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SPECIAL FEATURE

Climate mitigation and the future of tropical landscapes

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Land-use change to meet 21st-century demands for food, fuel, and fiber will depend on many interactive factors, including global policies limiting anthropogenic climate change and realized improvements in agricultural productivity. Climate-change mitigation policies will alter the decision-making environment for land management, and changes in agricultural productivity will influence cultivated land expansion. We explore to what extent future increases in agricultural productivity might offset conversion of tropical forest lands to crop lands under a climate mitigation policy and a contrasting no-policy scenario in a global integrated assessment model. The Global Change Assessment Model is applied here to simulate a mitigation policy that stabilizes radiative forcing at 4.5 W m^{-2} (approximately 526 ppm CO_2) in the year 2100 by introducing a price for all greenhouse gas emissions, including those from land use. These scenarios are simulated with several cases of future agricultural productivity growth rates and the results downscaled to produce gridded maps of potential land-use change. We find that tropical forests are preserved near their present-day extent, and bioenergy crops emerge as an effective mitigation option, only in cases in which a climate mitigation policy that includes an economic price for land-use emissions is in place, and in which agricultural productivity growth continues throughout the century. We find that idealized land-use emissions price assumptions are most effective at limiting deforestation, even when cropland area must increase to meet future food demand. These findings emphasize the importance of accounting for feedbacks from land-use change emissions in global climate change mitigation strategies.

agricultural productivity | climate change | integrated assessment | land use change

In order for global climate mitigation policies to account effectively for carbon emissions from land-use change, they must reflect the best understanding of large-scale dynamics of land-use decisions worldwide (1). The diverse, present-day drivers of emissions from deforestation are related to global pressures for food and other land-based products; in the future, societal demands may also include providing bioenergy resources and mitigating deforestation emissions. Given the global scope of the agriculture and energy systems, one approach to gain insights about future land use and inform mitigation strategy design is to examine alternative scenarios with a global integrated assessment model (IAM) (2). Recent studies (3, 4) have shown that, unless appropriate economic incentives are built into a climate mitigation policy, widespread deforestation could result from increasing demands for food and biofuels, in addition to the already existing threats from deforestation (5) and climate change (6).

IAMs include an integrated, global representation of human systems encompassing energy and land use (7) and can explore the potential interactions of demands for food and fuel in the context of future climate mitigation policies. A wide array of IAMs are routinely applied for climate mitigation research and policy analysis (3, 4, 8, 9). Here we apply the Global Change Assessment Model (GCAM) to examine to what extent future increases in agricultural productivity could offset tropical deforestation under both reference (i.e., business-as-usual) and emissions-pricing policy (i.e., mitigation) scenarios (3); a second objective was to explore the uncertainty of these scenarios by varying rates of change in agricultural productivity growth (APG). These simulations were conducted to gain insights into system interactions affecting tropical forest extent under uncertain climate mitigation policy and APG conditions; their results are not absolute predictions but rather best understood as exploring the relative effects of policy choices.

Land Use and Climate Stabilization

Stabilization of atmospheric radiative forcing requires that net anthropogenic emissions of greenhouse gases eventually approach zero (10). In IAM scenarios of climate mitigation, this imperative results in very high emissions prices that drive changes in energy and land use, including increased use of bioenergy. Concern over the effects of potential bioenergy expansion has prompted research on carbon stocks, food prices (11, 12), and indirect emissions from land-use change (LUC) (13–15). Mitigation scenario research with IAMs has shown that, if terrestrial carbon is not assigned an economic value, rising emissions prices drive a dramatic expansion of bioenergy production at the expense of forested lands (3, 4, 12); conversely, when terrestrial carbon stocks are given an economic value, bioenergy crop production is limited and widespread deforestation avoided (3).

Future mitigation policies could aim to expand forest lands to reduce LUC emissions, but their efficacy will depend on the evolution of the global economy and energy production (16). The mitigation scenario used in this study places an equal economic price on land-use emissions and energy and industrial emissions. The scenario is idealized and reflects the atmospheric value of greenhouse gas emissions: regardless of the emission source, all CO_2 contributes equally to climate change, and thus must be accounted for if radiative forcing of climate is to be stabilized. When terrestrial emissions are valued in this way, the cost of LUC emissions increases along with the cost of fossil-fuel emissions, resulting in a strong economic incentive to protect and increase forested lands (17).

