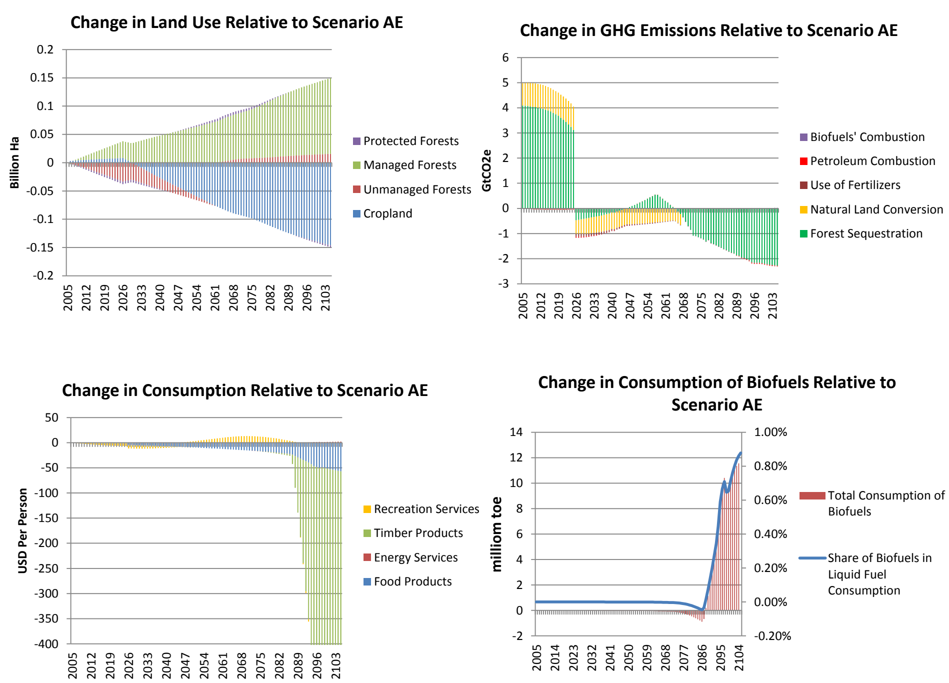

Figure 4: Scenario AET: Declining Growth of Agricultural Yield *and* Rising Fossil Fuel Costs *and* Land-Use Emissions Target

Figure 4 describes the results of simulations of changes relative to the scenario AE for the counterfactual scenario AET. This figure illustrates the effect of adding the land-use GHG emissions constraint to the effects of a permanent increase in the rate of growth in liquid fossil fuel costs and permanent decline in the rate of growth of agricultural yield to starting in 2025. The upper left-hand panel in Figure 4 shows the results for changes in allocation of land use relative to the scenario AE. Introduction of a land-use GHG emissions constraint has an intertemporal effect on allocation of global land use. As natural forest land conversion to agricultural land is the main short-term driver of GHG emissions from land-use, further expansion of agricultural land becomes more difficult after the GHG constraint is introduced. Therefore, in anticipation of GHG emissions target, there is a short-term increase in demand for conversion of natural forest land. Compared to the scenario AE, the cropland area expands by additional 8 million hectares (0.5 percent) in 2025. The demand for managed forest land also increases, as imposition of GHG emissions constraint requires greater sequestration by managed forests. In 2025 managed forest area expands by 28 million hectares (2 percent). The expansion of agricultural and managed forest area puts greater pressure on natural lands. Unmanaged and protected forest areas decline by respectively 32 and 4 million hectares (1 and 2 percent) in 2025. In the medium- and long-run, as the GHG emissions target becomes more stringent, there an increase in managed forest area used for GHG sequestration. Compared to the scenario AE, the managed forest area expands further by 59 million hectares (4 percent) in 2050 and by 128 million hectares (7.5 percent) in 2100. Most of the increase in the managed forest area is compensated by the reduction in cropland. The cropland area declines by 50 million hectares (2.5 percent) in 2050 and by 140 million hectares (8 percent) 2100. Natural land conversion declines in relative terms after 2025. Compared to the scenario AE, unmanaged forest area increases by 14.5 million hectares (1 percent) in 2100.

The upper right-hand panel in Figure 4 shows the results for changes in gross GHG emissions. Preceding the introduction of the GHG emissions constraint, there is a large increase in GHG emissions, which increases the GHG emissions stock and significantly reduces the effectiveness of the target. Two factors contribute to this increase. First, there is an increased conversion of natural forest lands. Second, GHG sequestration by managed forests decline, driven by the change in the vintage structure of managed forests. In 2025 the GHG emissions from natural land conversion and reduced forest sequestration increase by 0.92 and 3.12 $GtCO_2e$ (26 and 134 percent) compared to the scenario AE. After the introduction of the GHG emissions constraint, the GHG emissions from land use decline. In the medium run, the main source of reduction in GHG emission is due to decline in natural land conversion, which amounts to 0.61 $GtCO_2e$ (28 percent) in 2050, compared to the scenario AE. In the long-run, increased GHG sequestration by managed forests is the main factor contributing to the reduction in GHG emissions. Compared to the scenario AE, the reduction in GHG emissions due to increased forest sequestration amounts to 2.2 $GtCO_2e$ (46 percent) in 2100. Introduction of GHG target also results in a modest decline of consumption of petroleum and fertilizers, and a modest increase in consumption of biofuels. The GHG emissions from petroleum combustion and fertilizers' use decline by 26 and 19 MtCO_2e (0.7 and 5 percent) in 2100. The GHG emissions from biofuels combustion increase by 17 MtCO_2e (14 percent) in 2100.

