EXHIBITS 1-8

Exhibits to Center for Biological Diversity Comments
EPA Call for Information on Greenhouse Gas Emissions
Associated with Bioenergy and Other Biogenic Sources
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High-resolution forest carbon stocks and emissions in the Amazon

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Efforts to mitigate climate change through the Reduced Emissions from Deforestation and Degradation (REDD) depend on mapping and monitoring of tropical forest carbon stocks and emissions over large geographic areas. With a new integrated use of satellite imaging, airborne light detection and ranging, and field plots, we mapped aboveground carbon stocks and emissions at 0.1-ha resolution over 4.3 million ha of the Peruvian Amazon, an area twice that of all forests in Costa Rica, to reveal the determinants of forest carbon density and to demonstrate the feasibility of mapping carbon emissions for REDD. We discovered previously unknown variation in carbon storage at multiple scales based on geologic substrate and forest type. From 1999 to 2009, emissions from land use totaled 1.1% of the standing carbon throughout the region. Forest degradation, such as from selective logging, increased regional carbon emissions by 47% over deforestation alone, and secondary regrowth provided an 18% offset against total gross emissions. Very high-resolution monitoring reduces uncertainty in carbon emissions for REDD programs while uncovering fundamental environmental controls on forest carbon storage and their interactions with land-use change.

deforestation | forest degradation | Peru | Reduced Emissions from Deforestation and Degradation | United Nations Framework Convention on Climate Change

Between 10% and 15% of global carbon dioxide emissions originate from deforestation and degradation of tropical forests (1, 2). Emblematic of these emissions, the southwestern Peruvian Amazon is undergoing carbon changes via road building, mining, timber extraction, and farming. Meanwhile, the United Nations Framework Convention on Climate Change is working to develop a program to curb carbon emissions via the program for Reduced Emissions from Deforestation and Degradation (REDD) (3, 4). REDD has the potential to connect carbon emitters with governments positioned to reduce forest carbon losses through monetary compensation. In addition to offsetting emissions, REDD could provide indirect support for biodiversity conservation through reduced habitat loss, thus providing a unique solution to the longstanding tension between conservation interests and other land-use needs in tropical forest regions such as the Peruvian Amazon.

There are many challenges to making REDD work, and mapping forest carbon stocks and emissions at the high resolution demanded by investors and monitoring agencies remains a technical barrier. Satellite remote sensing offers a practical means to monitor forest cover (5, 6), but has not provided high-resolution estimates of carbon emissions (7). In contrast, field plots provide effective localized estimates of forest carbon stocks, but natural variation in forest carbon density may render plot-based approaches ineffective for estimating carbon over large areas. Furthermore, although plot-based studies are needed for long-term monitoring of forest dynamics, they are time-consuming and are usually placed to avoid land-use change, which is the main anthropogenic factor responsible for carbon flux to the atmosphere in tropical forests. New approaches are critically needed to extend the role of field plots to capture regional variation and to bridge a major gap between field and satellite observations.

One new approach is airborne light detection and ranging (LiDAR), which, when used with field calibration plots, is capable of estimating aboveground forest carbon densities (in units of Mg C ha^{-1}) (8). However, airborne LiDAR has not been proven for carbon mapping of high diversity Amazon forests, and a key obstacle to large-scale use of LiDAR for REDD monitoring is its relatively high cost of operation and small geographic coverage. However, combined with a strategic use of satellite data, airborne LiDAR may yield cost-effective, high-resolution maps of forest carbon stocks and emissions (9). This potential has never been realized at large geographic scales that would be pertinent to an international REDD program.

Here we report on a study to apply a new multiscale, multitemporal method to analyze carbon stocks and emissions throughout 4.3 million ha of lowland Amazon forest in the Department of Madre de Dios, Peru, as a procedure for achieving national-scale REDD mapping while assessing determinants of biomass stocks at a large geographic scale. Although subnational within Peru, the study area is equivalent to twice that of Costa Rica's forests, and our study was designed with a survey size that is logistically easy to implement multiple times to achieve necessary coverage for larger nations. The Madre de Dios region has undergone relatively moderate land-use change throughout the past century. However, paving of the Interoceanic Highway since 2006, along with new timber concessions and an influx of artisanal gold miners during the past 5 y, has rapidly increased land-use pressure. In this context, we sought to understand the sources of spatial and temporal variability in carbon stocks and emissions throughout this large and rapidly changing region of the Amazon basin. Our approach involves multiscale steps ranging from automated satellite mapping of deforestation and degradation to airborne LiDAR mapping to local-scale plot calibration measurements. The approach provides high-resolution maps of aboveground carbon densities and a retrospective mapping of carbon emissions based on current carbon densities and past forest cover changes (*SI Materials and Methods*).

Results and Discussion

Airborne LiDAR data yielded forest canopy height, underlying terrain, and canopy vertical profile, providing a comprehensive,

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EXHIBIT 1

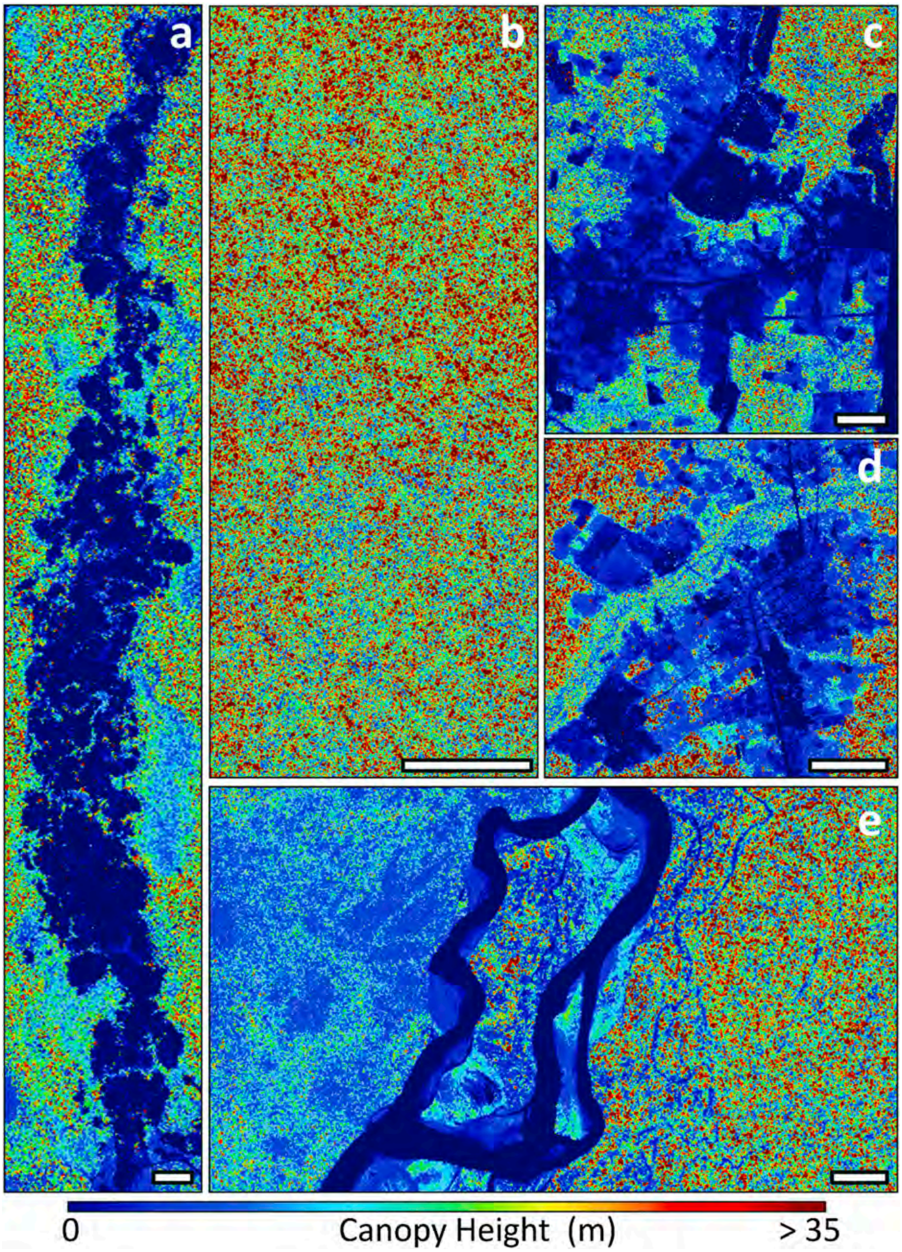

Fig. 1. Sources of variation in forest canopy height detected with high-resolution Carnegie Airborne Observatory LiDAR in the Peruvian Amazon: (*A*) artisanal gold mining; (*B*) selective logging; (*C*) deforestation for cattle ranching; (*D*) infrastructural development in towns, cities, and supporting land uses; and (*E*) alluvial and geologic substrate. White bars indicate a distance of 0.5 km in each example image.

regional inventory of both human-mediated and natural variation in Amazon forest canopy structure. Snapshot areas of 8,000 to 50,000 ha in size are shown in Fig. 1, each indicative of a major source of variation in canopy structure and carbon stocks throughout the region. Gold mining spans large areas of lowland swamp forest, leaving bare surface scars of up to 20 km in length with almost no remaining tree cover (Fig. 1*A*). Degradation from selective logging results in a spatially diffuse decrease in canopy height in otherwise intact forest (blue areas of Fig. 1*B*). Farming, cattle ranching (Fig. 1*C*), and infrastructural development (Fig. 1*D*) are major drivers of deforestation, leaving mosaics of depleted carbon stocks with diffusely scattered tree cover along roadways and in clearings. Finally, by virtue of being regional-scale, the data allowed us to assess gradients in forest structure mediated by geomorphic and fluvial processes (Fig. 1*E*).

During LiDAR overflights, a small, tactically placed network of field plots was established to convert LiDAR metrics of forest canopy structure to aboveground carbon density (Fig. S1). Extensive field validation, including both new and previously published estimates from field plots in the region (10, 11), indicated a LiDAR-to-carbon measurement correlation of 92% (Figs. S4–S6). Absolute mapping uncertainties were 23 Mg C ha^{-1} at 0.1 ha resolution, but decreased to just 5 Mg C ha^{-1}, or approximately 5% of the mean standing forest biomass stock, when the mapping results were integrated to 5 ha resolution (Figs. S7 and S8).

Application of LiDAR-based carbon statistics to forest type and condition maps derived from satellite data (*SI Materials and Methods*) yielded a 0.1-ha resolution map of aboveground carbon density throughout the 4.3 million ha region (Fig. 2). Total regional carbon storage was 395 Tg (million metric tons), and three

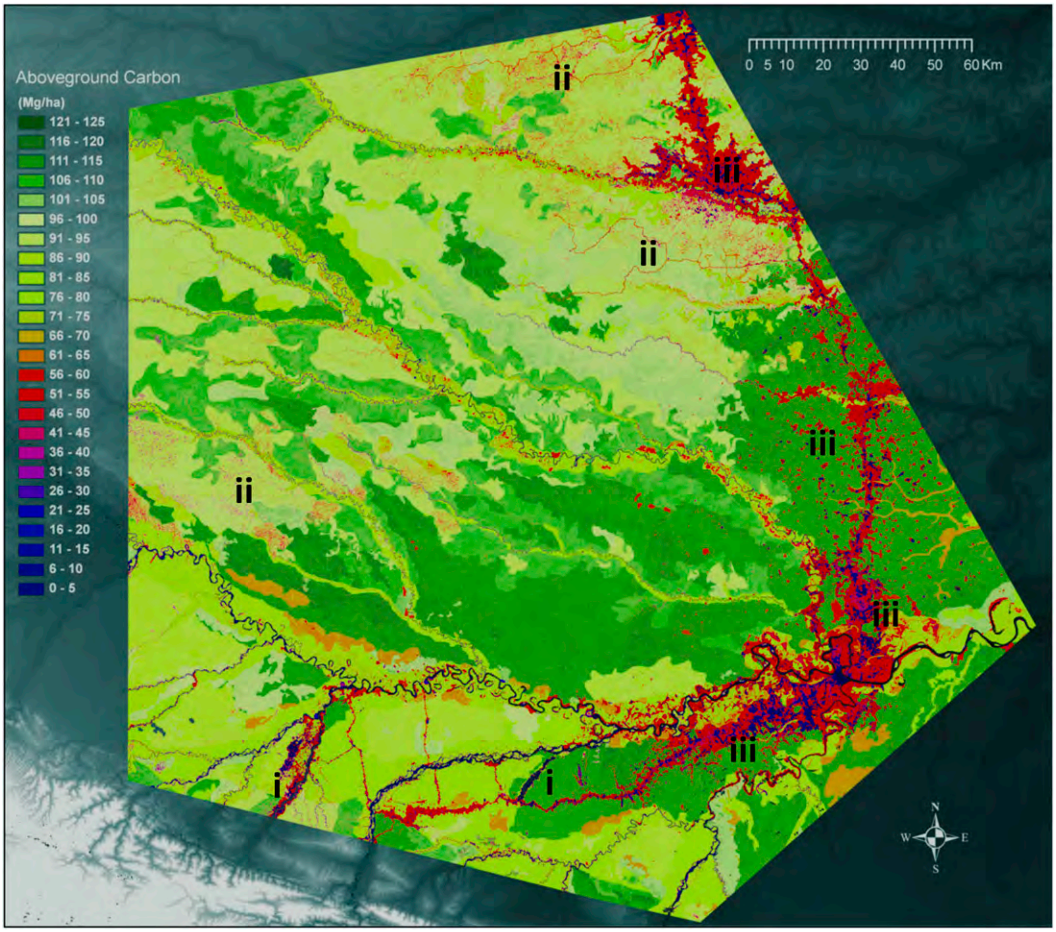

Fig. 2. Variation in aboveground carbon storage at 0.1 ha resolution throughout a 4.3 million ha region of the Peruvian Amazon, derived from an integrated use of CLASlite, LiDAR and field-plot data. Examples of (*i*) artisanal gold mining, (*ii*) selective logging and other forest disturbances, and (*iii*) deforestation for cattle ranching, road building, and other infrastructure are indicated.

major sources of variation in forest carbon were uncovered. First, we found a broad regional partitioning of standing carbon stocks mediated by geologic substrate (12, 13). To the north, older tertiary substrates support carbon densities with median values ranging from 85 to 100 Mg C ha^{-1}, whereas more fertile and flat Holocene alluvial surfaces in the central-east support 110 to 125 Mg C ha^{-1}. To the southwest, forests at the base of the Andes on Cretaceous surfaces maintain carbon densities in the range of 65 to 80 Mg C ha^{-1} (*t* test comparisons on randomly selected subsets, $P < 0.001$).

Stepping down in geographic scale from geologic controls, we uncovered enormous variation in standing carbon within and among forest types (Fig. 3*A* and Fig. S9). Median carbon density values were unique between forest types in most cases ($P < 0.001$; Fig. 2), but the highly varying distributions were the most revealing of ecological controls (Fig. 3*A*). Upland *terra firme* forests on low hills maintain the highest and widest range of carbon stocks, whereas inundated swamp areas with often monotypic palm cover are confined to a lower and narrower range of carbon storage conditions. Still wetter swamp forests with a dense shrub layer harbor even lower and narrower distributions of carbon. Areas that undergo periodic disturbance, such as floodplain forests and river edges, have highly skewed, multimodal distributions of carbon density, indicating a patch mosaic of distinct successional states. Finally, areas codominated by hardwood species and bamboo also show a bimodal distribution of carbon states.

Against this backdrop of geological and ecological control on carbon storage, the most pronounced, localized sources of carbon variation are deforestation, degradation, and secondary regrowth (Fig. 2). Although only 5% in geographic extent (Table 1), artisanal mine sites contain the lowest carbon densities among all land-use scenarios, just 16.7 ± 18.3 (SD) Mg C ha^{-1}. Selective logging and other forms of forest degradation are common, especially to the north, and account for 27% of the pixel-by-pixel changes in forest cover during the study period (Table 1). Forest degradation is diffusely distributed over large areas, but the individual pixels impacted within these areas support carbon stocks of only 35.6 ± 15.4 Mg C ha^{-1}, which is approximately 70% lower than background forest levels. Deforestation accounted for nearly 68% of forest loss throughout the region from 1999 to 2009. However, we found that deforestation results in a wide range of residual carbon stocks on the land: areas averaging 20% tree cover maintain 15.9 ± 32.8 Mg C ha^{-1}, whereas those maintaining at least 60% cover support 61.4 ± 56.2 Mg C ha^{-1} (Fig. S10).

Integrating historical deforestation and degradation results (Figs. S2 and S3) with 2009 carbon stocks (Fig. 2), we calculated annual gross aboveground carbon emissions from 1999 to 2009 (Fig. 3*B*). Results show a baseline emission rate for 1999 to 2006 of 0.26 ± 0.08 Tg C yr^{-1} from deforestation and 0.11 ± 0.02 Tg C yr^{-1} from degradation, for a sum of 0.37 Tg C yr^{-1}. Paving of the Interoceanic Highway since 2006, combined with new timber logging concessions and gold mining, caused an increase in deforestation emissions by more than 61% to 0.42 ±0.21 Tg C yr^{-1},

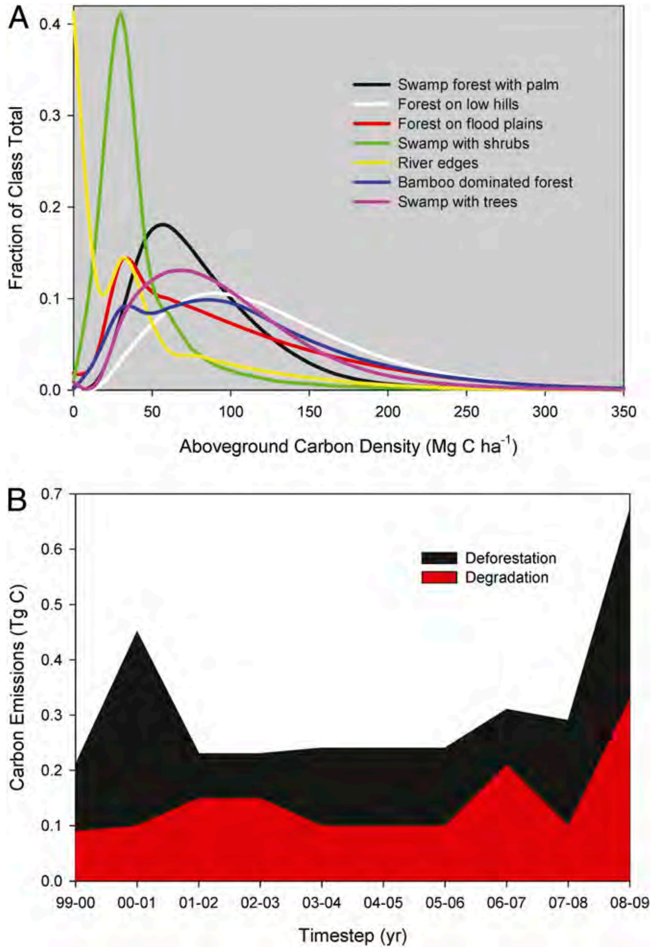

Fig. 3. (*A*) Distributions of aboveground carbon storage for the seven common forest types found in the Peruvian Amazon, derived from airborne LiDAR. (*B*) Annual emissions of carbon from deforestation and degradation mapped from time-series CLASlite imagery and LiDAR data.

whereas degradation emissions doubled to 0.21 ± 0.11 Tg C yr^{-1} (Fig. 3*B*). Critically, we found that degradation emissions averaged 47% of deforestation emissions (annual range, 22%–68%) during the 11-y study period, both before and during the recent increase in human activity throughout the region. In total, 4.529 Tg of aboveground carbon were committed to the atmosphere from 1999 to 2009, representing approximately 1.1% of the standing stock of forest carbon in the region.

Secondary forest regrowth, defined here as forests reestablished following any deforestation and degradation that occurred between 1999 and 2008, covered 24,823 ha in the study region, representing 38% of the total human-affected area by 2009 (Table 1). Forest regrowth resulted in a range of carbon densities (24-44 Mg C ha^{-1}) based on forest ages of 2 to 11 y (*SI Materials and Methods*). Nonetheless, the carbon density of secondary forest is 30.6 ± 16.7 Mg C ha^{-1}, or approximately 60% to 70% lower than the average carbon stocks for intact forests in the region. Integrated over the 11-y study period, secondary regrowth accumulated 0.812 Tg C, providing an 18% offset to gross emissions that resulted in a net regional loss of 3.717 Tg C to the atmosphere.

Our results uncover multiple spatial scales of variation in carbon stocks throughout the region, and change our understanding of how forest carbon is distributed and subsequently altered by land-use change in the southwestern Amazon. To our knowledge, this is the first study to detail regional-level variation in forest carbon densities mediated by geologic substrate and forest type (Figs. 2 and 3*A*). We also detected an interaction between geological controls on carbon storage and land-use effects on carbon emissions: deforestation emissions dominated the flatter quaternary substrates that are easier to access for road-building and farming. In contrast, degradation emissions from selective logging occurred mostly on eroded tertiary surfaces that are topographically dissected and difficult to access (Fig. 2).

The observed trend of increasing carbon emissions since 2006 following the development of the Interoceanic Highway is previously unmeasured (Fig. 3*B*), but more revealing is the large contribution of degradation to the total annual gross emissions for the region. Degradation added an average of 47% more carbon to the atmosphere than did deforestation alone, and increased in step with deforestation during the recent period of heightened land-use activity in the region. Degradation is diffusely distributed throughout the forested landscapes of Amazonia and other tropical regions, and only by combining very high-resolution airborne LiDAR techniques with large-area satellite mapping can these emissions be quantified and monitored over time.

The detailed statistical distributions of aboveground carbon density were also previously unmeasured because the majority of the region remains inaccessible on the ground. However, our airborne measurements reveal highly skewed, often multimodal, distributions of forest carbon. As a result, we contend that samples of forest carbon storage obtained with field plots, cannot account for the spatial variation in carbon stocks, especially in the context of the mosaic of anthropogenic land uses and resulting carbon emissions.

In support of REDD, the Intergovernmental Panel on Climate Change (IPCC) (14) issued a default tier-I estimation approach of forest carbon density based on average carbon values assigned for biomes. Applying the IPCC tier-I method to our study region produced an estimated 587 Tg C in aboveground biomass, whereas our spatially explicit mapping indicated just 395 Tg C (Fig. 2). This difference results primarily from the fact that forest carbon densities are not homogeneous at a variety of scales. Although our regional carbon estimates are 33% lower than IPCC tier-I estimates, the high-resolution, verifiable nature of our ap-

Table 1. Area of new land use and forest regrowth integrated from 1999 to 2009

Land use	Total area, ha	Proportion of human-affected area, %	Mean (SD) carbon density, Mg C ha^{-1}
Gold mining	3,207	4.9	16.7 (18.3)
Forest degradation*	17,740	27.3	35.6 (15.4)
Deforestation†	43,933	67.7	27.8 (16.9)
Secondary regrowth‡	24,823	38.3	32.7 (7.5)

Mean aboveground carbon densities are reported for 2009.

*Forest degradation is dominated by selective logging in this region.

†Deforestation is dominated by clearing for cattle ranching and farming in this region.

‡Regrowth calculated from deforestation and disturbance mapped between 1999 and 2008.

proach would likely yield increased investment per unit of carbon (15, 16). At the national scale, most tropical countries will rely initially on tier-I methods, which will generate large uncertainties and lower confidence, and thus potentially lower carbon credits (4, 15, 17). Developing monitoring capacities at higher accuracies—using procedures like those demonstrated here—will ultimately provide increased carbon credit, boosted carbon sequestration, and improved biodiversity protection.