Crop production is one of many drivers of deforestation today (5). In IAMs simulating future mitigation strategies, the success of establishing an emissions price as an incentive to hold forest carbon stocks may be partially offset by land clearing for agriculture, which in turn is influenced by crop productivity. During the past

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ECONOMIC SCIENCES

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60 y, crop productivity—the amount of food, fiber, or energy produced per unit area—has kept pace with increased demand (18, 19), although the trend has slowed in recent years (20). New research in crop management, crop breeding, and genetic modification may reverse this trend in the future (21, 22), but considerable uncertainty remains. Tropical forests would be particularly vulnerable to cropland expansion if agricultural productivity plateaus; such forests are highly productive (23, 24) and carbon-rich (25, 26) ecosystems whose future dynamics are important to the global carbon cycle and which are already subject to strong LUC pressures (27, 28).

Climate Mitigation Scenarios

The mitigation scenario discussed here [Representative Concentration Pathway (RCP) 4.5] is simulated with the GCAM, along with a companion reference scenario with no climate mitigation. RCP4.5 is one of four RCPs selected by the international research community to drive climate simulations for the fifth Climate Model Intercomparison Project (9, 29).* The GCAM reference and RCP4.5 scenarios are driven by exogenously supplied global population and income projections. Global population, based on a median scenario by the United Nations (30) and the Millennium Assessment Techno-Garden Scenario (31), reaches a maximum of more than 9 billion in 2065 and then declines to 8.7 billion in 2100. Global GDP growth, driven by growth in the labor force and in labor productivity, is determined exogenously based on the population projections and continues the upward trend from the 20th century, growing by an order of magnitude.

The GCAM reference scenario includes no explicit policies to limit carbon emissions and global energy consumption triples, dominated by fossil fuels; forest area declines to accommodate increases in cropland to meet food demands. After 2050 cropland expansion and LUC emissions decline as a result of exogenously specified increases in agricultural crop productivity and declines in population (7). The GCAM RCP4.5 mitigation scenario is based on the same population and income drivers as the reference scenario, but applies policies that tax all greenhouse gas emissions to stabilize radiative forcing at 4.5 W m^{-2} in 2100. RCP4.5 results in an atmospheric CO_2 concentration of 526 ppm in 2100, compared with 792 ppm in the reference case (Fig. S1). The emissions price explicitly applies to all emissions, including those from land use and LUC, which become viable candidates for emissions mitigation. When the model analytically solves for an economically efficient path to a climate target with this emissions price, a consistent result is an economically driven cessation of deforestation and expansion of forested area. No explicit forestry policy (e.g., Reducing Emissions from Deforestation and forest Degradation) is assumed; afforestation is driven by the emissions price (3). Similarly, bioenergy emerges as an effective climate mitigation option. RCP4.5 assumes full global participation in an emissions mitigation strategy and depicts declines in fossil fuel use, increases in renewable and nuclear energy, large-scale use of biofuels, and the rapid emergence of large-scale CO_2 capture and storage technologies (7).

Future APG rates in GCAM are determined by endogenously simulated changes in crop land in combination with an exogenous parameter set derived from Food and Agriculture Organization (FAO) projections out to 2030 (22). After 2030, these converge to a conservative rate of 0.25% annually by 2050, resulting in a total increase in productivity of 13% from 2050 to 2100. The uncertainty related to the assumptions regarding future crop productivity is a major factor in future simulated LUC, LUC emissions, and bioenergy crop supply (17).

The GCAM simulations for this study were designed to test to what degree future APG rates and RCP4.5 climate policies, alone or in combination, could affect the future extent of tropical forest lands. Both the reference and RCP4.5 mitigation scenarios were simulated with alternative rates of APG; the standard parameters described earlier, zero APG (zAPG), and high APG (hAPG). Hereafter, "scenario" is used to refer to simulations distinguished by their climate mitigation objective where "reference" refers to a scenario with no mitigation policy and "RCP4.5" refers to a scenario with a mitigation policy. The term "case" is used to indicate individual simulations within each scenario set, corresponding to one of three APG parameter cases, "standard," "zAPG," and "hAPG" (Table 1).

