Using Land to Mitigate Climate Change: Hitting the Target, Recognizing the Trade-offs

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This reprint is one of a series intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

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Using Land To Mitigate Climate Change: Hitting the Target, Recognizing the Trade-offs

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Supporting Information

ABSTRACT: Land can be used in several ways to mitigate climate change, but especially under changing environmental conditions there may be implications for food prices. Using an integrated global system model, we explore the roles that these land-use options can play in a global mitigation strategy to stabilize Earth's average temperature within 2 °C of the preindustrial level and their impacts on agriculture. We show that an ambitious global *Energy-Only* climate policy that includes biofuels would likely not achieve the 2 °C target. A thought-experiment where the world ideally prices land carbon fluxes combined with biofuels (*Energy+Land* policy) gets the world much closer. Land could become a large net carbon sink of about 178 Pg C over the 21st century with price incentives in the *Energy+Land* scenario. With land carbon pricing but without biofuels (a *No-Biofuel* scenario) the carbon sink is nearly identical to the case with biofuels, but emissions from energy are somewhat higher, thereby results in more warming. Absent such incentives, land is either a much smaller net carbon sink (+37 Pg C − *Energy-Only policy*) or a net source (−21 Pg C − *No-Policy*). The significant trade-off with this integrated land-use approach is that prices for agricultural products rise substantially because of mitigation costs borne by the sector and higher land prices. Share of income spent on food for wealthier regions continues to fall, but for the poorest regions, higher food prices lead to a rising share of income spent on food.

1. INTRODUCTION

Constraint of global temperature to less than 2 °C above preindustrial air temperatures will depend upon keeping atmospheric CO_2 concentrations below 450 ppmv.[1,2] To achieve this target, the concurrent deployment of several major climate-change mitigation strategies will be required including those involving changes in land use. Because deforestation accounts for almost 20% of annual global greenhouse gas (GHG) emissions—larger than the entire global transportation sector—reducing emissions from deforestation and forest degradation (REDD) has become a prominent potential mitigation strategy.[3] Second generation biofuels, cellulosic biofuels, have also been proposed as an important mitigation strategy. Production of these biofuels can potentially occur in a way that both yields large amounts of energy and generates an increase of carbon storage on the land.[4−8]

Climate-change mitigation strategies that use land will be in competition with new demands for land to produce food and forest products for a wealthier world population that may reach ten billion people by the end of the century. Climate-change mitigation policy, climate, biofuels, land-use changes, and economic activity are highly interactive. Previous investigations have mostly focused on describing these components, or at best, used loosely linked models to focus on one-way effects.[9−11] Using a linked modeling system[12] that simulates global economic activity, climate, atmospheric chemistry, and biogeochemistry of terrestrial ecosystems, we are able to model dynamic interactions and feedbacks of economic activity, climate, climate mitigation policies, land-use change (including the biofuel option) and examine the implications of multiple land pressures for the climate system, energy production, and food prices.

2. MATERIALS AND METHODS

The linked modeling system (Figure 1) consists of a computable general equilibrium (CGE) model of the world economy, The Emissions Predictions and Policy Analysis Model, EPPA,[13,14] and a Terrestrial Ecosystem Model, TEM.[11,15] This linked modeling process captures interactions among land use, atmospheric chemistry, climate, and the

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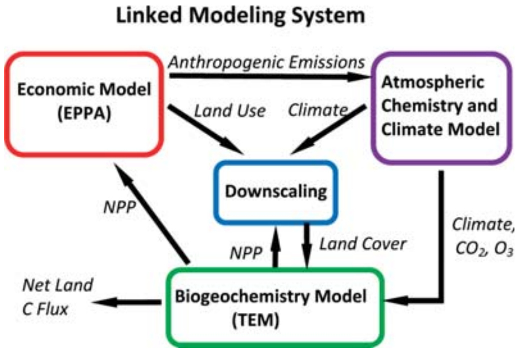

Figure 1. The dynamically linked modeling system. It consists of an economic model (EPPA), a terrestrial biogeochemistry model (TEM) using climate output from an atmospheric chemistry and climate model.

economy. Greenhouse gas emissions, as projected by EPPA, drive a coupled atmospheric chemistry and climate model[12] to simulate the future climate that then drives TEM. A set of projected changes in crop, pasture, and forest productivity, simulated in TEM due to changing climate, levels of CO_2 and tropospheric ozone, are then fed back to the EPPA model to change yields in the agricultural sectors. 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 are downscaled to the 0.5° latitude × 0.5° longitude grid level based on a statistical approach for use in TEM.[16] 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.

