MIT Joint Program on the Science and Policy of Global Change

Unintended Environmental Consequences of a Global Biofuels Program

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Abstract

Biofuels are being promoted as an important part of the global energy mix to meet the climate change challenge. The environmental costs of biofuels produced with current technologies at small scales have been studied, but little research has been done on the consequences of an aggressive global biofuels program with advanced technologies using cellulosic feedstocks. Here, with simulation modeling, we explore two scenarios for cellulosic biofuels production and find that both could contribute substantially to future global-scale energy needs, but with significant unintended environmental consequences. As the land supply is squeezed to make way for vast areas of biofuels crops, the global landscape is defined by either the clearing of large swathes of natural forest, or the intensification of agricultural operations worldwide. The greenhouse gas implications of land-use conversion differ substantially between the two scenarios, but in both, numerous biodiversity hotspots suffer from serious habitat loss. Cellulosic biofuels may yet serve as a crucial wedge in the solution to the climate change problem, but must be deployed with caution so as not to jeopardize biodiversity, compromise ecosystems services, or undermine climate policy.

Contents

1. INTRODUCTION

At the end of the 20th century, the world's commercial energy consumption was about 400 exa-joules (EJ) per year, with fossil fuels contributing about 85% and all others (nuclear, biofuels, hydro, wind, solar) contributing only 15%. Typical projections of the world economy

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imply energy demands in 2050 of 550-1000 EJ per year, depending on resource availability, and the price, scope and effect on energy demand of policies to limit greenhouse gas (GHG) emissions and air pollutants (Clarke *et al*., 2007). To limit GHG emissions, we will need a variety of low-carbon energy sources operating at very large scales; for example, sources supplying 55-100 EJ/year would meet only about 10% of the estimated demand. Biofuels are being promoted as an important part of the global energy mix in the coming decades to meet the climate change challenge (Pacala and Socolow, 2004; Farrell *et al*., 2006).

Recently, there has also been considerable emphasis on the social and environmental costs of current biofuels technologies (Tilman *et al*., 2006; Fargione *et al*., 2008; Scharlemann and Laurance, 2008; Searchinger *et al*., 2008; The Royal Society, 2008). Increased production of biofuel crops has the potential to compete with food production for arable land. In addition, increased biofuels production could require conversion of natural lands with resulting carbon emissions, threats to biodiversity, and possible likely increased use of fertilizers and pesticides. At the same time, a growing population will create increasing demand for food, while changes in the climate, CO_2 and tropospheric ozone will affect land requirements and the location of production activities. To date, most of the analyses of environmental impacts of biofuels have been done as local or sub-regional case studies without explicit consideration of concurrent environmental changes and growing demands for food. In addition, they make very simple assumptions about which land types are converted for biofuels production (Searchinger *et al*., 2008).

Here, we use a computable general equilibrium (CGE) model of the world economy, the MIT Emissions Predictions and Policy Analysis model (EPPA, Paltsev *et al*., 2005; Gurgel *et al*., 2007), coupled with a process-based terrestrial biogeochemistry model, the Terrestrial Ecosystem Model (TEM, Melillo *et al*., 1993; Felzer *et al*., 2004; Sokolov *et al*., 2008), to generate global land-use scenarios and to explore some of the environmental consequences of an aggressive global cellulosic biofuels program over the first half of the 21st century. The biofuels scenarios we focus on are linked to a global climate policy to control greenhouse gas emissions from industrial and fossil fuel sources that would, absent feedbacks from land-use change, stabilize the atmosphere's CO_2 concentration at 550 ppmv (Paltsev *et al*., 2008). The climate policy makes the use of fossil fuels more expensive and speeds up the introduction of biofuels, and ultimately increases the size of the biofuel industry, with additional effects on land use, land prices, and food and forestry production and prices.

2. METHODS

The amount of land used for biofuels production in a region depends not only on the ability of local environmental conditions to support crop productivity at a sufficient level, but also depends on competitive demands on the land to provide adequate food and fiber for the local population or to provide products for global trade. To examine the ability of terrestrial ecosystems to supply biofuels to meet a growing global demand for energy along with growing demands for food and fiber, we have developed an approach that links TEM to EPPA to generate world-wide land-use future scenarios at a spatial resolution of 0.5^o latitude x 0.5^o longitude that vary with climate change.

In our approach, greenhouse gas emissions, as projected by EPPA, drive a coupled atmospheric and climate module within the MIT Integrated Global System Model (IGSM, Prinn *et al*., 1999; Sokolov *et al*., 2005) to simulate the future climate that then drives TEM. What results of these model linkages is a set of projected changes in crop, pasture, and forest productivity as simulated in TEM due to changing climate, levels of CO_2 and tropospheric ozone. These projected changes in productivity are then fed back to the EPPA model to change yields in the agricultural sectors (Reilly *et al*., 2007a). Changes in yields, together with changing demand for these products, as driven by population and income growth, lead to reallocations of land among uses, and conversions of land among land types. The regionally aggregated land-use types used by EPPA are downscaled to the ½ by ½ degree grid level based on a statistical approach for use in TEM (Wang, 2008). This linked modeling process generates scenarios that capture first-order interactions among land use, climate, and the economy. The pattern of land use is affected by a number of factors including population and economic growth, changing climate, and atmospheric concentrations of CO_2 and tropospheric ozone as they concurrently affect both overall productivity and the regional pattern of production. In addition, climate policy and energy demand affect land use as they drive demand for biofuels. The TEM is then used to evaluate the magnitude of GHG emissions from the land associated with these land-use changes projected by EPPA such as the conversion of forests to areas that produce biofuels. Additional details about our approach of coupling TEM to EPPA are provided in the Appendix.

For this study, we develop two scenarios that have the same economic growth and meet the same limit on industrial and fossil fuel GHG emissions. One scenario makes all land available for biofuels crops or other managed uses as long as the economic return on the land exceeds the cost of conversion and improvement. The other scenario limits access to unmanaged (e.g., tropical forests), with the limits based on the recent history of regional land conversion rates. This approach results in slower rates of deforestation than would be predicted by cost estimates alone (Gurgel *et al*., 2007).