Overall, in the presence of intertemporal substitution, the land based GHG emissions target appears to be ineffective over the term of 100 years. After the introduction of the constraint, the GHG emissions from land use decline by 88.7 GtCO_2e. However, preceding the introduction of the constraint, cumulative GHG emissions from land use increase by 98.7 GtCO_2e, generating the intertemporal leakage of 111 percent.[21] This finding is consistent with the theory of "green paradox", which originates from intertemporal models analyzing climate policy effects on the optimal path of fossil fuel extraction (Sinn 2008, Eichner and Pethig 2011).

The lower left-hand panel in Figure 4 shows the results for changes in per-capita consumption of goods and services that draw on land resources. Compared to the scenario AE consumption of all goods and services does not change much in the short- and the medium-run. In the long run, there is a significant decline in consumption of services from processed food and timber. In 2100 they decline by 8 and 19 percent compared to the scenario AE. The expansion of biofuels sector leads to the growth in consumption of energy services, which increase by 1 percent in 2100, as compared to the scenario AE. The consumption of recreation services declines modestly by 0.5 percent.

The lower right-hand panel in Figure 4 shows the results for changes in biofuels. Introduction of GHG emissions constraint favours the displacement of petroleum for biofuels. This effect is small in the short- and medium-run. However, in the long run there is a significant increase in the consumption of biofuels. In 2100 the total consumption of biofuels increases by additional 10 million toe (14 percent) compared to the scenario AE. The share of biofuels in liquid fuel consumption also raises, and accounts to 6 percent of total liquid fuel consumption.

[21] The size of intertemporal leakage is reduced to 33 percent over the period of 200 years.

6 Conclusions

We analyze the optimal allocation of the world's land resources over the course of the next century in the unified economic framework, which integrates five, rather distinct strands of literature into a single, intertemporally consistent, analytical model at global scale. 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. We also consider 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 run. In the long-run there is a significant expansion of the forestry sector, and the area of protected natural lands, which deliver eco-system services, increases drastically. While the consumption of biofuels increases rapidly in the long-run, its share in gross liquid fuel consumption remains insignificant.

We then consider three counterfactual scenarios for changes in factors corresponding to the most important sources of uncertainty associated with this problem: energy prices, agricultural productivity, and global GHG emissions regulations. Though adverse productivity shocks from climate change have a modest effect on global land use, consumption of agricultural output declines significantly in the long-run. Energy prices and policies have a significant effect on the optimal deforestation rate and on the overall amount of land used in agriculture. In the long-run, cropland area increases drastically, and substantial deforestation occurs. The GHG emissions from land use also increase significantly, offsetting the emissions fall from reduced petroleum consumption. When we also expect the world's land base to deliver land-based GHG abatement, the pressure on global natural land resources becomes even more significant. While the introduction of the land based GHG emissions constraint leads to a significant reduction in GHG emission flows over the term of hundred years, its effectiveness is eroded by an even greater increase in GHG emissions before such constraint is introduced.

In further work it will be interesting to extend the scope of this study by (1) by explicitly incorporating uncertainty in the model's optimization stage; (2) incorporating the livestock sector and pasture lands; and (3) exploring the model's sensitivity to other important uncertainty sources, such as the economy's TFP and biofuels' production technology.

References

Antoine, B., Gurgel, A. and Reilly, J.: 2008, Will Recreation Demand for Land Limit Biofuels Production?, *Journal of Agricultural & Food Industrial Organization* **6**(2), 5.

Babiker, M., Gurgel, A., Paltsev, S. and Reilly, J.: 2009, Forward-looking versus Recursive-dynamic Modeling in Climate Policy Analysis: A Comparison, *Economic Modelling* **26**(6), 1341–1354.

Bucci, A. and Guerrini, L.: 2009, Transitional Dynamics in the Solow-Swan Growth Model with AK Technology and Logistic Population Change, *The BE Journal of Macroeconomics* **9**(1), 43.

Bulte, E., van Soest, D., Van Kooten, G. and Schipper, R.: 2002, Forest Conservation in Costa Rica when Nonuse Benefits are Uncertain but Rising, *American Journal of Agricultural Economics* **84**(1), 150–160.

Burney, J., Davis, S. and Lobell, D.: 2010, Greenhouse Gas Mitigation by Agricultural Intensification, *Proceedings of the National Academy of Sciences* **107**(26), 12052–12057.

Cassman, K., Grassini, P. and van Wart, J.: 2010, Crop Yield Potential, Yield Trends, and Global Food Security in a Changing Climate, *in* D. Hillel and C. Rosenzweig (eds), *Handbook of Climate Change and Agroecosystems*, Imperial College Press, pp. 37–51.

Chakravorty, U., Hubert, M., Moreaux, M. and Nostbakken, L.: 2011, Will Biofuel Mandates Raise Food Prices?, *Working Paper 2011-01*, Department of Economics, University of Alberta.

Choi, S., Ohrel, S. and Sohngen, B.: 2011a, Extending the GTAP Family of Models: A Partial Equilibrium Approach to Measuring the Costs of Carbon Sequestration and Avoided Deforestation, Selected Paper Prepared for Presentation at the GTAP 2011 Annual Meeting Venice, Italy.

