Confronting the Food-Energy-Environment Trilemma: Global Land Use in the Long Run*

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Abstract

Economic, agronomic, and biophysical drivers affect global land use, so all three influences need to be considered in evaluating economically optimal allocations of the world's land resources. A dynamic, forward-looking optimization framework applied over the course of the coming century shows that although some deforestation is optimal in the near term, in the absence of climate change regulation, the desirability of further deforestation is eliminated by mid-century. Although adverse productivity shocks from climate change have a modest effect on global land use, such shocks combined with rapid growth in energy prices lead to significant deforestation and higher greenhouse gas emissions than in the baseline. Imposition of a global greenhouse gas emissions constraint further heightens the competition for land, as fertilizer use declines and land-based mitigation strategies expand. However, anticipation of the constraint largely dilutes its environmental effectiveness, as deforestation accelerates prior to imposition of the target.

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1 Introduction

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

The goal of this paper is to 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 greenhouse gas (GHG) mitigation targets. We do so by developing a new model, nick-named FABLE: Forest, Agriculture, and Biofuels in a Land use model with Environmental services. This model determines the optimal allocation of scarce land, both across competing uses as well as across time. While market failures, including ill-defined property rights, poorly developed land markets, lack of information, and credit constraints preclude such a path from being achieved in reality, this optimal path is a useful point of reference for those seeking to influence patterns of global land use.

In addition to its comprehensive nature, dealing with all the elements of land use competition in the coming century, a key distinguishing feature of the model is its forward-looking nature, which can offer important insights regarding the investors’ behavior under alternative states of the world. In our model, land allocation decisions today are based on the future expectations of key drivers affecting global land use, such as e.g., demographics, preferences, input prices, and the rate of technological progress. Babiker et al. (2009) argue that forward looking models are better suited to addressing important economic and environmental policy issues such as: the 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.

Notwithstanding these important modeling advantages, the forward-looking approach adopted in our paper is relatively uncommon. Currently available forward looking models of land use are either stylized theoretical models (Chakravorty et al. 2008, Bahel et al. 2013) or focus on a particular land-intensive sector, where intertemporal issues are significant and cannot be ignored. One strand of this literature relates to commercial forestry, where current planting and harvesting decisions rely on expectations of future conditions (Stavins 1999, Sohngen and Mendelsohn 2003, Richards and Stokes 2004, Sohngen and Mendelsohn 2007, Daigneault et al. 2010). Another example is natural land conservation in light of significant option values attached to the future stream of biodiversity losses (Conrad 1997, 2000, Bulte et al. 2002, Leroux et al. 2009).

Most of the current research on global land use is based on large-scale computational models (see e.g., Paltsev et al. 2005, Bouwman et al. 2006, Wise and Calvin 2011, Rosegrant and IMPACT Development Team 2012, Van der Mensbrugghe 2013). These models have the advantage of offering detailed geographic and sectoral coverage, which allow them to capture a broad range of market mediated responses to changes in demand and supply factors affecting global land use. Because of these attractive features these computational models have been extensively used to analyze broad range of questions, such as e.g., implications of energy and climate policies affecting competition between food and biofuels (Searchinger et al. 2008, Melillo et al. 2009, Wise et al. 2009, Havlik et al. 2011), climate change impacts on yields and available area in agriculture and forestry sectors (Parry et al. 2004, Reilly et al. 2007, Hertel, Burke and Lobell 2010), and the effects of changing food preferences and technological progress in agriculture on spatial distribution of land and associated GHG emissions (Ianchovichina et al. 2001, Lotze-Campen et al. 2008, Popp et al. 2010). However, because of their complexity, these integrated assessment models are typically solved recursively rather than as fully inter-temporal forward-looking optimization problems. In addition, few of them deal with the full range of issues built into FABLE. In particular, most of them ignore the growing demand for biodiversity and the ensuing increase in protected natural lands.

The model we develop seeks to integrate all of these distinct strands of literature into a single, intertemporally consistent, analytical framework on a global scale. FABLE is a dynamic and forward-looking, multi-sectoral, computable partial equilibrium model for the world's land resources over the coming century. The optimal path for global land use maximizes the discounted net present value of the services from processed food (including crops and livestock prod-

ucts), liquid fuels (including first- and second generation biofuels), timber, forest carbon and biodiversity. A non-homothetic AIDADS utility function represents model preferences, and, as society becomes wealthier, places greater value on ecosystem services, and diminishing marginal value on additional consumption of food, energy and timber products. Given the importance of land-based emissions to any GHG mitigation strategy, as well as the potential impacts of climate change itself on the productivity of land in agriculture, forestry and ecosystem services, we also characterize the optimal path for the world’s land resources 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, but allow us to capture differential growth rates of harvestable timber and carbon stocks.

Our modeling approach is closely related to two recent studies, which employ computable forward-looking partial equilibrium models to analyze different aspects of land use. Chakravorty et al. (2011) develop multi-regional land use model with heterogenous agricultural land quality. This model focuses primarily on the trade-off between food and biofuels. Their approach, unlike our model, does not incorporate other key land-based sectors, including forestry and ecosystem services. Choi et al. (2011b) develop a multi-regional dynamic partial equilibrium model of agriculture and forestry. Their model is primarily concerned with the competition between agricultural and forest products, and, unlike our model, ignores energy sector, as well as the role of biodiversity demands in driving long run land use change.

We solve the model over the 200 year period beginning 2005, focusing analysis on the coming century. Our baseline 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 the comparative dynamic effects of incrementally adding more pressure on the world’s land resource base due to lower growth in agricultural productivity from higher temperatures, higher growth in oil prices, as well as global GHG emissions regulations.

We show in our model baseline that, even in the absence of climate regulation, optimal deforestation associated with cropland expansion, which currently accounts for a large share of land-use GHG emission, should decline in the

medium term. Climate impacts have mixed effects on yields - hurting food production, but benefiting biomass yields. The overall impact of climate change is to require additional cropland and encourage additional fertilizer use, both of which contribute to higher GHG emissions. Energy prices and policies have a strong effect on the overall amount of land used in agriculture, since higher prices encourage additional biofuel production, even while making intensification of production more costly. The net effect is even greater GHG emissions. The introduction of a constraint on GHG emissions from land use leads to a significant long-run reduction in cropland expansion. However, a jump in forest conversion before the constraint is introduced makes it less effective over the course of the entire century, thereby confirming the ‘green paradox’. Overall, with a ‘perfect storm’ of simultaneous high growth in energy prices, aggressive climate policy, but nonetheless adverse climate change impacts on agriculture, area for cropland is sharply reduced, as is food consumption. This underscores the intensity of the potential food-fuel-environment trade-off which the world faces in the 21st century.

2 Model Outline

FABLE is a deterministic, discrete dynamic, finite horizon partial equilibrium model. Income, population, wages, oil prices, total factor productivity, and other variable input prices are assumed to be exogenous. Figure 1 shows full model’s structure. There are two natural resources in the model: land and fossil fuels. The supply price of fossil fuels is exogenous, and expected to rise over time. The supply of land is fixed and faces competing uses that are determined endogenously by the model. There are nine sectors in the model, which produce intermediate and final land-based goods and services contributing to welfare. The production of other, non-land based goods and services is exogenous.

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 treated as a time-varying constraint on the flow of GHGs (emissions target). As the model focuses on the representative agent’s behavior, consumption products are expressed in per-capita terms.

The key model equations are described below, with more complete information on equations, variables, and parameter values offered in the technical

appendix.

Figure 1: Structure of the Model

2.1 Land Use

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

$$\bar{L} = L_t^N + L_t^M. \quad (1)$$

Following the previous literature on natural land use (Antoine et al. 2008, Gurgel et al. 2011) we assume that natural land consists of two types. Institutionally protected land, L^R , includes natural parks, biodiversity reserves and other types of protected forests. This land is used to produce ecosystem services for society, and cannot be converted to commercial use. Unmanaged natural land, L^U , can be accessed and either converted to commercial land (deforested) or to protected land. Once the natural land is deforested, its potential to yield ecosystem

services is diminished and cannot be restored within the (single century) time frame of the analysis. Thus, the conversion of natural lands for commercial use is an irreversible decision.¹ Equations describing allocation of commercial land across time and different uses are:

$$L_t^N = L_t^U + L_t^R. \quad (2)$$

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

and

$$L_{t+1}^R = L_t^R + \Delta L_t^{U,R}, L_0^R > 0, \quad (4)$$

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

Accessing the natural lands comes at per hectare cost, c_t^U , which derives from road construction and other infrastructure (Golub et al. 2009). In addition, converting natural land to protected land entails per hectare cost, c_t^R , associated with institutional and physical effort (e.g, passing legislation, creating recreational infrastructure) to create new natural parks. We assume that these costs are continuous, monotonically increasing, and strictly convex functions of the share of natural land previously accessed. There are no additional costs of natural land conversion to commercial land, as these costs are assumed to be offset by the revenues from the sale of the forest product. There are no additional costs of natural land conversion to commercial land, as these costs are offset by the revenues from deforestation.

Commercially managed lands are fully employed in crops, livestock or forestry sectors (we ignore residential, retail, and industrial uses of land in this partial

¹This point requires additional clarification. The biophysical and ecological literature suggests that restoration of forest structure and plant species takes at least 30-40 years and usually many more decades (Chazdon 2008), costs several to ten thousands dollars per hectare (Nesshöver et al. 2009), and is only partially successful in achieving reference conditions (Benayas et al. 2009). Modeling restoration of biodiversity under these assumptions introduces greater computational complexity without making significant changes relative to findings presented in this study.

equilibrium model of agriculture and forestry). Equations describing the allocation of commercial land across time and between uses are:

$$L_t^M = L_t^C + L_t^P + L_t^F. \quad (5)$$

and

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

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

2.1.1 Managed Forests

Managed forests are characterized by $v_{\max}$ vintages of tree species with vintage ages $v = 1, \dots, v_{\max}$. At the end of period t each hectare of managed forest land, $L_{v,t}^F$, has an average density of trees of vintage age v , with the initial allocation given and denoted by $L_{v,0}^F$. Each period of time the managed forest land can be either planted, harvested or simply left to mature. The newly planted trees occupy $\Delta L^{F,P}$ hectares of land, and reach the average age of the first tree vintage next period. The harvested area occupies $\Delta L_v^{F,H}$ hectares of forest land. If the managed forest land is harvested, it yields θ_v^w tons of forest product (raw timber), x_v^w , where θ_v^w is the merchantable timber yield function, which is monotonically increasing in the average tree density of age v . Forest land becomes eligible for harvest when planted trees reach a minimum age for merchantable timber, $\bar{v}$. Managed forest areas with the average density of oldest trees $v_{\max}$ have the highest yield of $\theta_{v_{\max}}^w$. They do not grow further and remain in this vintage until harvested.

The following equations describe land use of managed forests:

$$L_t^F = \sum_{v=1}^{v_{\max}} L_{v,t}^F, \quad (7)$$

$$L_{v+1,t+1}^F = L_{v,t}^F - \Delta L_{v,t}^{F,H}, \quad v < v_{\max} - 1 \quad (8)$$

$$L_{v_{\max},t+1}^F = L_{v_{\max},t}^F - \Delta L_{v_{\max},t}^{F,H} + L_{v_{\max}-1,t}^F - \Delta L_{v_{\max}-1,t}^{F,H} \quad (9)$$

$$L_{1,t+1}^F = L_t^{F,P}. \quad (10)$$

Equation (7) describes the composition of managed forest area across vintages. Equation (8) illustrates the harvesting dynamics of forest areas with the ages $v_{\max} - 1$ and $v_{\max}$. Equation (10) shows the transition from planted area to new forest vintage area.

The average planting costs per hectare of newly forest planted, c^P , are invariant to scale and are the same across all vintages. Harvesting managed forests and conversion of harvested forest land to agricultural land is subject to additional near term adjustment costs, c^H .

