

Competition for land in the global bioeconomy

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Abstract

The global land use implications of biofuel expansion have received considerable attention in the literature over the past decade. Model-based estimates of the emissions from cropland expansion have been used to assess the environmental impacts of biofuel policies. And integrated assessment models have estimated the potential for biofuels to contribute to greenhouse gas (GHG) abatement over the coming century. All of these studies feature, explicitly or implicitly, competition between biofuel feed stocks and other land uses. However, the economic mechanisms governing this competition, as well as the contribution of biofuels to global land use change, have not received the close scrutiny that they deserve. The purpose of this article is to offer a deeper look at these factors. We begin with a comparative static analysis which assesses the impact of exogenously specified forecasts of biofuel expansion over the period: 2006–2035. Global land use change is decomposed according to the three key margins of economic response: extensive supply, intensive supply, and demand. Under the International Energy Agency’s “New Policies” scenario, biofuels account for nearly one-fifth of global land use change over the 2006–2035 period. The article also offers a comparative dynamic analysis which determines the optimal path for first and second generation biofuels over the course of the entire 21st century. In the absence of GHG regulation, the welfare-maximizing path for global land use, in the face of 3% annual growth in oil prices, allocates 225 Mha to biofuel feed stocks by 2100, with the associated biofuels accounting for about 30% of global liquid fuel consumption. This area expansion is somewhat diminished by expected climate change impacts on agriculture, while it is significantly increased by an aggressive GHG emissions target and by advances in conversion efficiency of second generation biofuels.

JEL classifications: Q11, Q15, Q24, Q42, Q54

Keywords: Biofuels; Global land use; Partial equilibrium analysis; Comparative statics; Comparative dynamics; Climate change impacts; Carbon policies

1. Motivation and literature review

The global land use implications of biofuel expansion have received considerable attention over the past decade. The debate over the “indirect Land Use Change” (iLUC) induced by biofuel expansion has been particularly vigorous. Prior to the publication of the first high profile iLUC analysis in 2008 (Searchinger et al., 2008), the consensus seemed to be that many first generation biofuels, such as corn ethanol, contributed to net greenhouse gas (GHG) reductions due to the carbon uptake by feed stocks and the subsequent displacement of petroleum products

in liquid fuel combustion (Farrell et al., 2006). The idea that crops withdrawn from the food system might induce expansion of global croplands into carbon-rich natural environments had not become a focal point for policy makers. Recently, the number of publications examining the iLUC question has exploded (Al-Riffai et al., 2010; Banse et al., 2008; Dicks et al., 2009; Fabiosa et al., 2010; Gurgel et al., 2007; Hertel et al., 2010; Lotze-Campen et al., 2010; Melillo et al., 2009), and this research has brought with it increasingly sophisticated partial and general equilibrium modeling of global land use change.

Interest in, and funding for, iLUC research has been fueled by the desire of regulators to incorporate such indirect emissions estimates into their determination of the environmental fitness of biofuels (California Air Resources Board, 2009; European Council, 2009; US Environmental Protection Agency, 2009). This research is far-ranging and is undertaken at varying levels of detail. It is typically focused on near-

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medium-term impacts (e.g., up to a decade or two), this being the time frame of the renewable fuel mandates being evaluated. And it encompasses both econometric work and simulation modeling, although the latter has tended to dominate the policy-oriented studies due to its ability to deal more effectively with “counterfactual” analyses and the subtleties of biofuel policy implementation.

Authors in the iLUC literature have shown that estimates of the size and pattern of global land use change following biofuels expansion depends critically on a variety of factors, including: (a) the use of biofuel by-products—in the case of corn-ethanol, the use of dried distillers grains with solubles in livestock feed can reduce iLUC by as much as one-third (Taheripour et al., 2010; Tokgoz et al., 2007); (b) the productivity of the new land brought into production—the lower these yields, the more area must be brought into crops (Tyner et al., 2009); (c) potential for supply response at the intensive margin—with smaller yield elasticities giving rise to larger iLUC results (Berry and Schlenker, 2011; Huang and Khanna, 2010; Keeney and Hertel, 2008); (d) the “geography” of international trade—if the biofuel shock arises in a country which is closely connected via trade to other high-yielding regions, accounting for such geography can substantially reduce iLUC estimates (Villoria and Hertel, 2011); and (e) potential constraints to expansion of irrigated lands—limiting area expansion in high-yielding irrigated regions with over-drawn groundwater reserves boosts the resulting iLUC estimates (Taheripour et al., 2011). In short, estimating the change in global cropland due to biofuels has become a highly sophisticated enterprise which is well summarized in the forthcoming survey paper by Khanna and Crago (2011).

Despite the large and growing body of iLUC literature, we still remain a long way from having definitive answers to the complex question of how global land use change and associated GHG emissions are affected by the expansion of biofuels. Indeed, in the preface to the recent National Academies report on the environmental impacts of biofuels, Burke and Tyner note that: “Yet, with all the expertise available to us, our clearest conclusion is that there is very high uncertainty in the impacts we are trying to estimate.” This article will therefore not attempt to summarize all of the forgoing work on biofuels and land use change, nor will we extend it in the usual fashion, i.e., by taking an existing model and adding some new wrinkle, thereupon showing how this affects global land use following biofuels expansion. Such incremental work is important to advancing the science behind iLUC estimates. However, in this article we instead introduce two new, more stylized frameworks, therein seeking some new insights into the key determinants of competition for the world’s land resources in the future bio-economy over the very long run, and at global scale.