2.1. 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 (see the Supporting Information for more details). TEM has been used to examine patterns of land carbon dynamics across the globe including how they are influenced concurrently by multiple factors such as CO_2 fertilization, climate change and variability, land-use change, and ozone pollution.[11,16−19]

To determine the influence of environmental factors and land management on terrestrial carbon dynamics, we calculate the net carbon exchange (NCE) between land ecosystems and the atmosphere. The NCE accounts 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

$$\mathrm{NCE} = \mathrm{NEP} - E_C - E_P \tag{1}$$

Net ecosystem production is the balance between the net uptake of carbon by vegetation to produce biomass, i.e. net primary production (NPP), 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 land ecosystems, whereas a negative value means that land ecosystems are losing carbon. Further details of these TEM calculations may be found in the Supporting Information and elsewhere.[15,20,21]

To simulate the carbon, nitrogen, and water dynamics of both food and biofuel crops, we use the extant grassland parametrization of TEM in a manner similar to that used by Felzer et al.[15] for row-crop agriculture. In this study, we assume that both food crops and biofuels are optimally fertilized so that crop productivity is not nitrogen limited.

A dynamic cohort approach has been adopted to represent the influence of land-use change on land carbon dynamics in TEM. In this approach, TEM assumes that the terrestrial biosphere is represented by 67,420 grid cells with a spatial resolution of 0.5° latitude × 0.5° longitude and that each grid cell is initially 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, such as timber harvest or conversion to croplands (food or biofuels) or pastures, a new cohort is formed, and disturbed 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 an ecosystem are calculated, and the land 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 carbon dynamics of the disturbed cohort and the recovery of land carbon dynamics after abandonment within the context of local environmental conditions. 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 land 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.[22] or projected by a land-use model.

2.2. MIT Emissions Predictions and Policy Analysis (EPPA) Model. EPPA is a recursive-dynamic multiregional computable general equilibrium (CGE) model of the world economy.[13,14,16] The model is based on the Global Trade Analysis Project (GTAP) database[23] with the data aggregated into 16 regions and 25 sectors. The EPPA model projects the global economy, land use, and associated anthropogenic emissions into the future through the end of the 21st century at 5-year time steps (see the Supporting Information for more details).

In the version of the model used here (EPPA4[13,14,16]), five of these sectors (Crops, Forestry, Livestock, Electric: biomass, Liquid fuel from biomass) require land inputs that have been stratified into five land classes—cropland, pastureland, managed forest land, natural grasslands, and natural forest.[13] Land-use change, from one land class to another, depends on the prices of inputs and outputs and changing land productivities. To enable land-use change, each of the five land classes including natural forest and natural grassland has been assigned a region-specific unit price based on the Hurtt et al.[22] data set, GTAP land-value data,[24] and the Global Timber Market and Forestry Data Project.[25] The price ratio of natural forest to managed forest is then applied to the price of pastures to obtain the unit price for natural grasslands. The unit price of