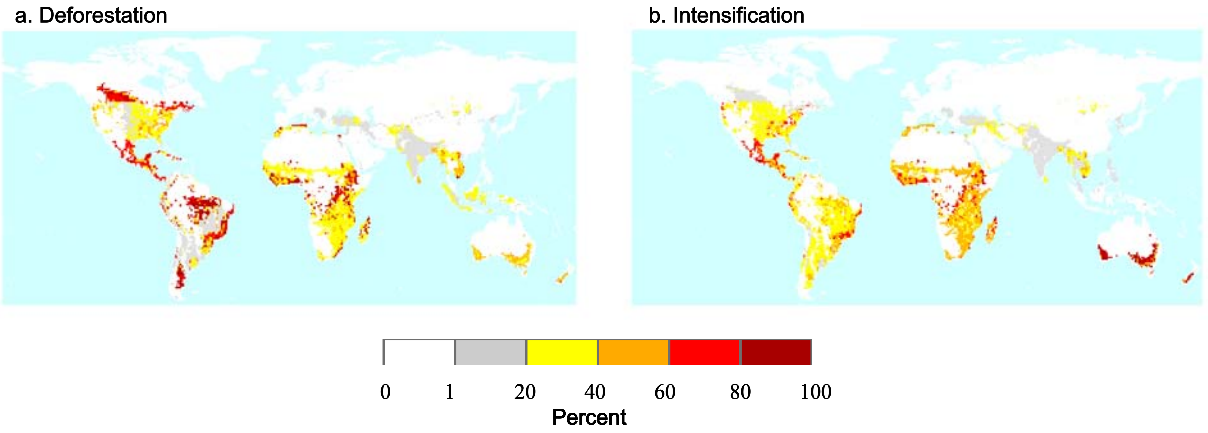
We refer to the first scenario as the "deforestation scenario" because it involves large-scale deforestation in support of biofuels production, either directly or indirectly. The direct link between deforestation and biofuels is when forests are cleared to establish biofuels crops (Fargione *et al*., 2008). The indirect link is when biofuels production moves on to croplands or pastures, and causes new forest clearing to relocate agriculture (Searchinger *et al*., 2008). We call the second scenario the "intensification scenario" because one possible result of limited access to new land is that existing managed lands will be used more intensively, with increased inputs of capital, labor and materials such as fertilizers. For each scenario, the initial land cover distribution is based on the land cover distribution for the year 2000, which has been derived by reorganizing the gridded land-use transitions data sets of Hurtt *et al*. (2006) for use by TEM and EPPA.

3. RESULTS AND DISCUSSION

Energy from cellulosic biofuels plays an important part in the global primary energy supply in 2050 in both scenarios – 141 EJ yr^{-1} in the deforestation scenario and 128 EJ yr^{-1} in the intensification scenario, with these levels of energy supply large enough to meet at least 10% of the projected global energy requirement in 2050. Our simulations with the two scenarios explore how the production of these large amounts of energy affects several features of the global environment. The features we consider include land area devoted to producing cellulosic biofuels, carbon storage on land and biodiversity, especially in the sub-tropics and tropics.

3.1 Changes in the Global Landscape – How Land is Used

At the beginning of the 21st century about 31.5% of the total land area of 133 million km^2 was in agriculture; 12.1% (16.1 million km^2) in crops and 19.4% (25.8 million km^2) in pasture (Hurtt *et al*., 2006), with no land devoted to cellulosic biofuels. Land used to produce the feedstocks for the current generation of biofuels (e.g., ethanol from maize (corn) and sugarcane) is included in the crop sector. In the deforestation scenario, we estimate that by 2050, the land area in cellulosic biofuels will grow to 14.8 million km^2, which is 11.1% of the earth's total land area **(Figure 1a)**. At the same time, we project that the area of croplands will grow to about 20.0 million km^2 and the area in pasture will shrink slightly to 24.5 million km^2. The growth of croplands by 3.9 million km^2 over the first half of the 21st century in the deforestation scenario is in response to increased food demands globally.


a. Deforestation

b. Intensification

Figure 1. Distribution of cellulosic biofuels in 2050 simulated for two scenarios: deforestation (a) and intensification (b). Data expressed as the percentage of each ½ by ½ degree grid cell devoted to biofuels production.

By 2050 in the intensification scenario, we estimate that the land area in cellulosic biofuels will grow to 13.9 million km^2 **(Figure 1b)**. We also project that by mid-century croplands area will grow by about 2 million km^2 to almost 18 million km^2 **(Table 1)**, and pasture areas will shrink by almost 8 million km^2 to just under 18 million km^2. Despite the loss of pastures, the intensification of land use allows nearly as much production of food as in the deforestation scenario.

Table 1. Areas of land-use changes associated with crops, pastures and biofuels over the first half of the 21st century. The estimated land surface of the earth is estimated to be 133.02 million km^2.

	Absolute land areas in different land uses (million km^2)		
	Current	**Deforestation Scenario**	**Intensification Scenario**
Year	2000	2050	2050
Total Land Area of the Earth	133.02	133.02	133.02
Total Area Co-opted for Human Use	41.96	59.29	49.84
Biofuels Area	0.00	14.79	13.91
Crop Area	16.12	20.01	17.99
Pasture Area	25.84	24.49	17.94

3.2 Carbon Balance

Energy production from biofuels together with agriculture expansion will result in a large loss in carbon from land ecosystems as natural vegetation such as forests and savannas is cleared to grow cellulosic feedstocks, crops and pastures **(Table 2)**. Such a reduction in terrestrial carbon storage associated with the expansion of biofuels and other land uses has been referred to as a "carbon debt" (Fargione *et al*., 2008; Searchinger *et al*., 2008). Through time, this debt can be canceled if biofuels production and use has net carbon (and other greenhouse gas) emissions that are less than the total emissions of the fossil fuels they displace. The overall "carbon balance" is thus initially negative, due to the carbon debt incurred by land conversion, but slowly rises as the annual credits from the biofuels repay (and eventually outweigh) the one-time debt.

Table 2. Effects of intensive management (food crops, pastures and biofuels) on the global carbon cycle simulated for two scenarios, deforestation and intensification, during the first half of the 21st century.

	Deforestation Scenario		Intensification Scenario	
Land Cover	**ΔCarbon (Pg C)**	**Co-opted NPP (Pg C yr^{-1})**	**ΔCarbon (Pg C)**	**Co-opted NPP (Pg C yr^{-1})**
Time Period	2000-2050	2040-2049	2000-2050	2040-2049
Biofuel Crops	-21.38	8.21	+4.34	7.18
Food Crops	-53.53	10.49	-18.73	9.63
Pasture	-28.23	10.29	-19.25	7.55
Total Agriculture	-103.14	28.99	-33.64	24.36
Percent Co-opted	--	50.09	--	42.09

The total carbon debt associated with biofuels is the sum of the direct and indirect carbon debts – direct debt consisting only of losses from the lands used for biofuels, and indirect debt consisting of losses due to displacement of food-crops and pastures. The expansion of food-crop agriculture and pastures as projected in our simulation is a complex response to several factors including a growing demand for food as the human population increases, competition for fertile lands to grow biofuels feedstocks, and reduced food crop yields per unit area in some regions as a consequence of climate change and increased tropospheric ozone pollution (Reilly *et al*., 2007a). Due to these complex interactions, the indirect carbon debt associated with biofuels is extremely difficult to quantify, but we can consider carbon losses from all food crops and pastures to be an upper bound.

In the deforestation scenario, we project a direct carbon debt of 21 Pg C by 2050, with much of this carbon coming from areas once covered by tropical forests in Brazil and in Southeast Asia **(Figure 2a)**. Indirect carbon debt could be as large as 82 Pg C, giving a total carbon debt of 21-103 Pg C (Table 2). This carbon debt is equal to 8-37% of the cumulative fossil fuel emissions for the period 2000-2050 in the climate policy we impose here to limit these emissions. Even considering the best-case, where total carbon debt is 21 Pg C, we estimate that the carbon debt associated with biofuels establishment in the deforestation scenario will last until the middle of the 21st century; that is, no net greenhouse gas reductions will be realized from biofuels until about 2045 **(Figure 3a)**. Moving towards the worst-case, where total carbon debt is 103 Pg C, it becomes clear that these large emissions from land-use change would substantially undermine the efforts to stabilize climate.

