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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.

Keywords Biofuels · Climate change · Deforestation · Energy · Environment · Food · Forestry · GHG emissions · Global land use

JEL Classification C61 · Q15 · Q23 · Q26 · Q40 · Q54

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-

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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; Havlík 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 et al. 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 intertemporal 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 products), 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. (2011) 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

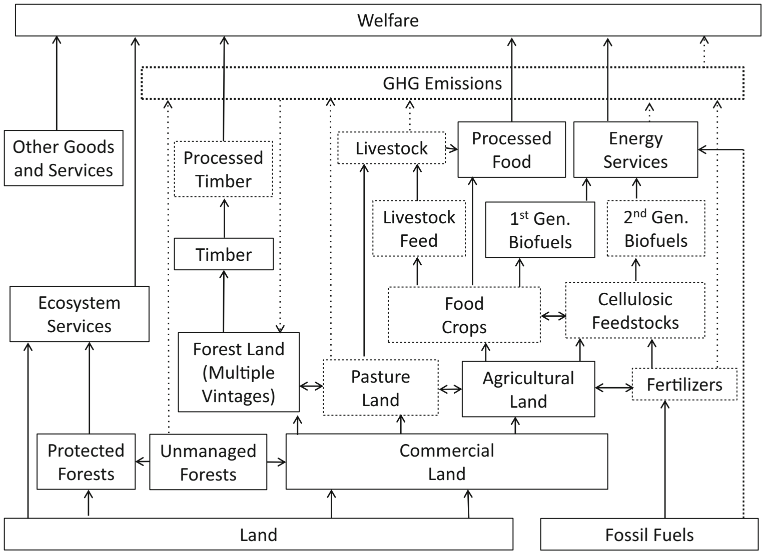

Fig. 1 Structure of the model

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 twentyfirst 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.

2.1 Land Use

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

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

Following the previous literature on natural land use (Antoine et al. 2008; Gurgel et al. 2011) we assume that 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:

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

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

and

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

Equation (2) shows that the total endowment of natural land is a sum of the hectares of protected and unmanaged natural land. Equation (3) shows that at each period of time the area of unmanaged natural land with initial stock, L_0^U, declines by the amounts allocated for conversion to commercial and protected land, $\Delta L_t^U = \Delta L_t^{U,M} + \Delta L_t^{U,R}$, 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 equilibrium model of

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

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

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

and

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

Equation (5) shows that total endowment of commercial land, L^M, is a sum of the hectares of commercial land dedicated to 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 $v = 1, ..., v_{\max}$. 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, $\overline{v}$. Managed forest areas with the average density of oldest trees $v_{\max}$ have the highest yield of $\theta_{v_{\max}}^w$. They do not grow further and remain in this vintage until harvested.

The following equations describe land use of managed forests:

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

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

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

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

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

$$x_t^f = x_t^{f,n} + x_t^{f,e}. \tag{11}$$

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 Fig. 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

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

and

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

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-CO_2 emissions from use of nitrogen fertilizers in agricultural production, (d) non-CO_2 emissions from the livestock sector (which include emissions from enteric fermentation 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 CO_2 equivalent (tCO_2e). A ton of oil equivalent (*toe*) of fossil fuel converted to fertilizer emits $\mu^{f,n}$ tCO_2e. The conversion of natural forest land to commercial land entails emissions of μ^L tCO_2e per hectare of land deforested. A ton of fertilizer applied to agricultural land emits μ^n tCO_2e.

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

GHGs can also be reduced by carbon forest sequestration.[2] A hectare of forest vintage v sequesters μ_v^w tCO_2e. Young forest vintages grow quickly and sequester carbon at a rapid rate. Older vintages grow slowly and eventually cease to sequester carbon. As the unmanaged forest land (both reserved and non-reserved) comprises mainly the older tree vintages, its potential to sequester additional GHGs is small, and may be ignored (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 $(1-\varphi)\mu_v^h$ tCO_2e per hectare of land harvested, where μ_v^h is the carbon stock associated with harvested tree vintage v, and φ is the share of permanently stored carbon in harvested forest products. We ignore the annual sequestration of carbon by agricultural product, as those crops are harvested and subsequently consumed in the form of food or bioenergy.