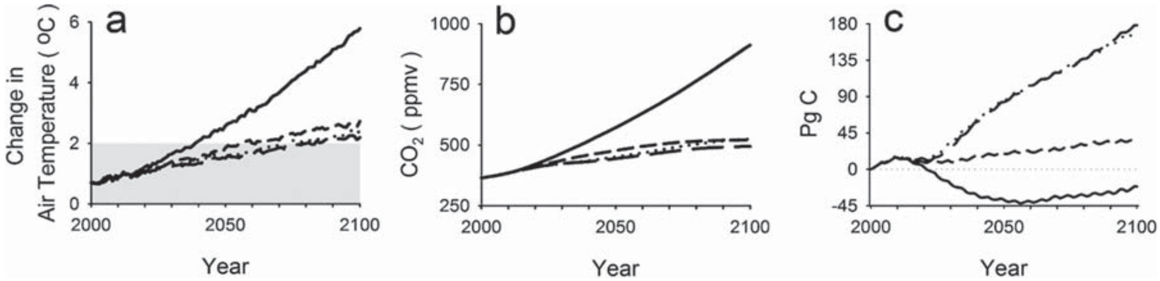

Figure 2. Changes in global mean temperature from preindustrial level (a), atmospheric carbon dioxide (CO_2) concentrations (b), and changes in cumulative land carbon fluxes (c) over the 21st century for different climate/energy policies: *No-Policy* (solid line), *Energy-Only* (short dashed line), *Energy+Land* (long dashed line), and *No-Biofuel* (dotted line). The shaded area in (a) represents the temperature goal of 2 °C above preindustrial of the Copenhagen agreement. Positive values in (c) represent net terrestrial carbon sequestration, while negative values represent net loss of terrestrial carbon to the atmosphere.

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.

In the policy analysis for climate mitigation, carbon emission or uptake from land is also a factor to affect land-use change and biofuel production. To price carbon emissions from land or credit carbon uptake on land, we deal with the fundamental dynamic nature of forest carbon accounting in the recursive structure by observing that for a hectare of land

$$CarbV_{i\rightarrow j,k} = \sum_{t=k}^{m} \frac{P_{C,k}(1+\gamma)^t Carb_t}{(1+r)^t} \tag{2}$$

where *CarbV* is the net present value of the change in carbon stock for a hectare of land transition from use *i* to *j* at time *k*, $P_{C,k}$ is the price of carbon at time *k*, γ is the rate of increase in the price of carbon, *r* is the discount rate, $Carb_t$ is the carbon flux from or to the land at time *t*, and *m* is the number of years to an equilibrium stock level of carbon after the land use change. With banking and borrowing of allowances, γ is assumed to equal *r* so that the annualized rate of return used in the recursive model reduces to

$$annualizedCarbV_{i\rightarrow j,k} = (r+\delta)P_{C,k}Carb_T \tag{3}$$

where the annualized return is a rental rate, consisting of the sum of the discount rate and δ (where $\delta = 1/m$) is multiplied by the price of carbon in year *k* and the integrated change in the carbon stock from transition *i* to *j* here labeled $Carb_T$. In general, pastureland has the lowest carbon stock, natural grassland the next lowest, then cropland, managed forest, and finally natural forest. We can then impose a system of carbon credits for uptake or require purchase of allowances for transitions that lower carbon stocks.

The decision to invest in biofuels is a dynamic problem because the land-use changes needed to produce biomass result in an initial carbon debt that is eventually repaid through repeated harvests that continue to offset fossil fuel use.[11] [See the section 2.7.3 of the Supporting Information for details on modeling economic dynamics.] We compare the value of emissions from using a hectare of land indefinitely to produce biofuel crops to the value of fossil fuel emissions it would replace by determining the ratio θ

$$\theta = \sum_{t=k}^{\infty} \frac{\dfrac{(P_{c,k}(1+\gamma)^t * BiofuelEmissions_t)}{(1+r)^t}}{\dfrac{(P_{c,k}(1+\gamma)^t * GasCarb_t)}{(1+r)^t}} \tag{4a}$$

where $BiofuelEmissions_t$ are the net land carbon emissions associated with the production of biofuels and *GasCarb* are emissions from gasoline. This simplifies to

$$\theta = \sum_{t=k}^{\infty} \frac{BiofuelEmissions_t}{GasCarb_t} \tag{4b}$$

The initial carbon debt means the net effect of biofuels is negative in the early years ($BiofuelEmissions_t > GasCarb_t$), but as emissions fall, the net effect of biofuels becomes positive ($BiofuelEmissions_t < GasCarb_t$). We credit biofuels production equal to (1-θ) per GJ of biofuel used when land carbon is priced.