Global Land-Use Change in the 21st Century

GCAM simulations of global land use in the 21st century are responsive to APG and climate mitigation. In the climate mitigation scenario, the rate of LUC is fastest early in the model period in response to the institution of a global emissions price. Although rapid, the absolute rate of LUC in these GCAM scenarios is within the range of LUC that has occurred during the past 100 y (32, 33).

Cropland area increases in the reference scenario and in all cases with zAPG. Global forest area declines by 19% in the reference scenario and by close to 50% in the zAPG reference (zAPGref) case. In contrast, when the RCP4.5 mitigation scenario is simulated, global forested land area increases 25% over the century reducing land-use emissions to near zero. GCAM simulates greater forest expansion in northern regions while croplands expand in higher-yield tropical and temperate regions. Forest growth and carbon accumulation in northern ecosystems is slower than in tropical regions, but the eventual carbon density is often greater as a result of accumulation in soils (34).

Much of the LUC observed in the RCP4.5 mitigation scenario can be attributed to the strong economic incentive to reduce LUC emissions that arises from the emissions price. In all three RCP4.5 cases considered here, LUC emissions are reduced to near zero by the end of the century, regardless of assumptions about agricultural productivity change (Fig. 1). In the zAPG4.5 case, LUC emissions are higher early in the century while demand for food is increasing. Reduced food demand as population declines enables more rapid reductions in LUC emissions late in the century.

The impact of agricultural productivity on LUC emissions is more significant in the reference cases, in which it is not affected by an emissions price. When agricultural productivity follows standard or high assumptions [i.e., hAPG reference (hAPGref)], LUC emissions remain relatively constant, with a slow decline over time as a result of increasing agricultural productivities and declining population. In the zAPGref case, there is an early increase in land conversion to crop production to meet increasing food demands; land conversions decrease later in the century as most of the potential cropland has been converted. Further increases in demand

Table 1. Scenarios considered in the present study

Name	Climate policy	Productivity growth
Reference	None	Standard*
RCP4.5	4.5 W m^{-2} stabilization	Standard*
zAPGref	None	Zero
zAPG4.5	4.5 W m^{-2} stabilization	Zero
hAPGref	None	High†
hAPG4.5	4.5 W m^{-2} stabilization	High†

*Standard GCAM assumption, following Bruinsma (22) to 2030 and then converging to 0.25% per year for all crops in all regions by 2100.
†Fifty percent greater than standard assumption.

*Four IAMs were selected by the international climate modeling community to provide scenarios that include a full set of greenhouse gas emissions and land use projections for the 21st century (http://www.iiasa.ac.at/web-apps/tnt/RcpDb/ and http://cmip-pcmdi.llnl.gov/cmip5/).

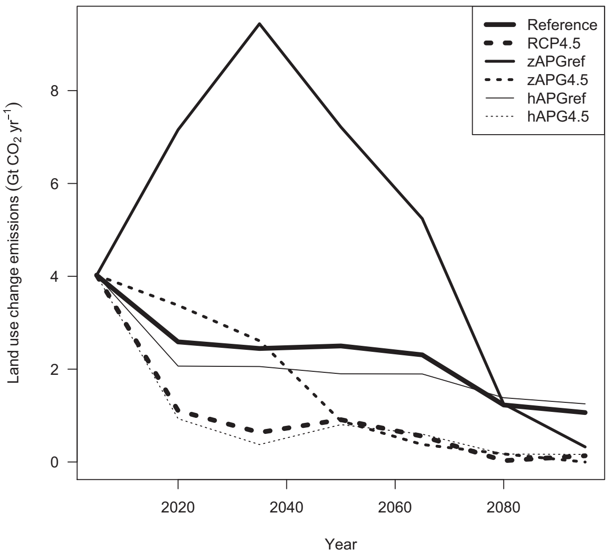

Fig. 1. Net CO_2 emissions from global land use change under GCAM reference and RCP4.5 scenarios with different levels of agricultural productivity assumed.

are met by concentrating crop production in high yielding regions and by international trade.