Choi, S., Sohngen, B., Rose, S., Hertel, T. and Golub, A.: 2011b, Total Factor Productivity Change in Agriculture and Emissions from Deforestation, *American Journal of Agricultural Economics* **93**(2), 349 –355.

Conrad, J.: 1997, On the Option Value of Old-growth Forest, *Ecological Economics* **22**(2), 97–102.

Conrad, J.: 2000, Wilderness: Options to Preserve, Extract, or Develop, *Resource and Energy Economics* **22**(3), 205–219.

Cranfield, J., Eales, J., Hertel, T. and Preckel, P.: 2003, Model Selection when Estimating and Predicting Consumer Demands using International, Cross Section Data, *Empirical Economics* **28**(2), 353–364.

Cubbage, F., Koesbandana, S., Mac Donagh, P., Rubilar, R., Balmelli, G., Olmos, V., De La Torre, R., Murara, M., Hoeflich, V., Kotze, H. et al.: 2010, Global Timber Investments, Wood Costs, Regulation, and Risk, *Biomass and Bioenergy* **34**(12), 1667–1678.

Deaton, A. and Muellbauer, J.: 1980, An Almost Ideal Demand System, *The American Economic Review* **70**(3), 312–326.

EIA: 2010a, Annual Energy Outlook, *Publication DOE/EIA-0383*, U.S. Department of Energy.

EIA: 2010b, International Energy Outlook, *Publication DOE/EIA-0484*, U.S. Department of Energy.

Eichner, T. and Pethig, R.: 2011, Carbon Leakage, the Green Paradox and Perfect Future Markets, *International Economic Review* **52**(3), 767–805.

European Commission: 2011, A Roadmap for Moving to a Competitive Low Carbon Economy in 2050, *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions COM(211) 112 Final*, European Commission.

FAO: 2010, Global Forest Resources Assessment 2010, *FAO Forestry Paper 163*, Food and Agriculture Organization of the United Nations.

Farrell, A., Plevin, R., Turner, B., Jones, A., O'Hare, M. and Kammen, D.: 2006, Ethanol Can Contribute to Energy and Environmental Goals, *Science* **311**(5760), 506.

Fearnside, P.: 2000, Global Warming and Tropical Land-use Change: Greenhouse Gas Emissions from Biomass Burning, Decomposition and Soils in Forest Conversion, Shifting Cultivation and Secondary Vegetation, *Climatic Change* **46**(1), 115–158.

Golub, A., Hertel, T. and Sohngen, B.: 2009, Land Use Modeling in Recursively-Dynamic GTAP Framework, *in* T. Hertel, S. Rose and R. Tol (eds), *Economic Analysis of Land Use in Global Climate Change Policy*, Routledge, pp. 235–278.

Gouel, C. and Hertel, T.: 2006, Introducing Forest Access Cost Functions into a General Equilibrium Model, *GTAP Research Memorandum 8*, Center for Global Trade Analysis, Purdue University.

Guerrini, L.: 2006, The Solow-Swan Model with a Bounded Population Growth Rate, *Journal of Mathematical Economics* **42**(1), 14–21.

Guerrini, L.: 2010, A Closed-form Solution to the Ramsey Model with Logistic Population Growth, *Economic Modelling* **27**(5), 1178–1182.

Gurgel, A., Cronin, T., Reilly, J., Paltsev, S., Kicklighter, D. and Melillo, J.: 2011, Food, Fuel, Forests and the Pricing of Ecosystem Services, *American Journal of Agricultural Economics* **92**(2), 342–348.

Gurgel, A., Reilly, J. and Paltsev, S.: 2007, Potential Land Use Implications of a Global Biofuels Industry, *Journal of Agricultural & Food Industrial Organization* **5**(2), 1–34.

Hanoch, G.: 1975, Production and Demand Models with Direct or Indirect Implicit Additivity, *Econometrica* **43**(3), 395–419.

Hartley, P., Medlock III, K. and Rosthal, J.: 2008, The Relationship of Natural Gas to Oil Prices, *The Energy Journal* **29**(3), 47–66.

Hertel, T.: 1997, *Global Trade Analysis: Modeling and Applications*, Cambridge University Press.

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

Hertel, T., Rose, S. and Tol, R.: 2009, *Economic Analysis of Land Use in Global Climate Change Policy*, Routledge.

Hertel, T., Stiegert, K. and Vroomen, H.: 1996, Nitrogen-land Substitution in Corn Production: a Reconciliation of Aggregate and Firm-level Evidence, *American Journal of Agricultural Economics* **78**(1), 30–40.

Hertel, T., Tyner, W. and Birur, D.: 2010b, The Global Impacts of Biofuel Mandates, *The Energy Journal* **31**(1), 75–100.

Houghton, R.: 2003, Revised Estimates of the Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use and Land Management 1850–2000, *Tellus B* **55**(2), 378–390.

Ianchovichina, E., Darwin, R. and Shoemaker, R.: 2001, Resource Use and Technological Progress in Agriculture: a Dynamic General Equilibrium Analysis, *Ecological Economics* **38**(2), 275–291.

IPCC: 2000, Summary for Policymakers, *in* N. Nakićenović, J. Alcamo, G. Davis, B. De Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, T. Jung, T. Kram et al. (eds), *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press.

IPCC: 2006a, Chemical Industry Emissions, *in* H. Eggleston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe (eds), *IPCC Guidelines for National Greehnouse Gas Inventories, Volume 3*, The Intergovernmental Panel on Climate Change, pp. 3.1–3.110.