The cost to implement this method of high-resolution carbon stock and emissions monitoring is decreasing. Satellite data costs are decreasing, and the major data sources are now free of charge to end users. The cost for analyzing the satellite data for forest cover, deforestation and degradation is also rapidly diminishing. The Carnegie Institution is making its Landsat Analysis System Lite (CLASlite) available for free to noncommercial organizations throughout the Amazon region (http://claslite.ciw.edu). LiDAR is a powerful airborne imaging technology that, like aerial photography in the 1970s and 1980s, is rapidly expanding throughout the world for use across a range of environmental sectors. There are now many airborne LiDAR mapping companies operating in the Americas, Europe, Africa, Asia, Australia, and the Pacific (http://www.airbornelasermapping.com). For this 4.3 million ha analysis, the Carnegie Airborne Observatory (CAO) operated its LiDAR, processed the data, and provided maps of forest structure at a cost of less than \$0.08/ha. More recent work in Madagascar has reduced the cost to approximately \$0.06/ha, and there exists a strong economy-of-scale effect whereby larger-area projects prove far more cost effective than small-area analyses. This runs opposite to plot-level work, which increases in cost on a per-area basis.

Finally, the procedure tested here can be scaled up to the national level. We selected this particular 4.3 million ha area for a variety of scientific purposes. The results can be directly extrapolated with the addition of highly available satellite imagery and CLASlite, and with no additional airborne or ground-based work, to an area of approximately 60 million ha based on the range of forest types found in Peru. However, the uncertainty in the regional variation of carbon densities applied to such a full national-scale satellite map would be reduced with additional LiDAR sampling throughout the region. Here we have reported the results of high-resolution mapping of carbon stocks and emissions in the Amazon region, and the approach is being implemented by three western Amazon countries.

Materials and Methods

Our approach involves four steps: (*i*) regional mapping of vegetation type and condition (forest cover, deforestation, degradation, regrowth) using moderate-resolution satellite data; (*ii*) regionally stratified large-area sampling of vegetation canopy 3D structure using airborne LiDAR; (*iii*) conversion of LiDAR vegetation structural data to aboveground carbon density using LiDAR allometrics developed at a limited number of field plots; and (*iv*) integration of the satellite maps with the calibrated LiDAR data to set a regional, high-resolution baseline carbon estimate, and mapping of carbon emissions retrospectively and into the future.

Forest condition—including deforestation, degradation, and regrowth—was assessed using the CLASlite (18) satellite mapping system with 30-m Landsat imagery in nearly annual time steps from 1999 to 2009 (Figs. S1–S3). Field validation surveys indicated that 2009 deforestation, degradation, and secondary regrowth maps had errors of 0% to 1.2%, 1.9% to 6.4%, and 2.6% to 2.9%, respectively (Tables S1 and S2). A map partitioning the study area into 26 vegetation classes, combined with CLASlite results, was used to locate 27 LiDAR survey areas covering a total of 514,317 ha for collection at a spatial resolution of 1 m or less throughout the 4.3 million ha region (Fig. S1). The LiDAR data were collected using the CAO (19). Calibration and validation of the airborne- and satellite-based estimates of aboveground carbon density were carried out during the overflights. Detailed information on each of these steps is provided in *SI Materials and Methods*.

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ISSUES IN ECOLOGY

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A Synthesis of the Science on Forests and Carbon for U.S. Forests

Michael G. Ryan, Mark E. Harmon, Richard A. Birdsey, Christian P. Giardina,
Linda S. Heath, Richard A. Houghton, Robert B. Jackson, Duncan C. McKinley,
James F. Morrison, Brian C. Murray, Diane E. Pataki, and Kenneth E. Skog

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EXHIBIT 2

A Synthesis of the Science on Forests and Carbon for U.S. Forests

SUMMARY

Forests play an important role in the U.S. and global carbon cycle, and carbon sequestered by U.S. forest growth and harvested wood products currently offsets 12-19% of U.S. fossil fuel emissions. The cycle of forest growth, death, and regeneration and the use of wood removed from the forest complicate efforts to understand and measure forest carbon pools and flows. Our report explains these processes and examines the science behind mechanisms proposed for increasing the amount of carbon stored in forests and using wood to offset fossil fuel use. We also examine the tradeoffs, costs, and benefits associated with each mechanism and explain how forest carbon is measured.

Current forests are recovering from past land use as agriculture, pasture, or harvest, and because this period of recovery will eventually end, the resulting forest carbon sink will not continue indefinitely. Increased fertilization from atmospheric nitrogen deposition and increased atmospheric carbon dioxide may also be contributing to forest growth. Both the magnitude of this growth and the future of the carbon sink over the next hundred years are uncertain. Several strategies can increase forest carbon storage, prevent its loss, and reduce fossil fuel consumption (listed in order of increasing uncertainty or risk):

- Avoiding deforestation retains forest carbon and has many co-benefits and few risks.
- Afforestation increases forest carbon and has many co-benefits. Afforesting ecosystems that do not naturally support forests can decrease streamflow and biodiversity.
- Decreasing harvests can increase species and structural diversity, with the risk of products being harvested elsewhere and carbon loss in disturbance.
- Increasing the growth rate of existing forests through intensive silviculture can increase both forest carbon storage and wood production, but may reduce stream flow and biodiversity.
- Use of biomass energy from forests can reduce carbon emissions but will require expansion of forest management and will likely reduce carbon stored in forests.
- Using wood products for construction in place of concrete or steel releases less fossil fuel in manufacturing. Expansion of this use mostly lies in the non-residential building sector and expansion may reduce forest carbon stores.
- Urban forestry has a small role in sequestering carbon but may improve energy efficiency of structures.
- Fuel treatments trade current carbon storage for the potential of avoiding larger carbon losses in wildfire. The carbon savings are highly uncertain.

Each strategy has risks, uncertainties, and, importantly, tradeoffs. For example, avoiding deforestation or decreasing harvests in the U.S. may increase wood imports and lower forest carbon elsewhere. Increasing the use of wood or forest biomass energy will likely reduce carbon stores in the forest and require expansion of the area of active forest management. Recognizing these tradeoffs will be vital to any effort to promote forest carbon storage. Climate change may increase disturbance and forest carbon loss, potentially reducing the effectiveness of management intended to increase forest carbon stocks. Finally, most of these strategies currently do not pay enough to make them viable. Forests offer many benefits besides carbon, and these benefits should be considered along with carbon storage potential.

Cover photo credit: *Old-growth forest in the Valley of the Giants in Oregon.*
Photo by Mark E. Harmon, Oregon State University.
Inset: Logs harvested at Manitou Experimental Forest in Colorado.
Photo by Richard Oakes, USDA Forest Service.

A Synthesis of the Science on Forests and Carbon for U.S. Forests

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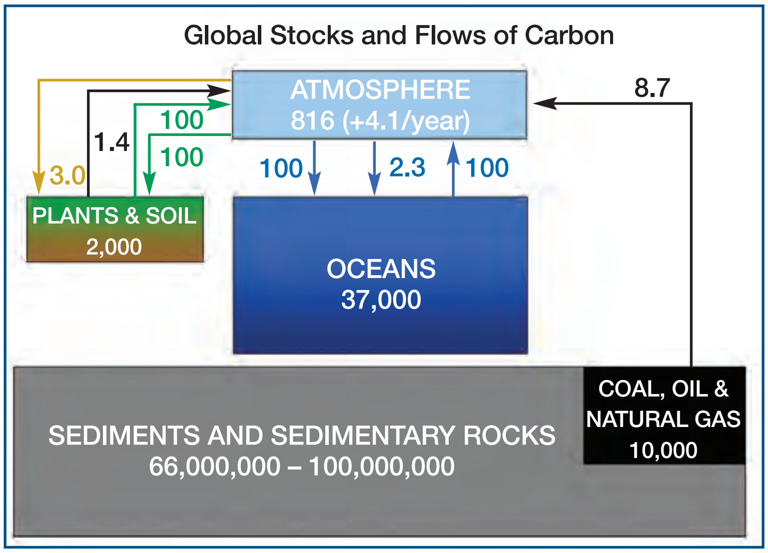
Introduction

The movement of carbon between the earth and its atmosphere controls the concentration of carbon dioxide (CO_2) in the air. CO_2 is important because it is a greenhouse gas and traps heat radiation given off when the sun warms the earth. Higher concentrations of greenhouse gases in the atmosphere cause the earth to warm. Before the Industrial Revolution, the concentration of CO_2 in the atmosphere was less than 280 parts per million. The burning of fossil fuel for energy and the clearing of forests for agriculture, building material, and fuel has led to an increase in the concentration of atmospheric CO_2 to its current (2010) level of 388 parts per million. This current level far exceeds the 180-300 parts per million found over the last 650,000 years.

As a result of rising CO_2 and other greenhouse gases in the atmosphere, global surface temperatures have increased by 0.74°C (1.3°F) since the late 1800s, with the rate of warming increasing substantially. As more CO_2 is added to the air, temperatures will continue to increase and the warmer earth will have an impact on the earth's climate, climate variability, and ecosystems. Rain and snowfall patterns will shift, and extreme weather events may become more common. Some regions that currently support forests will no longer do so, and other regions that currently do not support forests may become suitable for forest growth.

Forests store large amounts of carbon in their live and dead wood and soil and play an active role in controlling the concentration of CO_2 in the atmosphere (Figure 1). In the U.S. in 2003, carbon removed from the atmosphere by forest growth or stored in harvested wood products offset 12-19% of U.S. fossil fuel emissions (the 19% includes a very uncertain estimate of carbon storage rate in forest soil). U.S. forest growth rates are thought to be higher than those before European settlement because of recovery from past land use and disturbance, but the current growth rate will not continue indefinitely.

Given the role that U.S. forests play in offsetting CO_2 emissions, our report asks: 1) Which human actions influence forest carbon sinks (storage rates) and can these sinks be enhanced for a meaningful period of time through management and use of forest products? and 2) What are some of the major risks, uncertainties, tradeoffs, and co-benefits of using forests and forest products in proposed carbon emission mitigation strategies?



Courtesy of Richard A. Houghton, Woods Hole Research Institute, 2009.

Figure 1. Plants and soil play a large role in the global carbon cycle as shown by global stocks (boxes) and flows (arrows) of carbon in petagrams (1000 teragrams). Numbers in light blue and green are the historical fluxes between the oceans and the atmosphere and plants and soil and the atmosphere that would have occurred without human influence. The number in dark blue is the additional ocean absorption of CO_2, resulting from increased CO_2 in the atmosphere since the Industrial Revolution. The numbers in black are the fluxes to the atmosphere from fossil fuel combustion or deforestation. The number in brown is the flux from the atmosphere to the land, mostly from forest regrowth. The measured atmospheric increase of 4.1 petagrams per year is not equal to the sum of the additions and withdrawals because they are estimated separately and with associated uncertainties.

The purpose of our report is to answer these questions, or, if answers are not yet available, to present the best current information. We present the state of knowledge on the role of forests in the carbon cycle in a straightforward manner so that it can be understood by forest managers, policymakers, educators, and the interested public. We begin with a description of the forest carbon cycle and biophysical effects. We then present details on the strategies that have been proposed for using forests to slow the amount of CO_2 entering the air.

These strategies include:

- *Avoiding deforestation* – Keeping forests intact.
- *Afforestation* – The restoration of forest on land that has been without forest cover for some time, and the establishment of forest on land that has not previously been forested.
- *Forest management: decreasing carbon loss* – Increasing the harvest interval and/or decreasing harvest intensity.
- *Forest management: increasing forest growth* – Use of improved silvicultural practices, genetic improvement, and rapid regeneration.
- *Forest management: thinning to reduce fire threat.*
- *Urban forestry* – Planting trees in urban areas for carbon storage and shading for energy savings.
- *Biomass energy* – Using fuel from wood and biomass in place of fossil fuel.
- *Carbon storage in forest products and substitution* – Storing carbon in long-lived forest products (such as lumber) and substituting forest products for products (such as steel and concrete) whose manufacture releases much more CO_2 than does the processing of wood.

We then discuss carbon offsets and credits, how forest carbon could be monitored to determine whether changes result in the desired outcomes, and what the costs would need to be for carbon to encourage changes. We also discuss some of the uncertainties inherent in the use of forests for carbon storage, because changes in climate, population, and land use may lower projected carbon storage. We especially note the potential loss of carbon that might occur with increased disturbance in a warmer climate. Finally, we provide conclusions and recommendations.

Forests and carbon

Carbon in the forest

Forest carbon storage differs from many other mechanisms that control atmospheric CO_2 because forests have a life cycle during which carbon stocks, gains, and losses vary with forest age. Carbon enters a forest through photosynthesis, where leaves capture the energy in sunlight and convert CO_2 from the atmosphere and water into sugars that are used to build new leaves, wood, and roots as trees grow (Figure 2). About half of the CO_2 that is converted to sugars is respired by living trees to maintain their metabolism, and the other half produces new leaves, wood, and roots. As they grow, trees shed dead branches, leaves, and roots and some of the trees die. Microorganisms decompose this dead material, releasing CO_2 back to the atmosphere, but some of the carbon remains in the soil. Live and dead trees contain about 60% of the carbon in a mature forest, and soil and forest litter contain about 40%. The carbon in live and dead trees (50% of their biomass) varies the most with forest age.

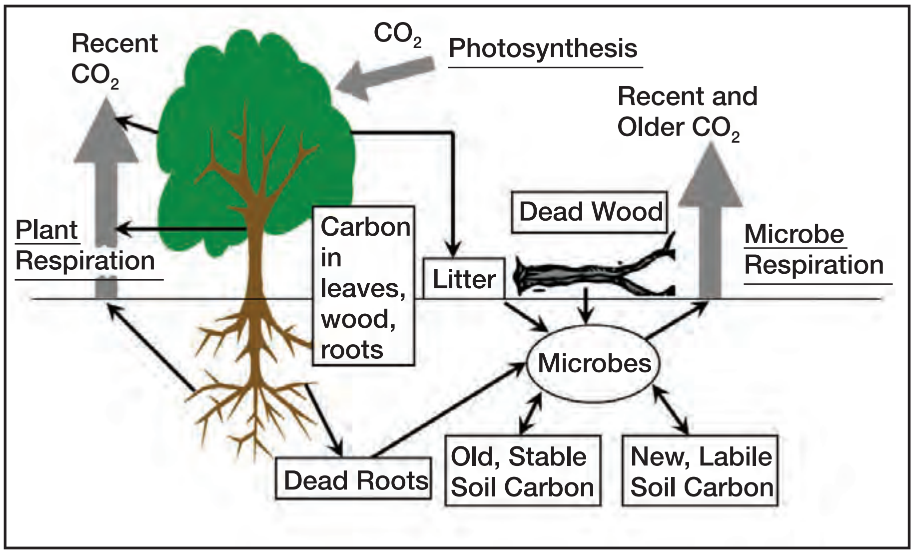


Figure 2. Flows of carbon from the atmosphere to the forest and back. Carbon is stored mostly in live and dead wood as forests grow.

Carbon can leave the forest in several ways besides tree and microorganism respiration. Forest fires release stored carbon into the atmosphere from the combustion of leaves and small twigs, the litter layer, and some dead trees and logs, leaving behind a great deal of stored carbon in dead trees and soil. Storms and insect outbreaks also kill trees and increase the amount of material available for decomposition. Harvesting removes carbon from the forest, although some of it is stored in wood products (preventing its immediate release to the atmosphere) and some is available for use as biomass energy (displacing fossil fuel use). In addition, water can remove carbon from a forest either by transporting soil and litter away in streams (especially from erosion after fire) or by transporting soluble carbon molecules created during decomposition. After fire, other disturbance, or harvest, regenerated forests will eventually recover all of the car-

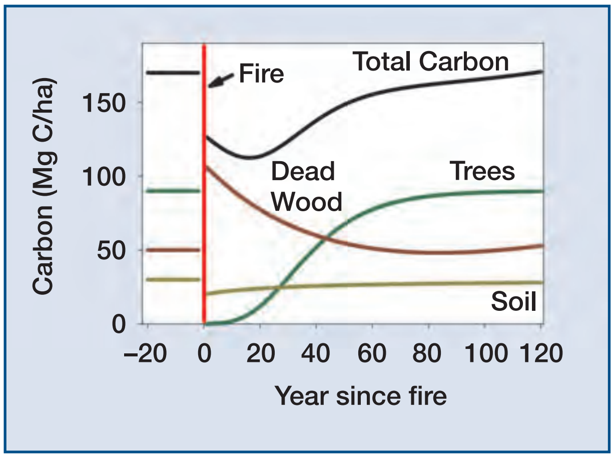


Figure 3. If a forest regenerates after a fire, and the recovery is long enough, the forest will recover the carbon lost in the fire and in the decomposition of trees killed by the fire. This figure illustrates this concept by showing carbon stored in forests as live trees, dead wood, and soil and how these pools change after fire. (Adapted from Kashian and others 2006. BioScience 56(7):598-606.)

bon lost so that a complete cycle is carbon neutral regarding storage if the recovery is long enough (Figure 3). But if disturbances increase, as is projected with climate change, a fire, storm, or insect outbreak may occur before the ecosystem recovers the carbon it had prior to the disturbance. In that case, the amount of carbon stored on the landscape will decrease.

Forests are biological systems that continually gain and lose carbon via processes such as photosynthesis, respiration, and combustion; whether forests show a net gain or loss of carbon depends on the balance of these processes. The observation that carbon is lost from forests has led to the notion that carbon cannot be permanently stored in forests. However, this view ignores the inevitable increase and eventual recovery of carbon that follows most disturbances. Thus over time, a single forest will vary dramatically in its ability to store carbon; however, when considering many different forests over a large area or landscape, such "boom and bust" cycles may not be apparent because the landscape is composed of forest stands that are in different stages of recovery from disturbance or harvesting (Figure 4).

To determine how quickly carbon increases in a forest system, it is important to know the starting point or "baseline." A forest that already stores a substantial amount of carbon is likely to lose carbon when converted to something else, and a system with the potential to store carbon but that does not currently store much is easier to convert to one that stores more carbon (Figure 5). A forest's timeline for increasing carbon storage is important because carbon must be removed quickly to reduce CO_2 in the atmosphere and thereby slow global warming.

While the biological processes of photosynthesis, respiration, and decomposition are similar for all forests, their relative importance differs by forest type and location. Some forests grow more rapidly, but dead trees in fast-growing forests also decompose more rapidly. In addition, disturbances vary regionally: for example, fire disturbance is more common in the western U.S. and hurricanes more common in the East. Forests are managed in different ways with varying harvest intervals and regeneration practices that will influence the optimum strategy for storing more carbon. Each forest has a different potential to store carbon. For example, this potential is particularly high in the Pacific Northwest where forests are relatively productive, trees live a long time, decomposition is relatively slow, and fires are infrequent. The differences between forests must therefore be taken into consideration when determining how they should be managed to store carbon.

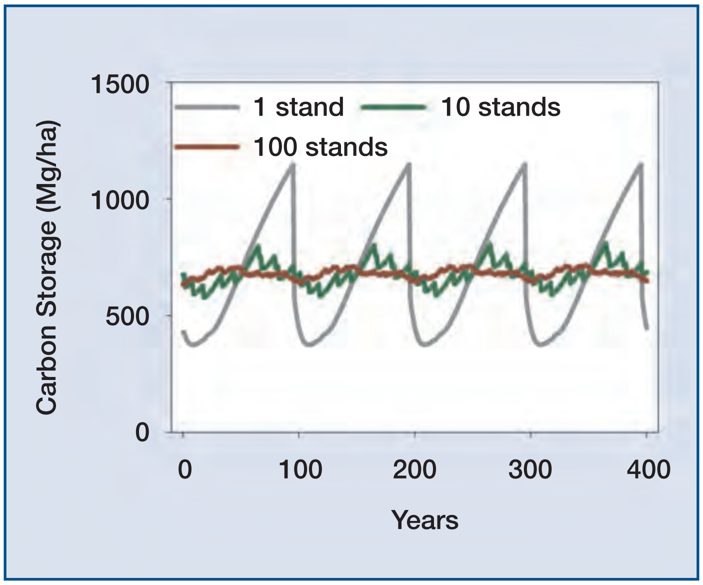


Figure 4. Management actions should be examined for large areas and over long time periods. This figure illustrates how the behavior of carbon stores changes as the area becomes larger and more stands are included in the analysis. As the number of stands increases, the gains in one stand tend to be offset by losses in another and hence the flatter the carbon stores curve becomes. The average carbon store of a large number of stands is controlled by the interval and severity of disturbances, as shown in Figure 7. That is, the more frequent and severe the disturbances, the lower the average becomes. (Courtesy of Mark E. Harmon, Oregon State University, 2009.)

Carbon from the forest

All forest products eventually decompose, but before they do, they store carbon. Some products have a short lifespan (such as fence posts) and some a longer lifespan (for example, houses) – the longer the lifespan, the more carbon is stored. Disposed forest products in landfills can have a very long lifespan; however, the decomposition in landfills generates methane, which is a much more potent greenhouse gas than CO_2, reducing the carbon storage benefit. In addition, wood and bark that are burned to run a mill or heat houses, or made into liquid biofuel, lower emissions from fossil fuel use. Once the carbon leaves the forest, it becomes more difficult to track and measure than carbon in the forest, particularly because imports and exports must then be tracked.

Biophysical effects may cause warming or cooling

Forests have other influences on climate besides that of carbon; these are known as biophysical effects (Figure 6) and include the reflection of solar radiation and transpiration of water vapor. Trees are dark and absorb more radiation than other types of land cover, such as crops or snow-covered tundra. Therefore, converting non-forested land to forest can warm the land and air. Evergreen trees absorb much more energy than deciduous trees in the winter and burned forests absorb more than unburned forests, so species and disturbance can also alter the energy absorbed by forests. In addition, transpiration from forests may have a cooling effect by contributing to the formation of clouds that reflect sunlight.

Biophysical effects sometimes act in a direction opposite to that of the effects of storing or releasing CO_2. For instance, whereas converting cropland to forest will sequester more CO_2, which *reduces* global warming, it will also increase solar absorption, which *increases* warming. Generally, biophysical effects on climate are not as strong as the effects of greenhouse gases. Biophysical effects will be most important in evaluating the benefits of afforestation because the land use change will cause large differences. Unfortunately, current estimates of biophysical effects are uncertain because few studies have been done.

Strategies for increasing carbon stores in forests

1. Avoiding deforestation

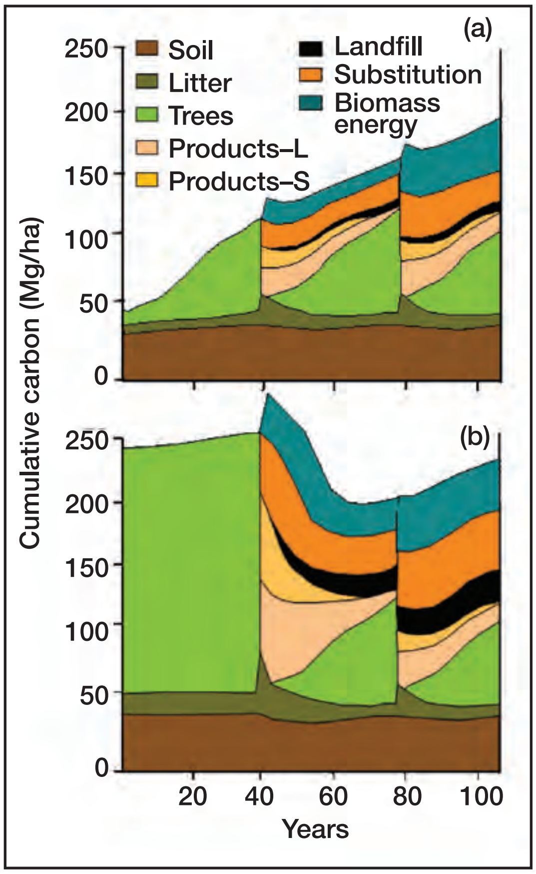


Figure 5. Projections of carbon storage and fossil fuel displacement if all biomass is used shows considerable storage and offsets for (A) a project that reestablishes forests with periodic harvests. Harvesting a high-biomass old growth forest (B) shows carbon losses, even under the best possible scenario, for several harvests. At each harvest, forest biomass (and thus carbon stock) is removed for use in long- and short-lived wood products ('Products-L' and 'Products-S', respectively) substituted for more carbon-intensive products, and for biomass energy to displace emissions from fossil fuel use. Because substitution generates more fossil fuel savings than the carbon it contains, substitution would yield a greater carbon benefit after harvest than that which is stored in the biomass. The biomass energy and substitution fossil fuel savings accumulate but represent only hypothetical carbon benefits, as currently little biomass energy use and substitution occurs in the U.S. (Adapted from IPCC 2007.)