2.2 Fossil Fuels

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

$$x_t^f = x_t^{f,n} + x_t^{f,e}. \quad (11)$$

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

2.3 Land Based Goods and Services

There are nine sectors in the model, which produce intermediate and final goods and services contributing to welfare (see middle part of Figure 1). The agrochemical sector converts fossil fuels into fertilizers, x^n , that are used to boost yields in the agricultural sector. The crops sector combines agricultural land and fertilizers to produce intermediate outputs (food crops, $x^{c,g}$, animal feed, $x^{l,g}$, and cellulosic feed stocks, $x^{b,g}$) that can be used to produce food, livestock products, or biofuels. The livestock sector combines pasture land and animal feed to produce livestock products, x^l . The food processing sector converts food crops and livestock products into processed grain products y^g , and processed livestock, y^l , that are used to satisfy the global food demand. The biofuels

sector converts food crops and cellulosic feedstocks into liquid fuels, x^b , which substitute for petroleum products in final demand. The energy sector combines petroleum products with the biofuels, and the resulting mix is further combusted to satisfy the demand for energy services, y^e . The forestry sector produces an intermediate product, x^w , which is sold to the timber processing sector which converts lumber into a final wood products, y^w . The ecosystem services sector provides a public good to society in the form of ecosystem services, y^r . The production functions for intermediate and final land-based goods and services can be illustrated by the following equations

$$x_t^{i,j} = h_1 \left(L_t^C, L_t^P, \Delta L_{v,t}^{F,H}, h_2 \left(x_t^{i,j} \right) \right), \quad i, j = b, c, g, f, l, n, w. \quad (12)$$

and

$$y_t^i = h_3 \left(L_t^k, x_t^{j,i} \right), \quad i = g, l, e, w, r; \quad j = b, c, f; \quad k = C, F, P, U, R. \quad (13)$$

Equations (12) and (13) implies that production of intermediate and final goods and services involves the combination of natural resources and other intermediate inputs, where $h_1(\cdot)$, $h_2(\cdot)$ and $h_3(\cdot)$ denote production functions for intermediate inputs. To preserve space we show the specific functional forms of $h_1(\cdot)$, $h_2(\cdot)$ and $h_3(\cdot)$ in technical appendix.

The production of intermediate inputs and final land based goods and services i incurs non land costs, c^i . We assume these costs are constant and scale-invariant.

2.4 GHG Emissions

The GHG emissions flows, z_t , in the model result from a number of sources: (a) combustion of petroleum products, (b) the conversion of unmanaged and managed forests to agricultural land (deforestation), (c) non-CO₂ emissions from use of nitrogen fertilizers in agricultural production, (d) non-CO₂ emissions from the livestock sector (which include emissions from enteric fermentation and manure management) and (e) net GHG sequestration through forest sinks (which includes the GHG emissions from harvesting forests). We differentiate between the emissions resulting from combustion of petroleum products and the emissions resulting from land use, z^L , because the price path (and therefore the bulk of the combustion path) for fossil fuels is predetermined, whereas the other

sources of GHG emissions are endogenous.

We assume that GHG emissions from the first three sources are linearly related to the use of fossil fuels, and the allocations of commercial lands. A ton of oil equivalent (*toe*) of fossil fuel combusted emits $\mu^{f,e}$ tons of CO₂ equivalent (tCO₂e). A ton of oil equivalent (*toe*) of fossil fuel converted to fertilizer emits $\mu^{f,n}$ tCO₂e. The conversion of natural forest land to commercial land entails emissions of μ^L tCO₂e per hectare of land deforested. A ton of fertilizer applied to agricultural land emits μ^n tCO₂e.

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

GHGs can also be reduced by carbon forest sequestration.² A hectare of forest vintage v sequesters μ_v^w tCO₂e. Young forest vintages grow quickly and sequester carbon at a rapid rate. Older vintages grow slowly and eventually cease to sequester carbon. As the unmanaged forest land (both reserved and non-reserved) comprises mainly the older tree vintages, its potential to sequester additional GHGs is small, and may be ignored (Odum 1969). However, the potential for GHG releases when these trees are cut down and burned or left as slash (Fearnside 2000, Houghton 2003) is large. Harvesting managed forests results in emissions of $(1 - \varphi)\mu_v^h$ tCO₂e per hectare of land harvested, where μ_v^h is the carbon stock associated with harvested tree vintage v , and φ is the share of permanently stored carbon in harvested forest products. We ignore the annual sequestration of carbon by agricultural product, as those crops are harvested and subsequently consumed in the form of food or bioenergy.

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

$$z_t = \mu^{f,e}x_t^{f,e} + \mu^{f,n}x_t^{f,n} + z_t^L, \quad (14)$$

and

$$z_t^L = \mu^L \Delta L_t^{U,M} + \mu^P L_t^P + \mu^n x_t^n + \mu^l x_t^l + (1 - \varphi) \sum_{v=1}^{v_{\max}} \mu_v^h \Delta L_{v,t}^{F,H} - \sum_{v=1}^{v_{\max}} \mu_v^w L_{v,t}^F. \quad (15)$$

Equation (14) describes the composition of GHG emissions flows. Equation (15) shows net GHG emissions from deforestation, food and livestock production, and

²GHG emissions flows are also sequestered by atmospheric and ocean sinks. We ignore this complication as our model does not provide comprehensive accounting of all GHG emissions flows, and focuses on understanding emissions from land use and related sectors.

forest sequestration.

Finally, we consider institutional control of GHG emissions' flows, 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, $\bar{z}^L$. We do not impose the emissions' constraints on GHG emissions from fossil fuels' combustion because they are exogenously determined. Rather we assume that emissions control instruments are reflected in exogenous prices of fossil fuels, which affect the demand for fossil fuels. Finally, because biofuels provide a renewable alternative to fossil fuels, we credit the emissions' quota, $\bar{z}^L$, by the fraction of fossil fuels' emissions displaced by the biofuels.³ The resulting relationships for emissions control are

$$z_t^L \leq \bar{z}_t^L = \theta_t^z \left(z_t^L - \left(1 - \frac{\mu^{b,i}}{\mu^x} \right) x_t^{b,i} \right), i = 1, 2, \quad (16)$$

where global warming intensity, θ_t^z is a function determining the evolution of the GHG emissions' quota over time, and $\mu^{b,1}$ and $\mu^{b,2}$ are non-land-use emissions of first and second generation biofuels production. Equation (16) describes the constraint on non-fossil fuel emissions in the atmosphere, and shows how this constraint is derived.

2.5 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.⁴ First, similar to the well-known AIDS demand system (Deaton and Muellbauer 1980) the AIDADS model is flexible in its treatment of Engel effects, as the model allows the marginal budget shares for each good to vary as a function of total real expenditures. Second,

³This 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.

⁴The 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).

AIDADS has global regularity properties, in contrast to the local properties of AIDS.⁵ This is essential for solution of the model over a wide range of quantities. In addition, a number of studies (Cranfield et al. 2003, Yu et al. 2004) have demonstrated that AIDADS outperforms other popular models of consumer demand in projecting global food demand, which makes it especially well-suited for the economic modeling of land use.

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

$$\sum_{q=g,l,e,w,r,o} F(y^q, u) = 1, \quad (17)$$

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

$$F(y^q, u) = \frac{\alpha_q + \beta_q \exp(u)}{1 + \exp(u)} \ln \left(\frac{y^q - \gamma^q}{A \exp(u)} \right). \quad (18)$$

In equation (18) the parameters α_q and β_q define the varying marginal budget shares of goods and services y^q in the consumers' total real expenditures. The parameter γ^q defines the subsistence level of consumption of goods and services q . The functional form of $F(y^q, u)$ implies that the consumption of goods and services y^q is always greater than their subsistence levels, γ^q . The parameter A affects the curvature of the transformation function $F(y^q, u)$. The AIDADS system imposes standard non-negativity and adding-up restrictions based on the economic theory. These restrictions ensure that the consumers' marginal budget shares and minimal consumption level of goods and services γ^q are greater or equal to zero, and the sum of marginal budget shares in total real expenditures does not exceed one.

Rimmer and Powell (1996, p.1615) demonstrate that maximizing the utility function (17) subject to the budget identity constraint (18) yields the following

⁵One 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).

system of inverse demand equations:

$$p_q(q) = \frac{\alpha_q + \beta_q \exp(u)}{1 + \exp(u)} \frac{y - \sum_q p_q y^q}{y^q - \gamma^q}, \quad (19)$$

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

2.6 Welfare

The objective of the planner is to maximize the welfare function, Ω , defined as the sum of net aggregate surplus discounted at a constant rate $\delta > 0$, and the bequest value of unmanaged and commercial forest areas.⁶ Net surplus is computed by integrating the marginal valuation of each product, less the land access costs and non-land-based costs of producing each good. Thus, for food and timber products, this represents non-land production costs. For energy, these are non-land biofuels costs and fossil fuel costs. For fertilizers, these are non-energy costs. For forestry, these are harvesting and planting costs. And for recreation, these are the costs of maintaining natural parks. The planner allocates commercial land for agricultural crops, livestock, and timber production, and the scarce fossil fuels and reserved natural forest land to solve the following problem:

$$\max_{g,l,e,w,r} \Omega = \sum_{t=0}^{T-1} \delta^t \left[\begin{aligned} & \sum_{q=g,l,e,w,r,o} \int_0^{y^{q*}} (p_q(y^q) - c_q(y^q)) dy^q \\ & - c_t^U (\Delta L_t^{U,M} + \Delta L_t^{U,R}) - c_t^R \Delta L_t^{U,R} - c_t^n x_t^n \\ & - \sum_i c^{g,i} x^{g,i}_t - c^l - c^p \Delta L_t^{F,P} - c_t^w \end{aligned} \right] + \delta^T \Gamma(L_T^U, L_T^F) \quad (20)$$

s.t. constraints (1)-(19), where Γ is the scrap value function.

3 Model Baseline

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

Figure 2 depicts the optimal allocation of global land use, consumption of

⁶We do not consider the bequest value of protected forests, as they cannot be “scrapped” in our model.

Figure 2: Model Baseline

land-based goods and services and associated GHG emissions in the model baseline over the course of the coming century. Beginning with the upper left-hand panel of Figure 2, we see that, in the near term decades, area dedicated to food crops increases by 10 percent compared to 2004, reaching its maximum of 1.55 billion hectares in 2035. Area dedicated to animal feed expands rapidly, adding 150 million hectares, whereas pasture land declines, losing 120 million hectares by 2035. Managed and unmanaged forest areas decline by 3 million and 205 million hectares respectively. Changes in areas dedicated to biofuels feedstocks and protected natural forests remain insignificant. By mid-century, slower population growth, rising real income, shifting diets, and technology improvements in food processing, storage and transportation result in a decline in demand for food crops. By 2100 area dedicated to food crops falls to 1.25 billion hectares, which is 12 percent lower than in 2004. Improvements in crop technology and agricultural yields result in greater intensification of livestock production. Pasture land continues to decline, reaching 2.33 billion hectares, which is 15 percent smaller than 2004. Area dedicated to animal feed increases significantly to reach 0.73 billion hectares, which is nearly six times greater than 2004. Rising energy prices in the baseline result in significant growth in the land area dedicated to

biofuels, which reaches 0.14 billion hectares by 2100. Managed forest area is little changed. Rising real incomes, growing demand for ecosystem services, and improvements in management of natural forest lands result in strong growth in protected natural land area, which increases significantly to 0.68 billion hectares (about three times greater than 2004) in 2100.

The upper right-hand panel in Figure 2 reports gross land based annual GHG emissions flows and their net accumulation over time.⁷ Positive bars in this panel denote emissions, whereas negative bars denote GHG abatement through forest sinks and biofuels offsets. Conversion of natural forest lands is a significant driver of land-based GHG emissions in the near term, which amounts to 3.2 GtCO₂e/yr in 2025. By mid-century, increasing access costs of natural land combined with declining demand for food crops, results in a sharp decline in deforestation. GHG emissions from deforestation are eliminated by 2050 along this optimal global path of land use. GHG emissions from application of fertilizers remain stable for most of the century, and increase closer to the end of the century along with continued expansion of animal feed. In 2100 annual flows of GHG emissions from the use of fertilizers amount to 0.73 GtCO₂e/yr, which is 40 percent larger than 2004. Continued growth in consumption of meat and dairy products results in a significant increase in GHG emissions from livestock. In 2100, annual flows of GHG emissions from livestock amount to 1.84 GtCO₂e/yr, which is 2.2 times larger than 2004. GHG emissions sequestration from managed forests does not change significantly. In 2100 sequestered GHG emissions amount to 2.1 GtCO₂e/yr, which is about 5 percent smaller than 2004. GHG emissions offsets from biofuels are insignificant in the near term. With the arrival of commercial scale production of second generation biofuels, these become a significant source of land based GHG abatement due to their low emissions intensity relative to petroleum (Dunn et al. 2011). In 2100 annual biofuels offsets account for 1.4 GtCO₂e/yr. Overall, accumulation of land based GHG emissions increases in the first part of this century, reaching its maximum of 80 GtCO₂e around 2040. It then declines in the second part of the century reaching 12 GtCO₂e by 2100. Declining population growth, accompanied by rising agricultural productivity, along with higher oil prices, expansion of biofuels, and declining deforestation are the reasons for falling GHG emissions of land based sectors in the second half of the 21st century.