Implications for Tropical Land Use

When downscaled, these global results indicate significant change in land use in tropical regions by the year 2100 compared with 2005 (Fig. 2 and Fig. S2). Although GCAM simulates changes in multiple land cover types, including pasture, grassland, and shrubland, here we focus on changes to crop and forested lands. When the standard assumptions about APG and the climate mitigation policy are combined in the RCP4.5 case, cropland declines over a widespread area throughout the tropics (Fig. 2*A*). This abandoned cropland then reverts to a secondary land type determined by potential vegetation, leading to moderate afforestation in the tropics, particularly in Africa (Fig. 2*B*).

In contrast, cropland expands throughout the tropical forest and grassland regions of South America, Africa, and Indonesia under the zAPGref case (Fig. 2*C*). The consequence is widespread deforestation (Fig. 2*D*), particularly in South America. This widespread deforestation and cropland expansion is also observed in the reference case with standard APG (Fig. S2 *C* and *D*). In the zAPG4.5 mitigation case, large areas of tropical forest are lost in South America and Southeast Asia, whereas forested area expands in central Africa (Fig. S2 *A* and *B*).

Bioenergy Resources

When APG is high, more bioenergy is produced under both RCP4.5 and reference scenarios (Fig. 3*A*). In the zAPG cases, the production of dedicated bioenergy crops is one third the production in the corresponding hAPG cases. Bioenergy demand is higher in the RCP4.5 scenario, leading to increased utilization of crop residues and waste resources in addition to the dedicated bioenergy crop production (Fig. 3*B*). In all but one case (hAPGref), residue and waste represent a larger bioenergy resource than dedicated crops.

Dedicated bioenergy crops are grown in all model regions, with Africa supplying the greatest amount in the reference scenario and Southeast Asia and India producing the largest amount under the climate mitigation scenario. This results from the incentive to preserve large forested areas of Africa, as a result of the price on land use emissions, which limits expansion of bioenergy cropping. When APG assumptions are altered, the total amount of bioenergy produced is altered; however, the geographical distribution of production is not affected.

Implications for Future Food Prices

Within the RCP4.5 mitigation cases, the cost of crop production is more sensitive to mitigation policy than to future agricultural

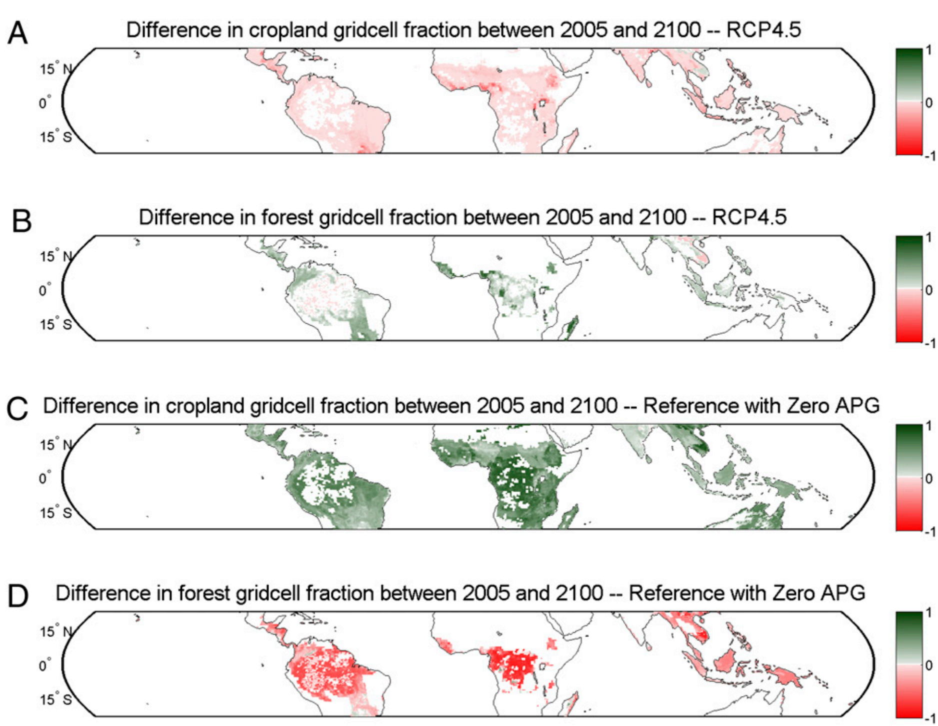

Fig. 2. Tropical land use change as fraction of grid-cell area in 2100 minus fraction of grid-cell area in 2005 for (*A*) cropland (including bioenergy crops) under the RCP4.5 case, (*B*) forest lands under the RCP4.5 case, (*C*) cropland (including bioenergy crops) under the zAPGref case, and (*D*) forest lands under the zAPGref case.