Deforestation, or the conversion of forest land to other uses, has a significant impact on global CO_2 emissions. Globally, deforestation converts approximately 90,000 km^2 (about the size of Indiana) of forests per year (0.2% of all forests) to other land uses. Deforestation annually releases 1,400-2,000 teragrams of carbon (10^{12} grams; see Box 1 for units) to the atmosphere, and two-thirds of this release occurs in tropical forests. The amount of carbon released by deforestation equals 17-25% of global fossil fuel emissions every year and is roughly the amount of U.S. annual fossil fuel emissions. If current deforestation rates continue, more than 30,000 teragrams of carbon could be released to the atmosphere from deforestation in the Amazon alone by the year 2050.

In the U.S., forested area increased 0.1% per year from 2000-2005, and this gain in forested area is partially responsible for the current forest sink of 162 teragrams of carbon per year. The net growth in forested area results from both deforestation and afforestation: About 6,000 km^2 are deforested annually, but more than 10,000 km^2 of non-forest are afforested. The net increase in forestlands results from changes in land use and possibly from reduced demand for U.S. timber.

Although the U.S. forest carbon sink benefits from increased forest area, these carbon benefits need to be weighed against the global consequences of land use change within the U.S. If afforestation or avoided deforestation in the U.S. pushes crop and cattle production to other countries, it can lead to deforestation

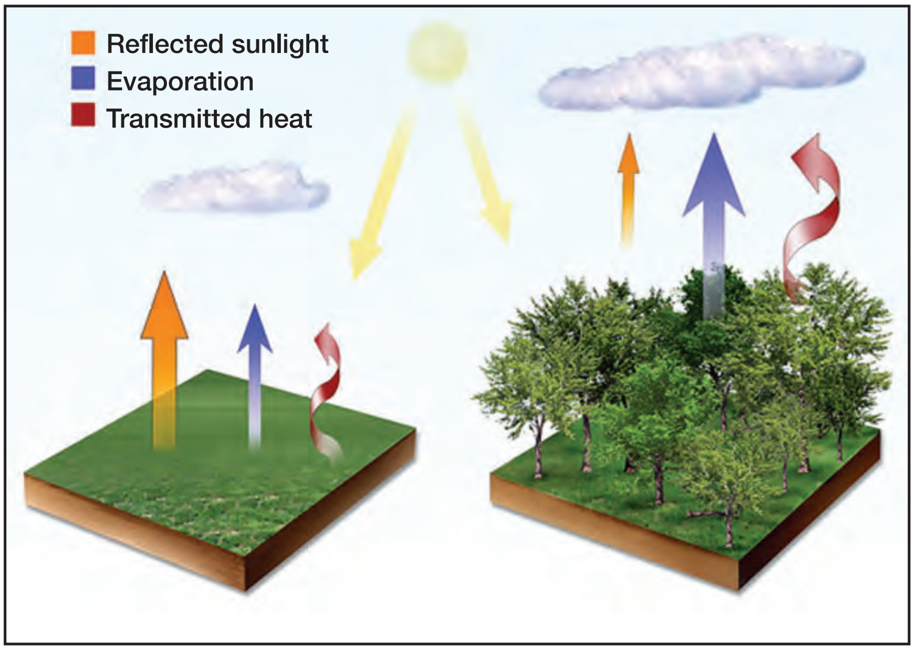


Figure 6. Biophysical effects of different land use can have important impacts on climate. Cropland reflects more sunlight than forest, produces less water vapor, and transmits less heat. (From Jackson et al. *2008. Environmental Research Letters 3:article 044006.)*

and loss of forest carbon elsewhere to create pasture and cropland. Carbon loss associated with such deforestation – especially in the tropics – is greater than carbon gain associated with tree growth from afforestation in the U.S.

Forest retention in the western U.S. may be even more important in the future as climate changes. Our warming climate is very likely causing, at least in part, the current increase in forest fire size and intensity, insect outbreaks, and storm intensity. If forest regeneration fails because the disturbances or regeneration conditions are outside of the ecological norms, disturbances can convert forests to meadows or shrublands. When this type of deforestation occurs, substantial carbon is lost to the atmosphere and not recovered by the ecosystem. Tree planting would help recover forest carbon where natural regeneration fails.

Box 1. UNITS FOR CARBON

When discussing regional, national, or global carbon stores and fluxes, the numbers get large quickly. We report carbon in teragrams (10^{12} grams). Other reports may use other units, so we provide a conversion table below. For stand- or forest-level stores and fluxes, we use megagrams (Mg) per hectare (10^{6} grams). Our report uses carbon mass, not CO$_2$ mass, because carbon is a standard "currency" and can easily be converted to any other unit. Many reports give stocks and fluxes of the mass of CO$_2$, not carbon. To convert carbon mass to CO$_2$ mass, multiply by 3.67 to account for the mass of the O$_2$.

1000 teragrams (Tg)	1 petagram (Pg)
1000 teragrams	1 billion metric tonnes
1000 teragrams	1 gigatonne
1 teragram	1 million metric tonnes
1 teragram	1 megatonne
1 megagram (Mg)	1 metric tonne
1 metric tonne	0.98 U.S. long ton
1 metric tonne per hectare	0.4 U.S. long tons per acre
carbon (C) mass * 3.67	carbon dioxide (CO$_2$) mass

There are not many risks associated with avoidance of deforestation. Three to note, however, would be risks related to highly fire-prone ecosystems near human settlement, economic consequences for not developing agricultural or pasture land, and an increase in forest products harvested elsewhere. On the other hand, avoiding deforestation has many of the co-benefits identified in Box 2.

2. Afforestation

We define afforestation as both reestablishing forests on land that has been without forest cover for some time and the establishment of forest on land that has not previously been forested (note that some entities involved in carbon markets and reporting use different definitions for this term). Afforestation can remove substantial CO$_2$ from the atmosphere. Between 1850 and 2000, global land-use change resulted in the release of 156,000 teragrams of carbon to the atmosphere, mostly from deforestation. This amount is equivalent to 21.9 years of global fossil fuel CO$_2$ emissions at the 2003 level.

The rate of carbon storage in tree growth varies with species, climate, and management, ranging widely from about 3-20 megagrams (Mg, 10^{6} grams) per hectare per year. In the continental U.S., the highest potential growth rates are found in the Pacific Northwest, the Southeast, and the South Central U.S. Much land currently in pasture and agricultural use in the eastern U.S. and in the Lake States will naturally revert to forests if left fallow, while reestablishing forests in many western forests requires tree planting.

The benefits of afforestation (outlined in Box 2) are enhanced where forests include a substantial proportion of native species. Planting native species or allowing natural succession to recreate the forest that historically occupied the site will yield the greatest benefits for species diversity and wildlife habitat and the lowest risk for unintended consequences. Because native species often grow more slowly than exotics or trees selected for improved growth, restoration of the historical ecosystem may yield lower carbon accumulation rates than other forest reestablishment practices. Planting monocultures of non-native or native improved-growth species on historical forest land will likely yield greater carbon accumulation rates but fewer benefits in terms of biodiversity.

Afforestation can have negative consequences, too. Planting forests where they were not present historically can have drawbacks such as lower species diversity (if trees are planted in native grassland), changes in water table, and a higher energy absorption compared to the native ecosystem. In addition, afforestation generally reduces streamflow regardless of the ecosystem type because trees use more water than grass or crops.
Conversion of agricultural or grazing lands to forest reduces revenue from agricultural products. If afforestation efforts include the addition of nitrogen fertilizer, emissions of nitrous oxide (a greenhouse gas roughly 300 times as powerful as CO_2) will increase.

Box 2. CO-BENEFITS OF FORESTS

Our report focuses on forests seen through the lens of carbon, and only carbon. However, forests are managed for many purposes, and carbon storage and the growth of wood for products and fuel to offset fossil fuel use are far from the only reasons forests are valuable. Forests also provide many other ecosystem services that are important to the well-being of the U.S. and its inhabitants: protection of watersheds from erosion, nutrient retention, good water quality, reduction of peak streamflow and an increase in base streamflow, wildlife habitat and diversity, recreational opportunities and aesthetic and spiritual fulfillment, and biodiversity conservation. Americans are strongly attached to their forests. In some cases, managing strictly for carbon would conflict with other co-benefits of forests. The option of avoided deforestation retains the co-benefits of forests and the carbon in forest ecosystems, while afforestation adds these co-benefits in addition to increasing carbon storage. Even simple forests, such as plantations, generally reduce erosion, regulate streamflow, and increase wildlife habitat and biodiversity compared to crops or livestock pasture because the frequency of harvest or stand–replacing disturbance is much less for forests.

3. Forest management: decreasing carbon loss

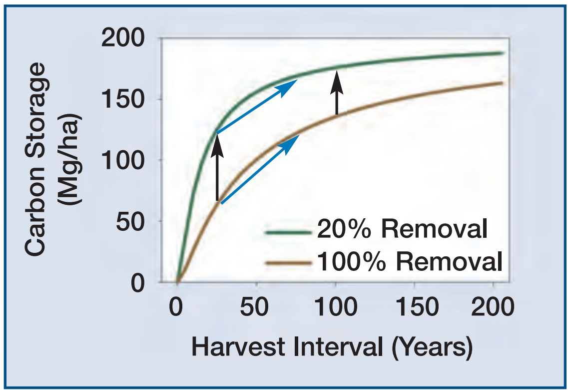
Lengthening the harvest interval or reducing the amount removed in a harvest will store more carbon in the forest. The greater the increase in harvest interval over the current level, the higher the increase in carbon storage. For example, a five-year increase in the harvest interval would lead to a 15% increase in carbon storage if the harvest interval was changed from 25 to 30 years, but only a 4% increase if the interval was changed from 55 to 60 years (Figure 7). A 50-year increase from 25 to 75 years would increase carbon storage 92% (Figure 7).

The carbon impact of reducing the amount of trees removed in a harvest also varies with the harvest interval. For example, reducing the harvest from 100% to 20% of the live trees would increase the average forest carbon stock by 97% for a 25-year harvest interval, but only by 30% for a 100-year harvest interval (Figure 7). Some natural forests are dominated by small disturbances that kill a few trees at a time. Reducing harvest amounts in these systems from complete removal of trees to simply a percentage, for example, could mimic the natural disturbance regime common to the northeastern and midwestern United States. In addition, reducing harvests could be desirable in public forests that are managed for multiple purposes, such as recreation, biodiversity, and water.

These strategies would be most suitable in forest regions with active management and a high potential to store carbon, such as those with long-lived species and slowly decomposing dead plant matter, which are common in the Pacific Northwest. The carbon benefit of either of these practices will depend on the temporal and spatial scales at which they are administered – applying these practices over longer timeframes and larger landscapes leads to greater carbon benefits.

In addition to an increase in carbon storage, benefits of decreased harvesting also include an increase in structural and species diversity. On the other hand, the costs are an increased risk of carbon loss due to disturbance and the potential for increased harvesting elsewhere to compensate for the reduction in forest products generated.

Figure 7. Average carbon stored on a landscape will vary with the time between harvests (harvest interval) and how much biomass is removed each harvest. Lengthening the harvest interval will have a greater effect for harvests where removals are high (blue arrows show an increase in harvest interval from 25 to 75 years). Decreasing harvest intensity from 100% of trees to 20% of trees (black arrows) will have a greater effect for shorter harvest intervals. (Courtesy of Mark E. Harmon, Oregon State University, 2009.)



4. Forest management: increasing forest growth

In addition to afforestation, another strategy for increasing carbon storage is to increase the growth rate of existing or new forests.
Management practices that can increase forest growth include: regenerating harvested or damaged forests, controlling competing vegetation, fertilizing, planting genetically improved trees, and selecting species for superior productivity. Yield gains from these practices can be impressive. In pine forests in the southern U.S., tree breeding has improved wood growth (and carbon storage rate) by 10-30%, and fertilization can show 100% gains for wood growth. For southern

Figure 8. A hydro-axe is used to grind up trees to reduce canopy fuel loads and lower the risk of crown fire. Photo by Dan Binkley, Colorado State University.

U.S. pines, operational plantations using improved seedlings, control of competing vegetation, and fertilization grow wood four times faster than naturally regenerated second-growth pine forests without competition control. The potential to increase forest growth varies by climate, soil, tree species, and management.

Increases in carbon stocks will generally be proportional to increases in growth rates. That is, a 10% increase in growth will result in a 10% increase in carbon stocks, assuming that the harvest interval and amount harvested do not change. As shown in Figure 3, the rate of forest growth will naturally slow down as the forest ages. Management decisions for increasing carbon stocks should take into account forest growth over time, the amount of timber that would end up in wood products if the forest were harvested, and how long the harvested carbon would remain sequestered in the wood products. Knowledge of these variables will help determine when or whether to harvest.

The area of forestland in the U.S. that could be managed to increase forest growth includes more than 500 million acres and consists of almost all U.S. public and private forestland, excluding remote and reserved areas such as national parks. However, even reserved areas could potentially be managed to restore damaged ecosystems, which could also lead to increased forest growth.

Increasing forest growth through management has benefits and costs. The benefits include increased wood production and the potential for planting species and genotypes adapted to future climates. The costs include reducing the carbon benefit by emissions of nitrous oxide from forest fertilization, reduced water yield (faster growth uses more water), and a loss of biodiversity if faster growth is accomplished by replacing multi-species forests with monocultures.

5. Forest management: fuel management to reduce fire threat

Fuel management uses thinning (Box 3) to lower foliage biomass to reduce the risk of crown fire because crown fires are difficult, if not impossible, to control. Fuel management occurs in forests with a variety of historical fire regimes – from forests where historical forest density was lower and the natural fires were mostly surface fires, to forests with stand-replacement fire regimes in which crown fires naturally occurred. Fuel management temporarily lowers the carbon stored in forest biomass and dead wood because the thinned trees are typically piled and burned or mulched and then decompose.

If a crown fire burns through a forest that was thinned to a low density, the fire may change from a crown to a surface fire in which many of the trees can often survive the fire. In contrast, many or all of the trees in an unthinned stand will be killed by a crown fire. This contrast in survival has led to the notion that fuel treatments offer a carbon benefit: removing some carbon from the forest may protect the remaining carbon.

There are two views regarding the science on carbon savings through fuel treatments. Some studies have shown that thinned stands have much higher tree survival and lower carbon losses in a crown fire, or have used modeling to estimate lower carbon losses from thinned stands if they were to burn. However, other stand-level studies have not shown a carbon benefit from fuels treatments, and evidence from landscape-level modeling suggests that fuel treatments in most forests will

Box 3. THINNING AND CARBON

Thinning is an effective forest management technique used to produce larger stems more quickly, reduce fire risk, and increase tree resistance to insects and disease. Thinning increases the growth of the remaining individual trees, but generally decreases overall forest wood growth until the remaining trees grow enough to re-occupy the site. The carbon stock in a thinned stand is generally lower than that in an unthinned stand. If the harvested trees are used for biomass energy or long-lived forest products, these carbon benefits may compensate for the lower biomass and the wood growth of the thinned stand. Because of lower overall growth of a thinned stand, even 100% use of the harvested trees for products or biomass energy may not produce a total carbon benefit greater than that of the higher storage and storage rate in an unthinned stand. The net carbon consequences of thinning will depend the most on whether the harvested trees are used for long-lasting wood products or biomass energy, but also on the change in risk of a crown fire relative to the probability of fire occurring, the species, the site, the thinning regime, and the length of the harvest interval.

decrease carbon, even if the thinned trees are used for biomass energy. More research is urgently needed to resolve these different conclusions because thinning to reduce fuel is a widespread forest treatment in the U.S. We recommend that such research focus on the landscape scale because carbon loss in thinning needs to be placed in the context of the expected fire frequency and extent, and the potential for regeneration after fire. Regardless of the outcome of such research, the carbon benefits of fuel treatments can be improved by using the harvested trees for wood or biomass energy.

6. Urban forestry

Urban forestry offers very limited potential to store carbon, but we address urban forests here because of the large interest in using them to offset carbon emissions and because urban trees provide many co-benefits, including aesthetic benefits and environmental advantages in addition to carbon sequestration. The potential for carbon offsets of greenhouse gas emissions through urban forestry is very limited for two reasons: 1) urban areas make up only a small fraction of the U.S. landscape and 2) urban forests are intensively managed and may require large energy, water, and fertilizer inputs for planting and maintenance.

Urban forests can have important biophysical effects on climate. Trees have a cooling effect on local temperatures due both to shading effects and to evaporative cooling in transpiration. Shading intercepts incoming radiation in the daytime, which can reduce both day and night surface temperatures. When trees are planted very close to buildings, they cool building temperatures and reduce the fossil fuel emissions associated with air conditioning. When urban forests are planted over very large regions, the climate effects are less certain, as trees can have both warming (absorption) and cooling effects.

The higher the maintenance required for urban trees, the less likely they will help mitigate climate change. In some regions, cities are located in what would naturally be forested areas; thus, urban forests serve to restore forests to land that was previously deforested. In such regions, trees may have relatively low maintenance requirements. In cities located in grasslands and deserts, urban forests require large amounts of irrigation water for maintenance.

Figure 9. Sycamores lining Sycamore Street in Los Angeles, California. Photo by Diane E. Pataki, University of California, Irvine.

Because of these many tradeoffs, the following factors must be taken into account to determine the net climate impact of urban trees: 1) the carbon storage rate of the trees, 2) fossil fuel emissions from energy associated with planting and maintenance, 3) fossil fuel emissions resulting from the irrigation process, 4) nitrous and nitric oxide emissions from fertilizer use, and 5) the net effect of trees on local air temperature and its impact on building energy use. These factors are likely to be highly variable by region and by species.

7. Biomass energy, carbon storage in products, and substitution

Biomass energy

The use of forest biomass energy prevents carbon emissions from fossil fuel use. In 2003, biomass energy was 28% of the U.S. renewable energy supply and 2% of the total U.S. energy use. Biomass energy is used primarily for electric power in the forest products industry and for residential heating. In the future, biomass may become an important feedstock for liquid biofuels.

If cost were not a constraint and the public supported this use of forests, U.S. forests could potentially provide energy production offsetting 190 teragrams of fossil fuel carbon emissions per year, or the equivalent of 12% of U.S. fossil fuel emissions in 2003 (as discussed further in *Environmental costs* below). It has been estimated that by 2022, forest biomass feedstocks could produce 4 billion gallons of liquid biofuel per year (offsetting 2.6 teragrams of fossil fuel carbon emissions).

Figure 10. *Logs harvested at Manitou Experimental Forest in Colorado. Photo by Richard Oakes, USDA Forest Service.*

Carbon storage in wood and paper products

In the U.S., forest products are stored in two major "pools": those that are in use, and those held in landfills. Current additions of carbon to these pools from trees harvested in the U.S. are greater than decomposition losses from these pools, so carbon stored in these pools is increasing. In 2007, the net increase in carbon stored as products in use and in landfills was 30 teragrams of carbon (offsetting 1.7% of 2003 U.S. fossil fuel emissions), with about two thirds of the 30 teragrams being net carbon additions to landfills. Recently, additions have been declining due to decreases in U.S. timber harvests.

Carbon is also accumulating in "products in use", primarily in buildings. The total carbon held in single and multifamily homes in 2001 was about 700 teragrams of carbon. Annual net carbon accumulation in landfills is larger than that for products "in use" because about 80% of wood and 40% of paper decays very slowly under the anaerobic conditions in landfills. However, these same anaerobic conditions that slow decomposition also produce methane, a greenhouse gas with greater than 25 times the warming potential of CO_2. Because only 50% of methane is captured or oxidized before release, methane release reduces the carbon storage benefits in landfills. If we were to use the 30 teragrams per year of forest products currently going into landfills as biomass energy, we would offset 1.2% of U.S. fossil fuel use, lower emissions of methane, and extend the life of landfills.

Substitution

Carbon emissions can be offset by substituting wood products for products such as steel and concrete, which generate more greenhouse gas emissions in their production. A review of studies suggests that if wood products containing one unit of carbon were used in buildings as a substitute for steel or concrete, fossil fuel emissions from manufacturing would be reduced by two units or more. Opportunities for increased substitution in the U.S. will mostly need to be found outside of the housing industry because most housing is already built using wood.

Environmental costs of biomass energy and forest products use

The carbon benefits of increasing the use of wood for biomass energy and for product substitution would require more intensive forest management over a much broader area than currently occurs. For example, to obtain the aforementioned 190 teragrams per year of biomass energy would involve harvesting all of the current annual net forest growth in the U.S. To do that would require intensive management on much of the U.S. forest estate and would reduce the carbon stored in the forest. If branches and foliage were to be removed for biomass energy, fertilization would likely be needed to replace the nutrients removed to maintain productivity. Additionally, dead wood will decrease and soil carbon may decrease under harvesting, creating a carbon debt that will require time to pay off.

Links between strategies

Strategies can be combined to increase the carbon benefit. For example, Figure 5 shows that the maximum potential benefit from a project that reestablished forest increases if the stand is periodically harvested and the wood is used for substitution and the biomass used for fuel. Increased wood use for forest products and biomass energy would be compatible with afforestation, increasing forest growth, and fuel management to reduce fire threat. However, increased wood use may conflict with increasing carbon stores on the landscape from reducing harvests and avoiding deforestation. Increased forest growth would be compatible with reducing harvests and avoiding deforestation if the increased growth frees land for these other uses.

Carbon offsets and credits

A carbon offset is a reduction in greenhouse gas emissions (or an increase in carbon sequestration) by one entity, which can compensate for – or “offset” – emissions by another entity. The latter can thus continue with business as usual and avoid directly reducing its own emissions. Offsets are typically traded (bought and sold) as “carbon credits.” Typically, offset projects are certified, which instills confidence that the offsets are real and enables the associated carbon credits to be sold or traded to those who voluntarily wish to reduce their reductions or are regulated to do so. In the U.S., carbon credits are traded as part of a voluntary market, and the certification process varies widely. Europe, which ratified the Kyoto Protocol, has a regulated carbon market. Some of the forest management strategies discussed in this paper could “earn” carbon credits, such as afforestation, decreasing harvest intensity, increasing forest growth, use of biomass energy, and substitution.

Figure 11. Tree harvesting at Manitou Experimental Forest in Colorado. Photo by Richard Oakes, USDA Forest Service.

Carbon offsets require *additionality*, meaning that the carbon benefits occur directly as a result of an action deliberately taken to increase carbon sequestration. Additionality is required because reducing greenhouse gas emissions over business as usual is a goal and because no one wishes to pay for something that would happen anyway. Demonstrating additionality for forest activities requires that the activity be compared against a baseline scenario without activity. Demonstrating additionality is relatively straightforward for afforestation, urban forestry, and biomass energy use because the “starting point” can be quantified. It is much more complex for management that reduces carbon outputs or increases forest growth because larger areas need to be monitored for a longer time to validate increased carbon storage. It is also difficult to show additionality for the strategy of avoiding deforestation because carbon storage does not necessarily increase if forests are simply retained.