The lower left-hand panel in Figure 2 illustrates the results for per-capita

⁷As this study focuses on optimal path of land based GHG emissions, the emissions from combustion of petroleum products are not shown in Figure 2.

consumption of goods and services that draw on land resources. The consumption of livestock products, timber products, and biofuels grow in absolute terms. In 2100 the per capita consumption of livestock and land-based energy services is considerably higher compared to their levels in 2004, whereas the increase in timber products consumption is more moderate. The per capita consumption of processed food crops remains unchanged over the course of this century. The consumption of ecosystem services declines in the near term decades as a result of deforestation. However, the consumption of ecosystem services subsequently increases with greater demand for recreation and continued growth in protected forest areas. Nonetheless, the consumption of ecosystem services in 2100 is still lower than their corresponding levels in 2004 – an indication of the intense competition for land-based services in our baseline scenario.

The lower right-hand panel of Figure 2 highlights the results for consumption of biofuels. The consumption of first generation biofuels grows slowly as oil prices and agricultural yields increase. However, along this optimal path, first generation biofuels do not become a significant source of energy consumption. In 2100 the consumption of first generation biofuels is 13 Mtoe, considerably higher than in 2004, but still small in relative terms. Second generation biofuels become competitive around 2035 and rapidly expand reaching 300 million toe in 2050, and 500 million toe in 2100. The share of biofuels in total liquid fuel consumption steadily increases, reaching its maximum of 36 percent in 2075. Further expansion of biofuels is crowded by even greater expansion of animal feed, and the share of biofuels in total liquid fuel consumption declines to about 30 percent in 2100. This is of comparable magnitude to findings in recent economic studies on bioenergy and land use (Gurgel et al. 2007, Chakravorty et al. 2011, Popp et al. 2011).⁸

4 Counterfactual Scenarios

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

⁸Direct comparison of model predictions of biofuels penetration is difficult due to considerable uncertainty in variety of factors, such as, e.g., evolution of biofuels' production technologies, land access costs, yield growth rates, and energy demand projections. We show model sensitivity to these factors in counterfactual simulations below, and in technical appendix.

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 the dynamic allocation of land. These sources include (but are not limited to) variations in agricultural yields, liquid fossil fuels’ costs, c^f , and the future valuation of GHG abatement, expressed through the stringency of the GHG emissions constraint, $\bar{z}^L$. 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:⁹

Scenario A: *The permanent decline in potential food crop yields due to adverse effects of climate change.* The impact of climate change on food crop yields depends critically on their phenological development, which, in turn, depends on the accumulation of heat units, typically measured as growing degree days (GDDs). More rapid accumulation of GDDs as a result of the climate change speeds up phenological development, thereby shortening key growth stages, such as the grain filling stage, hence reducing potential yields (Long 1991). However, raising concentrations of CO₂ in the atmosphere results in an increase in potential yields due to the “CO₂ fertilization effect” (Long et al. 2006). When temperature increases are moderate, as we assume in the model baseline, these effects offset each other, and the food crop yields are unaffected by the climate change. In scenario A we consider rapid warming, corresponding to Representative Concentration Pathways 8.5 GHG forcing scenario (Moss et al. 2008), so the former effect quickly dominates the latter. We assume that yields of cellulosic feedstocks do not change under scenario A, as they appear to be relatively insensitive to further temperature increases (Brown et al. 2000).

Scenario E: *The permanent increase in growth of liquid fossil fuel costs over the medium term.* Petroleum and natural gas prices are key factors affecting the competitiveness of biofuels (Hertel, Tyner and Birur 2010, National Research Council 2011) as well as the price of nitrogen fertilizer which is critical for boosting agricultural yields (USGAO 2003). To characterize energy price increases in scenario E in the medium term, we employ the data for the high oil price scenario from Energy Information Administration (EIA) growth projections for

⁹We show the model sensitivity to changes in other important model parameters in technical appendix.

2035 (EIA 2010).¹⁰ We assume that the extent to which the energy prices can grow in the long term is limited by induced innovation (Popp 2002) and available backstop technologies (Nordhaus 1973)], so that it reaches its maximum of \$250/bbl at the end of the 21st century.

Scenario T: *The GHG emissions constraint is introduced.* The scenario is illustrative of the range of regulatory uncertainty surrounding global GHG emissions based on IPCC 4AR projections (IPCC 2007a,b), and recent aspirations of a number of countries to incorporate land based GHG mitigation in their climate policies.¹¹ In this scenario we introduce a maximum target, amounting to a 60% reduction in baseline GHG emissions from petroleum products, crop production and terrestrial carbon fluxes by 2100. This corresponds to the upper bound of regulation, aimed at achieving CO₂ – equivalent concentration (including GHGs and aerosols) at stabilization of 445-490ppm. After the target is introduced in 2025 it rapidly becomes more restrictive, reaching the maximum stringency (measured by implicit carbon price index shown in technical appendix, Figure B.2) around 2050.

We also consider 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 fully anticipated so that their effect is felt already at the outset in 2005. More detailed information on construction of counterfactual scenarios is provided in the technical appendix.

Figures 3, 4, and 5 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 alone are available in the technical appendix. This section concludes with a comparison of the ‘perfect storm’ (AET) to the baseline in

¹⁰Of course there are many factors contributing to a potential decline of highly uncertain fossil fuel costs (Pindyck 1999). Our choice of rising fossil fuel costs in this scenario is motivated by understanding global land use decisions under greater resource scarcity.

¹¹In 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).

order to understand the combined impact of adverse climate impacts, higher energy prices and stringent climate regulation on land use, and particularly food consumption.

4.1 Land Use Impacts of Climate Change

Figure 3: Scenario A vs. Baseline: Climate Change Impacts on Agriculture

Figure 3 describes the impact of counterfactual scenario A, corresponding to a reduction in potential agricultural yields as a consequence of climate change. Results are reported in terms of deviations from the baseline path for key variables. On the supply side, declining food crop yields result in greater requirements for cropland and fertilizers to produce agricultural output used in the production of processed food and livestock. On the demand side, consumption of both processed food and livestock products is diminished. In the forward looking model all these changes start to take place before the actual realization of climate impacts, as a consequence of economic agents' desire for consumption smoothing and minimization of adjustment costs.

Climate induced expansion of cropland appears relatively small (upper left-hand panel of Figure 3). Compared to the baseline scenario, the areas dedicated

to food crops and animal feed increase, respectively, by 9 million and 19 million hectares (0.75 and 2.5 percent) in 2100. Expansion of cropland comes at the expense of reduction in other land areas. Managed, unmanaged and protected forest areas all lose about 5 million hectares by 2100. Area dedicated to biofuels feed stocks declines by 3 million hectares in 2100. Finally, pasture land area declines by an additional 10 million hectares in 2100. As we show below, the reason for the modest increase in use of cropland is the accompanying decline in consumption of processed grains and livestock, as well as an increased use of fertilizers in the wake of climate-induced crop scarcity.

Accumulated GHG emissions change modestly relative to the baseline scenario, increasing by an additional 5 GtCO₂e in 2100 (upper right-hand panel of Figure 3). The most significant effects of declining agricultural productivity on the change in GHG emissions are from additional natural land conversion. Compared to the baseline scenario, the GHG emissions from natural land conversion increase by an additional 150 MtCO₂e/yr by 2045. In the long term, the increases in GHG emissions from increased use of fertilizers, reduced forest sequestration and smaller biofuels offsets are largely outweighed by a reduction in GHG emissions from livestock production.

Compared to the baseline scenario, consumption of all goods and services decreases – indicating declining per capita welfare in the wake of the adverse climate impacts (lower left-hand panel in Figure 3). There is a significant decline in the consumption of processed food services. In 2100 the real per capita consumption of processed grains and livestock each declines by 10 percent and 6 percent, respectively, relative to the baseline scenario. The reduction in consumption of services deriving from energy, timber, and ecosystems is less than 1 percent.

Declining food crop yields depress production of first generation biofuels (lower right-hand panel in Figure 3). In 2100 the total consumption of first generation biofuels decreases by 2.5 million toe (20 percent) compared to the baseline scenario. Though higher temperatures do not affect yields of cellulosic feedstock, their production also falls in light of increased competition for land used in food crops. However, the decline in second generation biofuels is modest and amounts to less 1 percent compared to the baseline scenario, and therefore the share of biofuels in liquid fuel consumption is little changed, by the adverse climate impacts on crops.

4.2 Land Use Impacts of Rising Fuel Costs

Figure 4: Scenario AE vs. A: Climate Change Impacts on Agriculture and Rising Fossil Fuel Costs

Figure 4 describes the results of simulations of changes for the counterfactual scenario AE *relative to scenario A*. This adds the effect of permanent increase in the rate of growth in liquid fossil fuel costs over the medium term to the effect of a permanent decline in potential food crop yields. 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 scenario A, agricultural areas dedicated to biofuels feedstocks expand significantly, adding 95 million hectares by 2035 (upper left-hand panel of Figure 4). The expansion of biofuels feedstock comes mainly at the expense of non-biofuel crops. Areas dedicated to food crops and animal feed decline by 65 and 11 million hectares. Pasture land and managed forest areas each decline by 5 million hectares, and unmanaged and protected forest areas decline, respectively,

by 10 million and 2.5 million hectares. In the long term, as energy prices become closer to baseline, their impact on land use becomes less pronounced. In 2100 combined cropland areas increase relative to scenario A, cumulatively adding 24 million hectares, whereas other land areas decline by a comparable amount.

In near decades, the increase in GHG emissions comes mainly from deforestation, caused by conversion of natural and managed forest areas to cropland in anticipation of raising energy prices (upper right-hand panel of Figure 4). In 2025 the GHG emissions from natural land conversion increase by 275 MtCO₂e/yr (10 percent) compared to scenario A, and continue to be significant by mid-century. In the medium term, GHG emissions also decline as biofuels expand and higher costs drive fertilizer consumption down. In 2035, GHG emissions abatement from biofuels offsets and the decline in fertilizers' use grow by 700 and 95 MtCO₂e/yr compared to scenario A. In the long term, the impact of energy prices on GHG emissions diminishes, as natural land conversion ceases and expansion of biofuels declines. Overall, compared to scenario A accumulated GHG emissions increase in the near decades, reaching their maximum of 2 GtCO₂e in 2025, and decline thereafter to a level 15 GtCO₂e lower than scenario A by 2100.

The expansion of the biofuels sector results in an increase in consumption of bio-energy services (lower left-hand panel of Figure 4). Compared to scenario A their real per capita consumption is 13 times higher in 2035 and 11 percent larger in 2100. The consumption of all other land-based goods and services decreases. The most significant decline is in consumption of services from processed grain and livestock products. Compared to scenario A their real per capita consumption declines by 11 percent and 8 percent in 2035, and by 2.5 percent and 1.5 percent, respectively, in 2100.

Higher oil prices increase the demand for biofuels, and facilitate faster commercial scale use of second generation biofuels, which become competitive in 2025 - 10 years earlier compared to scenario A (lower right-hand panel of Figure 4). By 2035 the consumption of second generation biofuels increases by additional 275 million toe compared to scenario A. Combined with a decline in consumption of petroleum products (see Table C.2 in the technical appendix) this results in a significant increase in the share of biofuels in total liquid fuel consumption, which accounts for 40 percent in 2035. In the longer term, as energy prices become closer to the baseline, the amount of biofuels produced, and their share in liquid fuel production returns nearly to the baseline levels.