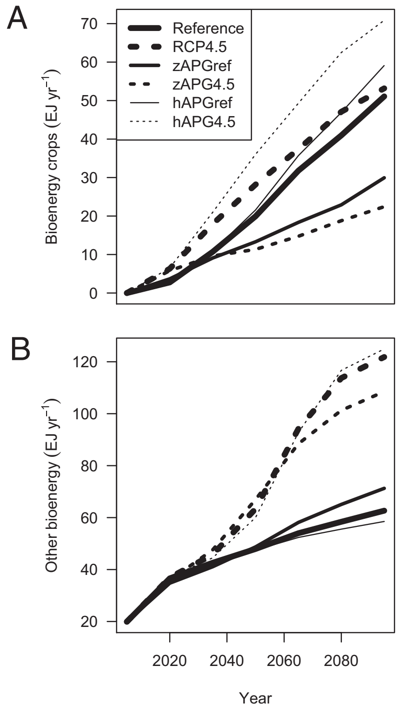

Fig. 3. Bioenergy use in the GCAM scenarios from (*A*) dedicated bioenergy crops and (*B*) crop and forestry residues and municipal solid waste.

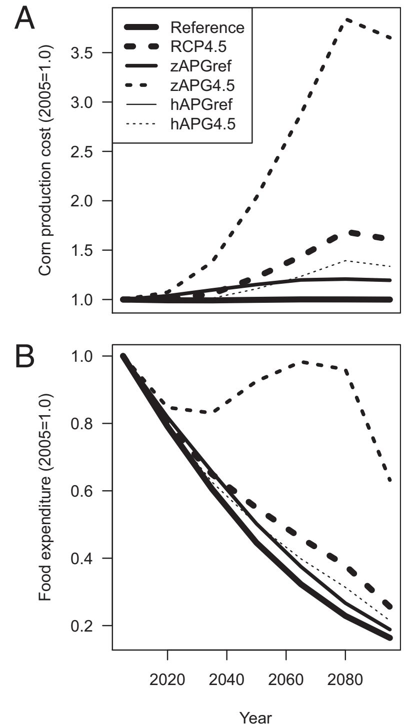

Fig. 4. Changes in (*A*) cost of corn production and (*B*) index of food expenditure as a fraction of GDP, indexed to 2005 values.

productivity (Fig. 4*A*). Within the reference cases, the cost of agricultural production remains level compared with 2005, although it increases slightly when crop productivity does not increase (i.e., zAPGref). Costs increase substantially under the RCP4.5 mitigation cases as a result of the increasing value of land for terrestrial carbon storage and bioenergy crop production. The effect of agricultural productivity assumptions becomes more apparent in zAPG4.5, with a more than threefold increase in corn price by 2080 (Fig. 4*A*).

Food expenditures vary significantly across the three agricultural productivity cases because of differences in food prices and protein consumption. In all scenarios, food expenditures as a fraction of income decline over time as a result of increasing GDP and, in some cases, declining food prices (Fig. 4*B*). A comparison of the three mitigation policy cases shows that the hAPG4.5 case results in the lowest food expenditure, and the zAPG4.5 case results in the highest food expenditure. Food expenditure more than quadruples by the end of the century with the zAPG assumption compared with the hAPG assumption.

Discussion

The results of the GCAM simulations provide several insights into large-scale dynamics of human influence on tropical forested lands. The incentive to preserve and increase forest lands through the pricing of land-use emissions in a climate mitigation policy emerges as a strong pressure influencing land-use change. In such cases, although some deforestation may still occur from competing pressures, the net effect is an increase in global forested lands, including those in the tropics. To a lesser, but still significant, extent, continued improvement in agricultural productivity also reduces deforestation by relieving the pressure to expand crop lands. When combined, these two factors lead to net increases in tropical forested lands during the 21st century.