2.3. Dynamic Linkage between EPPA and TEM.

Climate policy, land-use changes, energy production, and economic activities are highly interactive. To account for these interactions and feedbacks, a dynamic linkage between EPPA and TEM has been developed for passing information on changes in land productivities and land management iteratively between the two models (Figure 1). Changes of net primary productivity, simulated by TEM, are used to represent the changes of land productivity due to changing climate and the levels of CO_2 and O_3. The change of land productivity is one of the important factors to affect land use and land-use changes in EPPA.

Because the EPPA model simulates the global economy using a 5-year time step, and the TEM estimates carbon and nitrogen fluxes on a monthly step, the dynamic linkage between EPPA and TEM are developed on a five-year basis. The linkage consists of five steps. First, TEM runs for five years using known information on climate and atmospheric composition estimated from an atmospheric chemistry and climate model and an initial land cover and management from Hurtt et al.[22] to determine monthly net primary production (NPP) for this initial 5-year time period. Second, the monthly NPP estimates from TEM are aggregated to 5-year mean annual NPP values for each of the EPPA land sectors in each of the EPPA regions and for each grid cell for later downscaling. Third, the EPPA model uses the aggregated NPP estimates from TEM to predict changes in the land shares for each of the EPPA regions. Fourth, the changes in land shares in each of the EPPA regions are then downscaled to the 0.5° latitude × 0.5° longitude spatial resolution using a statistical approach based on climate and

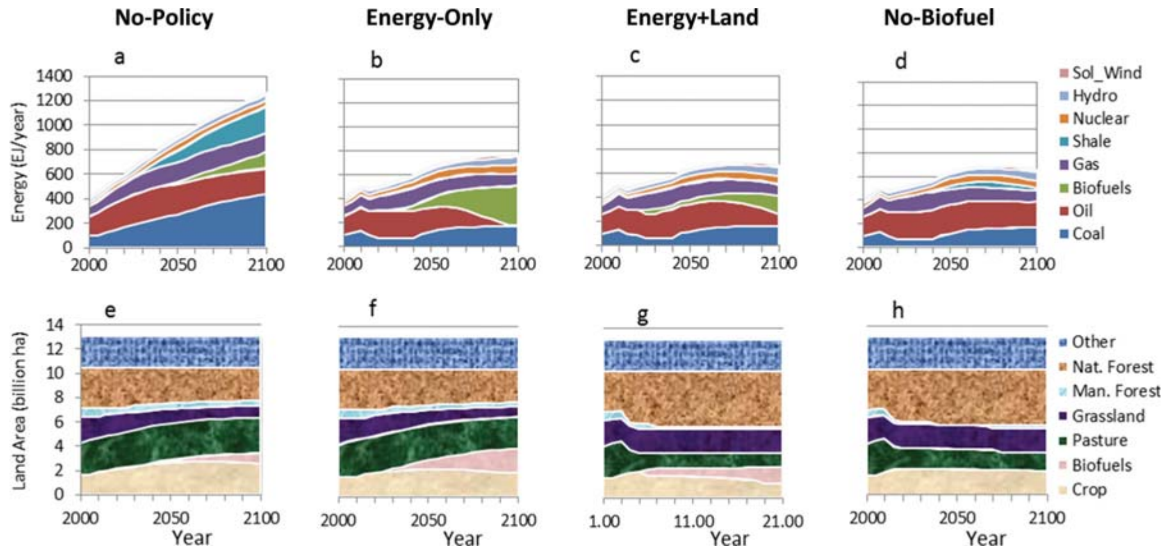

Figure 3. Changes in global primary energy (upper panel) and land use (lower panel) over the 21st century for different climate/energy policies: *No-Policy* (first column), *Energy-Only* (second column), *Energy+Land* (third column), and *No-Biofuel* (fourth column).

gridded 5-year mean NPP estimates and mapped to the land classes used by TEM.[11,16] Fifth, the projected land cover obtained from the downscaling is then used along with updated climate data from the atmospheric chemistry and climate model to run TEM to estimate NPP for the next five years. This procedure linking TEM to EPPA continues for each 5-year time step throughout the 21st century.