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

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

and

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

Equation (14) describes the composition of GHG emissions flows. Equation (15) shows net GHG emissions from deforestation, food and livestock production, and 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, $\overline{z}^L$. We do not impose the emissions' constraints on GHG emissions from fossil fuels' combustion because they are exogenously determined. Rather we assume that emissions control instruments are reflected in exogenous 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, $\overline{z}^L$, by the fraction of fossil fuels' emissions displaced by the biofuels.[3] The resulting relationships for emissions control are

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

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

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

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, 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):

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

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 $F\left(y^q, u\right)$ is a twice-diffirentiable monotonic function that is strictly quasi-concave in y^q. Based on Rimmer and Powell (1996), the functional form for $F\left(y^q, u\right)$ is

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

In Eq. (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 $F\left(y^q, u\right)$ 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 $F\left(y^q, u\right)$. 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.

[4] The most popular demand systems estimated in recent applied work are the homothetic Cobb-Douglas system (HCD), the linear expenditure system (LES), the constant difference of elasticities demand system (CDE), and the almost ideal demand system (AIDS).

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

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

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

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:

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

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 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 Fig. 2, we see that, in the near term decades, area dedicated to food crops increases by 10 % 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 % lower than in 2004. Improvements in crop technology and agricultural

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

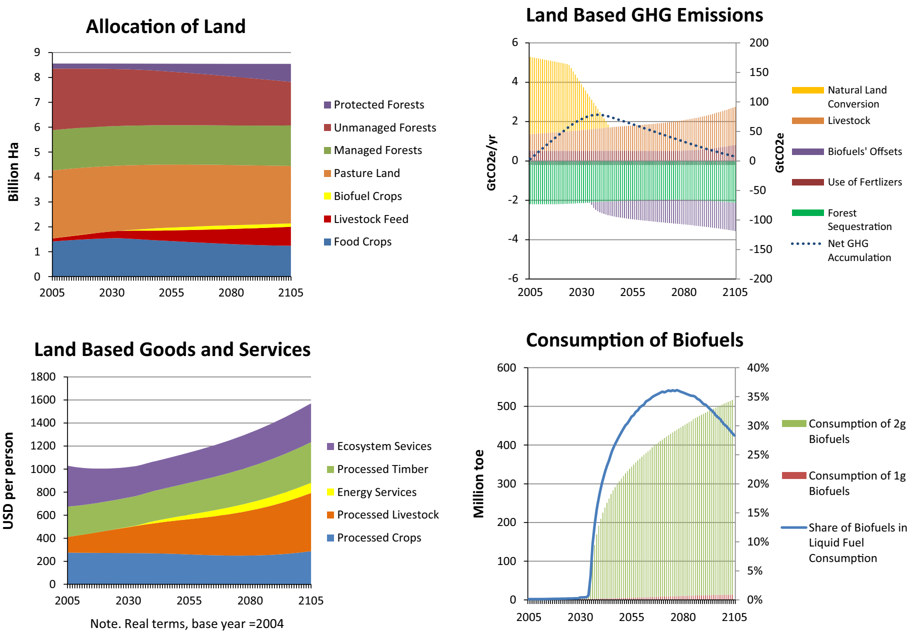

Fig. 2 Model baseline

yields result in greater intensification of livestock production. Pasture land continues to decline, reaching 2.33 billion hectares, which is 15 % 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 Fig. 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 $GtCO_2e/yr$ 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 $GtCO_2e/yr$, which is 40 % larger than 2004. Continued growth in consumption of meat and dairy products results in a significant increase in GHG emissions from livestock. In 2100, annual flows of GHG emissions from livestock amount to 1.84 $GtCO_2e/yr$, which is 2.2 times larger than 2004. GHG emissions sequestration from managed forests does not

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

change significantly. In 2100 sequestered GHG emissions amount to 2.1 $GtCO_2e/yr$, which is about 5 % 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 $GtCO_2e/yr$. Overall, accumulation of land based GHG emissions increases in the first part of this century, reaching its maximum of 80 $GtCO_2e$ around 2040. It then declines in the second part of the century reaching 12 $GtCO_2e$ by 2100. 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 twentyfirst century.