In addition to the iLUC literature, there is a separate and important body of work focusing on the role of biofuels in global land use over the course of the entire 21st Century. This research adopts a longer-run perspective and largely revolves around the so-called “Integrated Assessment Models” (IAMs)

used to evaluate the costs and benefits of GHG mitigation. The climate change mitigation literature has increasingly focused attention on the role of biofuels, and other land-based mitigation activities, in the broader portfolio of long-run mitigation options. Rose et al. (2012) summarize the findings from these IAMs with regard to the long-run allocation of the world’s land resources between biofuels, agriculture, and forests. They find that land-based mitigation options could contribute anywhere between 15% and 40% of the total mitigation required for stabilization of radiative forcing. Bioenergy (including both liquid fuel and solids) is an extremely important part of this land-based mitigation, with the authors of that report suggesting that it may be even more important than forest carbon sequestration. Rose et al. (2012) suggest that bioenergy could provide up to 15% of total primary energy requirements by the end of the century. This broad finding is further reinforced by the Intergovernmental Panel on Climate Change’s Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) which estimates that deployed bioenergy will contribute the greatest proportion of primary energy among all renewable energies, generating substantial GHG reductions.

Creutzig et al. (2012) note the disconnect between these two bodies of literature—one which emphasizes the economic and environmental costs associated with widespread biofuel expansion in the short to medium term, and one which emphasizes the GHG mitigation potential of biofuels in the long run. One might reasonably ask: *Are these two sets of literature intertemporally consistent?* In other words: Is there an economically coherent transition from an era in which biofuels are viewed as often boosting emissions, to one in which they represent a major vehicle for GHG mitigation? What assumptions about energy prices, climate policies, and technology are needed to attain this long-run goal for biofuels? This appears to be an issue warranting deeper exploration. One thing is clear—there is great uncertainty associated with bioenergy deployment. Based on the IPCC’s Special Report (IPCC, 2011), Creutzig et al. (2012) contrast the technical potential, which they suggest ranges from 50 EJ to 500 EJ, with the likely outcome under medium ambitions for climate mitigation, which is quite a bit smaller, but still large at 80–150 EJ. They argue that technological progress in the bioenergy industry, along with other factors such as energy prices and regulations, is critical to determining where in this range we will end up.

In their discussion of the IAMs, global land use and GHG emissions, Creutzig et al. (2012) point out that many of these models ignore iLUC altogether, while others assume it away by postulating local policies which will prevent conversion of carbon-rich land cover, forcing biofuels instead onto abandoned cropland. The idea that the location of biofuel production can somehow be dictated by scientists or planners is pervasive in much of the biophysical literature on this topic. For example, Campbell et al. (2008) compute the global potential for using abandoned agricultural land for biofuels and find that these lands could produce 32–41 EJ of bioenergy, suggesting this could be a modest, but meaningful contribution to

satisfying global primary energy demand. However, in a decentralized global economy, science-based rules for land use conversion are difficult—indeed largely impossible to enforce. Instead, the relevant question is: How do we expect decentralized economic agents to respond to market signals and GHG mitigation incentives in determining land use change? Recent evidence suggests that large-scale biofuels programs have significant market impacts. For example, in their assessment of the impact of U.S. corn ethanol expansion on corn markets Carter et al. (2012) conclude that this expansion (after 2005) added about 30% to corn prices over the 2006–2010 period. This type of price response to biofuels expansion has been shown to have an important impact, not only in the United States, but around the world (Villoria and Hertel, 2011), causing significant land use change—particularly if the price rise is sustained.

In this article, we seek to shed additional light on the long-run impacts of biofuels on global land use change. We focus on the economic margins of response, both in the context of a comparative static analysis of exogenous biofuel shocks and in the comparative dynamic analysis of optimal land use over time. The latter will help shed light on the intertemporal consistency of policies and projections related to biofuels' role in the global economy in both the near term and the distant future. We believe that the economic mechanisms governing the competition for land, as well as the parameters determining the contribution of biofuels to global land use change, have not received the close scrutiny that they deserve. The purpose of this article is to offer a deeper look at these factors. While the comparative static and dynamic frameworks used in this article are not suited for policy advising *per se*, we believe that they offer insights which have hitherto been missing in much of the literature.