Many traders of forest carbon credits are also concerned with permanence, because carbon credits associated with the offset are sold before the management is fully implemented. Some forest carbon can be temporarily lost in a disturbance or harvest. It can also be lost with land use changes, some of which can preserve the option of forest reestablishment (such as change to agriculture or pasture) and some of which do not (urban development). For land maintained as forest, forest carbon storage can be considered permanent as long as the climate remains suitable because the landscape will maintain a level of carbon determined by the disturbance or harvest interval.

The most serious concern in any effort where forest management is changed for carbon benefits is leakage – changes outside of the project boundary that reduce or eliminate the carbon benefit. For example, afforesting agricultural land in the U.S. may increase deforestation elsewhere to meet the demand for food. Or, subsidizing forest carbon in the U.S. could decrease harvests, increase imports of wood and wood products, and lead to increased forest harvest – and thus reduced forest carbon – elsewhere. Leakage occurs, but is very difficult to measure because of its global nature and the difficulty of identifying cause and effect.

Although carbon offsets and credits feature prominently in comprehensive climate-and-energy legislation and may be critical to a society-wide effort to address climate change, other systems for increasing forest carbon sequestration may be simpler than carbon offsets. For example, direct payments to landowners for a particular land use (as in the current Conservation Reserve Program) could ensure desired management, and could reward avoided deforestation. Land-use regulation could also be used to force behavior that sequesters carbon (for example, minimum harvest intervals or requirements to plant trees on agricultural lands).

Measuring, monitoring and verifying carbon offsets

As the U.S. does not have a regulated carbon market, this discussion of monitoring and verifying carbon offsets is based on processes

Figure 12. *Regeneration in Yellowstone National Park 19 years after the 1988 fires, with Dan Kashian (Wayne State University). Photo by Mike Ryan, USDA Forest Service.*

outlined for voluntary markets. Carbon management begins with a project design that has been validated by scientific study to increase carbon storage rates compared to baseline rates. Once additional carbon accumulates, credible and accepted measurement and monitoring methods must be used to document carbon gains. Next, many offset projects and activities demonstrate that they do not cause leakage, but not all voluntary markets require this important but difficult step. Finally, an independent verification confirms that the project was installed correctly, is performing as projected, and that the carbon reporting is valid.

Measurement of carbon at various scales

At the scale of individual forest stands, adequate measurements (accurate to about 20%) can be made to estimate the carbon stored in trees, plants, dead wood, and in litter on the forest floor using standard inventory methods. Improvements to these methods would likely involve increased monitoring costs. Stand-level measurements of belowground stocks are more difficult because of the large cost of sampling soil carbon and fewer equations for estimating belowground biomass. Soil and belowground carbon monitoring should receive attention in accounting for forest carbon because forest harvest may cause an average loss of 8% of soil carbon stocks and 30% of the organic layer (forest floor) carbon.

At the landscape level, projects can be monitored and verified using remote sensing. Remote-sensing methods enable direct monitoring of forest age, cover types, and disturbance. Changes in carbon stores can be estimated with this information using ecosystem or accounting models. Monitoring at the regional level assesses the large-scale impact of carbon management. The Forest Inventory and Analysis National Program conducts a national-level strategic forest inventory based on a combination of on-the-ground measurements of all forest carbon pools and remotely-sensed observations. The inventory produces estimates of forest age, cover types, and disturbance and uses modeling for components that are difficult to measure.

Carbon stored in wood products is more difficult to monitor than carbon in the forest. Carbon in solid wood products in structures could be estimated using current census data with deductions for the fraction of products that are imported. Rates of accumulation for all forest products could also be monitored using data on production rates, recycling rates, and discard rates (to landfills). Biomass energy use could be tracked through surveys of biomass energy facilities.

How should carbon stores be measured?

Since carbon-storage projects take place across many different scales (stand, landscape, regional, and national) and jurisdictions, multiple methods of measurement are needed. A list of approved methods for measuring carbon pools should include the minimum number of pools to be measured with methods having minimal bias (that do not lead to frequent over- or under-counts of carbon) as well as the minimum frequency of measurements. There is an inherent level of uncertainty associated with any method for measuring carbon, and there is a practical need to decide how to treat this uncertainty in decision-making. If we use high-end estimates for forest carbon storage, we may over-promise what forests can do and obscure the need for mitigation actions in other sectors. Given the urgent need to meet climate change mitigation objectives and the high risks to society associated with failing to meet them, we recommend discounting carbon estimates where they are uncertain. As sampling frequency and specificity increase, uncertainty should decrease, but costs will also rise. Individual groups or entities can decide which approved method should be used for each project based on a cost-benefit ratio, weighing cost against gaining potential carbon benefit. The potential for leakage and accounting for and underestimating disturbance losses can be reduced by implementing a national-level accounting system that validates the carbon storage at a national scale.

Economics of forest carbon

Most of the strategies for increasing forest carbon storage or the use of forest products would require carbon to have a substantial value through credits for offsets or through some other mechanism to compensate those that have an economic interest for additional costs or foregone profit. To sequester an additional 200-330 teragrams of carbon in forests (the equivalent of offsetting 13-21% of 2003 U.S. fossil fuel emissions) would require payments of between $110-$183 per metric tonne of carbon, or 23-60 billion dollars per year. The per-tonne payment requirement reflects the economic value of the current use. For example, for afforestation, landowners would expect compensation for both their lost agricultural revenues and for the cost of planting trees. For lengthening the harvest interval, landowners would need compensation for the reduced product flow.

Although the total costs of such an undertaking are large, the costs of implementing these forest activities to sequester carbon are often far less than the cost of reducing the same amount of greenhouse gas emissions by other means, such as through the transportation or electric power sectors. Therefore, forests can play a key role in reducing the overall cost of achieving greenhouse gas emission reduction targets. Economic modeling of U.S. climate policy proposals consistently shows that forest carbon sequestration and other “offset” activities can significantly lower the cost of complying with the proposed regulations.

Climate change and other risks to forest carbon storage

The potential to increase carbon storage in forests needs to be weighed against the projected increases in disturbances promoted by a changing climate that will lower carbon storage. Climate change may also make regeneration after disturbance more difficult or render the current tree populations genetically unsuitable. Finally, population increase and exurban development will decrease the general amount of forested area. Because disturbances are likely to increase in the future, we recommend conservative estimates of potential gains from forest carbon management.

A potential negative effect of forest management strategies to enhance carbon storage is that, as forest carbon storage increases, there is a potential for greater loss of carbon stores from forest fires, insect outbreaks, hurricanes, windstorms, and ice storms. Climate change threatens to amplify these risks by increasing the frequency of these disturbances. If climate change increases the frequency of disturbance, as observational and modeling studies for the U.S. suggest, many forests could release significant amounts of carbon to the atmosphere over the next 50-100 years – simultaneous with efforts to harness CO_2 emissions. It is important to remember that, at the landscape level over the long term, disturbance does not cause a net loss of forest carbon…as long as the forest regenerates. But if the frequency and/or severity of disturbance increase substantially, long-term carbon storage at the landscape scale *will* be reduced because the fraction of the landscape with large, older trees (that have high carbon stores) will decline. Climate change could also increase soil decomposition, leading to carbon losses from a part of the ecosystem that we consider to be relatively stable and that contains about 40% of the total carbon in U.S. forests.

The largest risk to carbon storage from disturbance is that the forest may not regenerate and instead be replaced by a meadow or shrubland ecosystem, losing much carbon in the process. As a result of past fire suppression, we see this happening currently in the western U.S. as high-severity fires occur in ecosystems that are adapted to low-severity fire regimes. Although actions are being taken to reduce the fire risk, the carbon-related effects are currently unknown. Climate change may also increase the likelihood that forests will not regenerate sufficiently since highly adapted species and genotypes may have a difficult time growing under altered climatic conditions.

Conclusions and Recommendations

U.S. forests and forest products currently offset 12-19% of U.S. fossil fuel emissions, largely owing to recovery from past deforestation and extensive harvesting. Increased nitrogen deposition and atmospheric CO_2 compared to historical levels may also be contributing to increased forest growth, but the science supporting their contribution is uncertain because of a limited number of experiments and the difficulty in assessing change over the diverse forests of the U.S.

How long will U.S. forests remain a carbon sink? Since 1940, forest regrowth in the U.S.

has recovered about a third of the carbon lost to the atmosphere through the deforestation and harvesting that occurred from 1700-1935 (Figure 13). To recover the remaining two-thirds of the carbon that was lost would require reestablishing forests in a significant portion of what is now agriculture and pasture land. However, reforesting this part of the U.S. (almost all land east of the Mississippi) is not feasible from an economic and food-security perspective. Today's recovery from the forest clearing and wood-based economy of the 1800s and early 1900s will likely sustain carbon storage rates at the current rate for decades, but not indefinitely.

But, forest carbon storage only gets us part of the way. Even under the best scenarios, the amount of carbon storage potential is finite. Strategies that combine increased use of forest products to offset fossil fuel use (such as use of biomass energy and substitution), in conjunction with increasing carbon storage on forested landscapes, are likely to produce the most sustainable forest carbon benefits.

Every strategy we examined has tradeoffs. Avoiding deforestation and increasing the harvest interval in the U.S. may move timber production elsewhere, resulting in no net benefit for carbon in the atmosphere. Reestablishing forests has great potential but will also displace current land uses such as farming and pasture. Increasing forest product use and forest biomass energy will require more active forest management over larger areas than currently occurs and may lower forest carbon stores. Intensive silviculture can increase growth, but decrease streamflow and biodiversity. Forest products in landfills increase carbon storage, but the resulting methane emissions pose a problem. A better use for waste material, therefore, is energy production. Recognizing these tradeoffs will be vital to any effort to promote forest carbon.

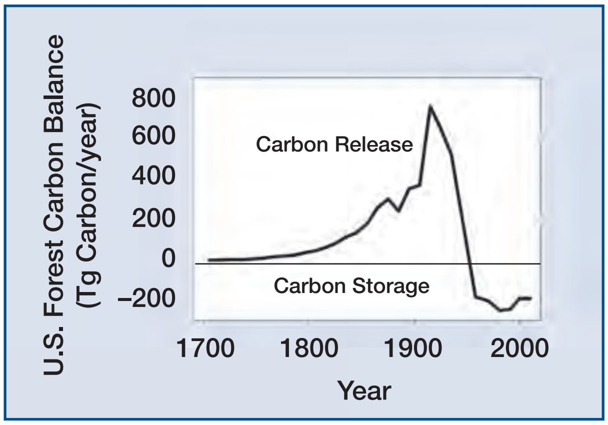


Figure 13. *The carbon balance of the U.S. forest sector shows that clearing for agriculture, pasture, development, and wood use released ~42,000 Tg of carbon from 1700 to 1935, and recovered about 15,000 Tg of carbon from 1935-2010. (Used with permission, from* Journal of Environmental Quality *35:1461-1469 (2006))*

Because forest carbon loss poses a significant climate risk and because climate change may impede regeneration following disturbance, avoiding forest loss and promoting regeneration after disturbance should receive high priority as policy considerations. Forest loss moves a large portion of the carbon sequestered in forests into the atmosphere, particularly where the loss includes not only trees but also the decomposition of soil carbon. Because of climate change, increasing threats from disturbance, and continued population growth and resulting exurban development, we cannot assume that all existing forests will remain. Because there is a high likelihood that climatic patterns will shift and the frequency of disturbances will increase – potentially making existing tree species less suited to their environment – it would be prudent to focus on regeneration after disturbance to help ensure maintenance of forests.

The various strategies for storing carbon in forests have different associated risks and levels of uncertainty. Retaining forests (which also includes regenerating after disturbance) and afforestation both involve low levels of uncertainty regarding carbon consequences and therefore low risk to carbon storage – aside from the risks of carbon loss in disturbance or that the deforestation will simply happen elsewhere. The carbon benefits of using biomass energy and long-lived forest products are also fairly certain, as long as forests regenerate. Lengthening harvest intervals involves a bit more risk because disturbance would occur in forests with higher carbon stores and because decision-makers can change harvest intensity quickly relative to forest growth.

Regardless of the risks and uncertainties, any policy to encourage forest carbon storage should: 1) promote the retention of existing forests; 2) account for other greenhouse gas effects, such as methane and nitrous oxide emissions and biophysical changes; 3) account for harvest moving elsewhere indirectly caused by changes in management with the project boundary; 4) recognize other environmental benefits of forests, such as biodiversity, nutrient management, and watershed protection; 5) focus on the most robust and certain carbon storage benefits in any compensation scheme; 6) recognize the difficulty and expense of tracking forest carbon, the cyclical nature of forest growth and regrowth, and the extensive movement of forest products globally; 7) recognize that the value of any carbon credit will depend on how well the carbon can be measured and verified; 8) acknowledge that climate change and population growth will increase the potential for forest loss and may keep large-scale projects from reaching their full potential; 9) recognize the tradeoffs; and 10) understand that the success of any carbon mitigation strategy depends on human behavior and technological advances in addition to forest biology. Finally, because CO_2 remains in the atmosphere for more than 100 years, any action to avoid further emissions should be undertaken as soon as possible.

Few forests are managed solely for carbon – rather, carbon storage serves as a co-benefit that accompanies or perhaps helps pay for other ecosystem services provided by forests (Box 2). As we have discussed above, elevating carbon storage to the primary focus of management could potentially impede the other co-benefits of forests. A focus on carbon storage to the detriment of other ecosystem services would be short-sighted.

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Quantification of global gross forest cover loss

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A globally consistent methodology using satellite imagery was implemented to quantify gross forest cover loss (GFCL) from 2000 to 2005 and to compare GFCL among biomes, continents, and countries. GFCL is defined as the area of forest cover removed because of any disturbance, including both natural and human-induced causes. GFCL was estimated to be 1,011,000 km^2 from 2000 to 2005, representing 3.1% (0.6% per year) of the year 2000 estimated total forest area of 32,688,000 km^2. The boreal biome experienced the largest area of GFCL, followed by the humid tropical, dry tropical, and temperate biomes. GFCL expressed as the proportion of year 2000 forest cover was highest in the boreal biome and lowest in the humid tropics. Among continents, North America had the largest total area and largest proportion of year 2000 GFCL. At national scales, Brazil experienced the largest area of GFCL over the study period, 165,000 km^2, followed by Canada at 160,000 km^2. Of the countries with >1,000,000 km^2 of forest cover, the United States exhibited the greatest proportional GFCL and the Democratic Republic of Congo the least. Our results illustrate a pervasive global GFCL dynamic. However, GFCL represents only one component of net change, and the processes driving GFCL and rates of recovery from GFCL differ regionally. For example, the majority of estimated GFCL for the boreal biome is due to a naturally induced fire dynamic. To fully characterize global forest change dynamics, remote sensing efforts must extend beyond estimating GFCL to identify proximate causes of forest cover loss and to estimate recovery rates from GFCL.

change detection | global change | monitoring | remote sensing | probability sampling

The synoptic nature of satellite-based earth observation data enables the consistent characterization of forest cover across space and over time. Information on forest cover and forest cover change is necessary for carbon accounting efforts as well as for parameterizing global-scale biogeochemical, hydrological, biodiversity, and climate models. Because of the vast area that must be examined, earth observation data offer one of the few viable information sources suitable for global-scale monitoring of forest cover dynamics. Such monitoring has been hindered by data access policies (costs of imagery), inadequate imagery acquisition protocols (few systematic global acquisition strategies), and data processing limitations (methods for processing global data for change monitoring). However, new data streams, freely available imagery, and improved methods now allow operational monitoring of global forest cover change. We present estimates of gross forest cover loss (GFCL) from 2000 to 2005 by using data from two sensor systems appropriate for global-scale inquiry. The global consistency of the methodology allows for comparisons of GFCL among biomes, continents, and countries. A GFCL map is also produced to provide a spatial depiction of primary areas ("hotspots") of GFCL.

Over the past three decades, methods for monitoring forest cover and change over large areas by using satellite data have evolved from the initial work highlighting the dramatic deforestation dynamic of the Brazilian Amazon (1) to the first annual large area deforestation monitoring system, Brazil's National Institute for Space Research PRODES project (2). Other countries have incorporated earth observation data into national monitoring schemes. India, for example, has a similar periodic forest extent and change product to that of Brazil (3). However, synthesizing global forest cover and change from national-scale mapping efforts is not feasible because national capabilities for forest monitoring vary greatly, and the methods and definitions concerning forest cover and extent differ among countries.

Global scale assessments using remotely sensed datasets involve either exhaustive mapping or sample-based approaches. Whereas global mapping at the high spatial resolutions (<50 m) required to adequately quantify forest extent and change may soon be viable, previous efforts employed coarse spatial resolution data sets (4–9) (>250 m), with only one attempting to quantify forest cover change (10). However, coarse resolution data lack sufficient spatial detail to provide reliable area estimates of forest extent and change. Probability-based sampling approaches that use high spatial resolution data have proven to be an effective alternative for quantifying forest extent and change over large areas, and biome-scale studies designed to overcome the varying quality and inconsistencies of national datasets have been implemented (11–13).

Our objective is to provide a global estimate of forest cover extent and GFCL. The methodology is based on a stratified random sample of 541 18.5-km × 18.5-km blocks (a sampling density of 0.22%) and employs data from two satellite-based sensors. Coarse spatial resolution data from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor enable the stratification of the earth's forested biomes into regions of homogeneous forest cover loss. Landsat Enhanced Thematic Mapper Plus (ETM+) data obtained for the sampled blocks were then used to quantify area of year 2000 forest and area of GFCL.

Forest cover is one category of terrestrial land cover. Land cover is the observed physical features, both natural and manmade, that occupy the earth's immediate surface (14). For this study, forest cover is defined as 25% or greater canopy closure at the Landsat pixel scale (30-m × 30-m spatial resolution) for trees >5 m in height. While various canopy closure thresholds are used to define forest cover (12, 15), our definition is based on the ability to identify tall woody vegetation unambiguously in multispectral imagery. For example, the Australian National Carbon Accounting System has employed a 20% threshold due to the fact that Landsat is able to provide consistent mapping of cover and change (16) at or above this canopy density. Our definition of forest having at least 25% cover for trees of at least 5 m in height lends itself more easily to global-scale monitoring from space when using earth observation systems such as Landsat and MODIS.

Human and natural disturbances often lead to changes in land cover, for example, fire converting forest to herbaceous cover. This study focuses on one disturbance dynamic at the global scale, the conversion of forest cover to nonforest cover (GFCL). Areas of GFCL are quantified by using per sample Landsat image pairs consisting of a reference 2000 image for mapping

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EXHIBIT 3

forest area and a 2005 image for mapping forest area loss. This globally consistent methodology for quantifying forest cover and GFCL permits comparisons among biomes, continents, and countries (*SI Methods*). Area of forest cover and GFCL for the boreal (17), temperate (18), dry tropics, and humid tropics (19) are presented here as a global synthesis.

The primary source for global information on forest resources to date is the United Nations Food and Agricultural Organization's (FAO) Forest Resource Assessment (FRA) (20). These data, supplied by the contributing member countries, are the current reference for global forest change from 2000 to 2005. However, several features of the FRA data prevent their utility for a global forest change assessment: (*i*) the methods used to quantify forest change are not consistent among all countries, thus hindering the ability to synthesize results; (*ii*) the definition of "forest" is based on land use instead of land cover and the land use definition obscures the biophysical reality of whether tree cover is present; (*iii*) forest area changes are reported only as net values; and (*iv*) forest definitions used in successive reports have changed over time (21). Earth observation datasets can be used to address these limitations by providing globally consistent and spatially explicit characterizations of forest cover extent and change. Such depictions can quantify both forest cover loss and gain independent of land use designations. Plans for the forthcoming FAO FRA 2010 report include a remote sensing survey of forests based on Landsat imagery and a systematic sample of 13,869 10-km × 10-km blocks, representing a sampling density of 1.03% (http://www.fao.org/forestry/fra).

A more recent source of information on forest change is the United Nations Framework Convention on Climate Change (UNFCCC), which tracks national reports on greenhouse gas emissions, including those associated with forest land use and land use change. These national inventories focus on the use of managed lands as a proxy for estimating direct human-induced emissions and removals related to land use. The area changed within forest land use areas is required to estimate emissions and removals, and this information is not available in the FAO FRA reports. Concerning both the FAO FRA and UNFCCC forest monitoring efforts, global-scale remote sensing forest cover change analyses can be of value in (*i*) verifying or confirming reported forest inventories and change and (*ii*) harmonizing data derived from reports that employ different methods or definitions. Inconsistencies in the definitions used and methods applied for forest monitoring at national scales will be unavoidable. Remote sensing data can be used to create an internally consistent global quantification of forest cover change.

This study quantifies a unidirectional change dynamic—GFCL—as a demonstration of the capabilities of remote sensing for global monitoring. Our focus on GFCL is predicated on the premise that Landsat data provide an unambiguous, quantifiable signal of both forest cover and its loss via stand-replacement disturbance. Consequently, we target a feature of the global forest change dynamic, gross loss in forest cover, for which Landsat imagery has a high capacity to detect. Results presented here include forest area and GFCL estimation at biome, continent, and national scales, the latter for each country with forest area >1,000,000 km^2. Data from the study can be viewed and accessed at globalmonitoring.sdstate.edu/projects/gfm. Gross forest cover gain is not quantified and, consequently, net forest cover change dynamics are not reported. Forest cover gain is a more gradual process than forest cover loss and would require adjustments to our methodology. Regional variation in forest land use, natural and human-induced drivers, and forest recovery is significant, and GFCL captures only a part of the global forest cover change dynamic.

Results

Biome-Scale Forest Area and Gross Forest Cover Loss. Forest area for 2000 and GFCL for 2000–2005 are spatially depicted in Fig. 1 *A* and *B* with rates of GFCL summarized in Fig. 2. Global 2000 forest area is estimated to be 32,688,000 km^2 with the humid tropics having the largest forest extent among all biomes (Table 1). The estimated area of GFCL at the global scale is 1,011,000 km^2, representing 3.1% of year 2000 forest area (0.6% per year). GFCL is highest in the boreal forest biome with nearly 60% of the cover lost due to fire (17). The remaining 40% of boreal GFCL is attributable to logging and other change dynamics such as insect and disease-related forest mortality; for example, loss of forest cover in British Columbia, Canada, due to mountain pine beetle infestations (22).

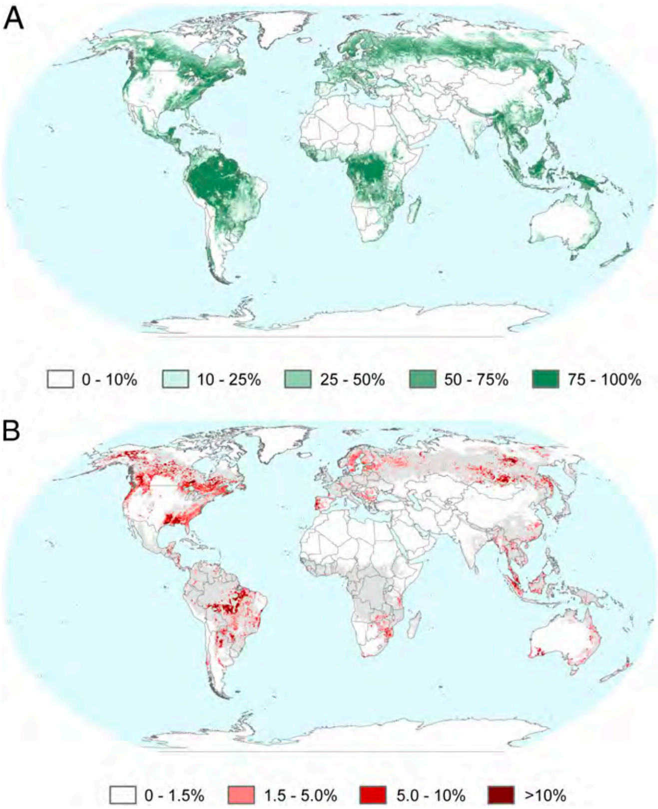

Fig. 1. Estimated percent forest cover, 2000 (*A*) and percent gross forest cover loss (GFCL), 2000–2005 (*B*), both per sample block.