IPCC: 2006b, N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application, *in* H. Eggleston, L. Buendia, K. Miwa, T. Ngara and K. Tanabe (eds), *IPCC Guidelines for National Greehnouse Gas Inventories, Volume 4*, The Intergovernmental Panel on Climate Change, pp. 4.1–4.54.

IPCC: 2007, Summary for Policymakers, *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor and H. Miller (eds), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–18.

Jorgenson, D. and Vu, K.: 2010, Potential Growth of the World Economy, *Journal of Policy Modeling* **32**(5), 615–631.

Lee, H., Hertel, T., Rose, S. and Avetisyan, M.: 2009, An Integrated Global Land Use Data Base for CGE Analysis of Climate Policy Options, *in* T. Hertel, S. Rose and R. Tol (eds), *Economic Analysis of Land Use in Global Climate Change Policy*, Routledge, pp. 72–88.

Leroux, A., Martin, V. and Goeschl, T.: 2009, Optimal Conservation, Extinction Debt, and the Augmented Quasi-option Value, *Journal of Environmental Economics and Management* **58**(1), 43–57.

Lobell, D., Schlenker, W. and Costa-Roberts, J.: 2011, Climate Trends and Global Crop Production Since 1980, *Science* **(forthcoming)**.

Narayanan, B. and Walmsley, T.: 2008, *Global Trade, Assistance, and Production: The GTAP 7 Data Base*, Center for Global Trade Analysis, Purdue University.

Nordhaus, W.: 2008, *A Question of Balance: Weighing the Options on Global Warming Policies*, Yale University Press.

Richards, K. and Stokes, C.: 2004, A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research, *Climatic Change* **63**(1), 1–48.

Rimmer, M. and Powell, A.: 1996, An Implicitly Additive Demand System, *Applied Economics* **28**(12), 1613–1622.

Rutherford, T.: 2002, Lecture Notes on Constant Elasticity Functions, `http://www.gamsworld.org/mpsge/debreu/ces.pdf`. [Online; accessed 14-April-2011].

Searchinger, T., Heimlich, R., Houghton, R., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. and Yu, T.: 2008, Use of US Croplands for Biofuels

Increases Greenhouse Gases through Emissions from Land-Use Change, *Science* **319**(5867), 1238.

Sedjo, R.: 1983, *The Comparative Economics of Plantation Forestry: A Global Assessment*, Johns Hopkins University Press.

Sinn, H.: 2008, Public Policies Against Global Warming: a Supply Side Approach, *International Tax and Public Finance* **15**(4), 360–394.

Sohngen, B., Golub, A. and Hertel, T.: 2009a, The Role of Forestry in Carbon Sequestration in General Equilibrium Models, *in* T. Hertel, S. Rose and R. Tol (eds), *Economic Analysis of Land Use in Global Climate Change Policy*, Routledge, pp. 279–303.

Sohngen, B. and Mendelsohn, R.: 2003, An Optimal Control Model of Forest Carbon Sequestration, *American Journal of Agricultural Economics* **85**(2), 448–457.

Sohngen, B. and Mendelsohn, R.: 2007, A Sensitivity Analysis of Forest Carbon Sequestration, *in* M. Schlesinger (ed.), *Human-Induced Climate Change: An Interdisciplinary Assessment*, Cambridge University Press, pp. 227–237.

Sohngen, B., Tennity, C., Hnytka, M. and Meeusen, K.: 2009b, Global Forestry Data for the Economic Modeling of Land Use, *in* T. Hertel, S. Rose and R. Tol (eds), *Economic Analysis of Land Use in Global Climate Change Policy*, Routledge, pp. 49–71.

Sorrell, S. and Dimitropoulos, J.: 2008, The Rebound Effect: Microeconomic Definitions, Limitations and Extensions, *Ecological Economics* **65**(3), 636–649.

Stavins, R.: 1999, The Costs of Carbon Sequestration: A Revealed-preference Approach, *The American Economic Review* **89**(4), 994–1009.

Taheripour, F. and Tyner, W.: 2011, Introducing First and Second Generation Biofuels into GTAP Data Base Version 7, *GTAP Research Memorandum 21*, Center for Global Trade Analysis, Purdue University.

United Nations Department of Economic and Social Affairs Population Division: 2011, World Population Prospects: The 2010 Revision, `http://esa.un.org/unpd/wpp/index.htm`. [Online; accessed 10-June-2011].

USGAO: 2003, Natural Gas: Domestic Nitrogen Fertilizer Production Depends on Natural Gas Availability and Prices, *Report to the Ranking Democratic Member, Committee on Agriculture, Nutrition and Forestry, U.S. Senate GAO-03-1148*, United States General Accounting Office.

Van Der Werf, E. and Peterson, S.: 2009, Modeling Linkages between Climate Policy and Land Use: an Overview, *Agricultural Economics* **40**(5), 507–517.

Winston, A.: 2009, Enhancing Agriculture and Energy Sector Analysis in CGE Modelling: An Overview of Modifications to the USAGE Model, *Centre of Policy Studies/IMPACT Centre Working Paper G-108*, Monash University, Centre of Policy Studies/IMPACT Centre.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S., Janetos, A. and Edmonds, J.: 2009, Implications of Limiting CO2 Concentrations for Land Use and Energy, *Science* **324**(5931), 1183.

World Energy Council: 2008, *Energy Efficiency Policies around the World: Review and Evaluation*, World Energy Council, London, UK.