2. Comparative static analysis of biofuels and land use

A useful starting point for analysis of the global land use impacts of biofuels is the simple comparative static framework laid out in Hertel (2011). This treats the global crops sector as a single aggregate and decomposes supply response into the extensive and intensive margins, respectively. The impact of a given percentage shock to the global demand for agricultural crops due to increased biofuels production, Δ_A^D , on long-run equilibrium global land use, may then be expressed as follows:

$$q_L^* = \left[\Delta_A^D / \left(1 + \eta_A^{S,I} / \eta_A^{S,E} + \eta_A^D / \eta_A^{S,E} \right) \right], \quad (1)$$

where q_L^* is the percentage change in global land use attributable to the biofuels shock, $\eta_A^{S,I} \geq 0$ and $\eta_A^{S,E} \geq 0$ are the intensive and extensive margins of agricultural (i.e., crop) supply response, and $\eta_A^D \geq 0$ is the absolute value of the long-run price elasticity of demand for agricultural crops. If, for some reason, $\eta_A^{S,I} = \eta_A^D = 0$, then the entire burden of accommodating the

shock is placed on the extensive margin and $q_L^* = \Delta_A^D$, so that global land use expands in equal proportion to the size of the biofuels-induced shift in global demand for crops. Of course, exactly *where* this area expansion will occur depends on the responsiveness of land supply in each region, with regions such as Sub-Saharan Africa and Latin America likely showing much larger area response than the more land supply constrained regions such as Western Europe. Once the intensive and demand margins come into play, the global land use change predicted from a given biofuels shock is diminished. For example, if all three of these elasticities were of equal magnitude, then long-run area response would only be one-third of the proportional shift in global crop demand due to biofuels.

Baldos and Hertel (2012) attach quantitative estimates to Eq. (1) by laying out a global crop model dubbed “SIMPLE” (Simplified International Model of Agricultural Prices, Land use and Environment) in which supply is disaggregated by continent and demand is disaggregated by income level and by crop use (i.e., direct food consumption, feedstuffs, processed food inputs, and biofuel feedstock). They retain the assumption of a globally integrated market for crops, so that Eq. (1) is still valid, after appropriate aggregation on the demand and the supply sides. The authors first validate their model over a 45-year historical period (1961–2006), and find that the model does a good job of predicting the changes in total output, based on changes in income and population. It also decomposes that output expansion into changes at the intensive and extensive margins that match reasonably well the changes in area and yield observed over this period. The authors then undertake projections for the period 2006–2050. For purposes of this article, we have truncated these projections at 2035 (Table 1), since this is the time horizon for the global projections on biofuel consumption from the IEA World Energy Outlook (2008, 2010).

The IEA projections for biofuels are generated from a detailed world energy model given assumptions on growth in gross domestic product, population, energy prices, CO₂ “prices,” and technology. Projections of biofuel use are generated under three scenarios—Current Policies (CP), New Policies (NP), and 450 ppm climate Policies (450P). The CP scenario takes into account all policies enacted as of mid 2010 while the NP scenario adapts CP's assumptions plus GHG emissions and energy policies which are still being discussed. Examples of these include the implementation of the Copenhagen Accord commitments, the continuation of the EU emissions trading scheme and the phase-out of fossil fuel subsidies by all net-importing regions by 2020. Finally, the 450P scenario builds on policies under the NP scenario but with more ambitious targets aimed at GHG stabilization at 450 ppm.

Given the biofuel sector's share of global crop use, projections under the CP, NP, and 450P scenarios translate into increases of about 8.7%, 11.2%, and 22.6%, respectively, in global crop demand. Table 1 shows that, if the demand and intensive margins were not active these demand increases, as predicted by Eq. (1), would result in long-run global crop land changes of similar magnitude (8.7%, 12.9%, and 24.7%,

Table 1
Global land use impacts of IEA projected biofuels growth: 2006–2035

Distribution of cropland change (in %)	Biofuel growth + extensive margin	Biofuel growth + intensive and extensive margins	Biofuel growth + all margins	All drivers + all margins + TFP growth
“Current Policies” scenario				
Global in Mha (% chg)	123.7 (8.7)	54.4 (3.8)	43.8 (3.1)	198.7 (14)
East Asia and Pacific	12.0	10.3	10.4	7.4
Europe and Central Asia	12.5	12.3	12.3	11.7
L. America and Caribbean	22.8	24.2	24.1	26.8
M. East and N. Africa	4.6	4.5	4.5	4.3
North America	8.2	8.1	8.1	7.1
South Asia	18.8	18.2	18.3	18.1
Sub-Saharan Africa	21.1	22.4	22.3	24.6
Total	100.0	100.0	100.0	100.0
“New Policies” scenario				
Global in Mha (% chg)	182.9 (12.9)	79.7 (5.6)	64.4 (4.5)	214 (15.1)
East Asia and Pacific	11.5	10.2	10.3	7.5
Europe and Central Asia	12.1	12.2	12.2	11.6
L. America and Caribbean	23.5	24.3	24.2	26.8
M. East and N. Africa	4.6	4.5	4.5	4.3
North America	7.9	8.0	8.0	7.1
South Asia	18.7	18.2	18.2	18.1
Sub-Saharan Africa	21.8	22.5	22.4	24.6
Total	100.0	100.0	100.0	100.0
“450 Policies” scenario				
Global in Mha (% chg)	349.7 (24.7)	148.8 (10.5)	121.5 (8.6)	256.6 (18.1)
East Asia and Pacific	10.2	10.0	10.1	7.7
Europe and Central Asia	11.0	11.9	12.0	11.4
L. America and Caribbean	25.3	24.8	24.6	26.8
M. East and N. Africa	4.5	4.5	4.5	4.3
North America	7.2	7.8	7.9	7.0
South Asia	18.3	18.1	18.2	18.0
Sub-Saharan Africa	23.4	22.9	22.8	24.7
Total	100.0	100.0	100.0	100.0

respectively; Table 1, column 1).¹ This column also reports the regional contributions to these changes in land use, by continent. Note that the one of the largest responses is in Latin America, where estimates based on recent developments suggest that land supply is quite elastic (Gurgel et al., 2007).