The intensification scenario differs dramatically. Energy production from biofuels results in a direct carbon credit of 4 Pg C by 2050 (Table 1). The small carbon gains in many of the areas devoted to bioenergy production **(Figure 2b)** are mostly in soils in response to nitrogen fertilization, which stimulates plant growth and carbon inputs to soil. However, the indirect carbon debt is still potentially as large as 38 Pg C, giving a total carbon debt of -4 – 34 Pg C over the first half of the 21st century. While the upper bound on the total carbon debt is still substantial, it is much less than the 103 Pg C in the deforestation scenario (Table 1). This upper-bound debt of 34 Pg C in the intensification scenario is nearly repaid by the middle of the 21st century **(Figure 3b)**.

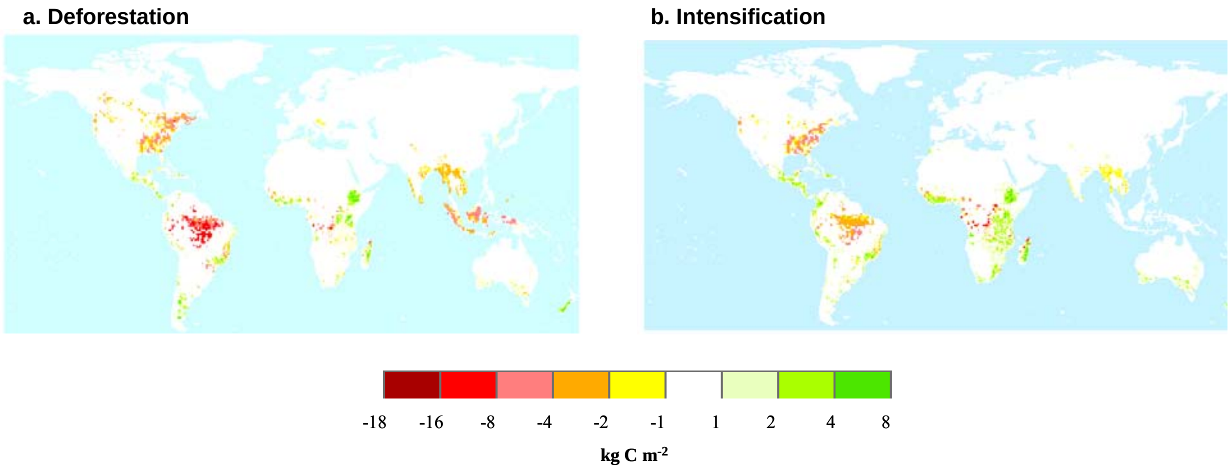


Figure 2. Effects of cellulosic biofuels on terrestrial carbon storage over the first half of the 21st century as simulated for the deforestation scenario (a) and the intensification scenario (b). Negative numbers indicate a release of carbon from land ecosystems and positive numbers indicate an accumulation of carbon by land ecosystems.

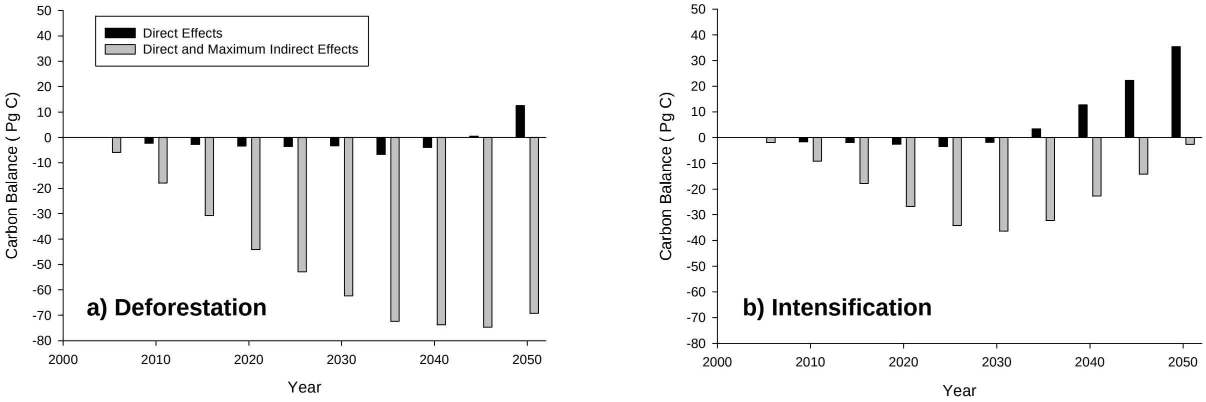


Figure 3. Carbon balance associated with all land use change and that directly associated with biofuels over the period 2000-2050 as simulated by the deforestation (a) and intensification (b) scenarios. Carbon balance is calculated as the savings associated with the substitution of biofuels for fossil fuels minus the carbon released from the land used for biofuels (direct effects) along with food crops and pastures (indirect effects). Negative numbers indicate a net loss of carbon and positive numbers indicate a net gain.

3.3 Impacts on Biodiversity

One of the great challenges with cellulosic biofuels is developing ways to produce large quantities of plant feedstocks in a region without destroying its biodiversity. Evaluation of potential impacts should include both the direct effects of converting land to biofuels production and the indirect effects of the displacement of food crops and pastures to new areas as described earlier. In both the deforestation and intensification scenarios, we project that by the middle of the 21st century, many regions will substantially increase the fraction of land they devote to meeting the combined demands for food and biofuels at the expense of natural ecosystems including a number of biodiversity "hotspots" in the sub-tropics and tropics. To qualify as a hotspot, a region must meet two strict criteria: it must contain at least 1,500 species of vascular plants (> 0.5 percent of the world's total) as endemics, and it has to have lost at least 70 percent of its original habitat (Conservation International, 2008). Biodiversity hotspots currently at risk include the Mesoamerican forests, the cerrado of Brazil, the Guinean forests of West Africa, Madagascar, the Indo-Burma region of tropical Asia, and the forests of the Philippines, Malaysia and Indonesia in Southeast Asia **(Figure 4)**.