2.4. Development of the Scenarios. For this study, we develop four scenarios to explore possible linkages between climate and land use as the world's population grows and becomes wealthier: 1) a *No-Policy* scenario that assumes no climate policy, continued economic growth and land productivity growth of 1% per year; 2) an *Energy-Only* scenario that assumes a worldwide common GHG tax applied to all emissions except CO_2 emissions from land-use change, starting at \$26/t CO_2, rising at 4% per year to \$730/t by the end of century; 3) a *No-Biofuel* scenario that extends carbon pricing in 2) to land but allows no biofuel production; and 4) an *Energy+Land* scenario that extends 3) and allows biofuel production. The *No-Biofuel* and *Energy+Land* policies create incentives to sequester and store carbon in vegetation and soil.

3. RESULTS AND DISCUSSION

3.1. Climate Change Projection. Underlying our results, continued regional population growth as projected by the United Nations,[26] region-specific economic growth globally averaging 2.3% per year, continued increases in agricultural and energy productivity, continued structural transition in poorer regions that leads to greater commercial energy use, and a shift toward more meat consumption are assumed. In the absence of climate policy (*No-Policy* scenario) these factors lead to a global mean temperature increase of ~5.8 °C by 2100 from preindustrial, with the CO_2 concentration at more than 900 ppmv in comparison to the current ~400 ppmv (Figure 2a and 2b). The projected temperature increase will require considerable adaptation of many human systems and will leave some aspects of the earth's environment irreversibly changed.[27] An ambitious global *Energy-Only* policy reduces our estimate of warming from the likely catastrophic ~5.8 °C increase above preindustrial to 2.7 °C and CO_2 to ~520 ppmv (Figure 2a and 2b). A 2.7 °C increase is an amount of warming that would still threaten the stability of large ice sheets of Greenland and the West Antarctic and otherwise profoundly affect natural and managed systems of the earth as detailed, for example, in the IPCC Fourth Assessment Report.[28]

The *Energy-Only* policy does not provide any incentive to avoid deforestation and degradation or to reforest. The *Energy+Land* and *No-Biofuel* scenarios retain the identical carbon price trajectory as in the *Energy-Only* policy, but extend pricing to any change in carbon storage in vegetation and soils to approximate a globally successful idealized REDD-like policy, where the *Energy+Land* allows biofuel production while the *No-Biofuel* does not. These policies redirect land use away from areas that would result in large losses of carbon and toward land where the new use would be carbon neutral or result in additional carbon storage. The policies cause some cropland to be abandoned and reforested. However, the statistically based downscaling land-use algorithm for locating land-use change includes distance to urban areas as an explanatory variable, and it continues to have a preference for developing cropland where there is more population and greater access to the land. The land-use algorithm also leads to the retention of forest land in more remote areas with less access subject to the requirement that fairly large additions to cropland are needed to meet future demands for food and/or biofuels. The land carbon incentives lead to global mean temperature increase of ~2.4 °C by 2100 from preindustrial in the *No-Biofuel* policy, with the CO_2 concentration at ~525 ppmv. The *Energy+Land* policy reduces the warming further to 2.2 °C by 2100, very near the 2 °C target, and CO_2 concentration to ~490 ppmv (Figure 2a and 2b).

3.2. Biofuel Production and Land Use Change. Biomass plays an important role in supplying liquid fuels needed for transportation, but fossil fuels continue to supply over 80% of primary energy needs in the *No-Policy* case (Figure 3). In the *Energy-Only* policy, biofuels contribute more than 40% of the global primary energy by 2100, with more land devoted to biofuels (2.1×10^9 ha) than conventional crops (1.9×10^9 ha). In the *Energy-Only* scenario, total energy use is reduced from about 1300 EJ in 2100 to 800 EJ due to higher energy costs and energy-efficiency reflecting carbon pricing.