4.3 Land Use Impacts of Climate Regulation

Figure 5: Scenario AET vs. AE: Climate Change Impacts on Agriculture *and* Rising Fossil Fuel Costs *and* Land-Use Emissions Target

Figure 5 describes the impact of adding the land-use GHG emissions constraint starting in 2025. These results are reported as the deviation of scenario AET (GHG target in place) from scenario AE (baseline plus the effects of a permanent increase in the rate of growth in liquid fossil fuel costs in mid-century along with a permanent decline in the potential food crop yields). Introduction of a land-use GHG emissions constraint has several important cross-sectoral and inter-temporal effects, which our forward-looking model is particularly well suited to illustrate. First, before the GHG emissions target becomes binding, consumption smoothing results in optimal conversion of additional natural forest land, thus causing a substantial increase in GHG emissions. This argument is known in environmental economics literature as intertemporal emissions leakage or the intertemporal “green paradox”¹² (Fischer and Salant 2012). A second important feature of these results is the fact that land-based climate abatement strategies imply greater demand for newly planted forests, (which, as

¹²The term “green paradox” was first introduced by Sinn (2008).

explained in section 2.4 are very effective in carbon sequestration) and change in forest management strategies, choosing harvesting age to jointly maximize benefits from producing merchantable timber as well as climate abatement. A third result of significance is the way in which the GHG emissions target shifts the competition between food and biofuels for land in favor of biofuels, due to additional environmental benefits of bioenergy. Finally, land based climate regulation affects both the intensive and extensive margins of food and biofuels production by making more costly the use of fertilizer (intensive margin) as well as natural forest land conversion (extensive margin).

Introduction of a land-use GHG emissions constraint has an intertemporal effect on the allocation of global land use (upper left-hand panel of Figure 5). In anticipation of the implementation of a GHG emissions target, a fraction of natural forest land is converted to newly planted managed forests, which, as explained in section 2.4, are very effective in land based climate abatement. Compared to scenario AE, the managed forest area expands by an additional 15 million hectares in 2025. As the GHG emissions target becomes more stringent, there is an increase in managed forest area used for GHG sequestration. Compared to scenario AE, the managed forest area expands further by 40 million hectares in 2050 and by 160 million hectares in 2100. There is also an expansion in the area dedicated to biofuels feedstocks. Compared to scenario AE this area increases by 16 million hectares in 2050 and 27 million hectares in 2100. Introduction of the GHG constraint puts significant pressure on cropland and pasture land areas. Compared to scenario AE, cropland areas dedicated to food crops and livestock feed decline by 18 million and 92 million hectares, respectively, in 2100. Pasture land declines by 112 million hectares. As natural land conversion stops, unmanaged natural forest areas increase after the target is introduced. Compared to scenario AE, unmanaged natural forest area increases by 47 million hectares in 2100.

Preceding the introduction of the GHG emissions constraint, there is a large increase in GHG emissions, which in turn increases the GHG emissions stock and significantly reduces the effectiveness of the target (right-hand panel of Figure 5). Two factors contribute to this increase. First, there is an increased conversion of natural forest lands. Second, GHG sequestration by managed forests declines, 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 0.7 and 1.2 GtCO₂e/yr compared to scenario AE. After introduction of the GHG emissions constraint, the GHG emissions from land

use decline. By mid-century, the main source of reduction in GHG emissions is due to the decline in natural land conversion, which amounts to 2.8 GtCO₂e/yr, immediately after the target is introduced. In the long term, greater GHG sequestration by managed forests is the main factor contributing to the reduction in GHG emissions. Compared to scenario AE, the reduction in GHG emissions due to increased forest sequestration amounts to 0.7 GtCO₂e in 2100. Introduction of the GHG target also results in a small increase in GHG abatement from additional use of second generation biofuels. In 2100 the land based GHG mitigation from biofuels offsets is 5 MtCO₂e/yr larger compared to scenario AE. Finally, the emissions from fertilizers and livestock farming and management both decline after the GHG target is introduced. Compared to scenario AE, GHG mitigation from fertilizer use and livestock farming and management decline by 112 MtCO₂e/yr and 200 MtCO₂e/yr, respectively.

Overall, in the presence of intertemporal substitution, the land based GHG emissions target appears to be rather ineffective over the 100 year time horizon. Preceding the introduction of the constraint, cumulative GHG emissions increase by 97 GtCO₂e. After the introduction of the constraint, the GHG emissions from land use cumulatively decline by 114 GtCO₂e. The resulting intertemporal leakage (the ratio of cumulative increase in GHG emissions preceding the GHG target to cumulative decline after the GHG target) is 85 percent.¹³

Introduction of the GHG emissions constraint lowers the consumption of GHG intensive services from processed food and livestock (left-hand panel of Figure 5). Compared to scenario AE real per capita consumption of services from processed grains and livestock declines by 7 percent and 13 percent, respectively. The consumption of bio-energy and ecosystem services expands with the increase in biofuels consumption and the decline in deforestation. Compared to scenario AE, real per capita consumption of bioenergy and ecosystem services increases by 3 percent and 1 percent, respectively, in 2100.

Introduction of the GHG emissions constraint favors the displacement of petroleum products by biofuels (lower right-hand panel of Figure 5). However, the expansion of second generation biofuels is limited as the GHG emissions constraint hinders expansion in agricultural area. In 2100 the consumption of biofuels is just 17 million toe larger compared to scenario AE. The biofuels share in liquid fuel consumption increases significantly as petroleum consumption fur-

¹³The size of intertemporal leakage is reduced to 37 percent over the period of 200 years.

ther declines after the GHG target is introduced, accounting for 46 percent in 2100.

4.4 Assessing the Impacts of a “Perfect Storm”

Figure 6: Scenario AET vs. Baseline: Assessing the Impacts of a Perfect Storm

Thus far, we have analyzed the impacts of each scenario individually and incrementally, however, it is also relevant to consider their combined effect. In a sense, this represents a type of ‘perfect storm’ in global land use in which climate change slows productivity growth, high energy prices intensify the food-fuel tradeoff as well as raising the cost of intensification, and finally, climate regulations places increased value on leaving land in forests. Figure 6 reports 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 this scenario (AET), which are incremental to the model baseline.

As shown in the upper left-hand panel in Figure 6, the combined effect of higher energy prices and climate regulations induces a significant expansion of land dedicated to biofuels crops as well as forested lands. Compared to the baseline scenario, managed and unmanaged forest areas increase by 150 million

and 30 million hectares, respectively, and the area dedicated to biofuels feedstocks increases by 35 million hectares in 2100. The second-generation biofuels are deployed much earlier now, in 2023 (lower right-hand panel in Figure 6). Their deployment is rapid and accounts for a significant share of liquid fuel consumption (60 percent by late in the 21st century), as petroleum consumption is squeezed by the combined effect of higher oil prices and stringent climate regulations. The expansion of biofuels and commercial forestry sectors, and GHG abatement-based forest management strategies result in a significant decline in land based GHG emissions in the long term (upper right-hand panel in Figure 6). However, the effectiveness of GHG climate regulations is distorted by accelerated deforestation and shifts in forest management strategies before the emissions target is introduced. The resulting intertemporal leakage for scenario AET as compared to the model baseline is 56 percent.

As a consequence, even though adverse climate impacts on crop yields suggests the need for additional crop land, such expansion does not happen in this ‘perfect storm’ scenario, as higher energy prices and climate regulations force cropland to contract. Compared to the baseline scenario, areas dedicated to food crops and animal feed decline respectively by 5 million and 67 million hectares (0.5 and 9.5 percent) in 2100. Pasture land also declines by an additional 128 million hectares (5.5 percent) in 2100. The combined effect of adverse climate impacts on crop yields, higher energy prices and climate regulations thus results in a significant decline in services from processed food and livestock, which decline sharply, relative to the model baseline (lower left-hand panel in Figure 6). Compared to the baseline scenario, the consumption of processed grains declines by 18 percent, whereas the consumption of processed livestock declines by 19 percent by 2100. This underscores the food-fuel-environment tradeoff which the world may face over the coming century.

5 Discussion and Limitations

The analysis of the optimal allocation of the global land use over the course of the coming century presented above is based on a novel economic framework, which focuses on the temporal aspect of the land use problem. As with most new model developments, introducing this intertemporal dimension into the model is costly; as a consequence, at this early stage, we are unable to offer the kind of geographic and sectoral coverage that is usual in the land-based integrated

assessment models. Instead, we are forced to consider the competition for land use in food, fuel, forest products and ecosystem services at global scale. This necessarily limits our model’s ability to capture important aspects of land use change arising from regional differences in quality of agricultural land, types of forest cover, natural land access costs, and local governance and property rights. To evaluate the significance of these regional factors to our estimates of global land use change, we compared our baseline results to baseline predictions of ten large-scale, dynamic-recursive spatial land-use models surveyed in Schmitz et al. (2014). Our baseline increase in area dedicated to food crops falls in the mid-range of surveyed models predictions, and is very close to GCAM (Wise and Calvin 2011) and GLOBIOM (Havlík et al. 2011) model results. Our baseline decline in pasture land is consistent with the predictions of AIM (Fujimori et al. 2012), GCAM, and EPPA (Paltsev et al. 2005) models. Based on this comparison we can conclude that, while regional aspects of land use change are important for many questions, our model is reasonably robust for land use analysis at global scale – the focus of our present work.¹⁴

In a forward-looking model, optimization over time implies that land allocation decisions today are contingent on future expectations about the global economy. In the perfect foresight setting of FABLE, the economic actors know exactly what will happen in the future over all periods covered by the model baseline. Inter-temporal optimization with perfect foresight thus fails to capture situations where agents face high levels of uncertainty (Babiker et al. 2009). This is particularly relevant for our scenario AET, where we observe the “green paradox” when the GHG emissions target is anticipated. Though many countries profess their commitment to reduce greenhouse gas emissions, taking concrete steps, such as imposing a GHG emissions target depends on a host of political considerations. Climate policies are thus highly uncertain. In the recent paper by Smulders et al. (2014), the authors demonstrate theoretically that, even if climate policy is uncertain, the “green paradox” still holds, although full consumption smoothing is no longer possible. In future work we plan to treat the date of implementation of the GHG target as uncertain.

FABLE model is a partial equilibrium framework, in which income, population, the rate of technological progress, and variable input prices are all

¹⁴Lack of regional disaggregation also impedes our ability to speak to the heterogeneous impacts of climate change in light of geographic shifting of production as an adaptation strategy to changing climate (Nelson et al. 2009). Accounting for such shifts would further moderate the impact of adverse climate change on global land use.

exogenous. We believe this framework is appropriate for the analysis of global land use as land based goods and services account for a small fraction of global economy. However, we cannot entirely rule out possible reverse causalities from land use. For example, falling food production due to adverse impacts of climate change could present a check on further population growth as approximately a billion people today are chronically malnourished (Foley et al. 2011). Our model attempts to account for this problem to some extent by imposing subsistence levels for food consumption. However, establishing elasticities of population growth with respect to food consumption is econometrically challenging, and is beyond the scope of this paper.

One of the most important questions for this intertemporal investigation of land use competition over the 21st century is the sensitivity of the path of optimal land use to model parameters. Therefore, we have undertaken a series of alternative baseline simulations in which key parameters are perturbed and we investigate the impact on model results. These are reported in the technical appendix. These sensitivity analyses indicate that the most important parameter governing baseline land use is the discount rate. Raising our discount rate from 1.5% to 2.25% (i.e. boosting it by half) results in a significant shift away from unmanaged and protected lands (150 Mha less by 2100), towards commercial use in food, timber and biofuel production. As a consequence, future ecosystem services, which only acquire strong demand later in the century, are significantly reduced in favor of commercial services from land.

The next most important parameter for setting the optimal profile of land use over the 21st century is the elasticity of substitution between fertilizer and land which governs the ease of intensification. When this is increased, land devoted to food crops and livestock feed production increases over the baseline due to the rising cost of fertilizer which reduces fertilizer use in the baseline. This is followed by the short run marginal cost of land conversion. Not surprisingly, reducing this cost results in more land conversion – about 60 Mha by 2100. However, these parameter changes are generally found to have a small effect on the deviations from the baseline due to our three scenarios: A, AE and AET.¹⁵ In other words, while they do make a difference in the baseline, they have little effect on the insights obtained from our counterfactual analyses.

An important limitation of our study is our assumption that the incentive to expand biofuel production is driven solely by oil prices. Government mandates

¹⁵The only exception is the interplay of GHG emissions target and higher discount rate, where the decline in natural land conversion is larger compared to the model baseline.

have played an important role in biofuel expansion in the US and the EU, in particular. However, in the long run, the fate of biofuels will be largely determined by oil prices. Recent evidence for the US suggests that biofuel mandates were either not binding (e.g., for corn ethanol see Meyer et al. 2011) or unlikely to be met (e.g., for US-RFS2 mandate for cellulosic biofuels, see National Research Council 2011). More generally, we expect that budgetary pressures will limit the extent to which governments will be willing to subsidize biofuels in the coming decades. However, even if these mandates were implemented, when oil prices are rising steadily (as in our baseline) the global biofuels mandates do not play a large role in our framework, since there is a market incentive to expand in any case (Steinbuks and Timilsina 2014). It is the case, however, that rather than forcing second generation biofuels into the mix over the next decade, the model suggests that, under current technology and the baseline oil price trajectory, these biofuels will not enter a socially optimal land use path until after 2030.