The biome with the second highest area of GFCL is the humid tropics. The majority of this loss is attributable to large-scale agro-industrial clearing in Brazil, resulting in nonforest agricultural land uses, and in western Indonesia and Malaysia, resulting in agro-forestry land uses (19). When GFCL is expressed in terms of the proportion of year 2000 forest, the humid tropical biome is the least disturbed. Large regions of forest absent of large-scale forest disturbance still exist in the humid tropics (Fig. 1). The Amazon interior is the largest remaining intact forest landscape, primarily due to its inaccessibility. The interior Congo Basin also lacks significant forest loss (23, 24). Even though selective logging occurs in many parts of the Congo Basin (25), large-scale agro-industrial clearing is absent.

The dry tropics biome has the third highest estimated area of GFCL. Forests in this biome are predominantly open-canopied and often fire-adapted. The main areas of GFCL in this biome occur in Australia and South America, with Brazil, Argentina, and Paraguay contributing most to South America in the form of agro-industrial scale clearing. The temperate biome has the lowest total area of forest cover of all biomes, as the majority of this biome has long been converted to agricultural and settlement land uses. However, GFCL as a proportion of year

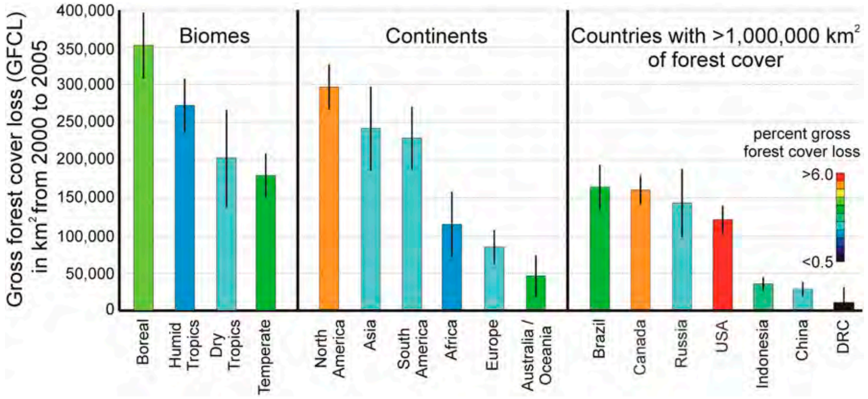

Fig. 2. Estimated gross forest cover loss (GFCL) by biome, continent, and country (error bars represent 95% confidence intervals for area of gross forest cover loss).

2000 forest in the temperate biome is second highest among all biomes. Nearly half of all temperate GFCL is found in North America.

Continental-Scale Forest Area and Gross Forest Cover Loss. Asia and South America are the continents with the largest area of forest cover, each with one-quarter of the global total (Table 2). North America has the greatest area of GFCL, followed by Asia and South America. North America alone accounts for nearly 30% of global GFCL and features the highest proportional GFCL of 5.1%. Africa has the lowest proportional GFCL of 0.4%, reflecting a lower overall use of forests for commercial development. Combined, North and South America account for more than one-half of the global total area of GFCL. South America has the largest remaining intact forests within the tropics (26), areas that are under increasing pressure from agro-industrial development. North America features a spatially pervasive GFCL dynamic with logging and fire as primary causes.

National-Scale Forest Area and Gross Forest Cover Loss. The seven countries exceeding 1,000,000 km^2 in year 2000 forest cover account for 57% of total forest cover and 65% of GFCL during 2000–2005 (Table 3). Russia has the most extensive forest cover, followed by Brazil, Canada, and the United States. Brazil, with significant forest cover in both the humid and dry tropics, has the highest GFCL of any nation. Of the total area of 165,000 km^2 of GFCL from 2000 to 2005 (33,000 km^2 per year), 26,000 km^2 per year is lost within the Brazilian humid tropics and 7,000 km^2 per year within the Brazilian dry tropics. For this time period, our national-scale GFCL area estimate of 33,000 km^2 is close to the FAO FRA estimate of 31,000 km^2 per year (20). Conversely, Brazil's National Institute for Space Research (INPE) reported 111,000 km^2 (2) of tropical deforestation for the Legal Amazon for the 2000–2005 period (22,000 km^2 per year). Our estimate of 165,000 km^2 is higher because our sample represents the entire land surface of Brazil, thus capturing humid tropical GFCL outside of the INPE study area (27) as well as GFCL in the dry tropical cerrado ecoregion. For a product intercomparison of the region common to both our humid tropical biome and the PRODES Legal Amazon forest region, see *SI Methods*. GFCL is found in nearly every region of Brazil, except the interior Amazon and the largely nonforested northeast Caatinga ecoregion and the agricultural south.

Other large tropical forest countries include Indonesia and the Democratic Republic of Congo. Indonesia's GFCL is concentrated in the western Sumatra and Kalimantan island groups. Although Indonesia is considered a nexus of tropical forest cover loss, the GFCL for Indonesia as a proportion of year 2000 forest is estimated to be 3.3%, just above the global estimate of 3.1%. The annualized proportional GFCL for 2000–2005 in Indonesia reflects a reduction in GFCL when compared with estimates of GFCL for 1990–2000 (28). The Democratic Republic of the Congo has the lowest GFCL at 10,000 km^2, or 0.6% of year 2000 forest cover (with the caveat that only seven sample blocks fell in this country). Compared with other more politically and economically stable humid tropical forest regions, Central Africa has a considerably lower rate of GFCL because of less investment in infrastructure and commercial agro-industrial development.

The United States includes temperate and boreal (Alaska) forest cover and has the highest percentage of year 2000 GFCL (6.0%). Although fire is a major contributor, particularly in Alaska and the western part of the country, logging is a primary and widespread cause of GFCL. Regional centers of logging are found mainly in the southeastern states, but also along the west coast and in the upper Midwest. Canada also covers portions of the temperate and boreal biomes, and has substantial GFCL in every province and territory, except Prince Edward Island. The FAO FRA (20) reports 0% net change in Canadian forest area, illustrating the discrepancy in estimates depending on whether forest is defined based on considerations of forest land use or the biophysical presence of tree cover. Our estimate is based on defining forest cover, whereas the FRA estimate is based on a forest land use definition that includes "temporarily unstocked areas, resulting from human intervention or natural causes, which are expected to regenerate" (20). Our estimate of the total GFCL of 160,000 km^2 places Canada a close second to Brazil

Table 1. Biome-scale forest cover and GFCL, 2000–2005, ordered by area of GFCL

Biome	2000 forest cover in km^2	% of total forest cover	2000–2005 GFCL, km^2 (s.e.)	GFCL as % of 2000 forest cover	% of total GFCL
Boreal	8,723,000	26.7	351,000 (22,000)	4.0	34.7
Humid Tropical	11,564,000	35.4	272,000 (17,000)	2.4	27.0
Dry Tropical	7,135,000	21.8	204,000 (32,000)	2.9	20.2
Temperate	5,265,000	16.1	184,000 (15,000)	3.5	18.2
Total	32,687,000	100	1,011,000 (45,000)	3.1	100

Table 2. Continental-scale forest cover and GFCL, 2000–2005, ordered by area of GFCL

Continent	2000 forest cover in km^2	% of total forest cover	2000–2005 GFCL, km^2 (s.e.)	GFCL as % of 2000 forest cover	% of total GFCL
North America	5,829,000	17.8	295,000 (15,000)	5.1	29.2
Asia	8,442,000	25.8	240,000 (28,000)	2.8	23.7
South America	8,414,000	25.7	228,000 (21,000)	2.7	22.6
Africa	5,635,000	17.2	115,000 (21,000)	2.0	11.4
Europe	3,099,000	9.5	86,000 (11,000)	2.8	8.5
Australia/Oceania	1,268,000	3.9	47,000 (13,000)	3.7	4.6
Total	32,687,000	100	1,011,000 (45,000)	3.1	100

(165,000 km^2). Logging predominates in the settled south of Canada, and fire in the largely uninhabited north. Russia has the third highest area of GFCL, but its percent of year 2000 forest cover loss (2.8%) is slightly below the global average. Russia's GFCL is geographically widespread, with logging in the European and far-eastern parts of the country, and fire throughout Siberia (17, 29). Of the seven major forested countries, China is next to the Democratic Republic of Congo in terms of least GFCL. Whereas China's proportional GFCL of year 2000 forest is comparable with Russia's, the overall area of 28,000 km^2 represents only 2.8% of the global total.

For these seven countries with >1,000,000 km^2 of forest cover, Fig. S1 compares the 2000–2005 FRA forest area and net forest area change data (20) with the forest area and GFCL area estimates of this study. Forest area is largely in agreement, except for Russia. Forest area totals for Russia have historically been obscured by complex national definitions (30). Additionally, the application of a 25% canopy cover threshold omits forest area that would be included in many other assessments, including that of the FRA, which employs a 10% cover threshold. Although North America is the site of negligible net change in the FRA report, our estimates depict it as a primary contributor to global GFCL. Similarly, the net gain of forest cover in China from the FRA data does not capture a forest cover loss dynamic of some significance.

Other countries with significant areas of GFCL include Australia, Paraguay, Argentina, and Malaysia (Fig. 1*B*). Fire is the principal cause of forest loss in Australia with significant GFCL in nearly every state. Paraguay continues to have intensive forest clearing related to agricultural development, from the humid tropical Atlantic Interior forests of the east to the dry tropical Chaco woodlands of the west (31). Argentina has a similar dynamic with change in the remaining Atlantic Interior forests of Misiones province, and more widespread clearing of Chaco woodlands in the northwest (32). Malaysia has significant GFCL in every state, largely associated with palm oil expansion and agroforestry.

Discussion

The globally consistent data and methodology used in this study enable direct comparisons of GFCL areas and rates across biomes, continents, and select nations. The inherent inconsistency in previous data collection efforts precluded synoptic, global overview analyses (21). Results augment current global information, namely the FAO FRA data (20), by providing (*i*) gross forest cover loss information, which is not derivable from net change estimates; (*ii*) quantification of the biophysical extent and loss of forest cover, absent of land use considerations, thereby better reflecting the biophysical reality of whether forest cover is present; and (*iii*) improved consistency of forest area and loss data through space and time, enabled by the use of the global remotely sensed data inputs. Results illustrate a globally pervasive GFCL dynamic from 2000 to 2005.

Global variation in GFCL is related to environmental, economic, political, and social factors that determine forest use. Stable political and economic conditions, coupled with access, leads to clearing, a concept consistent with current land cover and land use change theory (33). This simple model of forest clearing has led to the continual reduction of intact forests on every continent (26). The two biomes with largely inaccessible forest regions, the boreal and humid tropics, have comparatively low GFCL when GFCL is expressed as a proportion of year 2000 forest and boreal fires are discounted. Concerning humid tropical forest, mechanisms such as the UNFCCC's REDD (34) initiative aim to reduce tropical deforestation by promoting payments for forest ecosystem services such as carbon storage. Global monitoring of forest cover change will help in evaluating the effectiveness of programs such as REDD.

The often publicized phenomenon of forest conversion within the humid tropics is observed in our results, but significant GFCL is evident in all biomes. For example, rates of GFCL in regions such as the southeast United States are among the highest globally. While many such regions have forest land use designations where forest cover is eventually re-established, the resultant carbon dynamics vary significantly between ecosystems and management regimes. These dynamics are not the same for forest land uses in places as different as Canada and Malaysia.

Table 3. National-scale forest cover and GFCL, 2000–2005, for countries with >1,000,000 km^2 of year 2000 forest cover, ordered by area of GFCL

Country	2000 forest cover in km^2	% of total forest cover	2000–2005 GFCL, km^2 (s.e.)	GFCL as % of 2000 forest cover	% of total GFCL
Brazil	4,601,000	14.1	164,000 (14,000)	3.6	16.3
Canada	3,045,000	9.3	160,000 (10,000)	5.2	15.8
Russian Federation	5,122,000	15.7	144,000 (22,000)	2.8	14.2
United States of America	1,992,000	6.1	120,000 (9,000)	6.0	11.8
Indonesia	1,084,000	3.3	35,000 (4,000)	3.3	3.5
China	1,209,000	3.7	28,000 (5,000)	2.3	2.8
Dem. Rep. of Congo	1,673,000	5.1	10,000 (10,000)	0.6	1.0
Total	18,726,000	57.3	661,000 (30,000)	3.5	65.4

Improved quantification of forest cover change dynamics within areas of designated forest land use are needed, because rates of clearing and recovery are not uniform globally.

The method employed in this analysis was predicated on spectral signatures indicating complete canopy removal. However, the proximate cause of each disturbance was not identified. Only within the boreal biome was forest cover loss due to fire differentiated from forest cover loss in general. Natural forest change processes, such as fire, disease, or storm damage, are sometimes not systematically monitored by forest agencies. However, changing spatiotemporal trends in such disturbances may have significant long-term ecological consequences. Discerning proximate causes of forest loss at the global scale, particularly human-induced clearing versus natural factors, is a valuable line of research inquiry. Such information will be necessary for improved quantification of carbon dynamics. For example, significant aboveground carbon can remain after a fire, such as standing and fallen deadwood (35) in contrast to mechanical harvesting of forest stands.

The capacity for monitoring forest change at the global scale is still being developed. Remote sensing offers an efficient and synoptic method for doing so (36). It is incumbent that such information sources are made available to as wide a user group as possible. This goal is achieved by performing systematic global acquisitions and providing data at no cost with easy access. Systems used in this study, namely MODIS and Landsat, meet these requirements and are the only ones viable for global-scale inquiry. The methodology implemented to estimate GFCL could be applied at finer time scales, for example annually, and at national scales, or within specific subregions, such as unmanaged areas or protected areas. Additionally, it could be modified to estimate gross forest cover gain. Although research on quantifying forest degradation is ongoing (37, 38), operational methods are not ready for implementation at the global scale.

The primary limitation of the sampling method employed in this study is the lack of a fine spatial resolution map product. The block-scale spatial depiction of global GFCL depicts the total area of GFCL as implemented through the regression estimator procedure. However, disaggregation of the change is limited to those areas with a sufficient number of samples to provide estimates of GFCL with small standard errors. For many science applications, spatially explicit map products at finer spatial resolutions are required. For example, exhaustive Landsat-scale resolution mapping has been performed to characterize patterns of forest disturbance and recovery at a continental scale (39), resulting in map outputs appropriate for calibrating carbon cycle models. Spatially explicit global-scale mapping of forest cover dynamics at Landsat-scale will be required for many global change science studies.

Methods

The efficiency of our sampling design was achieved by taking advantage of data from the MODIS sensor to create an effective stratification for forest cover loss. The Landsat ETM+ sensor then provided the primary data for quantifying global GFCL from 2000 to 2005. The probability sampling design was implemented sequentially in four biomes, the humid tropics, boreal, dry tropics, and temperate. Estimates of forest area in 2000 and GFCL area for 2000–2005 were obtained for each biome separately (17–19). The sampling unit was an 18.5-km × 18.5-km block. Each biome was partitioned into high, medium, and low forest cover loss strata based on MODIS-derived GFCL, with the stratum breakpoints selected independently for each biome (Fig. S2). A stratified random sample of blocks was then selected from each biome, and Landsat imagery was analyzed to quantify forest extent and GFCL per sample block. Example block analyses per biome are shown in Figs. S3 and S4. Stratum-specific regression estimators incorporating MODIS-derived GFCL as the auxiliary variables were applied to generate the mean GFCL estimates. These same estimated regression models were then used to provide a spatial depiction (map) of each biome at the block scale. By construction, the aggregate GFCL portrayed by the map equals the area of GFCL estimated from the sample, thus ensuring internal consistency between the map and estimated area of GFCL. The sample size was sufficient to generate precise estimates of forest cover and GFCL at a continental scale and also at a national scale for those countries containing >1,000,000 km^2 of forest cover. Year 2000 forest area estimates were derived separately for each biome by regressing sample block forest area (all pixels ≥ 25% canopy closure) against global MODIS Vegetation Continuous Field 2000 data (8).

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Goodbye to carbon neutral: Getting biomass footprints right

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ABSTRACT

Most guidance for carbon footprinting, and most published carbon footprints or LCAs, presume that biomass heating fuels are carbon neutral. However, it is recognised increasingly that this is incorrect: biomass fuels are not always carbon neutral. Indeed, they can in some cases be far more carbon positive than fossil fuels. This flaw in carbon footprinting guidance and practice can be remedied. In carbon footprints (not just of biomass or heating fuels, but all carbon footprints), rather than applying sequestration credits and combustion debits, a 'carbon-stock change' line item could be applied instead. Not only would this make carbon footprints more accurate, it would make them consistent with UNFCCC reporting requirements and national reporting practice.

There is a strong precedent for this change. This same flaw has already been recognised and partly remedied in standards for and studies of liquid biofuels (e.g. biodiesel and bioethanol), which now account for land-use change, i.e. deforestation. But it is partially or completely missing from other studies and from standards for footprinting and LCA of solid fuels.

Carbon-stock changes can be estimated from currently available data. Accuracy of estimates will increase as Kyoto compliant countries report more land use, land use change and forestry (LULUCF) data.

1. Carbon footprints of biomass fuels: current guidance and practice

Prominent guidance for carbon footprinting (Table 1) presumes that biomass is inherently carbon neutral. Carbon dioxide emitted in biomass combustion is automatically excluded from carbon footprints.

Guidance from the World Business Council for Sustainable Development and the World Resources Institute (WBCSD, 2004; WRI, 2006; WRI, 2007) recognises that presuming carbon-neutrality is problematic, but it still excludes biomass carbon-combustion emissions from its footprint definitions.

Most published footprint or life-cycle assessment studies take the same approach; they automatically exclude carbon dioxide emitted in the combustion of biomass. This has been reported by Rabl et al. (2007), and it has been confirmed by the author. In an early 2008 survey of over 100 publications by 56 researchers about solid biomass fuels, 25 researchers were identified who had estimated footprints of wood fuel (in log, pellet or chip form). Of those 25 researchers, only Börjesson and Gustavsson (2000) did not presume wood to be carbon neutral.

Published studies presume carbon neutrality of biofuels in either of two approaches: *implicit* sequestration credit or *explicit* sequestration credit. Most studies apply the former approach, simply ignoring the CO_2 flux within a biofuel (Rabl et al., 2007), presuming that 'CO_2 in equals CO_2 out', so using a net flux of zero. Others, such as EcoInvent (2003), use the latter approach, offsetting biomass-combustion CO_2 emissions with a sequestration credit that is nearly equal to the combustion emission. Either way, the biomass combustion footprint is zero or close to it, i.e. carbon neutral.

Disaggregated carbon footprints, using both of these approaches to carbon neutrality, are shown below (Tables 2 and 3), using figures from EcoInvent (2003) for forested logs used as heating fuel. In both cases, for reference to a fossil fuel[1] they are compared to natural gas in residential heating, again using figures from EcoInvent.

2. Problems with current guidance and practice

Current guidance and practice are problematic for three reasons. It defies common sense, contravenes UNFCCC rules and ISO standards and ignores a large body of existing research.

2.1. It defies common sense

If a tree is harvested for fuel, this reduces carbon stocks. However, current approaches to carbon footprinting – by presuming carbon neutrality – do not recognise this.

This is problematic, because first, as Rabl et al. (2003) point out, this can lead to absurd conclusions: for example, if carbon neutrality is presumed, it makes no difference to a carbon footprint if a forest is standing or if it has been chopped down for fuel wood.[2] Second,

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[1] Fossil fuels do not receive sequestration credits, either implicit or explicit, in current guidance and practice.

[2] As long as the land use has not been changed, i.e. the forest is allowed to regrow.

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EXHIBIT 4

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Table 1
Prominent guidance that presumes bio-based products to be carbon neutral

Guidance	Where biomass carbon-neutrality is presented	Reference
European Union Emissions Trading Scheme	Table 4	European Commission (2007)
European Union Renewable Energy Directive (proposed)	Annex VII	Renewable Energy Directive (proposed) (2008)
PAS 2050 — Specification for GHG emissions of goods and services	Clauses 3.25, 5.3.1 and 5.4	PAS 2050 (2008)
UK Standard Assessment Procedure for Energy Rating of Dwellings, 2005	Table 12	Standard Assessment Procedure (2008)
UK Building Regulations	Table 17	UK Building Regulations (2008)

Table 3
Current footprint method, including explicit sequestration credit and combustion debit

Approach	Explicit sequestration credit	No sequestration credit
Fuel	Harvested logs	Natural gas
Footprint g CO_2eq/MJ		
Sequestration credit	−164.25	0
Cultivation-to-harvest or production	2.5	3.6
Processing	0	3.5
Transport	0.25	7.8
Combustion[a]	166.4	55.1
Total	4.9	70.0

[a] All GHGs, including CO_2.

presumed carbon neutrality generally leads to an understatement of biomass footprints. For instance, if a forest is harvested intensively for fuel, as opposed to being preserved, this makes no difference in today's footprint, even if the carbon stock of the latter clearly exceeds that of the former.

The problem here is not academic; it is real. Global forest stocks are declining, and a significant reason for this is harvesting for use as fuel (FAO, 2005).

2.2. It contravenes UNFCCC rules and ISO standards

The basis of UNFCCC reporting rules, the Kyoto Protocol, states in Article 3.3 that "net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities… measured as verifiable changes in carbon stocks in each commitment period, shall be used…" to measure compliance with Kyoto targets. At least two leading Kyoto-compliant countries, Switzerland (BAFU, 2008) and the UK (UK DEFRA, 2006), report on this basis, showing that Article 3.3 is put into practice.

Measuring net changes in carbon stocks (as opposed to presumptive carbon neutral) is also the principle behind International Standard 14064-2 for greenhouse-gas reporting. This ISO standard, in sections A.2.1 and A.3.3–A.3.5, includes requirements to report GHG sources, sinks and reservoirs (ISO14064-2, 2006). Although this standard applies to project footprinting and is presented rather generically, clearly it can be applied to footprinting of organisations or products.

2.3. It ignores a large body of existing research

Although much guidance and practice presumes biomass to be carbon neutral, there exists a robust, credible and well-known body of research suggesting that this is not automatically justified. The principle, as Marland and Marland (1992) put it, is that:

> "Trees are equally effective in preventing the accumulation of CO_2 in the atmosphere if they remove a unit of C from the atmosphere or if they supply a sustainable source of energy that substitutes for a unit of C discharged by burning fossil fuels….The most effective strategy for using forest land to minimize increases in atmospheric CO_2 will depend on the current status of the land, the productivity that can be expected, the efficiency with which the forest harvest is used to substitute for fossil fuels, and the time perspective of the analysis. For forests with large standing biomass and low productivity the most effective strategy is to protect the existing forest. For land with little standing biomass and low productivity, the most effective strategy is to reforest or otherwise manage the land for forest growth and C storage. Where high productivity can be expected, the most effective strategy is to manage the forest for a harvestable crop and to use the harvest with maximum efficiency either for long-lived products or to substitute for fossil fuels. The longer the time perspective, the more likely that harvesting and replanting will result in net C benefits."

In other words, the *Marland Approach* presumes that:

- Sequestration and biofuel usage are equally valid means of lowering net carbon emissions.
- For a given tract of existing or potential forest, the choice between preserving it and harvesting it for biofuel depends on: 1) energy conversion efficiency, and 2) productivity (or yield).