The pricing of land carbon in the *No-Biofuel* and *Energy+Land* scenarios results in a large, immediate incentive to reforest and limits conversion of natural grassland to pasture but reduces land available for crop and livestock production. The *No-Biofuel* scenario retains more land for food but has higher petroleum use and thus more CO_2 emissions. In the *No-Biofuel* scenario, 72% of the total energy use of 660 EJ in 2100 comes from fossil fuels. In the *Energy+Land* scenario, 53% of the 670 EJ of energy is fossil, with biofuels supplying 23% in 2100. Less area is used to produce biofuels (1.4×10^9 ha) and conventional crops (1.2×10^9 ha) in the *Energy+Land* than in the *Energy-Only* scenario. Today 1.6×10^9 ha is used for conventional crops. Because biofuels provide an indefinite offset to fuel use, and land used as a carbon sink eventually saturates, we might expect the use of land for biofuel production to dominate reforestation. However, the relative timing of the entry of biomass-based energy is important. With land incentives reforestation occurs immediately, and this investment in reforestation creates irreversibility, as returns from using biomass energy to avoid carbon emissions do not compensate for the large carbon penalty that would be involved with reclearing the land.

3.3. Net Carbon Emissions from Land. Land is a net carbon sink until 2020 for all four scenarios (Figure 2c). In the *No-Policy* scenario, net land emissions from deforestation begin in 2020 and continue through midcentury (solid line in Figure 2c), with some carbon accumulation in the second half of the century as economic pressures limit access to remaining forests, and carbon storage occurs in woody vegetation and associated soils in response to CO_2 fertilization and in agricultural soils in response to nitrogen fertilizer additions. Cumulative net emissions over the 21st century are 21 Pg C. In the *Energy-Only* scenario (short dashed line in Figure 2c), net land emissions from deforestation occurs during 2020 to 2030, followed by carbon accumulation, especially in soils, in response to fertilization of expanding biofuels crops. By the end of the 21st century, there is a cumulative net gain in land carbon of 36 Pg C. Net carbon emissions display a similar path in the *No-Biofuel* (dotted line in Figure 2c) and *Energy+Land* scenarios (long dashed line in Figure 2c). There is a net gain in land carbon storage over the century of 167 Pg C in the *No-Biofuel* scenario and 178 Pg C in the *Energy+Land* scenario as a consequence of reforestation and afforestation, with a particularly steep increase in accumulation in the first several decades. Our estimates for the *No-Biofuel* and *Energy+Land* scenarios are on the higher end of the range of estimates (0.2–2.9 Pg C yr^{-1}) projected by other studies for carbon sequestered by forests under a mitigation program during the 21st century,[29−32] not surprisingly given the fairly high CO_2 price incentives.

There are large regional and scenario differences in the sign and magnitude of carbon fluxes between the land and the atmosphere over the century (Figure 4). The largest net losses from the land occur in Africa, −47 Pg C for the *No-Policy* scenario and −20 Pg C for the *Energy-Only* scenario. There is a net accumulation of 22 Pg C in Africa for the *No-Biofuel* scenario and 29 Pg C for the *Energy+Land* scenario. Latin America shows the second largest cumulative regional net carbon gain of any region, 35 Pg C, in the *No-Biofuel* scenario, and the largest gain, 45 Pg C, in the *Energy+Land* scenario (see Table S15 in the Supporting Information for more details).