A more serious limitation to this study is our omission of the potential demand for biomass in power generation. Under some scenarios, authors have shown this to be an important source of feedstock demand by mid-century (Rose et al. 2012). However, absent a full representation of the electric power sector, our framework is ill-suited to addressing this issue. Nonetheless, we find that energy prices and GHG mitigation strategies do have a significant impact on land use. While our numbers seem large, they are not inconsistent with the findings of other studies. For example, the results of simulations based on the MIT EPPA model (Gurgel et al. 2007) suggest cropland expansion around 420-470 million Ha for bioenergy production by 2050 in their reference case. Similarly, the dynamic optimization model of Chakravorty et al. (2011) predicts biofuels feedstock area of about 150 Mha in the medium-income countries (per the World Bank’s classification) by 2025 in their reference case scenario.

6 Conclusions

We analyze the optimal allocation of the world’s land resources over the course of the coming century within a novel economic framework, which adopts a dynamic optimization approach to the computational land use modeling literature. The resulting long-run, forward-looking, computable partial equilibrium model, nicknamed FABLE, covers key sectors drawing on the world’s land resources,

and incorporates growing demands for food, renewable energy, and forest products, as well as 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 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 suggests that, even in the absence of GHG regulations, deforestation rates associated with cropland expansion decline along the optimal land-use trajectory in the medium term. This is important, since deforestation accounts for a large share of current global GHG emissions. In the long term there is a significant expansion of the livestock sector, driven by increasing per capita incomes, and this is fueled by increasingly intensive production practices. The area of protected natural lands, which deliver valuable ecosystem services, also increases strongly in the long run. However, this finding is sensitive to the choice of social discount rate. A higher rate of discount results in a sacrifice of forest cover and ecosystem services in favor of more immediate delivery of services from food and energy consumption. Along the baseline, the consumption of biofuels increases rapidly after second generation biofuels become commercially viable in 2035, and provides for about a third of total liquid fuel consumption by the end of this century, along the optimal path under our baseline scenario.

We consider three counterfactual scenarios aimed at capturing the most important sources of uncertainty associated with this long run trajectory for global land use. These include: climate impacts on agriculture, energy prices, and global GHG emissions regulations. Adverse climate impacts on crop yields curtail food production, requiring additional cropland and encouraging additional fertilizer use, thereby leading to higher GHG emissions. Energy prices affect the optimal deforestation rate as well as the overall amount of land used in agriculture. By mid-century, cropland area increases sharply under higher energy prices, due to the incentive for increased biofuel production as well as higher fertilizer prices which raise the cost of intensification. Substantially more deforestation occurs under this scenario and the increased GHG emissions from land use change outweigh the emissions fall from displacement of petroleum consumption by biofuels and declining fertilizer use. When we also require 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 21st century, its effectiveness is eroded by a substantial increase in GHG emissions after the policy is announced, but before the policy is actually implemented. This mimics the ‘green paradox’ found in other areas of environmental regulation. Since such pre-announcement seems inevitable from a political-economic perspective, it is an issue which deserves greater attention. Indeed, we find a leakage rate of 56 percent, which is very high and threatens to undo most of the GHG mitigation benefits of such a policy.

When all three ‘scenarios’ are simultaneously realized, the world’s land resources face a ‘perfect storm’ in which the cost of agricultural intensification is higher, biofuels expand their area, additional cropland is needed to offset the adverse impacts of climate change, and climate regulation also places new pressures on land availability for food. In this case the optimal path of food consumption is significantly lower, highlighting the potential for intense competition for land in the production of the world’s food, fuel and environmental services over the 21st century.

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Technical Appendix

A.1 FABLE Model Equations, Variables and Parameters

Equations

Land Use

$$\bar{L} = L_t^N + L_t^M, \quad (\text{A.1})$$

$$L_t^N = L_t^U + L_t^R, \quad (\text{A.2})$$

$$L_{t+1}^U = L_t^U - \Delta L_t^U = L_t^U - \Delta L_t^{U,M} - \Delta L_t^{U,R}, \quad L_0^U > 0, \quad (\text{A.3})$$

$$L_{t+1}^R = L_t^R + \Delta L_t^{U,R}, \quad L_0^R > 0, \quad (\text{A.4})$$

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

$$c_t^R = \xi_0^R + \xi_1^R \Delta L_t^{U,R}, \quad (\text{A.6})$$

$$L_t^M = L_t^C + L_t^P + L_t^F, \quad (\text{A.7})$$

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

Fossil Fuels

$$x_t^f = x_t^{f,n} + x_t^{f,e}, \quad (\text{A.9})$$

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

Agrochemical Sector

$$x_t^n = \theta^n x_t^{f,n}, \quad (\text{A.11})$$

Agricultural Sector

$$x_t^{g,c} = x_t^{c,g} + x_t^{l,g} + x_t^{b,g}, \quad (\text{A.12})$$

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

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

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

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

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

Livestock Farming Sector

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

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

Food Processing Sector

$$y_t^g = \theta_t^{g,y} x_t^{c,g}, \quad (\text{A.20})$$

$$y_t^l = \theta_t^{l,y} x_t^l, \quad (\text{A.21})$$

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

Biofuels Sector

$$x_t^{b,1} = \theta_t^{b,1} x_t^{b,g} \quad (\text{A.23})$$

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

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

Energy Sector

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

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

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

Forestry Sector

$$L_t^F = \sum_{v=1}^{v_{\max}} L_{v,t}^F, \quad (\text{A.29})$$

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

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

$$L_{1,t+1}^F = \Delta L_t^{F,P}, \quad (\text{A.32})$$

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

$$\theta_{v,t+1}^w = \theta_{v,t}^w + \kappa_v^w, \theta_{v,0}^w > 0 \quad (\text{A.34})$$

$$\begin{aligned} c_t^w &= \xi_0^w \sum_v \theta_{v,0}^w \Delta L_{v,t}^{F,H} + \xi_1^w \left[\sum_v \left(\Delta L_{v,t}^{F,H} - \Delta L_{v,t-1}^{F,H} \right) \right]^2 \\ &\quad + \xi_2^w \left(\sum_v \Delta L_{v,t}^{F,H} - \Delta L_t^{F,P} \right)^2, \end{aligned} \quad (\text{A.35})$$

Timber Processing Sector

$$y_t^w = \theta_t^{w,y} x_t^w, \quad (\text{A.36})$$

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

Ecosystem Services Sector

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

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

Other Goods and Services Sector

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

GHG Emissions

$$z_t = \mu^{f,e} x_t^{f,e} + \mu^{f,n} x_t^{f,n} + z_t^L, \quad (\text{A.41})$$

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

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

Preferences

$$p_q(q) = \frac{\alpha_q + \beta_q \exp(u)}{1 + \exp(u)} \frac{y - \sum_q p_q y^q}{y^q - \gamma^q}, \quad 0 \leq \alpha_q, \beta_q \leq 1 \quad (\text{A.44})$$

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

Welfare

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

Table A.1: Model Exogenous Variables

Parameter	Description	Units
<i>Exogenous Variables</i>		
Π_t	Population	Billion People
c_t^e	Total Energy Costs	USD'1000 per toe
c_t^f	Fossil Fuels' Costs	USD'1000 per toe
$\theta_t^{g,i}$	Agricultural Yield of Crop i	tons per Ha
θ_t^f	Food Processing Technology Index	
θ_t^e	Energy Efficiency Index	
$\theta_{v,t}^w$	Merchantable Timber Yield	tons per Ha
c_t^w	Forest Harvesting Costs	tons per Ha
$\theta_t^{g,y}$	Timber Processing Technology Index	
c_t^R	Protected Lands' Management Costs	
θ_t^o	Total Factor Productivity Index	
y_t^o	Other Goods and Services	USD Trillion
μ_v^w	Carbon Sequestration by Forest Vintage v	tCO ₂ e per Ha
θ_t^z	Land-Use GHG Emissions Quota	GtCO ₂ e

Table A.2: Model Endogenous Variables

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

Table A.3: Baseline Parameters

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

Table A.3: Baseline Parameters (continued)

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

Table A.3: Baseline Parameters (continued)

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

Table A.3: Baseline Parameters (continued)

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

Table A.3: Baseline Parameters (continued)

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

B.1 Empirical Implementation of FABLE

The model baseline extends for a period of 200 years, with an emphasis on the first century, and the starting point being the world economy in 2004. It is consistent with the IPCC (2000) A1B climate change scenario’s storyline that describes a future world of strong economic growth, global population that grows quickly until mid-century and slows thereafter, the rapid introduction of new and more efficient technologies, and balanced energy use across all sources. It also foresees that, as the economy grows, its economic structure changes toward a service economy, including the expansion of ecosystem services sector. The majority of model’s baseline parameters are based on the Global Trade Analysis Project (GTAP) v.7 data base (Hertel 1997, Narayanan and Walmsley 2008) and its satellite data for land use and global climate change policy (Hertel et al. 2009). The values of other model parameters come from variety of the international or government agencies (United Nations, FAO, U.S. Energy Information Administration) and economic, agronomic and environmental science

literatures. The values of baseline parameters are summarized in Table A.3 and Figure B.1.

Figure B.1: Projections of Exogenous Variables, 2005-2104

B.1.1 Population

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

$$\Pi_t = \frac{\Pi_T \Pi_0 e^{\pi t}}{\Pi_T + \Pi_0 (e^{\pi t} - 1)}, \quad (\text{B.1})$$

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 (2011) demographic projections.

B.1.2 Land

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

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

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

In equation (B.2), the variable c_t^u refers to the marginal access cost, implied by the marginal valuation of non-reserved natural land. The parameter ξ_1^N determines the long-run elasticity of natural land access costs with respect to cumulatively accessed hectares, which eventually becomes infinite as the remaining non-reserved natural land is exhausted. The parameter ξ_2^N governs the size of the short-term adjustment costs. We assume that additional costs per hectare of converting natural land to protected land are given by

$$c_t^R = \xi_0^R + \xi_1^R \Delta L_t^R. \quad (\text{B.3})$$

In equation (B.3), the parameter ξ_0^R refers to the long-run time-invariant costs of protecting land. The parameter ξ_1^R governs the size of the short-term adjustment costs. We set the value of the marginal access cost, c_t^u , equal to the shadow price of agricultural lands dedicated to food crops (see equation B.11 below). The parameter values defining natural land access cost function

(B.2), and natural land protection cost function (B.3) are calibrated based on FAO (2010) data to match deforestation rates in 2004 and ensure stable rates of natural land access and protection.

B.1.3 Fossil Fuels

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

$$c_t^f = \frac{c_T^f c_0^f e^{\kappa_f t}}{c_T^f + c_0^f (e^{\kappa_f t} - 1)}, \quad c_0^f > 0, \quad (\text{B.4})$$

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

B.1.4 Agrochemical Sector

The agrochemical sector consumes fossil fuels, $x^{f,n}$, and converts them into fertilizers, x^n , for use in the agricultural sector. The production of fertilizers, x^n , can be described by a linear production function:

$$x_t^n = \theta^n x_t^{f,n}, \quad (\text{B.5})$$

where θ^n is the rate of conversion of fossil fuels to fertilizers.

There are three types of fertilizer used in agricultural production: nitrogen fertilizers, phosphate fertilizers, and potash fertilizers. In our model we focus on nitrogen fertilizers. These fertilizers are particularly important in the climate

policy debate, because their production is the most energy- and GHG- intensive. They are also critical to boosting yields in response to scarcity of land.¹ We use the FAOSTAT database² to obtain the global production of nitrogen fertilizers in 2004. For fertilizers' production costs and conversion rates we consider anhydrous ammonia (NH₃), which is one of the most common nitrogen fertilizers. We use USDA ERS fertilizer use and price dataset³ 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).