Yu, W., Hertel, T., Preckel, P. and Eales, J.: 2004, Projecting World Food Demand Using Alternative Demand Systems, *Economic Modelling* **21**(1), 99–129.

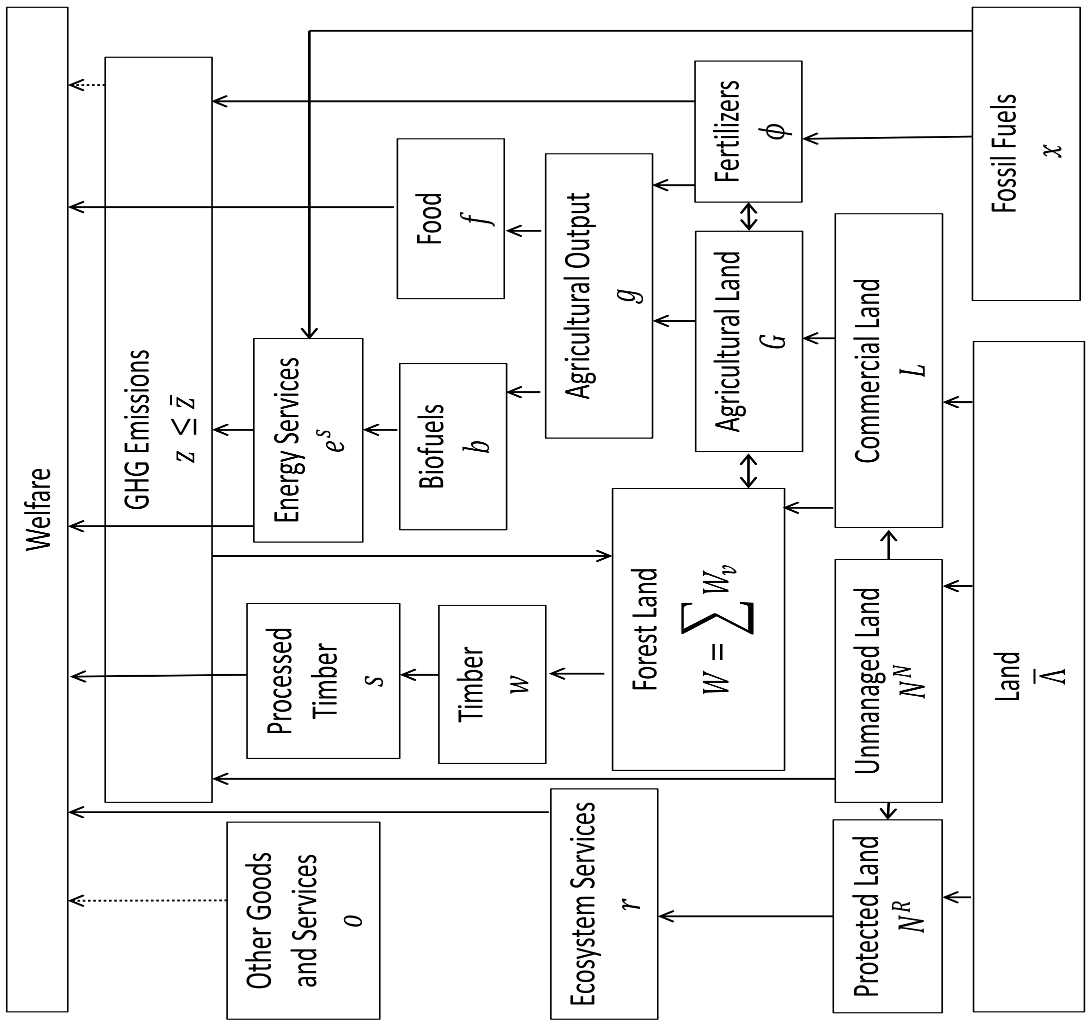

Figure 1: Structure of the Economy

Dynamic Land-Use Model Equations:

Land Use

$$\Lambda_t = \frac{\overline{\Lambda}}{\Pi_t} = N_t + L_t \tag{A.1}$$

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

$$N_{t+1}^N = N_t^N - \Delta L_t - \Delta N_t^R,\ N_0 > 0 \tag{A.3}$$

$$N_{t+1}^R = N_t^R + \Delta N_t^R,\ N_0^R > 0 \tag{A.4}$$

$$c_{t+1}^N = \xi_0^n - \xi_1^n \ln\left(\frac{N_{t+1}^N}{N_0^N}\right) + \xi_2^n \left(\frac{N_{t+1}^N - N_t^N}{N_t^N}\right)^2 \tag{A.5}$$

$$c_t^R = \xi_0^R + \xi_1^R \left(N_{t+1}^R - N_t^R\right)^2 \tag{A.6}$$

$$L_t = G_t + W_t \tag{A.7}$$

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

Fossil Fuels

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

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

Agrochemical Sector

$$\phi_t = \theta^\phi x_t^\phi \tag{A.11}$$

Agricultural Sector

$$g_t = \theta_t^g \left[\alpha^g \left(G_t\right)^{\rho_g} + \left(1 - \alpha^g\right)\left(\phi_t\right)^{\rho_g}\right]^{\frac{1}{\rho_g}} \tag{A.12}$$