The impacts on forested lands are mixed when only one of these two factors (agricultural productivity increases and greenhouse gas emissions pricing) is present. Under the RCP4.5 mitigation scenario with zAPG, the combined pressures lead to a mixed response of afforestation in some tropical areas and deforestation in others. When agricultural productivity increases but there is no mitigation policy in place, deforestation continues to occur, although it is somewhat mitigated. Thus we find that a specific incentive to preserve and increase forest lands, in this case through climate mitigation, is necessary; simply relieving the pressure on forests through improving crop productivity is not sufficient to prevent widespread tropical deforestation. The results enumerated here provide insights for present policy discussions concerning the appropriate accounting of terrestrial carbon in climate mitigation strategies. However, the findings are not intended to suggest a specific policy solution.

The results also point to the importance of continued increases in crop productivity as an important factor for the cost and effectiveness of global climate mitigation efforts, through their effect on bioenergy. Both bioenergy and terrestrial carbon storage mitigation options are reduced with the zAPG cases because of the increased demand for food-producing cropland. Lower agriculture productivity growth rates result in lower bioenergy crop production as well as higher crop prices. Under the RCP4.5 scenario, crop prices increase as a consequence of the land use emissions pricing. Higher terrestrial carbon values lead to higher land rental rates, which are an important component of land value. Thus, agricultural productivity improvements prove to be a critical factor both to keep food costs low and to provide opportunities for mitigation through bioenergy production and terrestrial carbon storage.

These findings raise several key questions for future integrated assessment analyses. The GCAM-simulated increase of forested land in boreal forest regions for mitigation through carbon sequestration has a potential positive feedback effect to the climate system through reductions in albedo (32, 35). The magnitude of this feedback is unknown, but if significant, could negatively affect climate mitigation efforts. In addition, LUC and agricultural productivity are simulated here assuming continuation of current climatic conditions. In reality, climate is likely to be altered in ways that are still uncertain under reference and climate mitigation policies; the resulting changes in agricultural productivity could be significant (36). An important area for future IAM development is tractably representing climate feedbacks that will occur in different emissions scenarios, assessing their effects on mitigation options, and understanding consequences of these climate impacts on land use options for society.

Methods

GCAM. The analysis reported here applies the GCAM (7, 37, 38), which is a dynamic recursive economic model driven by assumptions about population size and labor productivity that determine potential gross domestic product in each of 14 regions† (Fig. S3). The model is solved on a 15-y time step by establishing market-clearing prices for all energy, agriculture, and land markets such that all markets balance simultaneously. GCAM contains detailed representations of technology options that compete within a probabilistic model of market competition. GCAM has been developed over the course of 30 y and regularly participates in model intercomparisons, such as the Energy Modeling Forum (39), and is a member of the Steering Committee of the Integrated Assessment Modeling Consortium (http://www.iamconsortium.org). Emissions scenarios produced with GCAM have been used extensively by the Intergovernmental Panel on Climate Change and for research and policy analysis by national governments and other stakeholders.

Land cover, land use, agricultural and forestry production, and terrestrial carbon emissions are simulated endogenously in GCAM (17). The model is calibrated to 2005 crop production, harvested area and animal production from FAO (http://faostat.fao.org; accessed November 2007), and land use and terrestrial carbon pools are initialized with historical reconstructions for 1700 to 2005 (4, 40). Cropping systems are divided into nine categories (rice, wheat, corn, other grains, oil crops, fiber crops, fodder crops, sugar crops, and other crops) and animal production is represented by five categories (beef, dairy, pork, poultry, and other ruminants). Feed for animal production is supplied by both pasture land and grain and fodder crops, following the methodology of Bouwman et al. (41). Whereas demand for grain calories in GCAM is inelastic and therefore increases over the course of the century with population and income, demand for animal protein is subject to income elasticities. Production of bioenergy crops depends on their expected profitability relative to other land-use options and the price of other energy resources. Above- and below-ground terrestrial carbon stocks are distributed among all land use types (Fig. S4) starting from base year (2005) calibration values adapted from the Intergovernmental Panel on Climate Change (42) and area-weighted to the GCAM regions per Monfreda et al. (43). Carbon emission and sequestration result from changes in land use between model simulation periods, with plant growth occurring at various rates and below-ground carbon changing only on a decadal timescale.