B.1.5 Crops Sector

The crops sector combines agricultural land, L^C , and fertilizers, x^n , to produce food crops as well as cellulosic feedstocks (but only when it is profitable). Food crops, $x^{g,c}$, are used as inputs to production of food, animal feed, and first generation biofuels:

$$x_t^{g,c} = x_t^{c,g} + x_t^{l,g} + x_t^{b,g}, \quad (\text{B.6})$$

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

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

$$x_t^{g,i} = \frac{\theta_t^{g,i}}{\Pi_t} \left[\alpha^g \left(L_t^{C,i} \right)^{\rho_g} + (1 - \alpha^g) (x_t^n)^{\rho_g} \right]^{\frac{1}{\rho_g}}, \quad i = b, c, \quad (\text{B.7})$$

where Π_t is the exogenous population at time t , θ_t^g and α^g are, respectively, the crop technology (agricultural yield) index and the value share of cropland in production of agricultural product at the benchmark time 0, and $L_t^{C,i}$ are

¹Note that by von Liebig's Law of the Minimum (yield is proportional to the amount of the most limiting nutrient, whichever nutrient it may be) the production of other two types of fertilizers will follow the path of nitrogen fertilizers.

²Thorough description of the FAOSTAT database is available from the following website: <http://faostat.fao.org/>.

³Thorough description of the dataset is available from the following website: <http://www.ers.usda.gov/Data/FertilizerUse/>.

hectares of agricultural land allocated for food crops and cellulosic feed stocks. The parameter $\rho_g = \frac{\sigma_g - 1}{\sigma_g}$ is a CES function parameter proportional to the elasticity of substitution of agricultural land for fertilizers, σ^g . The production of agricultural output is also subject to non-land costs from use of fertilizers and other production factors (such as e.g., labor or capital), $c^{g,i}$, the prices of which are exogenous.

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

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

$$\theta_t^{g,c} = \frac{\theta_T^{g,c} \theta_0^{g,c} e^{\kappa_{g,c} t}}{\theta_T^{g,c} + \theta_0^{g,c} (e^{\kappa_{g,c} t} - 1)}, \quad (\text{B.8})$$

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

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

$$\theta_{t+1}^{g,b} = \theta_t^{g,b} + \kappa_{g,b}, \quad \theta_0^{g,b} > 0, \quad (\text{B.9})$$

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

We also account for the potential impact of climate change on the growth rate of agricultural yields. In the baseline we assume moderate temperature increase by the end of the century following Representative Concentration Pathways (RCP) 2.6 GHG forcing scenario (Moss et al. 2008). We assume that potential crop yields remain unchanged by the end of the century, as a decline in yields due to moderate increase in temperature is likely to be offset by CO₂ fertilization effect (Long et al. 2006). In contrast, second generation biofuels feed stocks benefit from higher temperatures and yields increase strongly (Brown et al. 2000). Based on the simulation results for switchgrass yields in the upper Midwest of the United States (Brown et al. 2000), agricultural yield growth for cellulosic feedstocks is expected to increase by 50% in 2100. We annualize the growth by assuming that agricultural yield growth rate of cellulosic feed stocks relative to 2005 increases by 10% every twenty years until 2100.

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

$$c_t^{g,i} = \frac{1}{\theta_t^{g,i}} \left((\alpha^g)^{\sigma_g} (c_t^{C,i})^{1-\sigma_g} + (1 - \alpha^g)^{\sigma_g} (c_t^f)^{1-\sigma_g} \right)^{\frac{1}{1-\sigma_g}}, \quad (\text{B.10})$$

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

$$L_t^{C,i} = \frac{x_t^{g,i}}{\theta_t^{g,i}} \left(\frac{\alpha^g}{c_t^{C,i}} \right)^{\sigma_g} \left(\alpha^{\sigma_g} (c_t^{C,i})^{1-\sigma_g} + (1 - \alpha^g)^{\sigma_g} (c_t^f)^{1-\sigma_g} \right)^{\frac{\sigma_g}{1-\sigma_g}}. \quad (\text{B.11})$$

B.1.6 Livestock Sector

The livestock sector combines pasture land, L^P , and animal feed, $x^{l,g}$, to produce domesticated animals, x^l . Pasture land and animal feed are imperfect

substitutes in the production of livestock. The per capita output of livestock, x^l , is thus determined by the constant elasticity of substitution (CES) function:

$$x_t^l = \frac{\theta_t^l}{\Pi_t} \left[\alpha^l (L_t^P)^{\rho_l} + (1 - \alpha^l) (\Pi_t x_t^{l,g})^{\rho_l} \right]^{\frac{1}{\rho_l}}, \quad (\text{B.12})$$

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

The initial output of livestock products (measured as the global physical production of meat, dairy and eggs) in 2004 come from the FAOSTAT database. We obtain the economic rent of global pasture land and the expenditures on animal feed, from GTAP v.7 database. The initial amount of animal feed comes from the USDA FAS PSD database.⁴ The elasticity of substitution of animal feed for pasture land is taken from Golub et al. (2009). The livestock technology index and value shares of agricultural land and fertilizers in 2004 are calibrated from known values of livestock output, animal feed, and the pasture land as described in Rutherford (2002). Non land livestock farming costs are given by

$$c_t^l = c_0^l x_t^l + \xi_0^l (\Delta L_t^P)^2. \quad (\text{B.13})$$

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

B.1.7 Food Processing Sector

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

⁴see <http://www.fas.usda.gov/psdonline>, last accessed in August 2013.

demand.⁵ The conversion process is represented by the following production functions:

$$y_t^g = \theta_t^{g,y} x_t^{c,g}, \quad (\text{B.14})$$

$$y_t^l = \theta_t^{l,y} x_t^l, \quad (\text{B.15})$$

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

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

$$\theta_{t+1}^{i,y} = \kappa_{i,y} \theta_t^{i,y}, \quad \theta_0^{i,y} > 0, \quad i = g, l, \quad (\text{B.16})$$

where the parameters $\theta_0^{i,y}$ and $\kappa_{i,y}$ reflect the initial level and annual growth rate in technologies of the food processing sector. We calculate the level of technology index of the grain and livestock processing in 2004 using GTAP v.7 database. For grains, we dividing the output of processed grains and crops (GTAP sectors 21, 23-25) by the output of grains and cereals (GTAP sectors 1-8). For livestock, we dividing the output of processed livestock and dairy (GTAP sectors 19-20, 22) by the output of livestock products (GTAP sectors 9-11). We set the growth rate of the technology in the food processing sector equal to the economy's TFP. We obtain the non-land food processing costs from GTAP v.7 database.

B.1.8 Biofuels Sector

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

⁵For example, technological innovation in food conservation results in fewer losses from spoilage, and, correspondingly, lower amounts of processed food needed to satisfy the commercial demand for food. Correspondingly, input requirements for agricultural product also decrease.

output of first generation biofuels is thus given by

$$x_t^{b,1} = \theta_t^{b,1} x^{b,g}. \quad (\text{B.17})$$

The biofuels sector also converts cellulosic feedstocks, $x^{g,b}$, into second generation biofuels, $x^{b,2}$, which are expected to take over the market gradually, under a growing energy price scenario. The temporal path of the share of the market controlled by this new technology is expected to follow an S-shaped function (Geroski 2000), reflecting gradual penetration in light of capital adjustment costs, scarcity of specialized engineering resources and equipment to install new capacity, and slow regulatory approval processes. In this study, the approach for representing the penetration process is based on McFarland et al. (2004), and is similar to that used in the MIT-EPPA integrated assessment model (Paltsev et al. 2005). We explicitly introduce in the production function an additional fixed factor specific to the new technology, ϕ , whose endowment in the economy is limited. As technology penetrates the market, the share of the technology fixed factor in the production function declines with the rate of factor-specific technological progress, θ_t^ϕ (Acemoglu 1998, van Meijl and van Tongeren 1999). Under these assumptions the production of second generation biofuels, $x^{b,2}$, is determined by the following CES function

$$x_t^{b,2} = \theta^{b,2} \left[(\alpha^b)^{\theta_t^\phi} (\phi)^{\rho_b} + (1 - \alpha^b) \left(x_t^{g,b} \right)^{\rho_b} \right]^{\frac{1}{\rho_b}}, \quad (\text{B.18})$$

where $\theta_t^{b,2}$ and α^b are, respectively, the technology parameter and the value share of fixed factor in production of second generation biofuels at the benchmark time 0. The parameter $\rho_b = \frac{\sigma_b - 1}{\sigma_b}$ is a CES function parameter proportional to the elasticity of substitution of technology fixed factor for cellulosic feed stocks, σ^b . The agricultural products' conversion to renewable fuel incurs additional non-food processing costs, $c^{b,i}$. We assume these costs are constant and scale-invariant.⁶

In the model baseline we define the first generation biofuels as a grain-based ethanol and the second generation biofuels as cellulosic biomass-to-liquid diesel obtained through Fischer-Tropsch gasification. The values for biofuels conversion rate and cost for ethanol and biomass-to-liquid diesel are taken from

⁶With introduction of second generation biofuels one would expect these costs to decline, and biofuels conversion rate to increase as the biofuels' production technology improves. We show the model sensitivity to changes in these parameters in section 5 below.

Taheripour and Tyner (2011). Following Winston (2009) we adjust the quantity of first generation biofuels produced by 0.7 to match the energy content of liquid fossil fuels. The elasticity of substitution of second generation biofuels feedstocks for fixed factor technology and their value shares in CES function (A.24) are calculated based on MIT-EPPA model (Paltsev et al. 2005, Tables 12 and 13, p.40).

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

$$\theta_{t+1}^{\phi} = \kappa_{\phi} \theta_t^{\phi}, \theta_0^{\phi} > 0. \quad (\text{B.19})$$

The rate of factor-specific technological change, κ_{ϕ} , is highly uncertain and is an important contribution to the uncertainty in projected deployment in second generation biofuels (Creutzig et al. 2012). Following the economic literature on biofuels modeling (Popp et al. 2011, Wise and Calvin 2011) we set the rate to 0.5 percent. In section D.1 we perform a sensitivity analysis with respect to a higher value of the rate of factor-specific technological change.

B.1.9 Energy Sector

The energy sector consumes petroleum products, x^e , and first and second generation biofuels, $x^{b,i}$. First generation biofuels (e.g., corn or sugarcane ethanol) blend with petroleum products in varying proportions,⁷ and the resulting mix is further combusted to satisfy the demand for energy services.⁸ Following the economic literature on biofuels modeling (Hertel, Tyner and Birur 2010), we assume that first generation biofuels and petroleum products are imperfect substitutes. Second generation biofuels (e.g., cellulosic biomass-to-liquid diesel obtained through Fischer-Tropsch gasification) offer a full ‘drop-in’ fuel alternative. We therefore assume that petroleum products and second generation biofuels are perfect substitutes. Under these assumptions the per capita pro-

⁷Blends of E10 or less are used in more than twenty countries around the world, led by the United States, where ethanol represented 10% percent of the U.S. gasoline fuel supply in 2011. Blends from E20 to E25 have been used in Brazil since the late 1970s. E85 is commonly used in the U.S. and Europe for flexible-fuel vehicles. Hydrous ethanol or E100 is used in Brazilian neat ethanol vehicles and flex-fuel light vehicles and in hydrous E15 called hE15 for modern petrol cars in Netherlands.

⁸The focus of this model is on services from liquid fuels, which account for about a third of global energy use EIA (2011).

duction of energy services, y_t^e , is given by the following CES function:

$$y_t^e = \theta_t^e \left(\alpha^e \left(x_t^{b,1} \right)^{\rho_e} + (1 - \alpha^e) \left(\frac{x_t^{f,e}}{\Pi_t} + x_t^{b,2} \right)^{\rho_e} \right)^{\frac{1}{\rho_e}}, \quad (\text{B.20})$$

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

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

$$c_t^e = \sum_i c^{b,i} + c_t^f, \quad i = 1, 2. \quad (\text{B.21})$$

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

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

$$\theta_{t+1}^e = \kappa_e \theta_t^e, \quad \theta_0^e > 0, \quad (\text{B.22})$$

where the parameters θ_0^e and κ_e reflect the initial level and annual growth rate in the energy efficiency. We set the energy efficiency in 2004 equal to one, and obtain the growth rate in the energy efficiency from World Energy Council (2008).