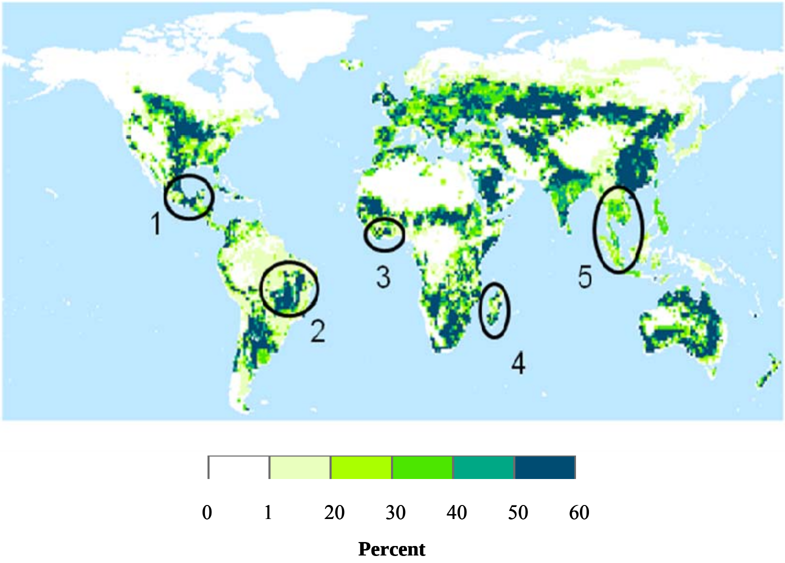


Figure 4. Natural areas in many biodiversity hot spots have already been converted to crop and pasture agriculture and limited remaining areas would face more threats from biofuels expansion. Data shown is for circa 2000 and expressed as the percentage of each ½ by ½ degree grid cell devoted to the crop and pasture agriculture. Several biodiversity hotspots are circled – Mesoamerican forests (1); the cerrado of Brazil (2); the Guinean forests of West Africa (3); Madagascar (4); and the forests of Southeast Asia (5).

We project that the region devoting the largest area to biofuels production during 2050 will be sub-Saharan Africa – 5.2 million km^2 in the deforestation scenario and 5.7 million km^2 in the intensification scenario. In addition to this land requirement, the area devoted to food crops is projected to expand by 0.2 million km^2 by 2050 in the deforestation scenario, whereas it is projected to decrease by 0.4 million km^2 in the intensification scenario. In both scenarios, the area of grazing lands is projected to decrease during the first part of the 21st century; by 0.5 million km^2 in the deforestation scenario and by 3.4 million km^2 in the intensification scenario. Because these changes in the area of agricultural lands are not enough to compensate for the area required for biofuels production, large tracts of natural forests, woodlands and grasslands will be converted to either food or cellulosic biofuels production. In the deforestation scenario **(Figure 5a)**, we project the loss of over 3.1 million km^2 of the natural forest area, which means that about 59% of the natural forest in place at the start of the 21st century will be cleared by 2050. We also project a loss of 1.2 million km^2 of natural woodlands (a reduction of 63% compared to 2000). By contrast, in the intensification scenario **(Figure 5b)** we project that a smaller, but still substantial loss of 2.0 million km^2 of forest area by 2050; a reduction of 38% of the natural forest area in 2000. In addition, we estimate a loss of 0.7 million km^2 of natural woodlands (a reduction of 38%).

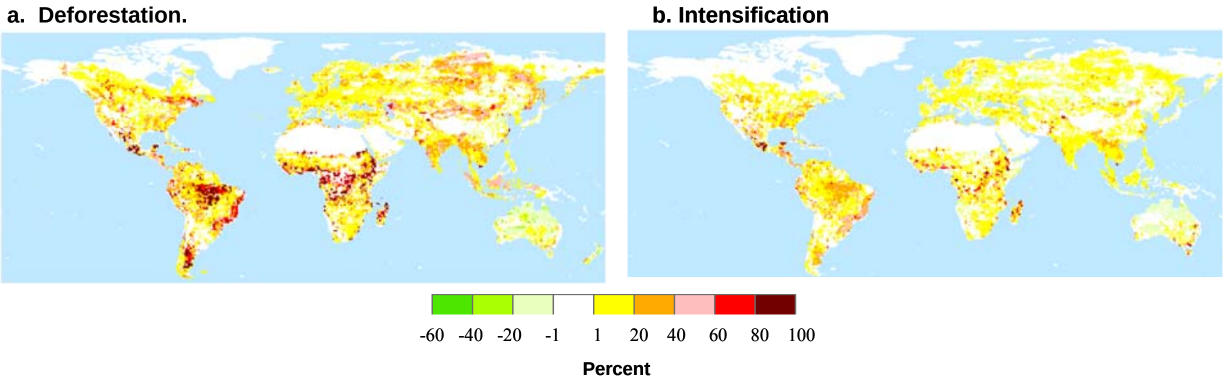


Figure 5. Loss of natural areas due to their conversion to crop and pasture agriculture and cellulosic biofuels between 2000 and 2050 as simulated by the deforestation (a) and intensification (b) scenarios. Data expressed as the percentage of each ½ by ½ degree grid cell devoted to agricultural and cellulosic biofuels production.

Latin America is the region with the second largest area devoted to cellulosic biofuels production, with 4.1 million km^2 in the deforestation scenario and 3.7 million km^2 in the intensification scenario by 2050. Also, in the deforestation scenario, the area devoted to grazing is projected to expand by 1.0 million km^2 between 2000 and 2050. These new requirements for managed lands are largely met through the clearing of species-rich forests and savannas (cerrado in Brazil). By 2050 in the deforestation scenario, we project the clearing of 5.2 million km^2 of natural forests (a reduction of 65%) and 0.6 million km^2 of natural woodlands (a reduction of 71%). Over the same period in the intensification scenario, we estimate the clearing of 1.6

million km^2 of natural forests (a reduction of 20%) and 0.2 million km^2 from savannas (a reduction of 20%). The reduced pressure on natural forests and savannas in the intensification scenario is due, in part, to the conversion of 0.4 million km^2 of managed forests producing woods products to areas producing biofuels.

Habitat destruction is a pervasive threat affecting biodiversity hotspots and is already causing extinctions in many areas. In both scenarios in our analysis, we project the loss of large areas of forest and savanna habitats due to the direct and indirect effects of implementing a large-scale biofuels program, although the areas lost are smaller in the intensification scenario. These losses have the potential to put thousands of endemic plant and animal species at risk across the globe, especially in the sub-tropical and tropical regions.

3.4 A Larger Human Footprint on the Land

The fraction of terrestrial net primary production (NPP, the amount of new plant material produced each year) that human activities have appropriated for our purposes is an important index of the scale of human intervention in the biosphere (Vitousek *et al*. 1986, 1997). With our deforestation scenario, the amount of NPP directly co-opted by humans to grow crops, graze animals and produce biomass for biofuels rises in both the deforestation and intensification scenarios over the first five decades of the 21st century, but more in the former. At the start of the century, we estimate that about 32% of the terrestrial NPP is co-opted for agriculture – crops and pastures – which is in the range of 24 to 37% estimated by Haberl *et al.,* (2007). By mid-century we project this will increase to about 50% with the deforestation scenario and to about 42% with the intensification scenario with biofuels added to the sum (Table 1). Most of the increase in co-opted NPP by 2050 in each of the scenarios can be attributed to the production of biomass for cellulosic biofuels.

The increases in co-opted NPP coupled with the loss of biodiversity have the potential to diminish the capacity of terrestrial ecosystems to deliver many of the support services that humans rely on, such as the cleansing of air and water. We currently do not understand the relationships between ecosystem structure and function well enough to predict when such disturbances in a region will move it beyond a critical threshold for delivering one or more essential ecosystem service (Carpenter, 2003; Walker and Meyers, 2004; Millennium Ecosystem Assessment, 2005).