The lower left-hand panel in Fig. 2 illustrates the results for per-capita consumption of goods and services that draw on land resources. The consumption of livestock products, timber products, and biofuels grow in absolute terms. 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 Fig. 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 % 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 % 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 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

[8] Direct 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.

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 CO_2 in the atmosphere results in an increase in potential yields due to the "CO_2 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 celluslosic 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 et al. 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 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 twentyfirst 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 CO_2—equivalent concentration (including GHGs and aerosols) at stabilization of 445–490 ppm. After the target is introduced in 2025 it rapidly

[9] We show the model sensitivity to changes in other important model parameters in Technical Appendix.

[10] Of 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.

[11] In 2008 New Zealand passed legislation to include commercial forestry sector in the emissions trading scheme. Regulation of other land-use emissions is expected to take place in 2015 (Source: the New Zealand's Ministry of Agriculture and Forestry website: www.maf.govt.nz). In 2010 the European Commission launched a public consultation on whether emissions and removals of greenhouse gases related to land use, land use change and forestry (LULUCF) should be covered by the EU's target of cutting GHG emissions to 30 % below 1990 levels by 2020 (Source: the European Commission's website: http://ec.europa.eu/commission_2010-2014/hedegaard/headlines/news/2010-09-10_01_en.htm).

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 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 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 Fig. 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 %) 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 $GtCO_2e$ in 2100 (upper right-hand panel of Fig. 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 $MtCO_2e/yr$ 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 Fig. 3). There is a significant decline in the consumption of processed