B.1.10 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

(Sohnngen and Mendelsohn 2007, Sohnngen et al. 2009b) we assume that the merchantable timber yield function is given by the following equation:

$$\begin{aligned}\theta_v^w &= \exp\left(\psi_1 - \frac{\psi_2}{v - \bar{v}}\right), \text{ if } v > \bar{v} \\ \theta_v^w &= 0, \text{ if } v \leq \bar{v}.\end{aligned}\tag{B.23}$$

In equation (B.23), the parameters ψ_1 and ψ_2 are growth parameters determining the support and the slope of the timber yield function, and $\bar{v}$ is a minimum age for merchantable timber. The yield function (B.23) parameters, the minimum age for merchantable timber, and the average planting and harvesting costs come from GTAP Global Forestry Data Base (Sohnngen et al. 2009b). Similar to the agricultural sector, we assume that the merchantable timber yield per hectare of forest land with the average tree age v grows linearly across time, adding a constant amount of technology gain per annum:

$$\theta_{v,t+1}^w = \theta_{v,t}^w + \kappa_v^w, \theta_{v,0}^w > 0,\tag{B.24}$$

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

The per capita output of forest products is given by

$$x_t^w = \sum_{v=1}^{v_{\max}} \frac{\theta_{v,t}^w}{\Pi_t} \Delta L_{v,t}^{F,H}.\tag{B.25}$$

Forest harvesting costs are given by

$$\begin{aligned}c_t^w &= \xi_0^w \sum_v \theta_{v,0}^w \Delta L_{v,t}^{F,H} + \xi_1^w \left[\sum_v \left(\Delta L_{v,t}^{F,H} - \Delta L_{v,t-1}^{F,H} \right) \right]^2 \\ &\quad + \xi_2^w \left(\sum_v \Delta L_{v,t}^{F,H} - \Delta L_t^{F,P} \right)^2,\end{aligned}\tag{B.26}$$

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

recent dynamics in commercial land-use.

B.1.11 Timber Processing Sector

The timber processing sector converts harvested forest product, x^w , into processed timber products, y^w , that are further consumed in final demand. Similar to food processing, the purpose of this sector in the model is to capture the efficiency gains from technology improvements in timber production, which result in lower requirements for forest products in final demand.⁹ The conversion process is represented by a linear production function:

$$y_t^w = \theta_t^{w,y} x_t^w, \quad (\text{B.27})$$

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

Technological progress in the timber processing sector is described by the following equation:

$$\theta_{t+1}^{w,y} = \kappa_{w,y} \theta_t^{w,y}, \quad \theta_0^{w,y} > 0, \quad (\text{B.28})$$

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

B.1.12 Ecosystem Services Sector

This sector combines different types of land to produce terrestrial ecosystem services. It is well known in both economic and ecological literatures that ecosystem services are difficult to define, and it is therefore challenging to characterize their production processes (National Research Council 2005). This stems in

⁹For 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.

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

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

$$y_t^r = \frac{\theta^r}{\Pi_t} \left[\sum_{i=C,P,F} \alpha^{i,r} (L_t^i)^{\rho_r} + \left(1 - \sum_{i=C,P,F} \alpha^{i,r} \right) (L_t^U + \theta^R L_t^R)^{\rho_r} \right]^{\frac{1}{\rho_r}}. \quad (\text{B.29})$$

where the parameter θ^r describes the technology index of ecosystem services “production”.¹⁰ The parameters $\alpha^{i,r}$ are the value shares of crop, pasture, and managed forest lands in production of ecosystem services at the benchmark time 0. The parameter $\rho_r = \frac{\sigma_r - 1}{\sigma_r}$ is a CES function parameter proportional to the elasticity of substitution of different types of land in production of ecosystem services, σ_r . By characterizing the production process of ecosystem services using equation (B.29) we assume that agricultural, managed forest, and natural lands substitute imperfectly in production of ecosystem services. Unmanaged and protected natural land produce the same types of ecosystem services (Costanza et al. 1997). However, protected forest lands are more efficient in delivering many ecosystem services and preserving biodiversity, as they have e.g., better management for reducing degradation of biodiversity, and better infrastructure

¹⁰We put the term “technology” in quotation terms because, as discussed above, characterizing “true” production process of ecosystem services is beyond the scope of the paper. Here we use the term “technology” as a scalar that maps ecological assets to ecosystem services in reference period 0.

for providing eco-tourism and recreation services (Hocking et al. 2000, Bruner et al. 2001, Rodrigues et al. 2004). The parameter θ^R captures the relative effectiveness of protected land in delivering eco-system services.

The parameters for production of ecosystem services in production function A.38 are based on the estimates of Costanza et al. (1997), who estimated values for 17 ecosystem services from 16 ecosystem types at global scale.¹¹ We exclude the services from the production of food and timber, as well as from based climate abatement, as those are determined endogenously in the model. We also exclude the production of ecosystem services from ecosystems not represented in the model (e.g., marine, grasslands and deserts). We use agroecological zone (AEZ) representation of GTAP land use database to differentiate between tropical and temperate/boreal forest land. Based on ecological literature (Ehrlich and Mooney 1983) we assume that there is a limited substitution between different land types in production of ecosystem services. Because effectiveness of protected land areas is very difficult to quantify (Chape et al. 2005), we set the parameter θ^R large enough to make sure new protected areas are established.

We assume that the non-land cost of producing ecosystem services is zero for agricultural and managed forest land, as production of ecosystem services is not their primary function. This cost is also zero for unmanaged natural lands. We assume that the non-land cost of managing protected natural areas declines over time with technological improvements in non-land inputs. We characterize the change in non-land costs of managing protected natural areas, c_t^R , by the following equation:

$$c_t^R = \frac{c_0^R}{(1 + \kappa_R)^t} c_0^R > 0, \quad (\text{B.30})$$

where the parameters κ_R reflect the annual rate of decline in the non-land cost of managing protected natural areas. We measure the non-land costs of managing protected natural areas based on GTAP v.7 database as public expenditures on outdoor recreation services per hectare of protected land.¹²

¹¹We are familiar with multiple criticisms of this approach National Research Council (2005, p. 188-189). However, there have been very few attempts to evaluate production of ecosystem services at global scale, and the work of Costanza et al. (1997) still remains most influential.

¹²Following Antoine et al. (2008), we define outdoor recreation services sector based on GTAP v.7 database. This sector comprises of hunting and fishing, wildlife viewing in reserves, and other wildlife viewing activities.

B.1.13 Other Goods and Services

The production of other goods and services, y_t^o , in this model is exogenous. The reason we include it in this partial equilibrium model is to complete the demand system (described in a section below), which determines welfare. As the supply of other goods and services is exogenous, we assume that they grow at the overall rate of total factor productivity (TFP) growth, which is roughly equal to the world economy's TFP growth rate.¹³

The growth of TFP is described by the following equation:

$$\theta_{t+1}^o = \kappa_o \theta_t^o, \theta > 0, \quad (\text{B.31})$$

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

Because the production of other goods and services does not draw on the land resource, we assume without loss of generality that their cost of production is zero.

B.1.14 GHG Emissions

The value of the GHG emission coefficient from combustion of liquid fossil fuels comes from the US Energy Information Administration (EIA) website¹⁴. The GHG emission coefficient from production of ammonia from fossil fuels comes from IPCC (2006a) Tier 1 estimates. We compute GHG emissions per ton of anhydrous ammonia applied to crop lands as follows. First, we calculate the nitrogen equivalent mass of anhydrous ammonia using conversion factor of $\frac{17}{28}$. We then use IPCC (2006b) Tier 1 estimates to compute the amount of nitrogen released to the atmosphere from ammonia application. We then convert the amount of nitrogen released to the atmosphere to nitrogen dioxide (NO_2) using

¹³The economy's output has a small fraction of endogenously determined output from land-use. We ignore this complication in this partial-equilibrium model.

¹⁴See <http://www.eia.doe.gov/oiaf/1605/coefficients.html>, last checked in August, 2013.

conversion factor of $\frac{44}{28}$. Finally, we find the carbon dioxide equivalent of the nitrogen dioxide using global warming potential of NO_2 .

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

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

$$\mu_v^h = \bar{\mu}^w \exp\left(\psi_1 - \frac{\psi_2}{v}\right). \quad (\text{B.32})$$

In equation (B.32) the parameter $\bar{\mu}^w$ 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 (B.23).¹⁵ Then the amount of GHG sequestered by a hectare of forest land of tree vintage v is

$$\mu_v^w = \mu_v^h - \mu_{v-1}^h. \quad (\text{B.33})$$

We obtain the carbon conversion factor and yield function (B.23) 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).

B.1.15 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 (A.45) are

¹⁵Note that the minimum age parameter, $\bar{v}$, is not included in equation (B.33). This is because at young ages, stands may have substantial carbon, but little merchantable timber (Sohngen et al. (2009b)).

estimated by maximum likelihood as described in Cranfield et al. (2003) and Yu et al. (2004). The parameters $\bar{q}$ define the subsistence level of consumption of goods and services q were calibrated to match the initial allocation of land resources. The social discount rate is the same as in the Dynamic Integrated model of Climate and the Economy (DICE), version 2007.¹⁶ We parameterize the scrap value function as

$$\Gamma(L_T^U, L_T^F) = \varpi_1 L_T^U + \varpi_2 \sum_{v=1}^{v_{max}} \frac{L_{v,T}^F}{\delta^{T-v}}, \quad (\varpi_1 > 0, \varpi_2 > 0), \quad (\text{B.34})$$

where the parameters ϖ_1 and ϖ_2 denote the scrap prices of unmanaged and commercial forests at the beginning of period T . We calibrate the values of ϖ_1 and ϖ_2 , so that forest replanting rates are stable over time and unmanaged natural lands are not depleted over 50 percent of their initial amount during the time horizon of the problem.¹⁷

B.2 Construction of Counterfactual Scenarios

The values of the model parameters corresponding to the three counterfactual scenarios are summarized in Table B.1 and Figure B.2.

¹⁶For 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>

¹⁷We 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 B.2: Projections of Exogenous Variables, 2005-2104

To quantify the impact of climate change impact on potential crop yields we follow Steinbuks and Hertel (2013), who obtained results from runs of the Decision Support System for Agrotechnology Transfer (DSSAT) crop simulation model (Jones et al. 2003), run globally on a 0.5° grid and weighted by agricultural output of four major food crops (maize, soybeans, wheat and rice) under most optimistic (RCP2.6) and pessimistic (RCP8.5) Representative Concentration Pathways GHG forcing scenarios (Moss et al. 2008) and alternate assumptions on CO_2 fertilization effects over the period between 1971 and 2099. For scenario A, we calculate the change in potential agricultural yield for food crops assume the pessimistic RCP8.5 without CO_2 fertilization effect.

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). We calibrate the value of the logistic oil price growth rate, κ_f , so that most of the additional increase in prices take place by mid-century (see Figure B.2).

For scenario scenario, T we set the land-use emissions' target in 2100 to 60%

less compared to 2004. The global warming intensity, $\theta_{zt}(z_\tau, t)$ defining the land-use GHG emissions' target is a logistic function:

$$\theta_t^z = \frac{z_T z_\tau e^{\kappa_\mu t}}{z_T + z_\tau (e^{\kappa_\mu t} - 1)}, \quad (\text{B.35})$$

where z_τ are GHG emissions in 2025, z_T are the GHG emissions cap in 2104, and κ_μ is the targeted rate of decline in land-use GHG emissions. We calibrate the targeted rate of decline so that the target's stringency increases rapidly after it is introduced, with larger GHG emissions' reductions taking place by 2050.