4. CONCLUSIONS

In our analyses, we have not accounted for all of the unintended consequences of intensification that are likely to occur and these additional effects are likely to differ between the two scenarios we have examined. Greater use of agricultural chemicals associated with intensification, such as fertilizers and pesticides, can lead to a variety of environmental problems. For example, additions of nitrogen fertilizer can result in the emission of nitrous oxide, a potent greenhouse gas, and the pollution of surface and ground water (Galloway *et al*., 2003). Confined livestock production can lead to methane emissions from manure handling and disposal (Denman *et al.,* 2007). In addition, over grazing can lead to damage of riparian areas and cause soil erosion. How these problems are addressed in different regions of the world will eventually determine the environmental consequences of agriculture over the next half century. However, the addition of significant biofuels industry would create further pressures on the environment either through intensified use of existing land, or with more extensive use of land that would then require substantial conversion of natural lands.

Europe and the US have mandated significant use of biofuels in part because they are seen as reducing greenhouse gas emissions. Unfortunately, such technological-based policies often go awry because they fail to account for unintended environmental consequences. Existing and proposed emissions trading systems are, in principle, a superior approach for controlling greenhouse gases, but also fail to fully protect or provide incentive to increase carbon stocks in vegetation and soils. These poorly designed policies put carbon stocks in vegetation and soils at risk and in doing so potentially undermine the goal of stabilizing the atmospheric concentration of carbon dioxide at the desired target.

Even though we see the potential for considerable intensification of production on land, and therefore a less than one-for-one conversion of land to meet biofuels demands, the risks of converting land in biodiversity hotspots are substantial. With the loss of biodiversity comes a cascade of environmental consequences including the loss of critical ecosystems services (Millennium Ecosystem Assessment, 2005). It is clear that we must think holistically and proceed cautiously as we develop policies to use plant-based biofuels to combat global warming.

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6. APPENDIX

Below, we first briefly describe TEM and EPPA along with recent modifications that enabled linkage between these two models. We then describe how land-use change estimates from EPPA are downscaled and organized for use in TEM. Finally, we describe the development of the future climate scenario and two future land-use change scenarios that allow us to explore alternative pathways for achieving a climate policy goal and the potential environmental consequences of those pathways.

A.1 The Terrestrial Ecosystem Model (TEM)

The TEM is a process-based ecosystem model that uses spatially referenced information on climate, elevation, soils, vegetation and water availability to estimate monthly vegetation and soil carbon and nitrogen fluxes and pool sizes. TEM is well-documented and has been used to examine patterns of terrestrial carbon dynamics across the globe including how they are influenced by multiple factors such as CO_2 fertilization, climate change and variability, land-use change, and ozone pollution (Melillo *et al.*, 1993; McGuire *et al.*, 1997, 2000a,b, 2001; Tian *et al.*, 1998, 1999, 2000, 2003; Xiao *et al.*, 1997, 1998; Prinn *et al.*, 1999; Reilly *et al.*, 1999, 2007a,b; Clein *et al.*, 2000; Webster *et al.*, 2003; Felzer *et al.*, 2004, 2005, 2007; Brovkin *et al.*, 2006; Sokolov *et al.*, 2008).

To determine the influence of land use change on terrestrial carbon dynamics, we calculate the net carbon exchange (NCE) between terrestrial ecosystems and the atmosphere by accounting for the carbon gained or lost due to ecosystem metabolism, as represented by net ecosystem production (NEP), the carbon lost during the conversion of natural ecosystems to agriculture (E_C) and the carbon lost during the decomposition of agricultural and wood products (E_P) as follows:

$$\mathrm{NCE} = \mathrm{NEP} - E_C - E_P \qquad \text{(A1)}$$

Net ecosystem production is the balance between the uptake of carbon by vegetation to produce biomass and the release of carbon from respiration of living organisms and decomposition of dead organic matter within an ecosystem. A positive value of NCE represents carbon sequestration by terrestrial ecosystems whereas a negative value means that terrestrial ecosystems are losing carbon. Further details of these TEM calculations may be found elsewhere (McGuire *et al*., 2001; Tian *et al*., 2003; Felzer *et al*., 2004).

To simulate the carbon, nitrogen and water dynamics of cellulosic biofuels, we use the extant grassland parameterization of TEM to represent a generic cellulosic biofuel crop in a manner similar to that used by Felzer *et al*. (2004, 2005) for row-crop agriculture. In this study, we assume that both food crops and biofuel crops are optimally fertilized so that the productivity of these crops do not experience any nitrogen limitations.

Recently, a dynamic cohort approach has been adopted to represent the influence of land-use change on terrestrial carbon dynamics in TEM. In this approach, TEM initially assumes a 0.5^o latitude x 0.5^o longitude grid cell is covered by undisturbed potential vegetation, which is represented by an initial cohort that is assigned the entire land area of the grid cell. When a disturbance occurs, a new cohort is formed and a certain amount of land area within the grid cell is then subtracted from the undisturbed potential vegetation cohort and assigned to the new disturbed cohort. Disturbance-related carbon fluxes from the terrestrial ecosystem are calculated and the terrestrial carbon stocks are adjusted within the new disturbed cohort to account for the initial effect of the disturbance. The TEM is then used to simulate the recovery of terrestrial carbon dynamics after a disturbance within the context of local environmental conditions for the new disturbed cohort. As time progresses in the TEM simulation and more disturbances occur, more cohorts are added to the grid cell. As each disturbance and its effects are tracked separately within TEM, different types of disturbances within a grid cell can be considered simultaneously and allows TEM to consider the impacts of multiple disturbances on terrestrial carbon and nitrogen dynamics. The timing, location and affected area of a disturbance are prescribed by a spatially-explicit time-series land cover data set such as that described by Hurtt *et al*. (2006).

A.2 MIT Emissions Predictions and Policy Analysis (EPPA) Model

The MIT Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic multi-regional computable general equilibrium (CGE) model of the world economy (Jacoby *et al*., 1997; Babiker *et al*., 2001; Paltsev *et al*., 2005; Gurgel *et al*., 2007; Reilly *et al*., 2007a,b; Wang, 2008). The model is based on the Global Trade Analysis Project (GTAP) data base (Hertel, 1997; Dimaranan and McDougall, 2002) with the data aggregated into 16 regions and 24 sectors (**Table A1**). In the version of the model used here (EPPA4, Paltsev *et al*., 2005, Gurgel *et* *al.*, 2007; Wang, 2008), five of these sectors (**Table A2**) require land inputs that have been stratified into five land classes—cropland, pastureland, managed forest land, unmanaged grasslands, and unmanaged forest. Managed forests are those forests which have been disturbed by timber harvest since 1700. Unmanaged grasslands and forests do not produce any goods in the economy, but do provide recreational and conservation services (Wang, 2008). Conversion among these land classes is driven by economics, which consider the competition for land among alternative uses including the production of food, biofuels and wood products. The EPPA model also incorporates United States EPA inventory data and projections on greenhouse gas (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) and air pollutant emissions (SO_2, NO_x, black carbon, organic carbon, NH_3, CO, VOC) to estimate anthropogenic emissions of these compounds. These emission estimates may then be used to determine effects on atmospheric composition, climate and productivity of terrestrial ecosystems. The EPPA model projects the global economy, land use, and associated anthropogenic emissions into the future using a 5-year time step.