Over the long run, higher crop prices are expected to also give an incentive for intensification of production via the application of additional fertilizer, labor, capital, etc. per hectare of land. In addition, we might expect an endogenous response by the research establishment, aimed at boosting yield growth. Based on a survey of the literature for U.S. maize, Keeney and Hertel (2009) place this intensive margin of supply response at $\eta_A^{S,I} = 0.25$. This is also the estimate of long-run yield response for U.S. maize obtained recently by Goodwin et al. (2012). It is larger than many estimates in the literature, which focus on short-term yield response (Berry and Schlenker, 2011). Bringing this intensive margin into play in the context of the biofuel expansion scenarios in Table 1 results in the more modest area expansion as reported in column 2 under the NP scenario, so that global cropland now expands by 3.8%, 5.6%, and 10.5%, under

CP, NP, and 450P, respectively, or about half of the previous amounts. Note also that there is significant interaction between these two margins of supply response in the model: area expansion relieves the pressure to increase yields, and increased yields relieve the pressure to expand area. As a consequence, their combined effect is less than the sum of the two individual components of supply response.

The final piece of Eq. (1) is the price elasticity of demand for crops, which Baldos and Hertel (2012) permit to vary across per capita income levels by type of product (crops, livestock, and processed foodstuffs), based on the estimates of Muhammad et al. (2011). In general, the absolute value of the price responsiveness of demand is smaller at higher income levels, and it is also smaller for bulk/staple products. Adding this element of the long-run equilibrium calculations under the NP scenario further reduces the global land use change from this 30-year growth in biofuel to just 4.5% of 2006 area, or about 64.4 Mha under the New Policies scenario.

In order to put this aggregate change in long-run perspective, the final column of Table 1 reports the changes in global land use which Baldos and Hertel (2012) project when other drivers of global land use over this period are also incorporated. These include: growth in population, income per capita, agricultural productivity, productivity in the food manufacturing and

¹ Unlike the prediction of Eq. (1), global land area in column 1 does not rise by precisely the same percentage as global demand, due the interaction between regional area response and regional yields.

livestock sectors, and encroachment of urban lands into agricultural areas. By comparing these estimates to the 3rd column in Table 1, we see that biofuels account for roughly 22% of the long-run equilibrium change in global crop land use over this 30-year period under the Current Policies scenario. Nearly half of this total expansion comes in Latin America and Sub-Saharan Africa.

As the bottom two panels of Table 1 illustrate, the contribution of biofuels to global cropland area expansion is quite sensitive to the ambitions of climate policy. Under the New Policies scenario, it rises to nearly 30% of the total, while under the 450P climate policies scenario, biofuels' share of land use expansion over this period approaches half of the projected total for this period. However, climate policies are themselves likely to be driven by expected climate impacts, and the use of biofuels within those policies will surely depend importantly on their impact on land prices and the cost of food. For all these reasons, it is interesting to *endogenize* biofuels production, asking how much would be optimal under alternative assumptions. This is the topic of the next section of this article.

3. Comparative dynamic analysis of biofuels and land use

In the preceding, *comparative static* analysis of biofuels, we have treated biofuels growth as *exogenous*—i.e., determined outside the model, and perhaps outside the market system such as would be the case with government mandates. This is the way the majority of studies deal with biofuels. However, in an environment of constrained budgets and slower economic growth, the long-run prospects for biofuels are likely to hinge on their economic and environmental contributions to global well-being. Despite the concerted efforts of biofuel advocates and opponents alike, it is these fundamental contributions which are likely to determine the long-run prospects of these feed stocks. At high oil prices, biofuels can be quite attractive. Similarly, with advances in both agricultural yields and cellulosic conversion technology for producing drop-in biofuels, there is scope for biofuels to significantly displace petroleum and reduce the GHG emissions associated with combustion of liquid fuels. For these reasons, it is useful to think about what the *optimal* path of global land use for biofuels might be over the next century, factoring in things like projected oil prices and potential GHG emissions targets, as well as potential changes in technology and evolving consumer preferences for food, fuel, and biodiversity. While we are under no illusion that the world will actually implement intertemporally optimal policies, such an analysis offers a valuable guide to how global land use is likely to evolve in the very long run.

These comparative dynamic results are drawn from FABLE (Forest, Agriculture, and Biofuels in a Land use model with Environmental services), a dynamic optimization model for the world's land resources over the next century (Steinbuks and Hertel, 2012). The model solves for the intertemporal paths of alternative land uses which together maximize global eco-

nomical welfare, potentially subject to a constraint on global GHG emissions. Alternative land uses incorporated into the model include: food crops, protected natural lands, managed (commercially exploited) forests, unmanaged forests, and first and second generation liquid biofuels. Key exogenous drivers include: population growth which we assume will plateau at 10 million people by 2100, global per capita income which rises at a rate of 2.25%/year, and oil prices which are assumed to rise at 3%/year over the 21st century. Technological progress is also assumed in the agriculture, forestry, energy, and recreation sectors. Based on the agronomic literature (Cassman et al., 2010) we assume that yields in agriculture and forestry grow linearly. We assume that energy efficiency grows at a rate of 1.6%/year. Technological progress in recreation sector is augmented by exogenous nonland inputs, whose efficiency grows at the same rate as the global economy. Complete documentation of the model's structure, including equations, variables, and parameters, is offered in technical documentation (Steinbuks and Hertel, 2012).