Table B.1: Parameters for Counterfactual Scenarios

Parameter	Description	Units	Value
<i>Scenario A (Declining Growth of Agricultural Yield)</i>			
$\theta_T^{g,c}$	Food Crop Yield in time T	tons / Ha	8.05
<i>Scenario E (Rising Fossil Fuel Costs)</i>			
κ_f	Logistic Oil Price Growth Rate		0.075
<i>Scenario T (Land-Use Emissions Target)</i>			
z_τ	GHG Emissions in 2025	GtCO ₂ e	
z_T	GHG Emissions in 2104	GtCO ₂ e	$0.4z_\tau$
κ_μ	Logistic Rate of Decline in Land-Use Emissions		0.04

D.1 Model Sensitivity to Parameter Values

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

Table C.1: Model Simulation Results, 2050

Variable / Scenario	Baseline (Level)	Scenario A (Deviation from Baseline)	Scenario E (Deviation from Baseline)	Scenario T	Scenario AE (ΔA)	Scenario AET (ΔAE)
<i>Land</i>						
Cropland Area, MHa	1951	16.9	29.9	-39.4	30.0	-38.7
- Food Crops, MHa	1459	11.0	-27.0	-27.0	-25.0	-20.0
- Animal Feed, MHa	399	8.7	-2.7	-41.8	-3.4	-34.7
- Biofuels Crops, MHa	93	-2.8	59.6	29.4	58.4	16.0
Pasture Land Area, MHa	2547	-4.9	-8.0	-41.0	-8.0	-39.2
Commercial Forest Area, MHa	1587	-3.0	-6.0	53.0	-6.0	40.0
Unmanaged Natural Land Area, MHa	2183	-7.0	-11.0	22.0	-11.0	29.0
Protected Natural Land Area, MHa	291	-2.4	-4.7	5.2	-4.7	8.7
<i>Intermediate Products</i>						
Agricultural Product, Mton	4407	-242.2	-437.9	-260.9	-419.2	-167.7
Livestock, Mton	890	-29.7	-60.9	-87.2	-60.3	-63.0
Fertilizers, Mton	128	6.5	-26.2	-10.6	-27.8	-6.5
Petroleum, Mtoe	773	0.0	-400.6	-270.2	-400.6	-111.8
Biofuels, Mtoe	314	-2.7	55.7	36.0	56.4	10.1
Timber Products, Mton	2515	0.0	0.0	0.0	0.0	0.0
<i>Final Consumption</i>						
Processed Food Services per capita, 2004 USD	263	-15	-27	-11	-25	-7
Processed Livestock Services per capita, 2004 USD	291	-10	-20	-28	-20	-21
Bioenergy Services per capita, 2004 USD	33	0	26	4	26	2
Processed Timber Services per capita, 2004 USD	271	0	0	0	0	0
Ecosystem Services per capita, 2004 USD	259	-1	-2	4	-2	5
<i>GHG Emissions</i>						
Natural Land Conversion, MtCO ₂ e	0	0	0	0	0	0
Fertilizers' Use, MtCO ₂ e	519	26	-106	-43	-113	-27
Biofuels Combustion, MtCO ₂ e	195	-2	35	22	35	6
Livestock Farming and Management, MtCO ₂ e	1241	-28	-58	-87	-57	-64
Net Forest Sequestration, MtCO ₂ e	-2029	12	28	-246	29	-76
Petroleum Combustion, MtCO ₂ e	2240	2	-1161	-790	-1162	-319
<i>GHG Emissions from Land Use, MtCO₂e</i>	-74	7	-101	-355	-106	-161
<i>Accumulated GHG Emissions from Land Use, GtCO₂e</i>	67.9	5.1	-8.2	5.4	-8.4	12.4

Table C.2: Model Simulation Results, 2100

Variable / Scenario	Baseline (Level)	Scenario A (Deviation from Baseline)	Scenario E (Deviation from Baseline)	Scenario T	Scenario AE (ΔA)	Scenario AET (ΔAE)
<i>Land</i>						
Cropland Area, MHa	2139	24.1	25.0	-83.5	25.0	-84.5
- Food Crops, MHa	1261	8.0	7.0	-16.0	7.0	-19.0
- Animal Feed, MHa	735	19.3	5.8	-96.7	6.0	-92.9
- Biofuels Crops, MHa	143	-3.2	12.2	29.2	12.0	27.4
Pasture Land Area, MHa	2330	-9.8	-6.7	-114.3	-6.8	-111.7
Commercial Forest Area, MHa	1616	-5.0	-2.0	171.0	-2.0	157.0
Unmanaged Natural Land Area, MHa	1795	-5.0	-11.0	39.0	-10.0	47.0
Protected Natural Land Area, MHa	678	-4.3	-4.9	-11.9	-4.9	-9.1
<i>Intermediate Products</i>						
Agricultural Product, Mton	6188	-629.8	-140.0	-659.8	-120.0	-549.8
Livestock, Mton	1577	-96.0	-23.1	-214.2	-21.8	-186.4
Fertilizers, Mton	179	5.7	-11.4	-31.1	-11.4	-27.8
Petroleum, Mtoe	1170	-10.0	-150.0	-469.9	-140.0	-399.9
Biofuels, Mtoe	507	-3.5	8.3	19.8	8.3	16.8
Timber Products, Mton	3399	0.0	0.0	0.0	0.0	0.0
<i>Final Consumption</i>						
Processed Food Services per capita, 2004 USD	275	-29	-7	-18	-6	-15
Processed Livestock Services per capita, 2004 USD	480	-29	-7	-65	-7	-57
Bioenergy Services per capita, 2004 USD	85	-1	9	3	9	3
Processed Timber Services per capita, 2004 USD	344	0	0	0	0	0
Ecosystem Services per capita, 2004 USD	329	-1	-2	4	-2	4
<i>GHG Emissions</i>						
Natural Land Conversion, MtCO ₂ e	0	0	0	0	0	0
Fertilizers' Use, MtCO ₂ e	727	25	-46	-124	-48	-112
Biofuels Combustion, MtCO ₂ e	322	-5	6	10	6	9
Livestock Farming and Management, MtCO ₂ e	1844	-101	-25	-234	-24	-202
Net Forest Sequestration, MtCO ₂ e	-2075	28	18	-768	19	-697
Petroleum Combustion, MtCO ₂ e	3382	-22	-417	-1346	-415	-1144
<i>GHG Emissions from Land Use, MtCO₂e</i>	817	-53	-47	-1115	-47	-1002
<i>Accumulated GHG Emissions from Land Use, GtCO₂e</i>	11.8	4.8	-15.4	-34.2	-15.7	-18.2

sensitivities with respect to the following changes¹⁸:

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

Table D.1 summarizes the changes in parameters values under consideration.¹⁹

Table D.1: Parameter Changes in Model Sensitivity Analysis

Parameter	Description	Baseline Value	New Value
ξ_2^u	Natural Land Access Cost Function Parameter	42,000	28,000
σ_g	Elasticity of Substitution between Land and Fertilizers	1.14	1.71
$\theta^{b,2}$	2G Biofuels' Conversion Technology	0.467	0.71
κ_ϕ	Factor Specific Tech. Change Growth p.a.	1.005	1.0075
κ_e	Energy Efficiency Growth Rate p.a.	0.016	0.011
δ	Social Discount Rate	0.015	0.0225

Figure D.1 shows the effects of a 50% decline in short-term adjustment costs of natural land conversion (all of the figures in this section report changes, relative to the baseline). Greater ease of natural land conversion results in a decline in unmanaged forest land, which decreases further by 65 million Ha in 2100. Agricultural land dedicated to food crops and animal feed expands in near decades and the medium term. In the long term, there is also an increase

¹⁸Because of a lack of space, we are unable to show sensitivity results across all parameters and scenarios. In this section we concentrate on the parameters subject to largest uncertainties. The additional results are available from authors upon request.

¹⁹The magnitudes of parameter changes in model sensitivity analysis are not based on projections from other studies. Rather these magnitudes represent a simple attempt to construct confidence intervals for baseline predictions.

Figure D.1: Sensitivity Analysis: 50% Decline in Short Term Adjustment Costs of Natural Land Conversion

in managed and protected forest areas and the area dedicated to biofuels feedstocks. The additional conversion of natural lands results in increased GHG flows, and net GHG accumulation increases by 25 GtCO₂e in mid-century, and remains constant thereafter. The consumption of ecosystem services declines in the mid term as a result of additional deforestation, but increases thereafter with the increase in protected lands. The consumption of all other land-based goods and services, and biofuels increase modestly in the long term.

Figure D.2: Sensitivity Analysis: 50% Increase in Elasticity of Substitution between Agricultural Land and Fertilizers

Figure D.2 shows the effects of a 50% increase in elasticity of substitution between agricultural land and fertilizers. Given the increase in fertilizers' costs in baseline scenario, better substitution between agricultural land and fertilizers implies additional demand for agricultural land, which increases by about 150 million Ha in 2100. All forest areas decline. GHG flows increase with the additional conversion of natural lands. However, the decline in fertilizers' use results in smaller GHG flows. The former effect dominates, and net GHG accumulation increases by 30 GtCO₂e in 2100. The consumption of all land based goods and

services declines. There is also a small decrease in the consumption of biofuels.

Figure D.3: Sensitivity Analysis: 50% Increase in Biofuels' Conversion Rate

Figure D.3 shows the effects of a 50% improvement in second generation biofuels production technology. This improvement makes second generation biofuels a more competitive alternative to petroleum products, and they enter large scale commercial production considerably earlier. After arrival of second generation biofuels, their production increases by 300 million toe, and the biofuels share in liquid fuel production increases to reach 47% in 2100. Agricultural area dedicated to cellulosic feedstocks increases by additional 30 million Ha in 2100, whereas areas dedicated to food crops, animal feed and natural forests decline. GHG flows increase with the additional conversion of natural lands, and later decline with biofuels' offsets. The latter effect dominates in the long run, and net GHG accumulation declines by 40 GtCO₂e in 2100. The consumption of energy services increases, and the consumption of other land based goods and services declines.

Figure D.4 shows the effects of a 50% increase in fixed factor specific technological change. Similar to the improvements in biofuels' production technology,

Figure D.4: Sensitivity Analysis: 50% Increase in Fixed Factor Specific Technological Change

faster technological progress in biofuels penetration make biofuels a more competitive alternative to petroleum products. Biofuels production increases by 150 million toe, and the biofuels share in liquid fuel production increases to reach 39% in 2100. Agricultural area dedicated to cellulosic feedstocks increases by additional 36 million Ha in 2100. All other areas decline. GHG flows increase because of additional conversion of natural lands, and decline due to greater biofuels' offsets. The latter effect dominates in the long run, and net GHG accumulation declines by 10 GtCO₂e in 2100. The consumption of energy services increases, and the consumption of other land based goods and services declines.

Figure D.5: Sensitivity Analysis: 50% Decline in Energy Efficiency Growth Rate per annum

Figure D.5 shows the effects a 50% decline in energy efficiency growth rate. Smaller energy efficiency implies increased requirements for energy fuels (here petroleum products and biofuels) to satisfy the demand for energy services. The increased consumption of petroleum and biofuels results in a greater demand for agricultural land. Areas dedicated to biofuels feedstocks add 3 million Ha. All other areas dedicated to commercial land decline in response to demand reduc-

tion for land based goods and services due to higher energy prices. Unmanaged forest lands increase by additional 26 million Ha in 2100. The GHG emissions flows from land use decline slightly in the medium term because of avoided deforestation. The consumption of biofuels increase by a small amount, although their share in liquid fuel consumption modestly declines because of even greater increase in demand for petroleum products. The income effect of increased requirements for petroleum products propagates into decline in consumption of all land based goods and services, except for energy services.

Figure D.6: Sensitivity Analysis: 50% Increase in Social Discount Rate

Figure D.6 shows the effects of a 50% increase in social discount rate. This results in a substitution of ecosystem services, which have relatively greater importance in more distant future, for all other land based goods and services. The conversion of unmanaged natural land increases substantially by mid-century, and protected forests decline by 150 million hectares in 2100. All other land areas expand. Areas dedicated to food crops and animal feed grow by additional 20 and 7 million Ha, pasture and managed forest areas gain additional 100 and 10 million Ha in 2100. Changes in social discount rate thus result in increase in

the GHG emissions flows from land use because of increased deforestation. Net GHG accumulation increases by nearly 75 GtCO₂e in 2100. The conversion of natural forest land result in a significant decline in consumption of ecosystem services. The consumption of biofuels and their share in liquid fuel consumption increases by a small amount.

D.1.1 Trade-off between GHG Emissions from Land Use Change and Fertilizers

AET with unregulated fertilizers' emissions – AET with regulated fertilizers' emissions

Figure D.7: Trade-off between GHG Emissions from Land Use Change and Fertilizers

As an additional model robustness check, we have undertaken one more scenario, in which we eliminate the regulation of GHG emissions from fertilizers, while retaining regulation of other sources of emissions. Figure D.7 shows the results of this modeling scenario, reported as the deviation of scenario AET with *unregulated* fertilizers' emissions from scenario AET with *regulated* fertilizers' emissions. The primary impact of this policy change is to lower the cost of

fertilizer use, thereby making intensification of crop and livestock production less expensive. As a consequence, production and consumption of food products rises, as does the production of biofuels. Land use in food and biofuels rises, and, by 2100, cumulative emissions are about 15 GtCO₂e higher.

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