Since being proposed in 1992, the Marland Approach has been developed in numerous other studies (Schlamadinger et al., 1994; Schlamadinger and Marland, 1996a; Schlamadinger and Marland, 1996b; Schlamadinger et al., 1997; Marland and Schlamadinger, 1997; and Schwaiger and Schlamadinger, 1998) and by an International Energy Agency Task Force (IEA Bioenergy Task 38). It is presented in the Encyclopedia of Energy (2004), and it has been applied by the

Table 2
Current footprint method, excluding biomass combustion emissions

Approach	Implicit sequestration credit	No sequestration credit
Fuel	Harvested logs	Natural gas
Footprint g CO_2eq/MJ		
Cultivation-to-harvest or production	2.5	3.6
Processing	0	3.5
Transport	0.25	7.8
Combustion	2.15[a]	55.1[b]
Total	4.9	70.0

[a] Non-CO_2 GHG emissions only, i.e. combustion of biomass (in this case, logs) is presumed to be carbon neutral.

[b] All GHGs, including CO_2.

Table 4
Proposed footprint method, with biomass carbon-stock depletion

Scenario	Biomass carbon-stock depletion	
Fuel	Harvested logs	Natural gas
Footprint g CO_2eq/MJ		
Cultivation-to-harvest or production	2.5	3.6
Processing	0	3.5
Transport	0.25	7.8
Combustion[a]	2.15	0.1
Carbon-stock decrease[b]	164.25	55.0
Total	169.15	70.0

[a] Non-CO_2 GHG emissions only.

[b] A decrease in carbon stock is shown as a positive number, because carbon footprints are measured as emissions. An increase in carbon stock would be shown as a negative number.

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UNFCCC (2003) in its guidance for national reporting of wood harvesting.

3. Liquid biofuels set a precedent

Challenging the presumed carbon neutrality of biofuels is not entirely new. Only a few years ago, transport biofuels – mainly bioethanol and biodiesel – were considered inherently carbon neutral. This was challenged by a number of studies (for example, EMPA, 2007; or RTFO, 2008) showing that land use change can make footprints highly carbon positive.

Today, researchers and governments generally accept that land-use change must be accounted in liquid biofuel footprints. This change of perception – accepting that biofuels are not automatically carbon neutral – was painful. It hurt biofuel producers, who had invested in new capacity with strong government encouragement, and governmental flip-flopping on biofuels' benefits damaged credibility with the public (Politics, 2008). Early action on the issue posed in this paper – which is similar but not the same as the land use issue – can minimise this sort of pain.

4. The fix: add a footprint line-item of carbon-stock change

To avoid absurd or inaccurate results and to comply with UNFCCC rules, this paper suggests that rather than applying sequestration credits and emission debits, carbon footprints should instead apply a 'carbon-stock change' line item. This method generates accounts more consistent with common sense, UNFCCC aims and the 'Marland branch' of existing literature.

To show how this proposed method would work, two scenarios for changes in carbon stocks are presented. In the first scenario (Table 4), standing trees are being cut and used for fuel. Net carbon stocks in the forest are being depleted, either via deforestation or conventional harvesting. The footprint is equal to that calculated by the current method, but without the sequestration credit (which in the case of carbon-stock depletion, is not justified).

In the second scenario (Table 5), the wood being combusted is not reducing carbon stock, i.e. carbon stocks in the forest are not affected. (It is presumed to be some sort of waste wood that would have decomposed or somehow returned its carbon to the atmosphere anyway.) The footprint is equal to that calculated by the current method, with the sequestration credit.

These are only two out of many possible scenarios for the biomass footprint. Clearly, a number of intermediate scenarios can be envisioned, depending on the extent of carbon stock depletion. Scenarios can also be envisioned where carbon-stock is accruing, which could lead to a net negative footprint for the biomass fuel. The effect over time should be considered (and time periods under consideration should become explicit, which they are not under current guidance and practice); carbon stock should somehow be integrated over time and multiple harvest cycles.

To show more precisely what is going on, carbon-stock change might be presented as a selection of subcategories (that are suggested by under UNFCCC rules and monitored by Switzerland, the UK and probably some others): afforestation, reforestation, deforestation and forest management. Perhaps over time it could be disaggregated even further into carbon in soil, carbon in technosphere reservoirs and other such categories.

Carbon-stock changes can be estimated from data currently made available by the Intergovernmental Panel on Climate Change (2008). Accuracy of estimates will increase as Kyoto-compliant countries report more land use, land use change and forestry (LULUCF) data.

Table 5
Proposed footprint method, without biomass carbon-stock depletion

Scenario	No biomass carbon-stock depletion	
Fuel	Waste logs	Natural gas
Footprint g CO_2eq/MJ		
Cultivation-to-harvest or production	2.5	3.6
Processing	0	3.5
Transport	0.25	7.8
Combustion[a]	2.15	0.1
Carbon-stock decrease	0	55.0
Total	4.9	70.0

[a] Non-CO_2 GHG emissions only.

5. What is carbon stock?

IPCC's guidance (2008, Annex A) defines carbon stock as "the quantity of carbon in a pool." Further, it defines carbon stock changes as: "The carbon stock in a pool can change due to the difference between additions of carbon and losses of carbon. When the losses are larger than the additions, the carbon stock becomes smaller, and thus the pool acts as a source to the atmosphere; when the losses are smaller than the additions, the pools acts as a sink to the atmosphere."

These appear to be useful definitions. Over time, it will likely be necessary to detail and disaggregate them further.

6. Areas for further research

To work well in practice, the argument of this paper will need to be detailed much further: how should carbon stock be defined, i.e. what constitutes a forest or other carbon stock; what is waste, i.e. what can be combusted with a presumed zero depletion of carbon stock[3]; how to integrate carbon stock over time; how to subcategorise its additions and depletions; and how to deal with various types and sources of biomass.

Much of this need not be original research. A large body of knowledge, based on the Marland Approach, can be adapted to this purpose.

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[3] A reviewer of an earlier version of this paper has pointed out that, for instance, some people might define used furniture as waste-wood, with a presumed carbon-stock decrease of zero upon combustion. Others might say that combusting the used furniture constitutes carbon-stock decrease. This paper does not resolve that difference of opinion, but recognizes its importance and suggests that it be studied further.

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Sciencexpress Report

Indirect Emissions from Biofuels: How Important?

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A global biofuels program will lead to intense pressures on land supply and can increase greenhouse gas emissions from land-use changes. Using linked economic and terrestrial biogeochemistry models, we examine direct and indirect effects of possible land-use changes from an expanded global cellulosic bioenergy program on greenhouse gas emissions over the 21st century. Our model predicts indirect land use will be responsible for substantially more carbon loss (up to twice as much) than direct land use; however, because of predicted increases in fertilizer use, nitrous oxide emissions will be more important than carbon losses themselves in terms of warming potential. A global greenhouse gas emissions policy that protects forests and encourages best practices for nitrogen fertilizer use can dramatically reduce emissions associated with biofuels production.

Expanded use of bioenergy causes land-use changes and increases in terrestrial carbon emissions (*1*, *2*). This recognition has led to efforts to determine the credit toward meeting low carbon fuel standards (LCFS) for different forms of bioenergy with an accounting of direct land-use emissions as well as emissions from land use indirectly related to bioenergy production (*3*, *4*). Indirect emissions occur when biofuels production on agricultural land displaces agricultural production and causes additional land-use change that leads to an increase in net greenhouse gas emissions (*2*, *4*). The control of greenhouse gases (GHG) through a cap and trade or tax policy, if extended to include emissions (or credits for uptake) from land-use change combined with monitoring of carbon stored in vegetation and soils and enforcement of such policies, would eliminate the need for such life cycle accounting (*5*, *6*). There are a variety of concerns (*5*) about the practicality of including land-use change emissions in a system designed to reduce emissions from fossil fuels, and that may explain why there are no concrete proposals in major countries to do so. In this situation, fossil energy control programs (LCFS or carbon taxes) must determine how to treat the direct and indirect GHG emissions associated with the carbon intensity of biofuels.

The methods to estimate indirect emissions remain controversial. Quantitative analyses to date have ignored these emissions (*1*), considered those associated with crop displacement from a limited area (*2*), confounded these emissions with direct or general land-use emissions (*6*–*8*), or developed estimates in a static framework of today’s economy (*3*). Missing in these analyses is how to address the full dynamic accounting of biofuel carbon intensity (CI), which is defined for energy as the GHG emissions per megajoule of energy produced (*9*); that is, the simultaneous consideration of the potential of net carbon uptake through enhanced management of poor or degraded lands, nitrous oxide emissions that would accompany increased use of fertilizer, environmental (e.g., climate change, enhanced carbon dioxide concentrations, ozone pollution) effects on terrestrial carbon storage, and consideration of the economics of land conversion. The estimation of emissions related to global land-use change, both those on land devoted to biofuel crops (direct emissions) and those indirect changes driven by increased demand for land for biofuel crops (indirect emissions), requires an approach to attribute effects to separate land uses.

Here, we apply an existing global modeling system that integrates land-use change as driven by multiple demands for land and that includes dynamic greenhouse gas accounting (*10*, *11*). Our modeling system, which consists of a computable general equilibrium (CGE) model of the world economy (*10*, *12*) combined with a process-based terrestrial biogeochemistry model (*13*, *14*), was used to generate global land-use scenarios and explore some of the environmental consequences of an expanded global cellulosic biofuels program over the 21st century. The biofuels scenarios we focus on are linked to a global climate policy to control GHG emissions from industrial and fossil fuel sources that would, absent feedbacks from land-use change, stabilize the

EXHIBIT 5

atmosphere's carbon dioxide (CO_2) concentration at 550 ppmv (*15*). 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 (*16*).

We consider two cases to explore future land-use scenarios: Case 1 allows conversion of natural areas to meet increased demand for land, as long as the conversion is profitable; Case 2 is driven by more intense use of existing managed land. To identify the total effects of biofuels, each of the above cases is compared to a scenario in which expanded biofuel use does not occur (*16*). In the scenarios with increased biofuels production, the direct effects such as changes in carbon storage and nitrous oxide (N_2O) emissions are estimated only in areas devoted to biofuels. Indirect effects are defined as the differences between the total effects and the direct effects.

At the beginning of the 21st century**,** about 31.5% of the total land area (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 (*17*). In both cases of increased biofuels use, land devoted to biofuels becomes greater than all area currently devoted to crops by the end of the 21^{st} century, but in Case 2 less forest land is converted (Fig**.** 1). Changes in net land fluxes are also associated with how land is allocated for biofuels production (Fig. 2). In Case 1**,** there is a larger loss of carbon than in Case 2, especially at mid century. Indirect land use is responsible for substantially greater carbon losses than direct land use in both cases during the first half of the century. In both cases, there is carbon accumulation in the latter part of the century. The estimates include CO_2 from burning and decay of vegetation and slower release of carbon as CO_2 from disturbed soils. The estimates also take into account reduced carbon sequestration capacity of the cleared areas, including that which would have been stimulated by increased ambient CO_2 levels. Smaller losses in the early years in Case 2 are due to less deforestation and more use of pasture, shrubland, and savanna, which have lower carbon stocks than forests and, once under more intensive management, accumulate soil carbon. Much of the soil carbon accumulation is projected to occur in sub-Saharan Africa, an attractive area for growing biofuels in our economic analyses because the land is relatively inexpensive (*10*) and because simple management interventions such as fertilizer additions can dramatically increase crop productivity (*18*).

Estimates of land devoted to biofuels in our two scenarios (15-16%) are well below the estimate of about 50% in a recent analysis (*6*) that does not control land-use emissions. The higher number is based on an analysis that has a lower concentration target (450 ppmv CO_2), does not account for price-induced intensification of land use, and does not explicitly consider concurrent changes in other environmental factors. In analyses that include land-use emissions as part of the policy (*6–8*), less area is estimated to be devoted to biofuels (3-8%).

The carbon losses associated with the combined direct and indirect biofuel emissions estimated for our Case 1 are similar to a previous estimate (*7*), which shows larger losses of carbon per unit area converted to biofuels production. These larger losses per unit area result from a combination of factors including a greater simulated response of plant productivity to changes in climate and atmospheric CO_2 (*15*) and the lack of any negative effects on plant productivity of elevated tropospheric ozone (*19*, *20*).

We also simulated the emissions of N_2O from additional fertilizer that would be required to grow biofuel crops. Over the century, the N_2O emissions become larger in CO_2-eq than carbon emissions from land use (Fig. 3). The net GHG effect of biofuels also changes over time; for Case 1, the net GHG balance is -90 Pg CO_2-eq through 2050 (a negative sign indicates a source; a positive sign indicates a sink), while it is +579 through 2100. For Case 2, the net GHG balance is +57 Pg CO_2-eq through 2050, and +679 through 2100. By the year 2100, we estimate that biofuels production accounts for about 60% of the total annual N_2O emissions from fertilizer application in both cases, where the total for Case 1 is 18.6 Tg N yr^{-1} and for Case 2 is 16.1 Tg N yr^{-1}. These total annual land-use N_2O emissions are about 2.5 to 3.5 times higher than comparable estimates from an earlier study (*8*). Our larger estimates results from differences in the assumed proportion of nitrogen fertilizer lost as N_2O (*21*) as well as differences in the amount of land devoted to food and biofuel production. Best practices for the use of nitrogen fertilizer, such as synchronizing fertilizer application with plant demand (*22*), can reduce N_2O emissions associated with biofuels production.

The CI of fuel was also calculated across three time periods (Table 1) for comparison with displaced fossil energy in a LCFS and identify the GHG allowances that would be required for biofuels in a cap and trade program. Previous CI estimates for California gasoline (*3*) suggest that values less than ~96 g CO_2-eq/MJ indicate that blending cellulosic biofuels will help lower the carbon intensity of California fuel and therefore contribute to achieving the LCFS. Entries that are higher than 96 g CO_2-eq/MJ would raise the average California fuel carbon intensity and thus be at odds with the LCFS. Therefore, the CI values for Case 1 are only favorable for biofuels if the integration period extends into the second half of the century. For Case 2, the CI values turn favorable for biofuels for an integration period somewhere between 2030 and 2050. In both cases, the CO_2 flux has approached zero by the end of the century when little or no further land conversion is occurring and emissions from decomposition are approximately balancing carbon added to the soil from unharvested components of the vegetation (i.e. roots). While the carbon accounting ends up as a nearly net neutral effect, N_2O emissions continue. Annual estimates start high, are variable from year-to-year because they depend on climate, and generally decline over time.

One of the perplexing issues for policy analysts has been predicting the dynamics of the CI over different integration periods (supporting online text). If one integrates over a long enough period, biofuels show a substantial greenhouse gas advantage, but over a short period they have a higher CI than fossil fuel (*3*). Drawing on previous analyses (*5*, *23*), we argue that a solution need not be complex and can avoid valuing climate damages by using the immediate (annual) emissions (direct and indirect) for the CI calculation. In other words, CI estimates should not integrate over multiple years, but rather simply consider the fuel offset for the policy time period (normally a single year). This becomes evident in Case 1, where despite the promise of eventual long-term economic benefits, a substantial penalty - in fact possibly worse than gasoline – in the first few decades may render the near term cost of the carbon debt difficult to overcome.

In Case 2, where there is less willingness to convert land, the economics of biofuels would be favorable sooner. Greater measures to protect forests could make the economics and CI of biofuels even more favorable because improved management on low quality or degraded land can lead to carbon accumulation in the soil, rather than a carbon loss (fig. S3). Interestingly, our results suggest tropical regions that are currently suffering significant amounts of deforestation may also be the most competitive producers of biofuels. Our suggested strategy of not integrating over future fuel offsets increases the near-term CI of biofuels unless forested lands globally are better protected. Success in avoiding deforestation will be reflected in lower estimates of indirect emissions, and a lower carbon penalty in carbon control areas for their use.

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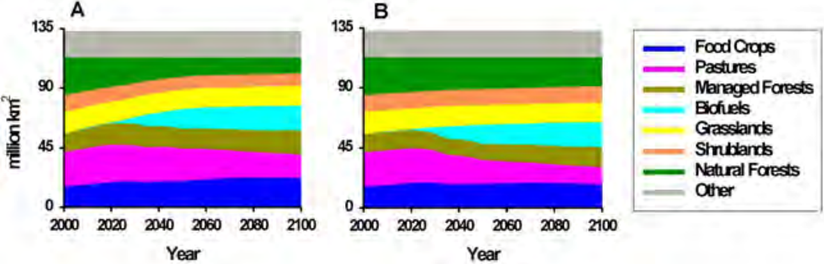
Fig. 1. Projected changes in global land cover for land-use Case 1 (**A**) and Case 2 (**B**). In either case, biofuels supply most of the world's liquid fuel needs by 2100. In Case 1, 365 EJ of biofuel is produced in 2100, using 16.2% (21.6 million km^2) of the total land area; natural forest area declines from 34.4 to 15.1 million km^2 (56%) and pasture area declines from 25.8 to 22.1 million km^2 (14%). In Case 2, 323 EJ of biofuels are produced in 2100, using 20.6 million km^2 of land; pasture areas decrease by 10.3 million km^2 (40%) and forest area declines by 8.4 million km^2 (24% of forest area). Simulations show that these major land-use changes will take place in the tropics and sub-tropics, especially in Africa and the Americas (fig. S2).

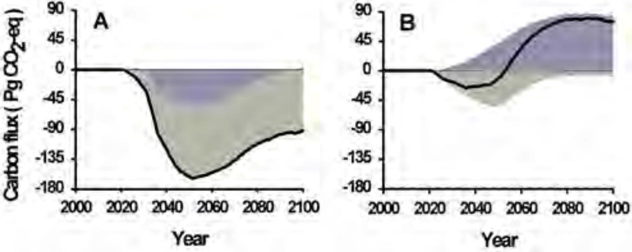
Fig. 2. Partitioning of direct (dark grey) and indirect effects (light grey) on projected cumulative land carbon flux since the year 2000 (solid black line) from cellulosic biofuel production for land-use Case 1 (**A**) and Case 2 (**B**). Positive values represent carbon sequestration whereas negative values represent carbon emissions by land ecosystems. In Case 1 the cumulative loss is 92 Pg CO_2-eq by 2100, with the maximum loss (164 Pg CO_2-eq) occurring in the 2050 to 2055 time frame, with indirect losses of 110 Pg CO_2-eq and direct losses of 54 Pg CO_2-eq. In the second half of the century there is net accumulation of 72 Pg CO_2-eq mostly in the soil in response to the use of nitrogen fertilizers. In Case 2, land areas are projected to have a net accumulation of 75 Pg CO_2-eq (see the black line in 1b) as a result of biofuel production, with maximum loss of 26 Pg CO_2-eq in the 2035 to 2040 time frame, followed by substantial accumulation.

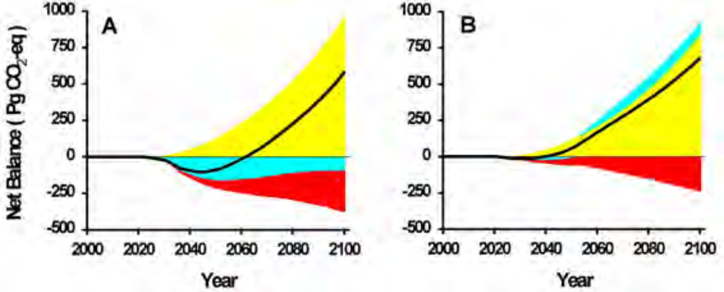
Fig. 3. Partitioning of greenhouse gas balance since the year 2000 (solid black line) as influenced by cellulosic biofuel production for land-use Case 1 (**A**) and Case 2 (**B**) among fossil fuel abatement (yellow), net land carbon flux (cyan), and fertilizer N_2O emissions (red). Positive values are abatement benefits and negative values are emissions. Net land carbon flux is the same as in Fig. 2. For Case 1, N_2O over the century are 286 Pg CO_2-eq; for Case 2, N_2O emissions are 238 Pg CO_2-eq.

Table 1. Carbon intensity index associated with cellulosic biofuel production for two land use scenario cases. Units are g CO_2-eq / MJ, with negative values indicating carbon accumulation.

Variable	**Case 1**			**Case 2**		
Time Period	2000–2030	2000–2050	2000–2100	2000–2030	2000–2050	2000–2100
Direct Land C	11	27	0	–52	–24	–7
Indirect Land C	190	57	7	181	31	1
Fertilizer N_2O	29	28	20	30	26	19
Total	229	112	26	158	32	13


A
B
135
90
45
0
million km^2
2000
2020
2040
2060
2080
2100
Year
Food Crops
Pastures
Managed Forests
Biofuels
Grasslands
Shrublands
Natural Forests
Other


A
B
Carbon flux (Pg CO_2-eq)
90
45
0
-45
-90
-135
-180
2000
2020
2040
2060
2080
2100
Year


A
B
Net Balance (Pg CO2-eq)
1000
750
500
250
0
-250
-500
2000
2020
2040
2060
2080
2100
Year

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Implications of Limiting CO2 Concentrations for Land Use and Energy

Marshall Wise, *et al.*

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Implications of Limiting CO_2 Concentrations for Land Use and Energy

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Limiting atmospheric carbon dioxide (CO_2) concentrations to low levels requires strategies to manage anthropogenic carbon emissions from terrestrial systems as well as fossil fuel and industrial sources. We explore the implications of fully integrating terrestrial systems and the energy system into a comprehensive mitigation regime that limits atmospheric CO_2 concentrations. We find that this comprehensive approach lowers the cost of meeting environmental goals but also carries with it profound implications for agriculture: Unmanaged ecosystems and forests expand, and food crop and livestock prices rise. Finally, we find that future improvement in food crop productivity directly affects land-use change emissions, making the technology for growing crops potentially important for limiting atmospheric CO_2 concentrations.

There is increasing concern over the connection between fossil and industrial emissions and terrestrial ecosystem emissions, and the implications of this interaction for climate change mitigation strategies. Several research studies (*1*–*8*) have shown that the outcome of imposing a mitigation regime that only values carbon from energy and industrial sources creates incentives to increase bioenergy. As the use of bioenergy increases, land uses shift from food and fiber crops, forests, and unmanaged ecosystems to dedicated biomass crops. This in turn increases terrestrial carbon emissions globally—a perverse result of curbing energy and industrial emissions.

Terrestrial systems hold ~2000 Pg C in soils and aboveground biomass (*9*), and a long history of research has highlighted the benefits of slowing or reversing carbon emissions that occur with land-use change. Because the total carbon emissions budget for 2005 to 2100 would have to be kept below ~500 Pg C to keep the atmospheric CO_2 concentration from exceeding 450 parts per million (ppm) (*8*, *10*), terrestrial emissions must be limited, in addition to energy and industrial emissions.