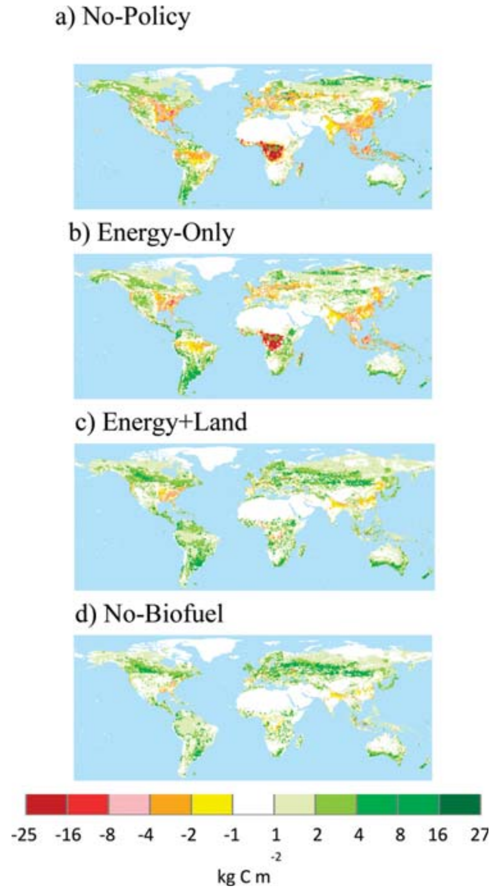

Figure 4. The redistribution of terrestrial carbon storage across the globe in year 2100 from year 2000 for different climate/energy policies: a) *No-Policy*, b) *Energy-Only*, c) *Energy+Land*, and d) *No-Biofuel*. Positive values represent net terrestrial carbon sequestration, while negative values represent net loss of terrestrial carbon to the atmosphere.

Projected deforestation, especially in the *No-Policy* and *Energy-Only* scenarios, is concentrated in the tropics. The estimates include CO_2 from burning and decay of vegetation and release of carbon as CO_2 from disturbed soils. With the *No-Biofuel* and *Energy+Land* scenarios, even though some regions continue to clear land for food and/or biofuels production, globally the REDD-like policy results in some regions of the tropics becoming less of a net carbon source or even a net carbon sink over the century (Figure 4).

3.4. Prices for Agricultural Products. Even with continued increase in agricultural productivity, the combination of the need to feed ten billion people and the additional stress of environmental change on the agricultural system increases global food prices by 22% by 2100 in the *No-Policy* scenario (Figure 5). This is accompanied by a 5-fold increase in global GDP per capita, with the share of food in total consumption falling from the current 15% to 7% by 2100. The food demand increase with income is lower in developed countries so that the food share in these regions is only about 2.5% in 2100, while it remains at 11% in China, 15% in Middle East and less developed Asian countries, and ∼20% in Africa. The effects on agricultural prices of the *Energy-Only* scenario are offsetting, as the benefits for the agricultural system of avoided environmental damage are largely offset by the increased cost of land

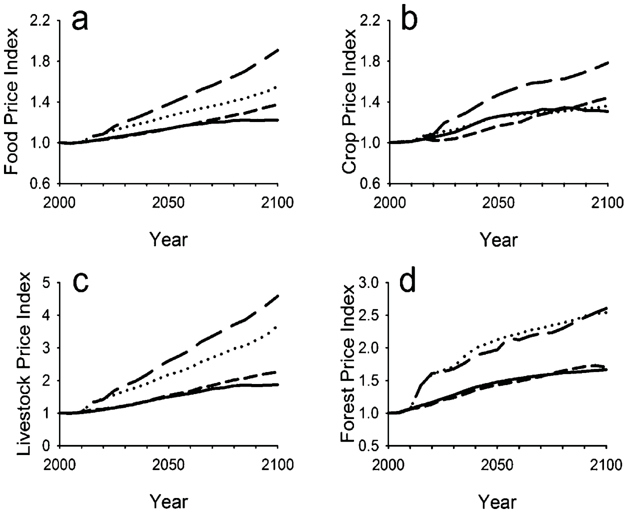

Figure 5. Changes of price indices for agricultural (a b, c) and forest (d) products for different climate/energy policies: *No-Policy* (solid line), *Energy-Only* (short dashed line), *Energy+Land* (long dashed line), and *No-Biofuel* (dotted line) using 2000 as the baseyear. Product prices are affected by changes in all input costs, including energy and land costs that are most strongly affected by the policy scenarios. Food prices (a) rise due to higher energy costs, crop prices (b), and livestock prices (c) which are intermediate inputs into food production.