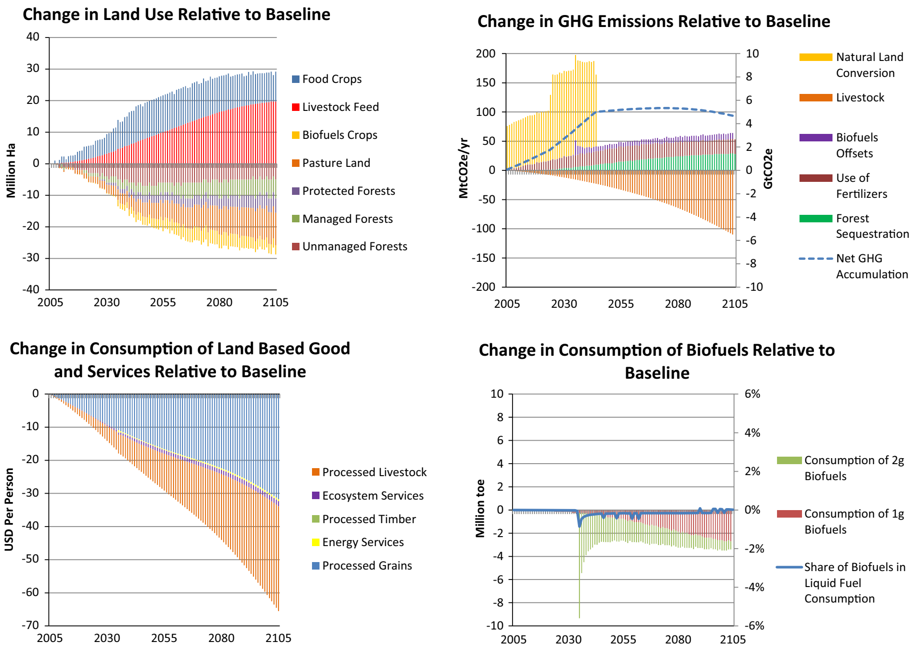

Fig. 3 Scenario A versus baseline: climate change impacts on agriculture

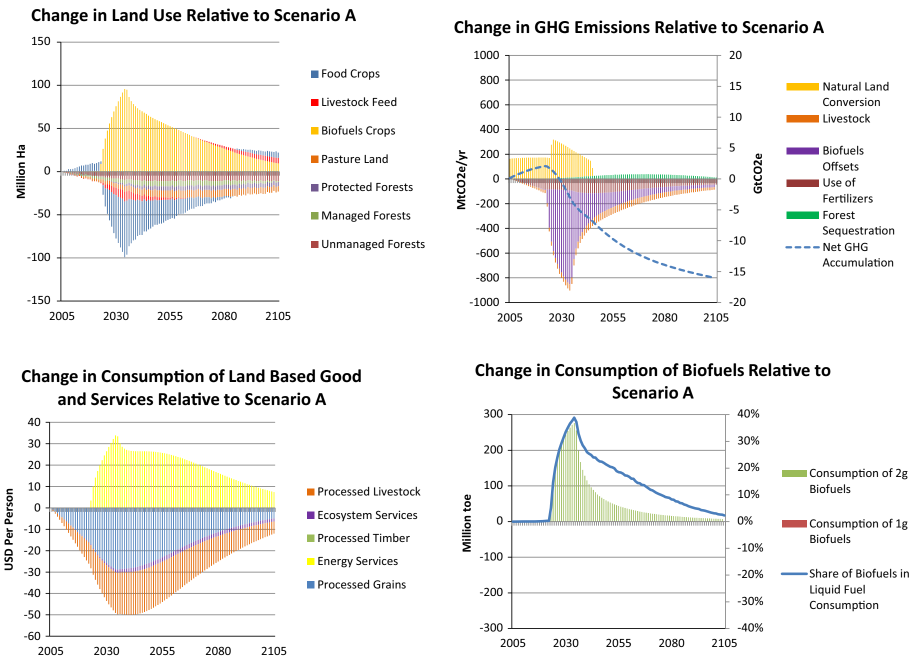

Fig. 4 Scenario AE versus A: climate change impacts on agriculture and rising fossil fuel costs

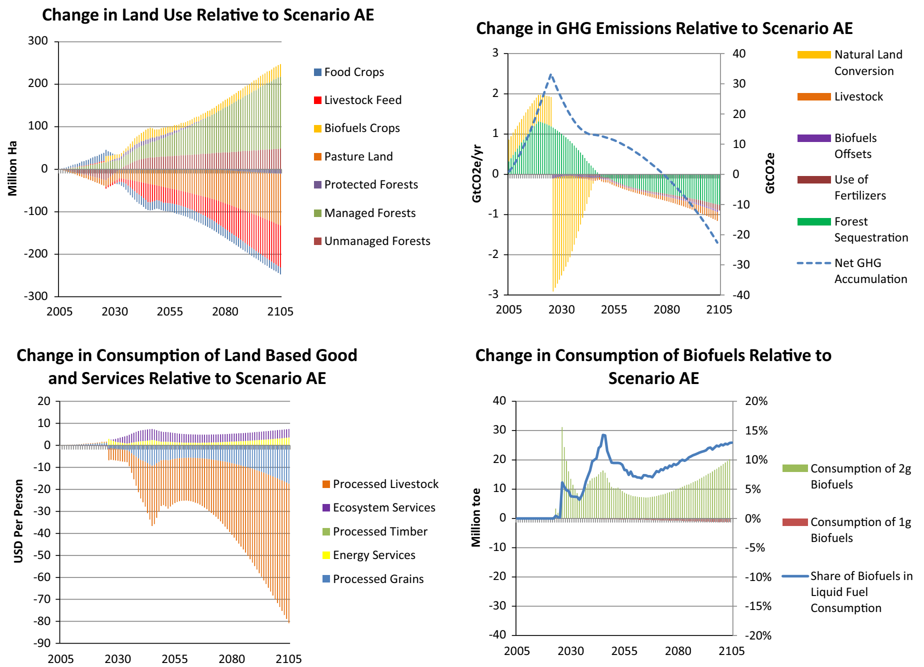

Fig. 5 Scenario AET versus AE: climate change impacts on agriculture and rising fossil fuel costs and land-use emissions target

food services. In 2100 the real per capita consumption of processed grains and livestock each declines by 10 and 6 %, respectively, relative to the baseline scenario. The reduction in consumption of services deriving from energy, timber, and ecosystems is <1 %.