Numerous integrated analyses have examined the implication of limiting the concentration of atmospheric CO_2 with prescribed land use and land-use change assumptions. This literature is summarized by the Intergovernmental Panel on Climate Change (IPCC) (*11*). Here, we examine

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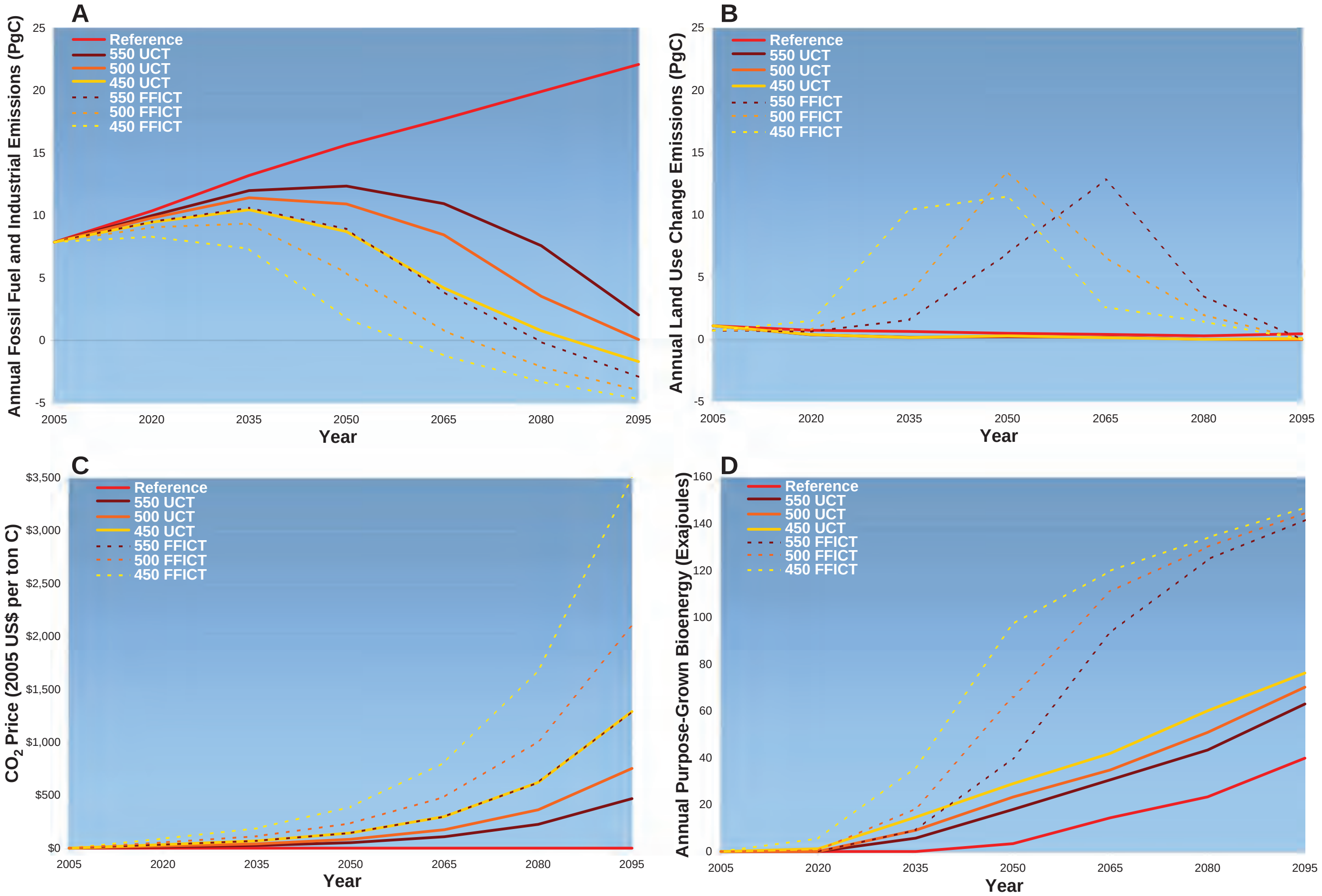

Fig. 1. A comparison of three alternative CO_2 concentration targets under UCT pathways that limit fossil fuel, industrial, and terrestrial carbon emissions with a common carbon tax on emissions to the corresponding FFICT scenarios in which only fossil fuel and industrial emissions are controlled to achieve the same CO_2 concentration. (**A**) Fossil fuel and industrial carbon emissions under these pathways. (**B**) Corresponding carbon emissions from land-use changes. (**C**) Carbon taxes associated with these CO_2 concentration targets and pathways. (**D**) Global quantity of purpose-grown biomass energy in each of these scenarios.

the implications for land use and land-use change from limiting atmospheric CO_2 concentrations in an analysis that endogenously integrates land use with demands in both the agriculture and energy systems.

The results from this integrated assessment study show that if terrestrial carbon emissions are valued equally with carbon emissions from energy and industrial systems in a regime designed to limit atmospheric CO_2 concentrations, there are wide-ranging differences from the case where only carbon emissions from energy and industrial systems are valued. Deforestation is replaced by afforestation, crop prices rise, purpose-grown bioenergy becomes an important agricultural product, and people shift away from consumption of beef and other carbon-intensive protein sources. Further, the total cost of limiting atmospheric CO_2 concentrations is reduced, relative to an alternative regime that prices only fossil fuel and industrial carbon emissions, which implies that lower atmospheric CO_2 concentrations are achievable for any commitment of society's resources, a result consistent with other studies (*12*–*14*) that have examined the potential role of afforestation in limiting CO_2 concentrations. We also find that for any given atmospheric CO_2 limitation goal, the reduction in the cost relative to an alternative regime that prices only fossil fuel and industrial carbon emissions becomes more pronounced as the concentration limit is lowered. We further find that the assumed rate of improvement in crop productivity has a strong influence on land-use change emissions and, correspondingly, on the cost of mitigating climate change.

We employ the Joint Global Change Research Institute's MiniCAM integrated assessment model (*15*–*20*) to explore the implication of limiting atmospheric CO_2 concentrations at levels ranging from 450 ppm to 550 ppm. MiniCAM is a dynamic recursive model of energy, economy, agriculture, land use, and land cover that fully integrates the energy and agriculture systems with economic equilibrium in energy and agriculture markets. Our analysis employs the MiniCAM scenario documented in (*8*) but with an updated, fully integrated terrestrial ecosystem component as described in (*15*, *16*). This MiniCAM scenario assumes a growing population, an increasing standard of living, and the improvement of technology over time. Available energy technology options include CO_2 capture and storage (CCS); hydrogen production and use; nuclear energy; wind, solar, and geothermal power; improved end-use energy technologies in the building, industry, and transportation sectors; and bioenergy. We consider bioenergy production from biological waste streams and next-generation bioenergy from cellulosic (purpose-grown) bioenergy crops. In our reference scenario, we assume that the productivity of land-based products is subject to change over time based on future estimates of crop productivity change up to 2030 (*21*) and then converges to 0.25% per year thereafter (*15*). Land use is determined endogenously in MiniCAM by market forces (*15*, *22*). We also consider fossil fuel, industrial, and land-use change emissions in response to policy intervention modeled as a carbon tax. The distribution of terrestrial carbon reservoirs and their rates of change are computed endogenously in MiniCAM. Emissions limitation scenarios treat bioenergy as carbon neutral in the energy system. We assume that bioenergy can be used in a wide range of applications, including liquefaction to create fuels for transport. We also consider options to gasify bioenergy and use it in conjunction with CCS to make electricity. Market forces are assumed to determine the highest value applications.

We limit the concentration of atmospheric CO_2 by imposing a global carbon tax on anthropogenic carbon emissions (*23*). We consider two canonical tax regimes: (i) a Universal Carbon Tax regime (UCT) in which all carbon emissions in all sectors—including emissions from land-use change—and all regions of the world have

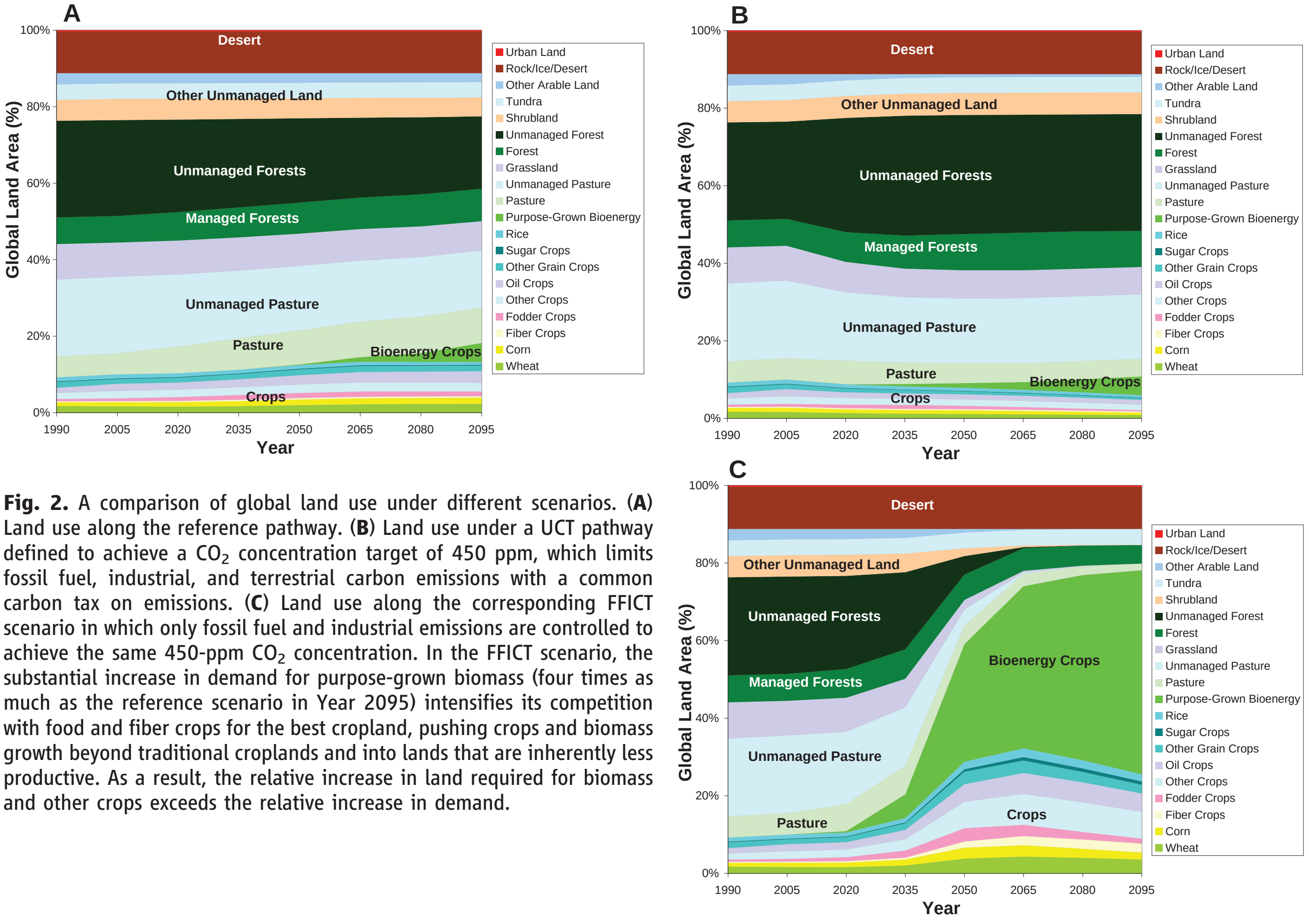

Fig. 2. A comparison of global land use under different scenarios. (**A**) Land use along the reference pathway. (**B**) Land use under a UCT pathway defined to achieve a CO_2 concentration target of 450 ppm, which limits fossil fuel, industrial, and terrestrial carbon emissions with a common carbon tax on emissions. (**C**) Land use along the corresponding FFICT scenario in which only fossil fuel and industrial emissions are controlled to achieve the same 450-ppm CO_2 concentration. In the FFICT scenario, the substantial increase in demand for purpose-grown biomass (four times as much as the reference scenario in Year 2095) intensifies its competition with food and fiber crops for the best cropland, pushing crops and biomass growth beyond traditional croplands and into lands that are inherently less productive. As a result, the relative increase in land required for biomass and other crops exceeds the relative increase in demand.

the same value at any point in time, and (ii) a Fossil Fuel and Industrial Emissions Carbon Tax regime (FFICT) in which the carbon tax is applied to fossil fuel and industrial emissions but not to terrestrial carbon emissions. In both cases, the carbon tax rises over time so as to limit atmospheric CO_2 concentrations to a prescribed level.

Whether the carbon tax is applied as a UCT or a FFICT has important implications for the source of emissions and for land-use patterns. Placing an increasingly stringent tax on only the fossil fuel and industrial carbon emissions without placing any corresponding tax on terrestrial carbon (i.e., the FFICT regime) causes land-use change emissions to increase to a peak greater than 10 Pg C per year, as lands are converted to meet the growing demands for purpose-grown bioenergy crops in a growing but decarbonizing energy system (Fig. 1). This is the same effect observed by earlier studies, including (*1*, *3*). The increased demand for bioenergy crops pushes land requirements beyond traditional croplands and into lands that are increasingly less productive, requiring increasing quantities of land to grow each successive unit of agricultural product. The result is that in the FFICT regimes virtually all land that is not required for growing food and forest products is used for growing bioenergy (Fig. 2).

Such grand-scale deforestation is hard to imagine in reality, because it is hard to imagine that society would find this result acceptable. Nevertheless, this admittedly extreme case stands in sharp contrast to the UCT regime in which land-use change emissions face the same carbon tax as fossil fuel and industrial emissions. The application of a carbon tax to terrestrial carbon emissions sends an increasingly strong price signal that expands forested land while land dedicated to bioenergy crop production is limited (Fig. 2) (*24*), although bioenergy remains an important technology in the overall mitigation portfolio. The difference in cumulative land-use change emissions between the FFICT and UCT regimes, from 2005 through 2100, ranges from >300 Pg C (550-ppm limit) to >400 Pg C (450-ppm limit).

For any given concentration limit, the proportion of emissions from fossil fuel and industrial sources and land-use change is affected by the tax regime. The UCT regime results in a higher proportion of emissions from fossil fuel and industrial sources, with a correspondingly lower proportion of emissions from land-use change (*25*). Equivalently, at any given carbon price, carbon emissions are lower when terrestrial carbon is valued.

Applying a carbon tax to all carbon emissions (the UCT regime) reduces economic impacts relative to the FFICT approach. At all atmospheric CO_2 concentration limits, we find that the resulting carbon tax under the UCT regime was less than half that of the carbon tax resulting from the FFICT regime. This reduction in economic impacts flows naturally from economic principles. The UCT regime covers all emissions sources rather than a subset of emissions sources and thus is economically more efficient.

We also note that crop (including food and fiber) prices rise in the UCT regime as a consequence of the economic impact from valuing terrestrial carbon, even in the absence of purpose-grown bioenergy crops. This follows directly from limitations on land availability and the expanded use of land in the form of managed forests and unmanaged ecosystems in the UCT scenarios. The crop price increase is highest for the most carbon-intensive agricultural activities, and the crop price effect becomes more pronounced for stricter concentration limits. Changing agricultural prices flowing from the UCT also drive changes in dietary composition, reducing emphasis on beef and other carbon-intensive protein sources, which in turn frees up land for bioenergy and other crop production.

By comparing results to scenarios in which no purpose-grown bioenergy crops are allowed, Fig. 3 decomposes the effects of valuing carbon on crop prices, using corn prices as representative. The figure shows that there is virtually no discernible effect on corn prices in the reference scenario when purpose-grown bioenergy crops are removed from the analysis. However, when CO_2 concentration is limited (to 500 ppm here, for example), both valuing terrestrial carbon and allowing purpose-grown bioenergy exert upward pressure on crop prices.

Finally, terrestrial carbon emissions are sensitive to crop productivity growth assumptions. As a sensitivity experiment, we held crop productivity constant at 2005 levels. Land-use change carbon emissions in a scenario where no climate policy was imposed were more than 70 Pg C higher over the 21st century because greater amounts of land were necessary to produce the same amount of food. In the "frozen productivity" scenario, crop land expansion dramatically encroaches on forested lands, releasing the carbon stored in forest vegetation and soils. The difference in land-use change emissions in 2050 is larger than one "wedge" (*26*), defined as approximately 1 Pg C per year in 2050. Improved crop productivity thus has the potential to reduce anthropogenic carbon emissions at a magnitude similar to the energy technologies identified by other studies (*26*, *27*).

Limiting atmospheric CO_2 concentrations through a comprehensive approach that fully incorporates both terrestrial emissions and fossil and industrial emissions carries with it profound implications for forests, crop and livestock prices, diet, the global energy system, and the cost of meeting environmental goals. However, in this study we have not examined the implications for non-CO_2 emissions, which are a major component of terrestrial system emissions. These interactions are important, as was shown by (*6*, *28*). Another limitation of this study is water, which we have not explicitly modeled.

Most of the world's fossil fuel and industrial carbon emissions today carry no value, explicit or implicit. Considerable research has investigated alternative mechanisms for pricing fossil fuel and industrial carbon, both explicitly through taxes or cap-and-trade regimes and implicitly through regulatory frameworks. Less attention has been placed on developing methods of associating carbon values with terrestrial systems, at least in part because they are less straightforward than those dealing with fossil fuel carbon emissions and because the cost of implementing emissions mitigation policies in terrestrial systems would probably be higher than in the energy system. The development of methods for conveying carbon values to land-use decision-makers could substantially improve the environmental effectiveness of global carbon emissions limitation systems. Improved land-use management and improved agricultural practices could reduce upward pressure on crop prices and the cost of emissions mitigation. However, the allocation of scarce land resources to competing ends will remain a major challenge for the 21st century.

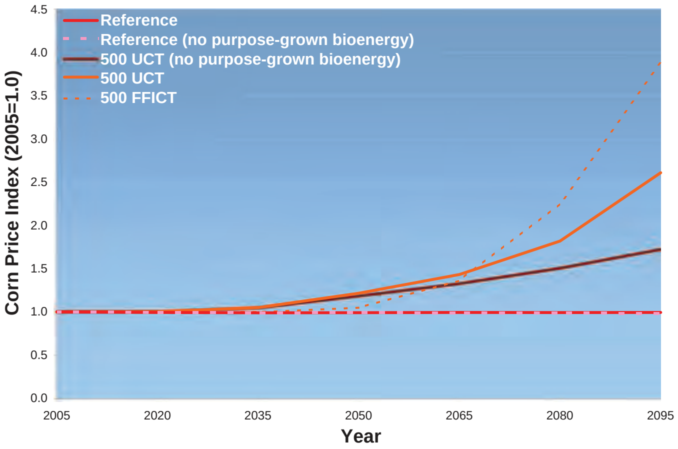

Fig. 3. The price of corn associated with a reference pathway; a pathway defined to achieve a UCT CO_2 concentration target of 500 ppm in 2095, which limits fossil fuel, industrial, and terrestrial carbon emissions with a common carbon tax on emissions; and a comparison to the corresponding FFICT scenario in which only fossil fuel and industrial emissions are controlled to achieve the same CO_2 concentration. To isolate the impact of bioenergy on the price, a second reference pathway and a second UCT-derived 500-ppm 2095 CO_2 concentration target pathway are constructed under the assumption that no purpose-grown bioenergy is available.

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24. Our analysis finds that bioenergy derived from biological waste streams (e.g., agriculture and forestry residues) is potentially of comparable magnitude to purpose-grown bioenergy production in the UCT policy regimes.
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Penultimate Deglacial Sea-Level Timing from Uranium/Thorium Dating of Tahitian Corals

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The timing of sea-level change provides important constraints on the mechanisms driving Earth's climate between glacial and interglacial states. Fossil corals constrain the timing of past sea level by their suitability for dating and their growth position close to sea level. The coral-derived age for the last deglaciation is consistent with climate change forced by Northern Hemisphere summer insolation (NHI), but the timing of the penultimate deglaciation is more controversial. We found, by means of uranium/thorium dating of fossil corals, that sea level during the penultimate deglaciation had risen to ~85 meters below the present sea level by 137,000 years ago, and that it fluctuated on a millennial time scale during deglaciation. This indicates that the penultimate deglaciation occurred earlier with respect to NHI than the last deglacial, beginning when NHI was at a minimum.

Fossil corals are a valuable archive of past sea level, but the density of coral data is biased toward sea-level highstands because of the inaccessibility of fossil corals that grew during lower sea level and are now further submerged. Reconstruction of lower sea levels has relied on dredging and submersible sampling, occasional fortuitous finds in uplifted terraces (*1*, *2*), and the challenging approach of coral-reef drilling. Such drilling, while technically demanding and expensive, has yielded valuable records of sea-level change for the last deglacial (*3*, *4*) and more limited constraints on the onset of the last interglacial (*5*).

To target deeper and earlier portions of the sea-level curve, Integrated Ocean Drilling Program (IODP) Expedition 310 (known as the "Tahiti Sea Level" expedition) drilled submerged reefs in seawaters ranging from 41.7 to 117.5 m (*6*). The island of Tahiti Nui (French Polynesia) is located in the southern tropical Pacific and is distant from locations of glacial ice sheets. Sea-level change at Tahiti during deglaciation is therefore dominated by the addition of meltwater to the oceans rather than by the effects of ice mass redistribution and isostacy. Steady subsidence of 0.25 m per 1000 years (*4*), resulting from the load of the island on the underlying oceanic plate coupled with a location distant from ice loading, makes Tahiti an ideal site to reconstruct past sea levels. Material from before the Last Glacial Maximum was recovered at each of the three locations where Tahiti drilling was performed (Faaa, Maraa, and Tiarei) (*6*) (fig. S1) and seven separate cores have yielded pre-LGM corals suitable for U/Th dating from 113 to 147 m below sea level (mbsl).

Corals were screened for secondary calcite and aragonite by x-ray diffraction (XRD) and thin-section petrography. Of the 25 pre-LGM corals analyzed for U-Th isotopes (*7*), 12 had values of $(^{234}\text{U}/^{238}\text{U})_i$ ($^{234}\text{U}/^{238}\text{U}$ ratios corrected for decay since deposition) between 137 and 151 per mil (‰), which we take as a reasonable range on the basis of known variability of past seawater $^{234}\text{U}/^{238}\text{U}$ ratios during the glacial-interglacial cycle (*5*, *8*). These 12 are considered pristine and are discussed further here; replicate measurements that differ significantly have been excluded from discussion (but are illustrated in Fig. 1B as small circles).

Corals of marine isotope stage 3 (MIS 3) age, after a correction for subsidence [0.25 m per 1000 years (*4*)], occur at 105 to 130 mbsl with ages

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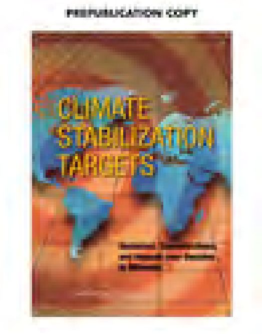

Stabilization Targets for Atmospheric Greenhouse Gas Concentrations

Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations; National Research Council

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EXHIBIT 8

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Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia

Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
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Summary

Society faces important choices in the coming century regarding future greenhouse gas emissions and the resulting effects on the Earth's climate, ecosystems, and people. Atmospheric concentrations of several important greenhouse gases have increased markedly since the start of the 20th century because of human activities, and the increased concentrations of these gases *very likely*[1] account for most of the globally averaged warming of the past fifty years. Carbon dioxide is responsible for more than half of the current impact of human emissions of greenhouse gases on Earth's climate, or radiative forcing[2], and its influence is projected to grow. Its atmospheric concentration has increased by more than 35 percent since 1750, and is now higher than at any time in at least 800,000 years. Looking to the future, the concentration of carbon dioxide could undergo a further doubling or tripling by the end of the century, greatly amplifying the human impact on climate.

Because of the long atmospheric lifetime of carbon dioxide and the time lags in the climate system (particularly slow processes in the ocean, see 3.2), human choices in the near-term have long-term ramifications on Earth's climate not only for the rest of the century but also for the next several millennia. Indeed, some effects of 21st century human choices would contribute to climate change for more than 100,000 years. {2.1, 3.2}[3]

One way of informing these choices is to consider the projected climate changes and impacts that would occur if greenhouse gases increase to particular concentration levels and then stabilize, as highlighted in the Statement of Task (see Appendix A). Alternative futures then can be represented by a broad range of atmospheric concentration "target" levels (hereafter referred to as stabilization targets). The committee was charged to evaluate different stabilization targets

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[1] In this report, uncertainty ranges indicated as *likely* correspond to >66% probability (2 out of 3 chance), while *very likely* is used for >90% (9 out of 10 chance). Assessed uncertainty intervals are not always symmetric about the corresponding best estimate, and include statistical information and expert judgment.

[2] **Radiative forcing (RF)** refers to the radiative flux change evaluated at the tropopause (which has been adjusted for stratospheric changes, see Ramaswamy et al., 2007). Greenhouse gases such as carbon dioxide, methane, and nitrous oxide exert a warming influence on climate, and differ in their radiative forcing of the global climate system due mainly to their different radiative properties and abundances in the atmosphere. Some greenhouse gas changes (e.g., stratospheric ozone depletion) and aerosols produce negative radiative forcing. The net RF is the sum of positive and negative terms, and each term is defined as the change relative to 1750. These warming influences may be expressed as **CO_2-equivalent concentrations**, corresponding to the concentration of CO_2 that would cause the same amount of radiative forcing as a given mixture of CO_2 and other forcing components.