and of energy and other greenhouse gas controls due to the mitigation policy. In contrast, in the *No-Biofuel* and *Energy+Land* scenario, average price increases of food, crops, livestock, and forest products are much higher than in the other two scenarios. Livestock prices are affected both by increases in pasture rents, as well as increases in feed grain prices. Forest product prices also rise substantially because land is a large cost share in production. Impacts on food prices are moderated by the fact that the additional value-added components of food sector production are not directly affected by the pricing of land carbon. The incentive to reforest immediately leads commodity prices to diverge substantially from the other scenarios in the near term even though the carbon uptake is only gradually realized. Compared with the *No-Policy* scenario, the regional food consumption shares in the *Energy+Land* scenario are decreased to 0.5% in USA, 18% in Africa, and 10.6% in China.

The MIT IGSM framework with a dynamically linked EPPA and TEM represents the entire global economy, including agriculture, forestry, pasture land and natural forest and grasslands explicitly. As such we are able to focus on a multistress analysis where changing climate and atmospheric chemistry (i.e., carbon dioxide, ozone), combined with a growing population and income that increases the demand for food and forest products and land devoted to such production, are resolved together with potential demand for land for biofuels and carbon sequestration in forests to mitigate climate change. It advances the methodology applied previously[11] by fully coupling the EPPA and TEM components of the IGSM. The previous effort focused on the partial effect of biofuels by creating model experiments whether biofuels were available or not. The current effort looks at different climate policy regimes and the combined effect they have on stocks of carbon stored in vegetation and soils, and the implications for energy, especially biofuels, and for the price of food and agricultural products.

Our results suggest that environmental, food, and energy challenges are likely to put significant pressure on land resources over the century, especially with a policy to reduce greenhouse gases. We find that overall, the fully coupled models yield similar results as our previous study[11] using loosely linked models, especially for global primary energy use, biofuel production, and agricultural prices. By allowing the interactions and feedbacks, however, managed and natural forest lands are around 10% more productive and pasture land 10% less productive by 2100. In contrast productivity of crop land and natural grass land are little affected by the coupling. When the biofuel option is implemented in the *Energy-Only* and *Energy+Land* scenarios, more managed forest land is diverted for biofuel production, especially in Africa, Latin America, and United States. Other modeling studies[10,33] have not included the tight coupling used here, nor have they had agriculture, energy, and forest sectors represented in an economy-wide model. The economy-wide model includes adjustments to prices on several margins (intensification of production on existing land, reduced food consumption and shifts away from land intensive livestock products) and a land supply elasticity that reflects institutional protection of forested land. Some studies have found complete loss of natural forestland in a carbon pricing scenario that does not include land.[10] Failure to include adjustments on multiple margins and resistance to deforestation for recreation and other values appears to have exaggerated the effect of land carbon pricing in these studies, with carbon difference of 300 to 400 Pg C, more than twice our estimate.

Our approach to create incentives for carbon storage does include incentives to avoid leakage, but it depends on an idealized system that is in place worldwide—thus it reflects the most we might hope to get from land carbon sequestration. Less than ideal systems with incomplete geographical coverage would suffer from leakage and generate less carbon storage but also smaller impacts on food prices. If implemented as a price instrument, then the quantity of abatement is uncertain and severe carbon loss from increases in fire or disease due to climate change, for example, could undermine benefits of reforestation. If implemented as a quantity constraint, leakage from land carbon would need to be offset by additional reductions in emissions from other sources, which could, in turn, increase the costs of meeting the target and have larger impacts on food prices. These trade-offs raise the stakes in international negotiations regarding the burden-sharing associated with climate agreements and compensation for direct and indirect effects of reduction measures.

■ ASSOCIATED CONTENT

Supporting Information

Complete description of the EPPA model and TEM; results and discussion about energy related economy, regional carbon dynamics. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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