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

Food Processing Sector

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

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

Biofuels Sector

$$b_t = \theta^b \left(g_t - \frac{f_t}{\theta^f_t} \right) \tag{A.16}$$

Energy Sector

$$e^f_t = \gamma^e \left(\alpha^b \left(b_t\right)^{\rho_b} + \left(1 - \alpha^b\right) \left(x^e_t\right)^{\rho_b} \right)^{\frac{1}{\rho_b}} \tag{A.17}$$

$$e^s_t = \theta^e_t e^f_t \tag{A.18}$$

$$\theta^e_{t+1} = \kappa_e \theta^e_t,\ \theta^e_0 > 0 \tag{A.19}$$

$$c^e_t = c^b_t + c^x_t \tag{A.20}$$

Forestry Sector

$$W_t = \sum_{v=1}^{V} W_{v,t} \tag{A.21}$$

$$\begin{aligned} W_{v+1,t+1} &= W_{v,t} - H_{v,t},\ v < V \\ W_{V,t+1} &= \sum_{V-1}^{V} W_{v,t} - H_{v,t} \end{aligned} \tag{A.22}$$

$$W_{1,t+1} = W^p_t \tag{A.23}$$

$$w_t = \sum_{v=1}^{V-1} \theta^w_{v,t} H_{v,t} + \theta^w_{V,t} \left(H_{V,t} + \Delta L_t\right) \tag{A.24}$$

$$\theta^w_{v,t+1} = \theta^w_{v,t} + \kappa^w_v, \theta^w_{v,0} > 0 \tag{A.25}$$

$$c^w_t = \xi^w_0 \sum\nolimits_v \frac{H_{v,t}}{\theta^w_{v,t}} + \xi^w_1 \left(\sum\nolimits_v H_{v,t+1} - \sum\nolimits_v H_{v,t} \right)^2 + \xi^w_2 \left(\sum\nolimits_v H_{v,t} - W^p_t \right)^2 \tag{A.26}$$

Timber Processing Sector

$$s_t = \theta^s_t w_t \tag{A.27}$$

$$\theta_{t+1}^{s} = \kappa_s \theta_t^s,\ \theta_0^s > 0 \tag{A.28}$$

Recreation Sector

$$r_t = \theta_t^r N_t^R \tag{A.29}$$

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

Other Goods and Services Sector

$$o_t = \theta_t^o o_0 \tag{A.31}$$

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

GHG Emissions

$$z_t = z_t^x + z_t^L \tag{A.33}$$

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

$$z_t^L = \mu^L \Delta L_t + \mu^\phi x_t^\phi + (1-\varphi) \sum_{v=1}^{V} \mu_v^h H_{v,t} - \sum_{v=1}^{V} \mu_v^w W_{v,t}. \leq \overline{z}_t^L \tag{A.35}$$

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

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

$$\Omega = \sum_{t=0}^{T-1} \delta^t \left[\begin{array}{c} \displaystyle\sum_{q=f,e,s,r,o} \int_0^{q^*} \left(p_q\left(q\right) - c_q\left(q\right)\right) dq \\ -c_t^N - c_t^R - c^\phi \phi_t - c^g g_t - c^p W_t^p - c_t^w \end{array} \right] + \delta^T \Gamma\left(N_T^N, W_T\right) \tag{A.39}$$