3.1. Baseline land use

Fig. 1 shows the optimal allocation of land between the alternative uses over this century *in the absence of binding GHG policies*. Protected forests expand in response to growing consumer demand for ecosystem services as households become wealthier. Cropland for food expands until 2040 due to increasing population and evolving consumption patterns, but declines thereafter as population and per capita demand growth both slow and are overtaken by technological progress in agriculture. Commercial forest area expands to satisfy the growing demand for wood products, worldwide, while unmanaged forest areas shrink. Land devoted to biofuels expands steadily—particularly after second generation biofuels become commercially competitive in 2041.

This date for second generation biofuels to enter the mix is endogenously determined in the model, and many might say that it seems very late, in light of the US-RFS2 ambitions for cellulosic biofuels to deliver 16bgly in fuel by 2022. However, close reading of the recent National Academy report on this subject confirms our pessimism. The authors of that report conclude their analysis of the economic competitiveness of cellulosic biofuels in 2022 that: “Only in an environment characterized by high oil prices, technological breakthroughs, and a high implicit or actual carbon price would biofuels be cost-competitive with petroleum-based fuels” (NRC, 2011). Nonetheless, even without subsidies or GHG targets, our baseline does suggest that, if oil prices continue to grow strongly (3%/year) throughout the century, the globally optimal land area devoted to biofuel feed stocks would amount to 225 Mha by the end of the century and biofuels would account for about 30% of global liquid fuel consumption—mostly from second generation, drop-in biofuels at the end of the century. Of course, this result is quite sensitive to the path of oil prices.

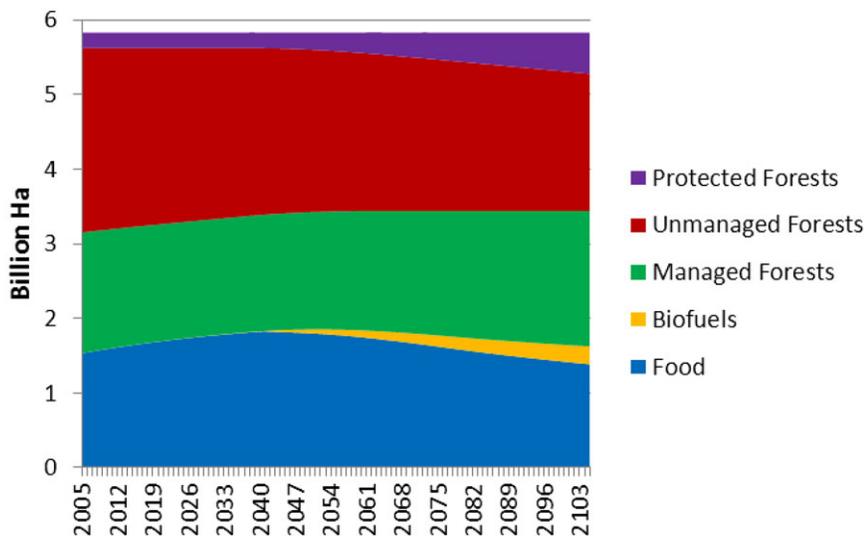


Fig. 1. Optimal allocation of global land resources, 2005–2105.

This socially optimal path for global land use is not intended to be strictly predictive. Global land use change is the result of hundreds of millions of household, firm, community, regional and national decisions around the world—often in the context of poorly defined property rights. However, by evaluating the optimal allocation of land, we can gain insight into the potential intertemporal impacts of a variety of important factors on global land use, and biofuels' contribution to that picture.

3.2. The role of second generation biofuels in the baseline

Consider first, the role of second generation biofuels in our global land use baseline. Figs. 2(a–d) show the impact of introducing these biofuels into the optimization decision—focusing on four key dimensions of the global land economy. Fig. 2(a) reports the impact on land use. With cellulosic feedstock expanding strongly, other land uses contract. In 2100, the largest percentage reductions occur in cropland and managed forestland. On the consumption side (Fig. 2b), increased competition for land resources translates into reduced consumption of food, timber, and recreation services from land, while the introduction of second generation biofuels as a cheaper drop-in alternative to petroleum products lends a substantial boost to the consumption of energy services. *In short, introducing a new technology on the supply side has important impacts on the optimal consumption path.*

The introduction of second generation biofuels also has important implications for GHG emissions—even in the context of a baseline in which GHG emissions are not explicitly constrained. As shown in Fig. 2(c), cumulative GHGs rise initially, as the anticipated arrival of second generation biofuels encourages more land conversion during the first half of the century. However, by the time we reach 2060, the change in cumulative GHG emissions turns negative, and, from that point forward, the presence of second generation biofuels contributes to reduced

global GHG emissions due to the 75% offset (net of indirect land use change and emissions from fertilizers' use) when compared to petroleum combustion. Consumption of second generation biofuels grows rapidly after their introduction in 2041, reaching 530 million tons of oil equivalent (toe), and accounting for about 30% of liquid fuel consumption. Introduction of second generation biofuels does not appear to significantly affect the consumption of first generation biofuels (Fig. 2d).