To enable linkages to TEM, each of the five land classes in each of the 16 EPPA regions has been assigned a unit price (i.e., the ratio of total land value over total land area) based on a comparison of the distribution of land cover in 1997 as described by the Hurtt *et al*. (2006) data set to the corresponding GTAP land-value data of cropland, pastured and managed forest (Lee *et al.*, 2005). For unmanaged forests, where services and prices are not explicitly reflected in normal economic accounting, we use data on access costs and timber output from the Global Timber Market and Forestry data Project (Sohngen, 2007) to assess the value of potential future harvest of the stock of standing timber and the residual value of land from future regrowth and harvest. The unit price of unmanaged forest is assumed to be the value of future harvests once the timber stock is gone, assuming that the value of the land rests in its ability to produce future harvests. The price ratio of unmanaged forest to managed forest is then applied to the price of pastures to obtain the unit price for unmanaged grasslands. The unit price of each land type is then used to determine changes in the land area required to support future market demand for food, biofuels and wood products based on associated changes in land value. The land use change is represented by economic relations that produce higher productivity land from lower productivity land by adding inputs—essentially investing in land improvements. Two versions of the model were developed—one that simply allowed any conversion that was economic, and a second that limited conversion through an elasticity of substitution that was based on observed willingness to convert natural land to agricultural use. As the first version tended to lead to more conversion than we would expect based on historical evidence, we called it the "deforestation" scenario. The second approach was called the "intensification" scenario, since it is based on land supply elasticities calculated from agricultural land expansion observed in last decades. Further details of this approach are provided in Gurgel *et al*. (2007).

Table A1. Regions and Sectors in the EPPA4 Model. (Paltsev *et al*., 2005).

Country/Region	Sectors
Annex B	**Non-Energy**
United States (USA)	Crops (CROP)
Canada (CAN)	Livestock (LIVE)
Japan (JPN)	Forestry (FORS)
European Union+ (EUR)	Food (FOOD)
Australia/New Zealand (ANZ)	Services (SERV)
Former Soviet Union (FSU)	Energy Intensive Products (EINT)
Eastern Europe (EET)	Other Industries Products (OTHR)
Non-Annex B	Industrial Transportation (TRAN)
	Household Transportation (HTRN)
India (IND)	**Energy**
China (CHN)	
Indonesia (IDZ)	Coal (COAL)
Higher Income East Asia (ASI)	Crude Oil (OIL)
Mexico (MEX)	Refined Oil (ROIL)
Central and South America (LAM)	Natural Gas (GAS)
Middle East (MES)	Electric: Fossil (ELEC)
Africa (AFR)	Electric: Hydro (HYDR)
Rest of World (ROW)	Electric: Nuclear (NUCL)
	Advanced Energy Technologies
	Electric: Biomass (BELE)
	Electric: Natural Gas Combined Cycle (NGCC)
	Electric: NGCC woth CO_2 Capture and Storage (NGCAP)
	Electric: Integrated Coal Gasification with CO_2 Capture and Storage (IGCAP)
	Electric: Solar and Wind (SOLW)
	Liquid Fuel from Biomass (BOIL)
	Oil from Shale (SYNO)
	Synthetic Gas from Coal (SYNG)

Table A2. Sectors requiring land inputs (see also Wang, 2008).

Sector	**Land-use class**
Crops (CROP)	Cropland
Forestry (FORS)	Managed Forests
Livestock (LIVE)	Pasture
Electric: biomass (BELE)	Cropland
Liquid fuel from biomass (BOIL)	Cropland

A detailed description of the biofuels sector in EPPA can be found in Gurgel *et al*. (2007). The sector considers the growth and conversion of a cellulosic crop to a liquid fuel, which is a perfect substitute for refined oil. Maximum biomass production, in dry tons per hectare per year (t ha^{-1} yr^{-1}), is assumed to vary by region, with highest initial productivity in Latin America (15 t ha^{-1} yr^{-1}), and lowest productivity in Canada (3 t ha^{-1} yr^{-1}). Other regions fall between these extremes, reflecting climatological limits to growth imposed by low moisture or temperature. Productivity of land in each region is allowed to change over time due to both technological improvement, and relative changes in NPP from the reference year, as simulated by TEM. Technological improvement include the possibility of both increased yield from biomass crops (1% increase per year) and increased efficiencies of cellulosic conversion processes. The energy embodied by biomass is considered to be 20 GJ per dry ton of biomass, with a conversion efficiency of 40% to liquid fuel. As a consequence, initial net energy yield per hectare ranges from 120 GJ ha^{-1} yr^{-1} in Latin America down to 24 GJ ha^{-1} yr^{-1} in Canada.

A.3 Downscaling EPPA Estimates of Land-use Change

Since the EPPA model estimates land-use changes at the regional scale in response to economic forces, the regional changes estimated by EPPA need to be distributed to the 0.5^o x 0.5^o grid level before this information can be used by TEM. To downscale this information, assume that the spatial distribution of land-use change is determined by the spatial variations in land cover type, land productivity, climate, and management decisions across and within the EPPA regions. After assigning each grid cell to an EPPA region based on political boundaries (**Table A3**), we have developed a statistical approach based on an adaptation of the mixed-entropy method of You and Wood (2006) that takes into account the effects of climate conditions, farmer's experience of land productivities and human accessibility on land-use changes. As in their approach, we use some information to estimate a "prior" land-use share (i.e. proportion of a grid cell under a particular land use) for each grid cell. Later, we adjust this prior to assure that the sum of areas in all grid cells within an EPPA region is consistent with regional EPPA shares. Basically, we seek to econometrically estimate the equation:

$$S_{l,n} = \alpha_l + \sum_i \beta_{l,i} NPP_{l,n} + \sum_i \chi_{l,i} NPP_{l,n}^2 + \delta_l T_n + \phi_l T_n^2 + \varphi_l P_n + \gamma_l P_n^2 + \eta_l D_n + \varepsilon_l \, , \tag{A2}$$

where: subscripts l and i represent the land use categories (i.e., cropland, pasture, managed forest, unmanaged forest and unmanaged grassland), n represents the grid cell, $S_{l,n}$ is the share of land use class l in grid cell n, $NPP_{l,n}$ is the averaged net primary productivity of the prior 5 years as estimated by TEM, T_n is the surface air temperature of grid cell n, P_n is the precipitation in grid cell n, D_n is distance between the center of grid cell n and the closest urban area. The parameters associated with each explanatory variable are represented by $\beta_{l,i}$, χ_{li}, δ_l, ϕ_l, φ_l, γ_l and η_l. α_l is the linear intercept and ε_l is the error term. Equation A2 is estimated for each land-use class in each EPPA region, based on historical and simulated data for the period 1970 to 2000.