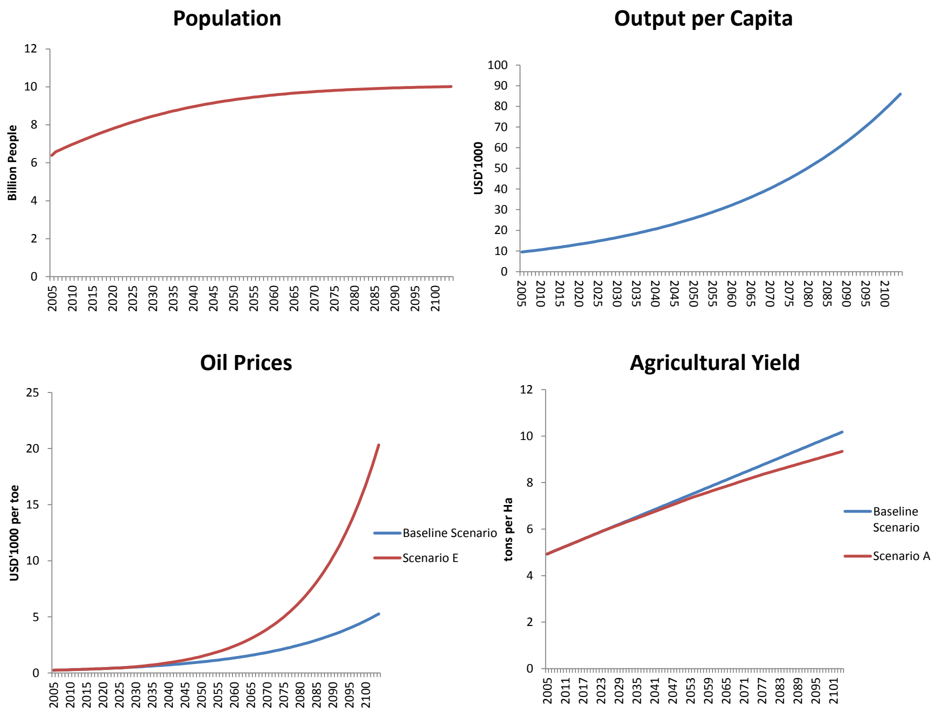

Figure 2: Projections of Exogenous Variables, 2005-2104

Table 1: Model Variables

Coefficient	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
θ_t^g	Agricultural Yield	tons per Ha
θ_t^f	Food Processing TFP	
θ_t^e	Energy Efficiency	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 TFP	
θ_t^r	Recreation Sector TFP	Ecosystem Services per Ha
θ_t^o	Total Factor Productivity	
o_t	Other Goods and Services	USD Trillion
μ_v^w	Carbon Sequestration by Forest Vintages	tCO_2e per Ha
θ_t^z	Land-Use GHG Emissions Quota	$GtCO_2e$
Endogenous Variables		
G_t	Agricultural Land Area	GHa
W_t	Commercial Forest Land Area	GHa
N_t^N	Unmanaged Natural Lands	GHa
ΔL_t	Converted Natural Lands per annum	GHa
N_t^R	Protected Natural Lands	GHa
ΔN_t^R	Flow of Protected Natural Lands per annum	GHa
W_t^p	Replanted Forest Land Area	GHa
$H_{v,t}$	Harvested Forest Land Area of Vintage v	GHa
x_t	Fossil Fuels	Gtoe
x_t^e	Petroleum Combusted	Gtoe
x_t^ϕ	Fossil Fuels Allocated to Fertilizers	Gtoe
ϕ_t	Fertilizers Produced	Gton
g_t	Agricultural Product	Gton
f_t	Processed Food Products	Gton
b_t	Biofuels	Gton
e_t^s	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 2: Baseline Parameters

Coefficient	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			
$\overline{\Lambda}$	Total Land Area	Billion Ha	5.83
G_0	Area of Agricultural Land in 2004	Billion Ha	1.533
W_0	Area of Commercial Forest Land in 2004	Billion Ha	1.62
N_0^N	Area of Unmanaged Natural Land in 2004	Billion Ha	2.47
N_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		90,000
ξ_0^R	Protection Cost Function Parameter		65
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^ϕ	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

Table 2: Baseline Parameters (continued)

Coefficient	Description	Units	Value
Agrochemical Sector			
c_ϕ	Non-Energy Fertilizer Costs	1000USD/ton	0.137
x_0^ϕ	Fertilizers' Consumption in 2004	Billion ton	0.937
θ_t^ϕ	Fertilizer's Conversion rate	ton/toe	1.07
Agricultural Sector			
θ_0^g	Agricultural Yield in 2004	tons / Ha	4.93
κ_g	Agricultural Yield Growth Rate per annum		0.053
c^g	Agricultural Production Cost	1000USD/ton	0.118
σ_g	Elasticity of Substitution between Land and Fertilizers		1.14
α^g	Share of Commercial Land in CES function		0.53
ρ_g	CES Parameter for Land and Fertilizers		0.123
Food Processing Sector			
θ_0^f	Food Processing TFP in 2004		1.5
κ_f	Food Processing TFP Growth Rate per annum		0.022
c^f	Food Processing Cost	1000USD/ton	0.081
Biofuels Sector			
b_0	Biofuels' Consumption in 2004	Billion Toe	0.041
θ^b	Biofuels' Conversion Rate	toe/ton	0.283
c^b	Biofuels' Conversion Cost	1000USD/ton	0.442
Energy Sector			
σ_b	Elasticity of Substitution between Fossil Fuels and Biofuels		2
α^b	CES Parameter for Fossil Fuels and Biofuels		0.5
ρ_b	Share of Biofuels in CES Function		0.048
γ^b	Technology of Energy Production		1.102
θ_0^e	Energy Efficiency in 2004		1
κ_e	Energy Efficiency Growth Rate per annum		0.016

Table 2: Baseline Parameters (continued)

Coefficient	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 TFP in 2004		15.2
κ_s	Timber Processing TFP Growth Rate per annum		0.022
c^s	Timber Processing Cost	1000USD/ton	1.74
Recreation Sector			
r_0	Recreational Services in 2004	1000USD/Ha	6.174
κ_r	TFP Growth in Recreation Sector		0.023
c^r	Cost of Producing Recreation Services	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 Application	tCO_2e per ton	2.843
μ^ϕ	GHG Emissions from Fertilizers Production	tCO_2e per ton	1.223
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
$\overline{\mu}^w$	Forest Carbon Stocking Density	MgC per m^3	1.1
φ	Share of Stored Carbon in Harvested Forest Products		0.5

Table 2: Baseline Parameters (continued)

Coefficient	Description	Units	Value
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		0.03
α_o	AIDADS Marginal Budget Share at Subsistence Income for Other Goods and Services		0.38
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		0.09
β_o	AIDADS Marginal Budget Share at High Income for Other Goods and Services		0.69
$\overline{f}$	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		0.18
$\overline{o}$	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 3: Parameters for Counterfactual Scenarios

Coefficient	Description	Period	Value
Scenario A (Declining Growth of Agricultural Yield)			
κ_g	Agricultural Yield Growth Rate per annum	2025-2054	0.048
κ_g	Agricultural Yield Growth Rate per annum	2055-2079	0.042
κ_g	Agricultural Yield Growth Rate per annum	2080-2104	0.037
Scenario E (Rising Fossil Fuel Costs)			
κ_x	Fossil Fuels' Costs Growth Rate per annum		0.05
Scenario T (Land-Use Emissions Target)			
ζ	Logistic Rate of Decline in Land-Use Emissions		0.04