The capacity for producing cellulosic biofuels depends critically on innovative technologies that improve the cellulosic biofuel production process. While there are several promising technologies undergoing laboratory testing and pilot-scale production, no commercial-scale facilities currently exist for the production of liquid fuels from cellulosic biomass. Moreover, there is considerable uncertainty about the amount of biofuel that can be extracted from cellulosic feedstock. Recent estimates of the conversion ratio have ranged from as low as 60 gallons per dry ton to theoretical values as high as 140 gallons per dry ton (Committee on Economic and Environmental Impacts of Increasing Biofuels of the National Research Council, 2011). Not surprisingly, the timing and penetration of these biofuels is highly sensitive to this conversion factor. If this efficiency is increased by 50%, relative to baseline, global land area allocated to second generation biofuels in 2100 rises by nearly 30 Mha, liquid fuel penetration rises by another 15 percentage points to 44% of total fuel consumption by 2100, and the initiation date for net cumulative GHG reductions from second generation fuels is moved up to 2038.

3.3. Climate change impacts and biofuels' competitiveness

Another important area of technological uncertainty surrounding the global land use impacts of biofuels relates to the impact of climate change on feedstock productivity. To date, this interaction has received relatively little attention, but

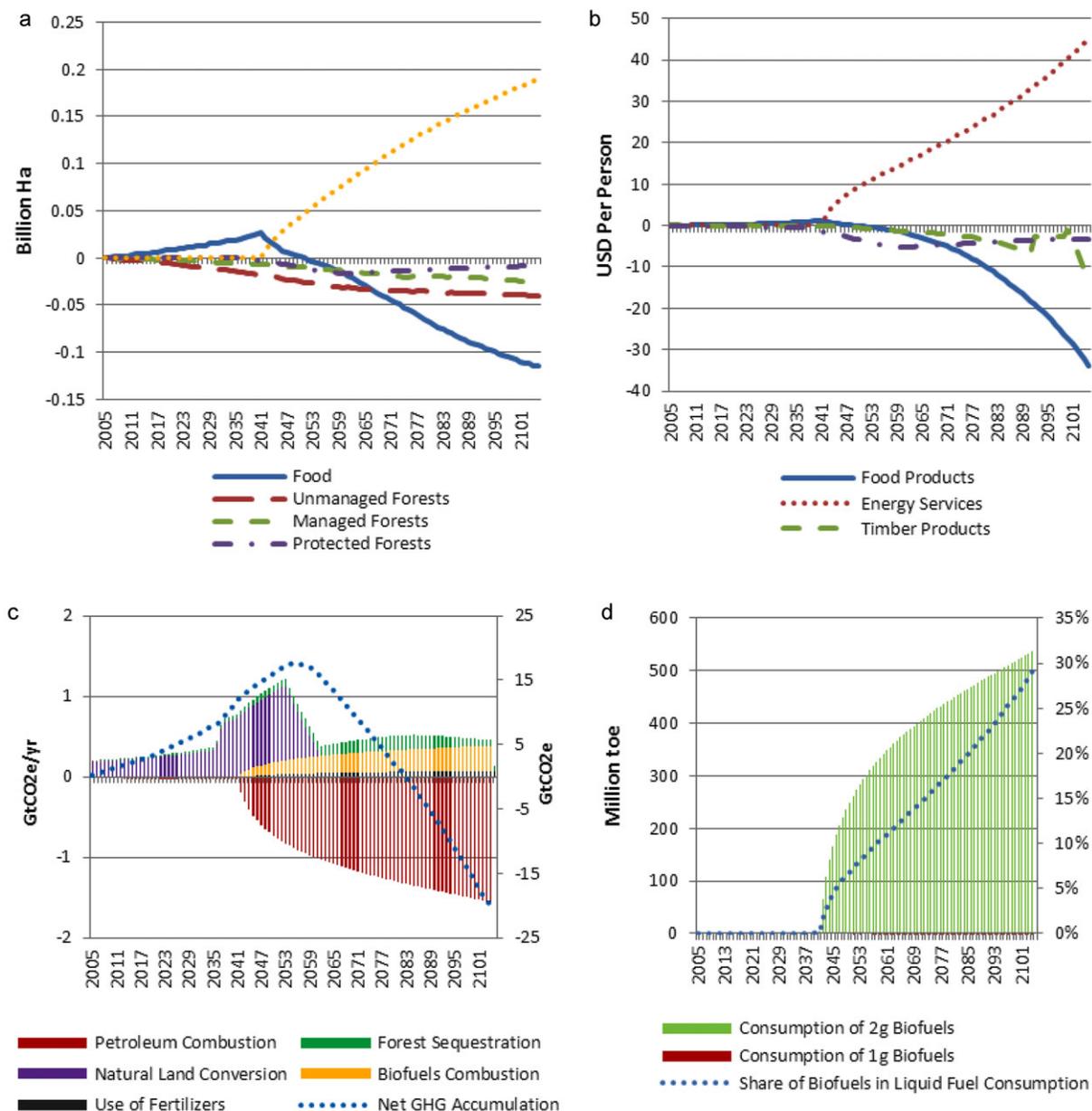


Fig. 2. (a) Changes in global land use from introducing second generation biofuels. (b) Changes in consumption of land-based goods and services from introducing second generation biofuels. (c) Changes in GHG emissions from introducing second generation biofuels. (d) Changes in biofuels' consumption from introducing second generation biofuels.