The historical data about $S_{l,n}$ are obtained from Hurtt *et al.* (2006), $NPP_{l,n}$ is determined by TEM simulations using the climate conditions and the Hurtt *et al*. (2006) land cover for this time period, historical grid data about T_n is from Brohan *et al.* (2006) and P_n from Hulme *et al.* (1998), and D_n data was calculated from Demographia (2007). Besides D_n, all other independent variables enter equation 1 as linear and squared terms (if significant). The NPP of all land classes affects the share of a particular land use class because the decision of changing a particular land-use has implications on other land classes in the grid cell. Human accessibility affects the decisions of land-use allocation because costs of transportation and access to inputs and markets decrease the likelihood a grid cell will be chosen for agriculture if it is far from an urban area. As emissions of greenhouse gases and other pollutants affect both climate and land productivity, equation A2 allows decisions of land use allocation to be influenced by climate policy.

Table A3. Association of EPPA4 regions to countries and territories across the globe.

EPPA region	Countries and Territories
AFR	Algeria, Angola, Benin, Botswana, Burkino Faso, Burundi, Cameroon, Canary Islands, Cape Verde, Central African Republic, Chad, Comoros, Democratic Republic of Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Europa Island, Gabon, Gambia, Ghana, Glorioso Islands, Guinea, Guinea-Bissau, Ivory Coast, Juan De Nova Island, Kenya, Lesotho, Liberia, Libya, Madagascar, Madeira, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Republic of Congo, Reunion, Rwanda, Saint Helena, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Tromelin Island, Tunisia, Uganda, Western Sahara, Zambia, Zimbabwe
ANZ	Australia, Cook Islands, New Zealand, Niue, Norfolk Island, Tokelau
ASI	Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand
CAN	Canada
CHN	China, Hong Kong, Paracel Islands
EET	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia
EUR	Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom
FSU	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
IDZ	Indonesia, Timor Leste
IND	India
JPN	Japan
LAM	Anguilla, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti. Honduras, Jamaica, Martinique, Montserrat, Netherland Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela, Virgin Islands
MES	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestinian Territories, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen
MEX	Mexico
ROW	Afghanistan, Albania, American Samoa, Bangladesh, Bhutan, Bosnia-Herzegovina, British Indian Ocean Territory, Brunei, Cambodia, Croatia, Cyprus, Fiji, French Polynesia, French Southern and Antarctic Lands, Futuna Island, Greenland, Guam, Kiribati, Laos, Macedonia, Maldives, Marshall Islands, Micronesia, Mongolia, Montenegro, Myanmar, Nauru, Nepal, New Caledonia, Northern Mariana Islands, North Korea, Pakistan, Palau, Papua New Guinea, Pitcairn Islands, Samoa, Serbia, Solomon Islands, Sri Lanka, South Georgia Island, Tonga, Turkey, Tuvalu, Vanuatu, Vietnam, Wallis Island
USA	United States of America

The historical cross-section land-use allocation decisions captured by the estimation of the parameters for equation A2 are then used to forecast the priors of gridded land use in the future using estimates of NPP projected by TEM and estimates of surface air temperature and precipitation projected by the MIT IGSM downscaled to grid level. Urban areas are assumed to remain constant over this period. Because cellulosic biofuels production is not present in the historical data, we determined a prior for biofuels by setting the share of land covered by cellulosic biofuels as the regional share of biofuels forecasted by EPPA in all grid cells where cropland area is at least 5%. This means that cellulosic biofuels are distributed equally across cropland areas in a region.

The land-use priors projected by the downscaling statistical model are then compared to the regional land shares from EPPA and consistently corrected to match them. This correction is done to assure that the sum of shares in each grid cell equals to one and, in each region, the sum of the areas of a particular land use class over all grid cells match the area predicted by EPPA. Both consistency conditions are assured simply re-scaling grid cells until these conditions are met. After downscaling, changes in land shares estimated by EPPA need to be mapped to the disturbance cohorts used by TEM.

A.4 Mapping EPPA Land Shares to TEM Cohorts

To represent contemporary land cover in this study, TEM uses the IGSMVEG classification described by Schlosser *et al*. (2007) and information from Hurtt *et al*. (2006) that describes annual changes in land cover from 1700 to 2000. The IGSMVEG classification stratifies global vegetation into 35 upland and wetland cover types and a 0.5^{o} latitude x 0.5^{o} longitude grid cell may be covered by a mosaic of land cover types based on spatially-explicit information from Melillo *et al*. (1993), Bonan *et al*. (2002) and Matthews and Fung (1987). The Hurtt *et al*. (2006) data describes spatially-explict transitions among primary vegetation, secondary vegetation, croplands and pastures. Primary vegetation is land cover that has not been directly disturbed by human activities. Secondary vegetation is a result of disturbance to primary vegetation (e.g., timber harvest or wood gathering) or abandonment of croplands or pastures. As described earlier, TEM assumes a grid cell is initially represented by a set of cohorts that describe the distribution of “potential” vegetation land cover before any disturbance occurs. The spatially-explicit transition data from Hurtt *et al*. (2006) is then used to determine the timing and location of the creation of disturbance cohorts and the introduction of new food crop, biofuel crop, and pasture land cover types to each grid cell. The data set also determines the area of the grid cell that is affected by these transitions and this area is subtracted from the area of the appropriate existing cohorts. As a result of this approach of tracking land-use history, a 0.5^o latitude x 0.5^o longitude grid cell may have up to 1210 cohorts by the year 2000. The distribution of TEM cohorts during 2000, is then used as the initial land cover for developing future land use scenarios using changes in EPPA land shares.

To determine future transitions in land cover, differences in the downscaled land shares estimated by EPPA are determined for successive 5-year time steps, interpolated to annual time steps and then mapped to the TEM cohort structure. The resulting spatially-explicit time-series transition data set includes transitions among croplands used to grow food crops, croplands used to grow cellulosic biofuels, pastures, managed forests, unmanaged forests, and unmanaged grasslands. The EPPA-derived transitions also indicate the timing and location of timber harvests in the managed forests.

For timber harvests, we assume that a fraction (i.e., 1/*rotationage*) of managed forests in a grid cell will be harvested each year based on the rotation age determined for those forests. Rotation age is assumed to vary with latitude as follows:

$$rotationage = 9 + 0.5\left|latitude\right|^{1.1} \tag{A3}$$

Thus, short rotation ages (e.g., 9 years) are assumed to occur near the equator and longer rotation ages (e.g., 60 years near the Arctic Circle) are assumed to occur with distance away from the equator in general agreement with other studies (**Table A4**).

The EPPA-derived transitions are mapped to the IGSMVEG types used by TEM (**Table A5**) based on the vegetation cover within the grid cell and used to create new disturbance cohorts into the future. No changes are assumed to occur in the distribution of tundra, wetlands, salt marshes, or deserts. The new spatially-explicit time-series cohort data set is then used to prescribe annual changes in land cover for TEM projections of future terrestrial carbon fluxes.