Declining food crop yields depress production of first generation biofuels (lower right-hand panel in Fig. 3). In 2100 the total consumption of first generation biofuels decreases by 2.5 million toe (20 %) 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 % 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 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 Fig. 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 Fig. 4). In 2025 the GHG emissions from natural land conversion increase by 275 $MtCO_2e/yr$ (10 %) 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 $MtCO_2e/yr$ 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 $GtCO_2e$ in 2025, and decline thereafter to a level 15 $GtCO_2e$ 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 Fig. 4). Compared to scenario A their real per capita consumption is 13 times higher in 2035 and 11 % 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 and 8 % in 2035, and by 2.5 and 1.5 %, 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 Fig. 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 % 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 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 explained in Sect. 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 Fig. 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 Sect. 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 Fig. 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 $GtCO_2e/yr$ 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 $GtCO_2e/yr$, 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 $GtCO_2e$ 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 $MtCO_2e/yr$ 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 $MtCO_2e/yr$ and 200 $MtCO_2e/yr$, respectively.

[12] The term "green paradox" was first introduced by Sinn (2008).

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 $GtCO_2e$. After the introduction of the constraint, the GHG emissions from land use cumulatively decline by 114 $GtCO_2e$. 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 %.[13]

Introduction of the GHG emissions constraint lowers the consumption of GHG intensive services from processed food and livestock (left-hand panel of Fig. 5). Compared to scenario AE real per capita consumption of services from processed grains and livestock declines by 7 and 13 %,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 and 1 %, respectively, in 2100.

Introduction of the GHG emissions constraint favors the displacement of petroleum products by biofuels (lower right-hand panel of Fig. 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 further declines after the GHG target is introduced, accounting for 46 % in 2100.

4.4 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 Fig. 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 Fig. 6). Their deployment is rapid and accounts for a significant share of liquid fuel consumption (60 % by late in the twentyfirst 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 Fig. 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 %.

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

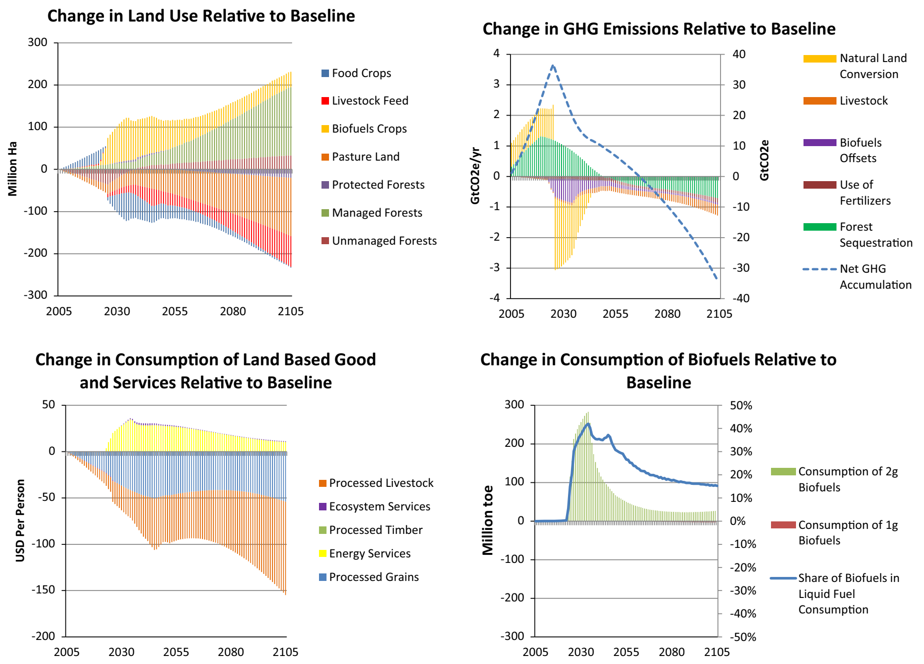

Fig. 6 Scenario AET versus baseline: assessing the impacts of a perfect storm

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 %) in 2100. Pasture land also declines by an additional 128 million hectares (5.5 %) 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 Fig. 6). Compared to the baseline scenario, the consumption of processed grains declines by 18 %, whereas the consumption of processed livestock declines by 19 % 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 is a partial equilibrium framework, in which income, population, the rate of technological progress, and variable input prices are all 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 twentyfirst 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.

14 Lack 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.

The next most important parameter for setting the optimal profile of land use over the twentyfirst 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 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 are 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

[15] The 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.

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 twentyfirst 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 %, 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 twentyfirst century.

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