Table 4: Model Simulation Results, 2050

Variable / Scenario	Baseline	Scenario A	Scenario E	Scenario T	Scenario AE	Scenario AET
	(Level)	(Deviation from Baseline)			(ΔA)	(ΔAE)
Land						
Cropland Area, GHa	1.75	0.005	0.14	-0.04	0.14	-0.05
Commercial Forest Area, Gha	1.64	-0.004	-0.09	0.07	-0.09	0.06
Unmanaged Natural Land Area, GHa	2.19	0.00	-0.04	-0.03	-0.03	-0.01
Protected Natural Land Area, GHa	0.25	0.00	-0.02	0.001	-0.01	0.002
Intermediate Products						
Agricultural Product, Gton	6.68	-0.07	-0.20	-0.24	-0.21	-0.18
Fertilizers, Gton	0.41	0.005	-0.07	-0.02	-0.07	-0.01
Petroleum, Gtoe	3.48	-0.001	-0.47	0.001	-0.47	0.001
Biofuels, Mtoe	3.54	-0.117	2.81	-0.02	2.7	-0.04
Forest Product, Gton	2.13	-0.001	-0.04	-0.001	-0.04	0.00
Final Consumption						
Processed Food Services per capita, 2004 USD	345	-3.68	-11.0	-12.4	-11.3	-9.4
Energy Services per capita, 2004 USD	187	-0.05	-24.8	-0.03	-24.8	0.003
Processed Timber Services per capita, 2004 USD	633	-0.25	-11.5	-0.28	-11	-0.1
Recreation Services per capita, 2004 USD	454	-0.89	-27.6	1.89	-27	2.8
GHG Emissions						
Natural Land Conversion, $GtCO_2e$	0.95	0.017	1.33	-0.46	1.23	-0.61
Fertlizers' Use, $GtCO_2e$	1.66	0.022	-0.28	-0.08	-0.28	-0.04
- Production of Fertilizers, $GtCO_2e$	0.50	0.007	-0.08	-0.025	-0.08	-0.01
- Application of Fertlizers, $GtCO_2e$	1.16	0.016	-0.19	-0.06	-0.19	-0.03
Biofuels Combustion, $MtCO_2e$	2.04	-0.141	-5.58	2.17	-5.38	2.32
Net Forest Sequstration, $GtCO_2e$	-2.62	0.021	0.43	0.31	0.43	0.19
Petroleum Combustion, $GtCO_2e$	10.2	-0.002	-1.37	-0.001	-1.37	0.00
GHG Emissions from Land Use, $GtCO_2e$	-0.51	0.053	1.56	-0.20	1.46	-0.46
GHG Emissions from Other Sources, $GtCO_2e$	10.7	0.005	-1.46	-0.026	-1.46	-0.01

Note. ΔA: Deviation from Scenario A. ΔAE: Deviation from Scenario AE.

Table 5: Model Simulation Results, 2100

Variable / Scenario	Baseline	Scenario A	Scenario E	Scenario T	Scenario AE	Scenario AET
	(Level)	(Deviation from Baseline)			(dA)	(dAE)
Land						
Cropland Area, GHa	1.44	0.011	0.36	-0.13	0.35	-0.14
Commercial Forest Area, Gha	1.96	-0.01	-0.26	0.15	-0.26	0.13
Unmanaged Natural Land Area, GHa	1.78	0.0025	-0.01	-0.01	0.00	0.01
Protected Natural Land Area, GHa	0.65	-0.003	-0.09	-0.01	-0.09	-0.003
Intermediate Products						
Agricultural Product, Gton	6.96	-0.46	-1.94	-0.94	-1.84	-0.31
Fertilizers, Gton	0.28	0.005	-0.19	-0.06	-0.20	-0.005
Petroleum, Gtoe	2.02	-0.005	-0.75	-0.03	-0.75	-0.01
Biofuels, Mtoe	19.4	-2.57	65.1	4.35	55.4	10.0
Timber Product, Gton	3.97	-0.01	-0.22	-0.71	-0.22	-0.71
Final Consumption						
Processed Food Services per capita, 2004 USD	1010	-67	-318	-140	-298	-51
Energy Services per capita, 2004 USD	228	-1.1	-67	-2.7	-69	1.6
Processed Timber Services per capita, 2004 USD	3350	-11	-185	-603	-185	-601
Recreation Services per capita, 2004 USD	3341	-17	-479	-44	-471	-14
GHG Emissions						
Natural Land Conversion, $GtCO_2e$	0.00	0.00	0.00	0.00	0.00	0.00
Fertlizers' Use, $GtCO_2e$	1.16	0.02	-0.79	-0.22	-0.80	-0.02
- Production of Fertilizers, $GtCO_2e$	0.35	0.006	-0.24	-0.07	-0.24	-0.006
- Application of Fertlizers, $GtCO_2e$	0.81	0.01	-0.55	-0.16	-0.56	-0.01
Biofuels Combustion, $MtCO_2e$	5.36	-0.09	-3.39	1.87	-3.32	1.28
Net Forest Sequstration, $GtCO_2e$	-6.03	0.04	1.23	-2.38	1.22	-2.20
Petroleum Combustion, $GtCO_2e$	5.92	-0.01	-2.22	-0.10	-2.20	-0.03
GHG Emissions from Land Use, $GtCO_2e$	-5.22	0.05	0.68	-2.53	0.66	-2.21
GHG Emissions from Other Sources, $GtCO_2e$	6.26	-0.01	-2.46	-0.17	-2.44	-0.03

Note. ΔA: Deviation from Scenario A. ΔAE: Deviation from Scenario AE.