it is potentially quite important. We contrast here the impact of climate change on food crops, such as grains and oilseeds, with the impacts on biomass-based second generation biofuels. These two types of feed stocks differ in important ways. Perhaps most significant is the fact that first generation biofuels are derived from the fruit of field crops, the yields of which depend critically on the phenological development of the crop. This development, in turn, depends on the accumulation of heat units, typically measured as growing degree days (GDDs). More rapid accumulation of GDDs speeds up phenological development, thereby shortening key growth stages, such as the grain filling

stage, thereby reducing yields (Brown et al., 2000). In contrast, for second generation biofuels, the harvested crop (e.g., switchgrass) provides the entire aboveground biomass as feed stock for biofuel. Higher temperatures favor overall biomass development and yields increase strongly under climate change (Brown et al., 2000). These gains are further reinforced with increased CO₂ concentrations which benefit both types of feed stocks by reducing water stress. However, such CO₂ fertilization appears to generate particularly strong gains for switchgrass yields in the upper Midwest of the United States (Brown et al., 2000).

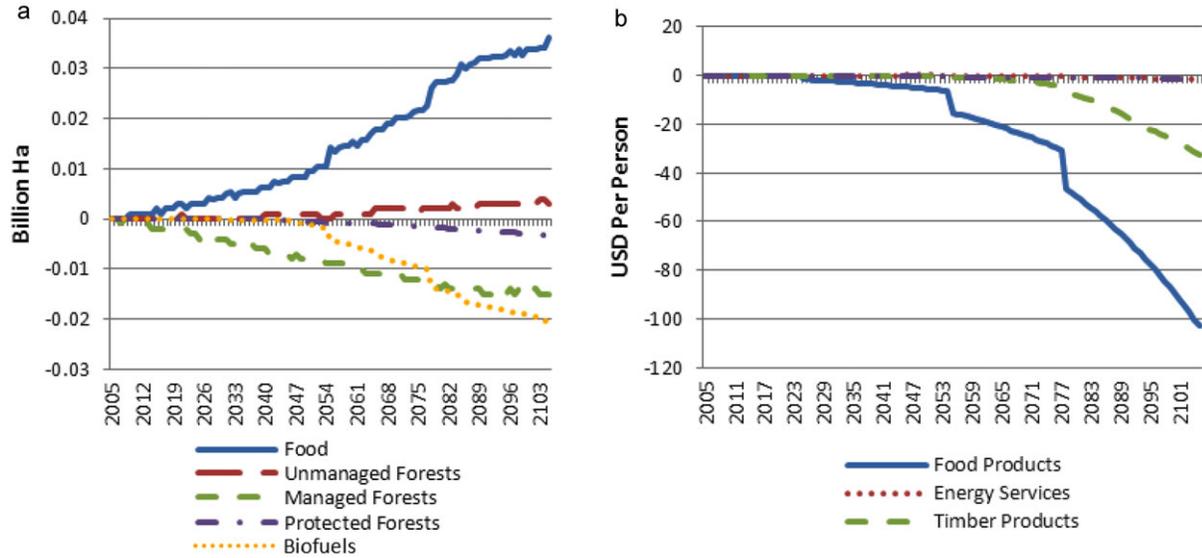


Fig. 3. (a) Changes in global land use from climate change impact on crop yields. (b) Changes in consumption of land-based goods and services from climate change impact on crop yields.

There are now quite a few studies of the impact of climate change on grain and oilseed yields. We choose here to draw on the recent work of (Lobell et al., 2011), which is based on empirical analysis of the historical impacts of climate trends on trend growth rates in yields at global scale. Similar to other recent studies they find that climate trends have a significantly negative effect on yields of major agricultural crops, such as wheat and maize. Their counterfactual simulations have shown that a 1°C rise in temperature due to global warming tends to lower yields globally² by up to 10%.³ Assuming a warming baseline of 0.3°C temperature raise per decade based on IPCC SRES A1B scenario (strong economic growth, global population that peaks in mid-century and declines thereafter, rapid introduction of new and more efficient technologies, and energy consumption balanced between fossil fuels and low carbon sources) this corresponds approximately to a 30% yield *loss* for agricultural crops by 2100. In contrast, there are very few studies on the impact of climate change on second generation feed stocks. We draw here on the study by Brown et al. (2000) who analyze the impacts of climate change on switchgrass yields in the Midwestern United States over the next century using the EPIC model. Their simulated yields of the perennial switchgrass increase at all sites with a mean yield increase of 5.0 Mg ha⁻¹ when the temperature increase exceeded 3°C. In our GHG/warming baseline this corresponds to approximately a 50% yield *gain* for cellulosic feed stocks by 2100. This will boost the competitiveness of second generation biofuels.

² Except for high-latitude countries where certain crops, most noticeably rice, gain from warming.

³ The trends upon which these estimates are based include the effect of CO₂ fertilization. In their absence, we expect that these temperature increases would have resulted in larger yield losses.