Arable land can be used for the production of food, forest products, and bioenergy, and is allocated among alternative uses based on expected profitability (Fig. S4). Crop productivity is calibrated to the base year and changes over time as a result of endogenous changes in land area in production as well as an exogenously supplied crop productivity growth parameter. Three main feedstocks for bioenergy are considered in GCAM: bioenergy crops, crop and forestry residues, and municipal solid waste (44). Bioenergy crops are grown explicitly for energy and in direct competition with food crops for land. Thus, their production is sensitive to assumptions about crop productivity growth. GCAM allows as much as 30% of crop residue to be harvested for energy, assuming that the remaining fraction is necessary for erosion control and maintenance of soil quality (45, 46).

IAMs, including GCAM, operate by calibrating thousands of parameters for a base period. GCAM is calibrated to reproduce historical reconstructions for the years 1975, 1990, and 2005 whereas the terrestrial carbon cycle reproduces the period from 1700 to 2005. Although it is relatively simple to pass through historical reconstructions, modeling the future is inherently fraught with uncertainty, including uncertain rates of economic development, future market prices for energy and carbon that could potentially be orders of magnitude outside historical experience, and the potentially broad range of future technology sets. Hence, GCAM is not applied to predict in the way that weather or ecosystem models are, but rather GCAM is used to create internally consistent representations of potential future developments to gain insights into the consequences of interactions between human and physical Earth system processes.

Land-Use Downscaling and Harmonization. To our knowledge, the RCP scenario process (9, 29) is the first to explicitly provide land-use projections in addition to future emissions pathways for input to global climate models. Because all four participating IAMs, and all receiving climate models, use different characterizations and definitions of land-use types and transitions, a harmonization was designed to provide a continuous, consistent set of land-use inputs for climate models from 1500 through 2100 with a smooth transition between historical data [i.e., 1500–2005 (40)] and future projections [i.e, 2005–2100 (47)]. To preserve the fidelity of the historical data, the harmonization algorithms generate future land use by applying projected changes in land use from the IAMs to the final state of the historical reconstruction. In the GCAM model results, land use is simulated for 14 geopolitical regions; LUC is not spatially attributed. GCAM land use was therefore first downscaled to the $0.5° \times 0.5°$ harmonization grid, following the algorithms of the Global Land-use Model (48), preserving GCAM regional land use area totals and generating smooth spatial patterns in the transition from historical to future states.

The downscaling algorithms first compute changes in the GCAM regional crop and pasture data between 2005 and 2010. For regional crop or pasture decreases, the regional annual percentage decrease is applied to half-degree grid cells in the region with nonzero crop or pasture in 2005, with a preference for reducing crop or pasture on naturally forested land, to generate half-degree crop and pasture maps for 2010. For regional crop or pasture increases, new crop or pasture land is added to the grid cells that already have existing crop or pasture in 2005 (i.e., in proximity to existing agricultural infrastructure). Each grid cell receives a share of the regional crop or pasture demand, weighted by the available land in the grid cell (assuming that ice and water fractions of each grid cell are constant throughout time). If the crop or pasture increase cannot be met within these grid cells, crop or pasture land is added to available land in neighboring cells, expanding the search radius until the increase can be met. The method is then repeated for the next GCAM time interval, and harmonized half-degree grids are linearly interpolated to create annual grids of crop and pasture.

The regional wood harvest data from GCAM is spatially downscaled following algorithms described by Hurtt et al. (48). Regional wood harvest is first downscaled into national wood harvest based on 2005 data from FAO (accessed April 2008). We then apply these national wood harvest demands to grid cells within each nation that already have existing human activity (agriculture or previous wood harvest). When the demand cannot be met in those grid cells, it is applied to neighboring cells, expanding the search radius until the demand has been met. If it cannot be met within a nation, it is applied to other nations within the region. If the demand cannot be met within a region, it is tracked as an "unmet wood harvest." This occurs in only one case discussed in this article, zAPGref, toward the end of the century of simulation. Within each grid cell, wood harvest is prioritized to occur on secondary (former Soviet Union, China, Western Europe, Eastern Europe, India, Japan and Korea, other South and East Asia) or primary (all other regions) forest; mature secondary-forested land is harvested before immature secondary-forested land (48). In addition to changing patterns of agricultural lands and wood harvest, certain regions [primarily forested, tropical areas (49)] contain shifting cultivators, and consequently, within those areas we abandon a fraction (7%) of cropland each year and clear additional forest within those grid cells to maintain the total crop area.

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