A.5 Development of the Climate Scenario

As biofuels are being promoted as an important part of the global energy mix to meet the climate change challenge, we have developed a single climate scenario based on a particular climate policy to examine the potential effects of alternative aggressive future cellulosic biofuels programs on the terrestrial biosphere within the context of concurrent climate change. The climate scenario is based on a policy to control greenhouse gas emissions from industrial and fossil fuel sources that would stabilize the atmosphere's CO_2 concentration at 550 ppmv (Paltsev *et al*., 2008). Under this climate policy, developed countries would gradually phase in a 50% reduction in emissions by 2050, like that suggested in recent G8 meetings and consistent with proposed goals in Europe and in pending bills before the U.S. Congress. Developing countries would delay their mitigation action until 2025, and intensify reductions in 2035. Similar to the provisions of other existing climate policies, fossil fuel emissions of CO_2, including those resulting from production of biofuels, are assumed to be controlled, but emissions from land-use change are not. As a result, the climate policy scenario used here does not provide incentives to avoid land-use emissions resulting from land clearing to produce biofuels.

Table A4. Examples of rotation age used for timber harvest by this study in comparison to the optimal rotation age from Sohngen *et al*. (1999).

Latitude	This Study's Rotation Age (years)	Sohngen's Rotation Age (years)
15^o N or S	19	20 for southern pine plantations 9 for southern eucalyptus plantations
30^o N or S	30	31 to 40 for natural and plantation pine plantations in the southern USA 12 for eucalyptus 30 for pine plantations in Oceania 27 for plantations in southern China 11 for plantations in the Iberian peninsula 17 for pine plantations in southern Central Asia
45^o N or S	42	49 to 60 for softwood forests in Eastern provinces and softwood and hardwood forests in Lake Provinces of Canada 30 for temperate forests in Central Asia
60^o N or S	54	54 for Nordic plantations in Europe 45 to 70 for US Pacific Northwest Douglas fir-hemlock forests, Western Pine, North-Eastern and Great Lakes softwood general type, oak-hickory and maple-beech-birch forests. 84 to 91 for conifers, temperate hardwoods and boreal hardwoods in Russia

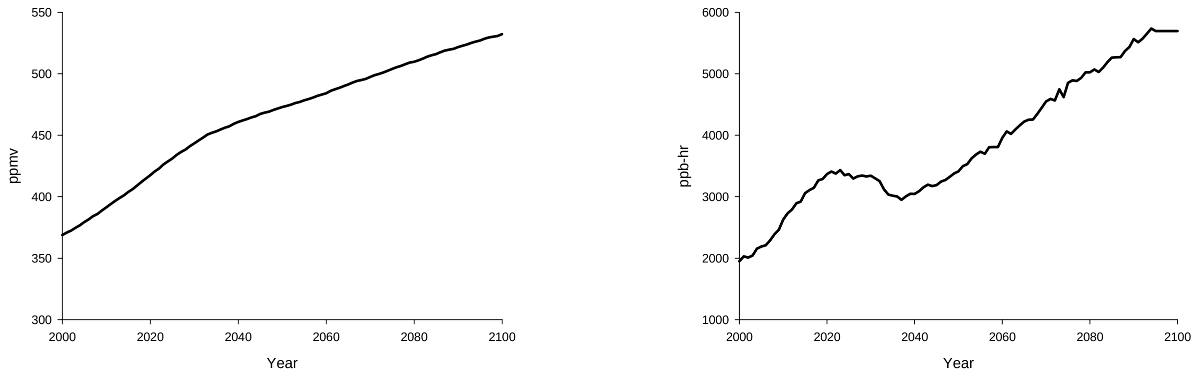
Table A5. Relationship of EPPA land shares to IGSMVEG vegetation types (Schlosser *et al*., 2007)

EPPA Sector/land-use class	IGSMVEG
CROP Cropland	Crop 1
BOIL Cropland	Crop 2
Pasture	Pasture
Managed Forests, Unmanaged forests	Needle-leaf Evergreen Tree (NET) temperate, Needle-leaf Evergreen Tree (NET) boreal, Needle-leaf Deciduous Tree (NDT) boreal, Broadleaved Evergreen Tree (BET) tropical, Broadleaved Evergreen Tree (BET) temperate, Broadleaved Deciduous Tree (BDT) tropical, Broadleaved Deciduous Tree (BDT) temperate, Broadleaved Deciduous Tree (BDT) boreal, Broadleaved Evergreen Shrub (BES) temperate, Broadleaved Deciduous Shrub (BDS) temperate, Broadleaved Deciduous Shrub (BDS) boreal, Floodplains (Tree tropical), Floodplains (Tree temperate)
Unmanaged grasslands	C3 grass, C4 grass, Floodplains (No-tree tropical), Floodplains (No-tree temperate)

The GHG and other pollutant emissions projected by EPPA based on this climate policy have been used to drive the coupled atmospheric and climate module within the MIT IGSM to estimate zonal (i.e., 4^o latitudinal bands) changes in atmospheric composition and climate over the 21st century. In the resulting climate scenario, atmospheric CO_2 concentrations increase by 163 ppmv; the global mean AOT40 ozone index, a measure of the accumulated hourly ozone levels above a threshold of 40 ppb, almost doubles; global mean air temperatures increases by 2.4^o; and global mean precipitation increases by 30 mm yr^{-1} by 2100 (**Figure A1**). The monthly zonal changes in climate are distributed to the 0.5^o x 0.5^o spatial resolution by applying these changes to a baseline climate (Cramer and Leemans, 2001) as described previously by Xiao *et al.* (1997). Zonal changes in the AOT40 index have been downscaled as described by Felzer *et al.* (2005). The downscaled climate is then used to downscale the land-use changes projected by EPPA as described in section A.3 and to drive TEM to develop gridded estimates of net carbon exchange between terrestrial ecosystems and the atmosphere.

a) Atmospheric CO_2 concentrations

b) AOT40 ozone index



c) Global mean air temperature

d) Global mean precipitation

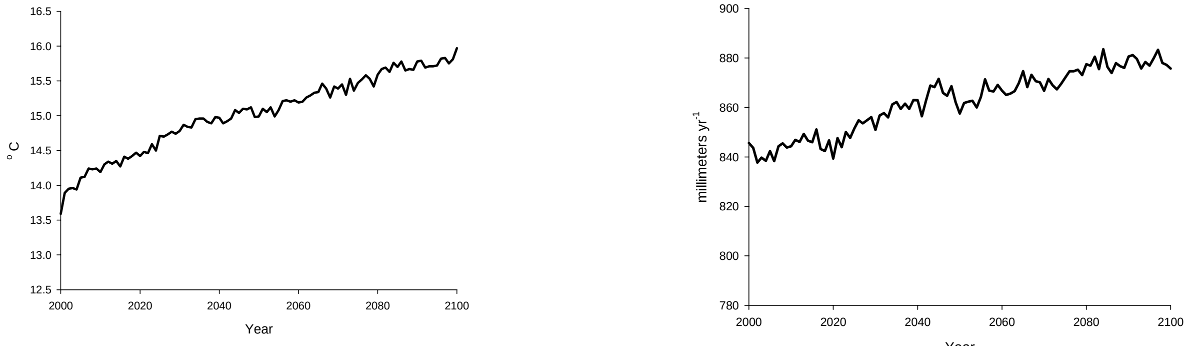


Figure A1. Projected changes in environmental factors from the climate policy including: a) global atmospheric CO_2 concentrations, b) mean global AOT40 ozone index, c) global mean annual air temperatures, and d) global annual precipitation.

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