Fig. 3(a) presents our estimates of the impact of climate change on the optimal allocation of global land use over the coming century (relative to baseline). The first point to note is that cropland requirements rise sharply in the face of slower growth in crop yields, requiring 30 Mha in additional cropland by 2100 to offset slower yield growth. Lower crop productivity also translates into diminished food consumption along the optimal path, with other land-based consumption streams (biofuels, timber products, and recreation services; see Fig. 3b) also adversely affected by land competition with food production. Increased competition for food thus implies that the climate-induced yield increase for second generation biofuels does not translate into higher output. Overall, there is little impact on net GHG emissions from this climate change scenario.

3.4. Implications of a GHG emissions constraint

As seen above, in the context of the comparative static analysis, policies aimed at reducing GHG emissions can have a significant impact on biofuel production and global land use. Accordingly, we wish to explore, within the context of this forward-looking model of global land use, the comparative dynamic impacts of a GHG constraint on global land use. We target a 50% reduction in baseline GHG emissions from fossil fuels, crop production and terrestrial carbon fluxes by 2100, while ignoring the impacts of climate change discussed previously. The target is announced in advance, and is introduced in 2025, rapidly becoming more stringent, with larger GHG emissions' reductions taking place by 2050. This target corresponds to IPCC 4AR estimates (Bernstein et al., 2007) aimed at achieving CO₂-equivalent concentration (including GHGs and aerosols) at stabilization between 445 and 490 ppm. The consequences for land use change are shown in Fig. 4.

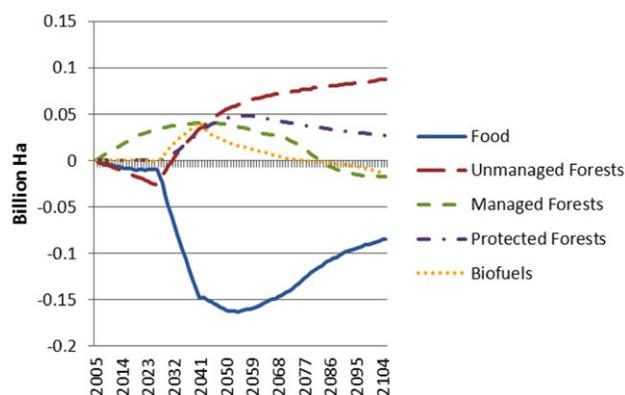


Fig. 4. Changes in global land use from GHG emissions constraint.

The most important aspect of the GHG constraint is to slow the rate of land conversion, subsequent to its implementation. Introduction of the GHG constraint increases the unmanaged forest area by 90 Mha in 2100. The largest area reductions, relative to baseline, are for croplands. As expected, implementation of this GHG constraint leads to increased supply of second generation feedstocks converted to biofuels in order to displace GHG emissions from petroleum combustion. Indeed, second generation biofuels now become competitive as early as 2025. This scenario also requires more land for managed forests at mid-century to extend forest management strategies for GHG emissions' sequestration. Toward the end of the century, this forest area is somewhat diminished.

4. Summary and conclusions

The global land use implications of biofuel expansion have received considerable attention in the literature over the past decade. Model-based estimates of the emissions from cropland expansion have been used to assess the environmental impacts of biofuel policies. And integrated assessment models have estimated the potential for biofuels to contribute to GHG abatement over the coming century. All of these studies feature, explicitly or implicitly, competition between biofuel feed stocks and other land uses. However, the economic mechanisms governing this competition have not always received the close scrutiny that they deserve. Much of this stems from the complexity of the models being used. Accordingly, this article adopts a simpler modeling approach and aims to uncover additional insights regarding the global land use impacts of biofuels over the coming decades/century.

We begin with a comparative static analysis which assesses the impact of exogenously specified forecasts of biofuel expansion over the 2006–2035 period. Global land use change is analyzed in a series of three successive models. The first only incorporates supply response at the extensive margin. In this case, IEA projections of biofuels growth under current policies results in 124 Mha of additional cropland over this 30-year

period, with the largest share coming from Latin America. In the next step, we bring in the intensive margin of supply response, which cuts in half the area expansion required to meet this growth in biofuel production. Finally, consumer demand response to the increased scarcity induced by biofuels expansion is added, and the total area required is estimated to be 44 Mha (64 Mha in the case of more aggressive climate policies). The largest share of this expansion comes in Latin America and Sub-Saharan Africa.

If, instead of exogenously specifying the growth in biofuels production, we ask how much land would optimally be allocated to first and second generation biofuels over the course of the next century, we enter the domain of comparative dynamics. Using a fully intertemporal model, but still at a highly aggregated level, we seek to reconcile the decadal scale iLUC literature with century scale literature on GHG mitigation. We find that, in the presence of a relatively ambitious GHG target (50% reduction of emissions from liquid fuels, fertilizers and land use change), second generation biofuels enter the optimal mix about 20 years into the simulation, and grow to account for much larger share of global land use by the end of the 21st century. This area expansion is somewhat diminished by climate change—even though this change in biophysical environment favors second generation feed stocks. This is due to the increased competition for land flowing from lower yields for food crops—the demand for which is relatively inelastic. This final point underscores the value of a model which captures competition not only for land, but also for consumer spending over the next century.

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