[3] Throughout this summary and the technical overview presented in the next section, numbers in curly brackets refer to sections of the main report where details and references are to be found.

with particular emphasis on the avoidance of serious or irreversible impacts on the Earth's climate system. This report does not evaluate the plausibility of any stabilization target, nor does it make any recommendations regarding desirable or "safe" targets.

It should be emphasized that choosing among different targets is a policy issue rather than strictly a scientific one, because such choices involve questions of values, e.g., regarding how much risk to people or to nature might be considered too much. Some climate changes could be beneficial for some people or regions, while being damaging to others.

The primary challenge for this study is to quantify, insofar as possible, the outcomes of different stabilization targets using analyses and information drawn from the scientific literature. Expected changes based on broad scientific understanding are discussed, as well as projected values based upon models. Where there is sufficient understanding to be quantitative, numerical values for projected climate change and impacts are provided as a function of stabilization target. A number of important aspects of climate change that are currently understood in a qualitative manner, or for which the time horizon of the response is poorly constrained, are also reviewed. The report represents a brief summary of a vast scientific literature and seeks to be illustrative and representative rather than comprehensive. Special emphasis is placed on climate changes and impacts in North America and the United States.

The report focuses on human forcing of the climate system from carbon dioxide emissions and rising atmospheric concentrations because of the dominant role and unique influences of carbon dioxide on long-term climate change. The role of other anthropogenic greenhouse gases, such as methane, nitrous oxide and halocarbon, and aerosols are also briefly discussed. For many purposes, the total radiative forcing of the suite of anthropogenic greenhouse gases and aerosols can be cast in terms of an equivalent level of atmospheric carbon dioxide, also known as the CO_2-equivalent concentration.

APPROACH

The goal and implications of stabilizing climate change are most often discussed in terms of stabilizing atmospheric concentrations of CO_2. This report takes a different approach by 1) using global temperature change as the frame of reference, and 2) focusing in part on the relationship between accumulated carbon emissions and global mean temperature change.

The motivation for this approach is both practical and conceptual. Available data and modeling suggest that the magnitudes of many key impacts can be quantified for given amounts of global warming through scaling of local to global warming and through coupled linkages to warming (such as alterations in the water cycle that scale with warming). But while published analyses of future climate impacts can be tied to specific warming levels in particular studies, this information often cannot readily be linked to CO_2-equivalent concentrations (because, for example, of lack of information on aerosol forcing used in many future climate impact studies based on emission scenarios).

Moreover, using warming as the frame of reference provides a picture of impacts and their associated uncertainties in a warming world – uncertainties that are distinct from the uncertainties in the relationship of CO_2-equivalent concentrations to warming. Use of warming as a metric of change also permits coverage of the transient climate changes and impacts while concentrations increase, as well as the lock-in to further changes after stabilization. Further, the approach taken here facilitates cataloguing ranges of impacts that should be expected for 1°C, 2°C, 3°C, or other levels of warming. The reader can thus consider how much warming s/he considers to be an appropriate target. Information is also provided to translate warming into best estimates of associated CO_2-equivalent target concentrations with these best estimates accompanied by estimated likely uncertainty ranges derived from uncertainty in climate sensitivity.

Furthermore, this report also describes the cumulative carbon framework, a perspective that has recently received considerable attention. Rather than CO_2-equivalent concentration levels, this approach considers the amount of carbon emissions accumulated over time and the implications of different accumulated emissions targets. Models consistently suggest a persistent temperature response to a given level of cumulative carbon emissions. Accumulated carbon emission targets link to impacts through temperature (or warming) and are clearly relevant to policy aimed at controlling emissions and reducing the risk of dangerous impacts. The approaches used here thereby provide additional policy-relevant information that would be lost in an analysis that only related impacts to CO_2-equivalent concentration levels.

KEY FINDINGS

There are three key findings of this report, which correspond to the structure of this summary:

1. Climate change in the very long term: Future stabilization targets correspond to altered states of the Earth's climate that would be nearly irreversible for many thousands of years, even long after anthropogenic greenhouse gas emissions ceased. The capacity to adapt to slow changes is generally greater than for near-term rapid climate change, but different stabilization levels can lock the Earth and many future generations of humans into large impacts that can occur very slowly over time, such as the melting of the polar ice sheets; similarly, some stabilization levels could prevent such changes.

2. Climate change in the next few decades and centuries: Understanding the implications of future stabilization targets requires paying attention to the expected climate change and to the emissions required to achieve stabilization. Because of time-lags inherent in the Earth's climate, the observed climate changes as greenhouse gas emissions increase reflect only about half of the eventual total warming that would occur for stabilization at the same concentrations. Moreover, emission reductions larger than about 80% (relative to whatever peak global emission rate may be reached) are required to approximately stabilize carbon dioxide concentrations for a century or so at any chosen target level (e.g., 450 ppmv, 550 ppmv, 650 ppmv, 750 ppmv, etc.), Even greater reductions in emissions would be required to maintain stabilized concentrations in the longer term. It should be emphasized that this finding is not linked to any particular policy choice about time of stabilization or stabilization concentration, but applies broadly, and is due to the fundamental physics of the carbon cycle presented in Chapter 2.

3. Climate changes, impacts and choices among stabilization targets: A number of key climate changes and impacts for the next few decades and centuries can now be identified and estimated at different levels of warming. Many impacts can be shown to scale with warming (see Figure S.5). Scientific progress has resulted in increased confidence in the understanding how global warming levels of 2, 3, 4, 5°C, etc. (see Figure S.1) affect precipitation patterns, extreme hot seasons, streamflow, sea ice retreat, reduced crop yields, coral bleaching, and sea level rise. This increased confidence provides direct scientific support for evaluating the implications of different stabilization targets. However, other climate changes and impacts are currently understood only in a qualitative manner. Many potential effects on human societies and the natural environment cannot presently be quantified as a function of stabilization target (see Figure S.6). This shortcoming does not imply that these changes and impacts are negligible. Some of these impacts, such as species changing their ranges or behavior, could be very important; indeed, some may dominate future risks due to anthropogenic climate change. Uncertainty in the carbon dioxide emissions and concentrations corresponding to a given temperature target is large, and choices about stabilization targets depend upon judgments regarding the degree of acceptable risk associated with both quantifiable and non-quantifiable impacts and changes.

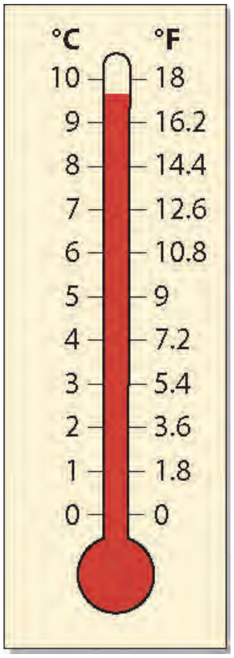

FIGURE S.1 Illustration of how temperature change in degrees Celsius (left side of thermometer) relates to temperature change in degrees Fahrenheit (right side of thermometer). For example, a warming of 5 degrees Celsius is equal to a warming of 9 degrees Fahrenheit. In this report estimates of temperature change are made in degreees Celsius in accordance with international scientific practice.

SUPPORTING EVIDENCE

1. Cumulative Carbon Dioxide Emissions and Climate Change Over Millennia

Climate changes that occur because of carbon dioxide increases are expected to persist for thousands of years[4] even if emissions were to be halted at any point in time. Recent scientific

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[4] Approaches to ‘geoengineer’ future climate, e.g., to actively remove carbon from the atmosphere or reflect sunlight to space using particulate matter or mirrors are topics of active research. If effective, these may be able to reduce or reverse global warming that would otherwise be effectively irreversible. This

literature has shown that the contribution to global warming caused by anthropogenic CO_2 can be directly related to the cumulative emissions of carbon dioxide.

For example, our best estimate (see Figure S.2) is that one thousand gigatonnes of anthropogenic carbon (GtC) emissions leads to about 1.75°C increase in global average temperature[5], implying that approximately 1150 gigatonnes of carbon (or 4200 Gt CO_2) would lead to a global-mean warming of 2°C (the stated aspirational goal of the 'group of eight' nations). Based on current understanding, this warming is expected to be nearly irreversible for more than 1,000 years (Figure S.3). Figure S.2 shows best estimates and likely uncertainty ranges for cumulative carbon emissions leading to a range of warming levels, along with cumulative emissions to date (about 500 GtC). Carbon dioxide alone accounted for about 55 percent of the total CO_2 equivalent concentration of the sum of all greenhouse gases in 2005. The contribution of carbon dioxide increases to between 75 and 85 percent of total CO_2-equivalent by the end of this century based on a range of current emission scenarios. Some anthropogenic carbon dioxide is removed by the oceans and biosphere in decades to centuries, but the slow time-scales of the long-term uptake of carbon in the ocean means that some is expected to persist in the atmosphere for many thousands of years. This behavior is unique to carbon dioxide among major radiative forcing agents. Choices regarding continued emissions or mitigation of other warming agents such as methane, black carbon on ice/snow, and aerosols can affect the global warming of coming decades but have little effect on the lock-in to longer-term warming of the Earth over centuries and millennia; that commitment is primarily controlled by carbon dioxide. {2.1, 2.2, 2.3, 3.4}

BOX S.1
GtC (Gigaton of carbon)

One gigaton of carbon is one billion tons of carbon, where "carbon" refers literally to the mass of carbon, *not* the mass of a molecule as a whole (i.e., all the atoms), but just the mass of carbon atoms.
Example: Burning 1 gallon of gasoline emits approximately 19.6 lbs of CO_2 (http://cdiac.ornl.gov/pns/faq.html), so if you assume a typical American vehicle gets 20 miles per gallon and it travels 15,000 miles per year, then the typical American vehicle emits about 1.8 tons of carbon per year. Stated differently, about 550,000,000 average American vehicles would emit 1 GtC per year.

The Earth is now entering a new geological epoch, sometimes called the Anthropocene, during which the evolution of the planet's environment will be largely controlled by the effects of human activities, notably emissions of carbon dioxide. Actions taken during this century will determine whether the Anthropocene climate anomaly will be a relatively short term and minor deviation from the Holocene climate, or an extreme deviation extending over many thousands of years.

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study does not evaluate geoengineering options, and statements throughout this report regarding the commitment to climate change over centuries and millennia from near term emissions should be read as assuming no geoengineering. Reforestation or other methods of sequestration of carbon are also not considered.

[5] The quasi-linear response of temperature to cumulative carbon is discussed in detail in Section 2.7.

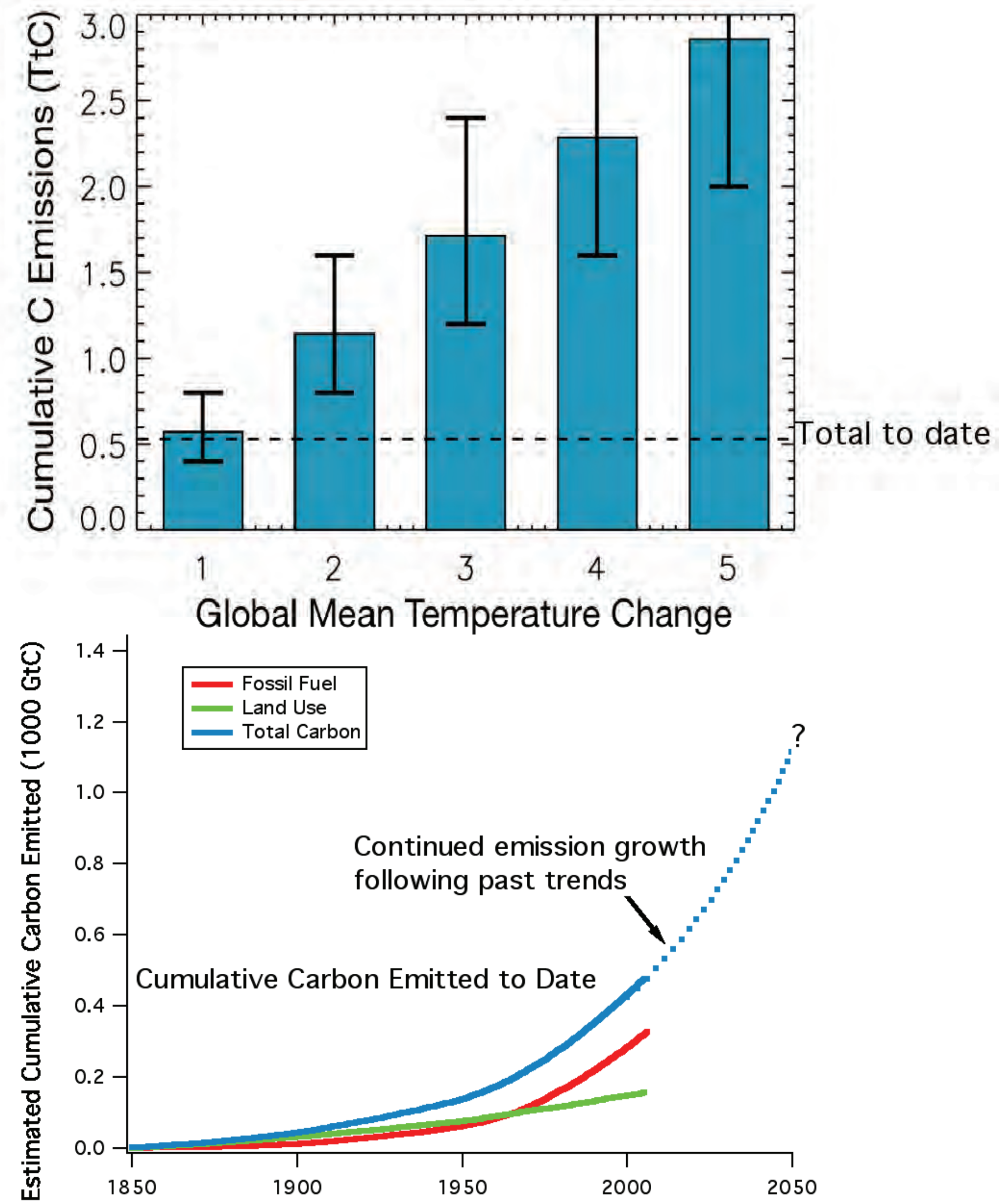

FIGURE S.2 (top) Best estimates and likely range of cumulative carbon emissions that would result in global warming of 1, 2, 3, 4, or 5°C (see Figure S.1), based on recent studies which have demonstrated a near-linearity in the temperature response to cumulative emissions (see Section 3.4) Error bars reflect uncertainty in carbon cycle and climate responses to CO_2 emissions, based on both observational constrainsts and the range of climate-carbon cycle model results (see Section 3.4). (bottom) Estimated global cumulative carbon emissions to date from fossil fuel burning and cement production, land use, and total. The figure also shows how much cumulative carbon would be emitted by 2050 if past trends in emission growth rates were to continue in the future, based upon a best fit to the past emission growth curve. {3.4}

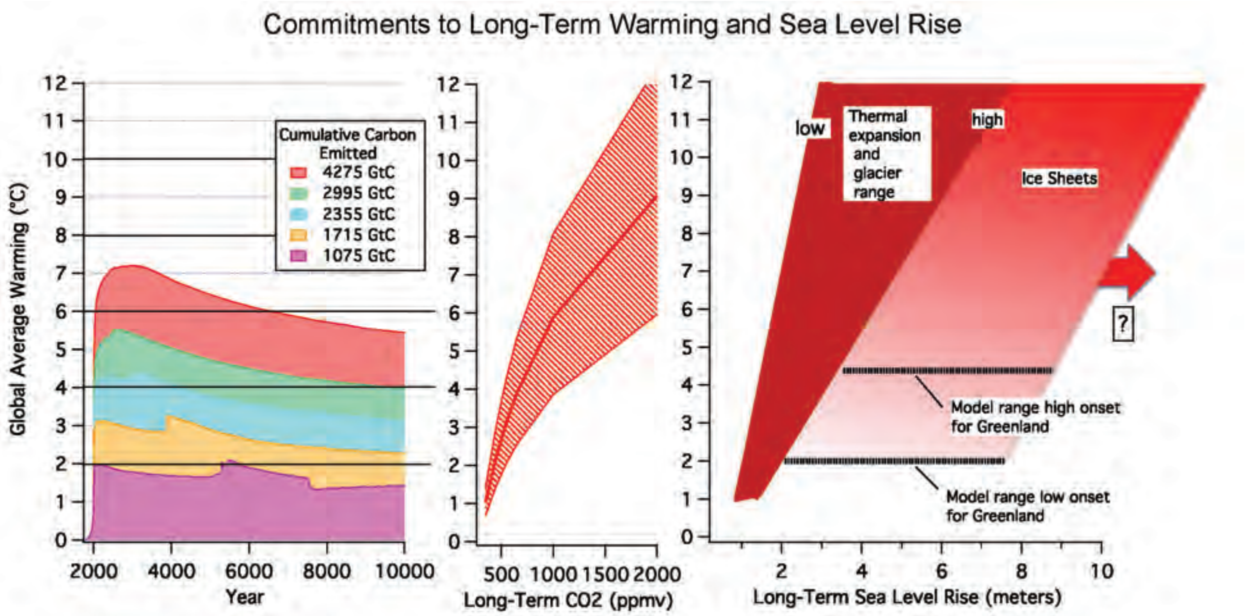

FIGURE S.3 Commitments to global warming over thousands of years, expressed as best estimates depending upon the cumulative anthropogenic carbon emitted (direct human emission plus possible induced feedbacks such as release of carbon from clathrates, see below) by the end of the next few centuries from a model study (left, from the calculations presented in Eby et al., 2009), the corresponding long-term carbon dioxide concentrations, shown as best estimates and likely ranges (middle, from Table 3.1 of this report), and estimated range of corresponding global average sea level rise (right, see Section 6.1; the adopted equilibrium long-term thermal sea level rise is 0.2-0.6 m per degree as noted in Meehl et al., 2007). The 'low' and 'high' onset values in the right panel reflect differences between available climate models in the global mean temperature at which the Greenland ice sheet will disappear after thousands of years since the accumulation cannot sustain the ice loss by melt in the ablation area and rapid ice flow-related loss along the margins. This depends not only on increased ice loss from warming but also on increased accumulation from greater snowfall in a warmer world, and the balance between these terms differs from model to model. The range across models is taken from Meehl et al., 2007, based on a detailed analysis of the models evaluated in the IPCC report. Additional contributions from rapid ice discharge are possible (see Chapters 4 and 6). The climate sensitivity used to construct the likely ranges shown in the middle panel is discussed in chapter 3 where it is noted that larger or smaller warmings than the estimated likely value for a given carbon dioxide concentration cannot be ruled out. Bumps in the warming curves in the left panel are because of adjustments in ocean circulation in response to warming in this particular climate model and should be thought of as illustrative only. {3.2, 6.1}

Higher cumulative carbon emissions result in both a higher peak warming and a longer duration of the warming (see Figure S.4). The duration of the warming is critical, because an extended period of warming provides more time for the components of the Earth system that may respond very slowly (such as the deep oceans and the great ice sheets) to assert themselves, even very long after anthropogenic emissions have ceased. {6.1}

The sea level rise implications of the Anthropocene could lead to major changes in the geography of the Earth over the coming millennia. Model studies suggest that a cumulative carbon emission of about 1000 to 3000 GtC would lead to eventual sea level rise due to thermal expansion and glacier and small ice cap loss alone of the order of 1 to 4 meters. Additional contributions from Greenland could contribute as much as a further 4 to 7.5 m on multi-millennial timescales, for a possible total of order 5 to 11.5 meters from thermal expansion, glaciers and small ice caps, and Greenland.

Widespread coastal inundation would be expected if anthropogenic warming of several degrees is sustained for millennia; while these slow changes allow time for adaptation, they are essentially irreversible. The projected fragility of the Greenland ice sheet is in accord with studies suggesting that Greenland was essentially free of ice during the Pliocene era (which was probably about 3°C warmer than pre-industrial times in the mid-Pliocene, about 3-3.3 million years ago). Changes in Antarctica are less clear, in part because both the West and East Antarctic ice sheets must be considered: one study suggests that cumulative carbon emission of about 2000-5000 GtC could also contribute up to five meters of additional sea level rise from West Antarctic ice sheet loss. Future changes in East Antarctica could offset at least part of West Antarctic changes. While carbon emissions in the 21st century are expected to determine the commitments to these eventual future changes, the sea level rise expected to occur in the 21st century is considerably smaller, in the range of 0.5 to 1.0 meters. Some semi-empirical models predict sea level rise up to 1.6 m by 2100 for a warming scenario of 3.1°C, a possible upper limit which cannot be excluded. {6.1, 4.8}

Some slow climate components could act as amplifiers that would greatly increase the size and duration of the Anthropocene.

If elevated global temperatures were to persist for a thousand years or more, some studies suggest that the resulting warming of the deep ocean could release deep-sea carbon stored in the form of methane clathrates[6] in marine sediments. Other contributions could come from the substantial reservoir of near-surface organic carbon in soils and permafrost, whose stability is poorly understood. For example, a release rate of a half GtC per year from such sources would add 2500 Gt of carbon over 5000 years to the carbon emitted directly by humans. For reference, paleoclimate studies suggest that during the Paleocene-Eocene Thermal Maximum (about 55 million years ago), similar amounts of carbon were released in less than 10,000 years. A number of recent studies show that large methane releases from particular local sites have been observed, but these are too limited to imply that globally significant changes are already occurring or will occur for warming levels in the near term. {6.1}

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[6] Methane clathrates, also called methane hydrates, are material in which methane is trapped inside a larger crystalline water chemical structure.

2. Stabilization and Climate Change of the Next Few Decades and Next Several Centuries

Because the global anthropogenic source of carbon dioxide greatly exceeds the net global sink (through removal mechanisms in the ocean, land, and biosphere), stabilization of carbon dioxide concentrations at any selected target level would require reductions in total emissions of at least 80 percent (relative to any peak emission level).

Unless the source matches the sink, concentrations of carbon dioxide (and resulting warming influences) will continue to rise, much like the water in a bathtub when water is coming in faster than it is going out. Because current carbon dioxide emissions exceed removal rates, stabilization of carbon dioxide *emissions* at current rates will not lead to stabilization of carbon dioxide concentrations (see Figure S.4). A robust consequence of the stock and flow nature of atmospheric carbon and the physics of the carbon cycle is that emission reductions larger than about 80% (relative to whatever peak emission level occurs) are required to approximately stabilize carbon dioxide concentrations for a century or so and even greater reductions in emissions would be required in the longer term; this applies for any chosen stabilization target.

Observed climate responses in coming decades will be smaller than the longer-term temperature response to any given stabilization level. If carbon dioxide equivalent concentrations were to be stabilized at some point in the future, there would be a lock-in to further warming of comparable magnitude to that already occurring at the time of stabilization.

The instantaneous response of the Earth's atmosphere and oceans to increases in greenhouse gases and net radiative forcing represents a transient climate change, which can be linked to 'transient climate response'.[7] The transient climate response is smaller than the longer-term 'climate sensitivity' that includes adjustments by the oceans to the added heat. For example, if carbon dioxide equivalent concentrations (including aerosols and other gases) were to increase from today's best estimate levels of about 390 parts per million by volume (ppm) to 550 ppm at rates of growth similar to those occurring today, averaged warming would be expected to increase in a manner that scales with the change in radiative forcing relative to the transient climate response; for 550 ppm the best estimate total warming since pre-industrial times is about 1.6°C (within a likely uncertainty range of 1.3-2.2C). In the hypothetical case where concentrations are then immediately stabilized at 550 ppm, further warming would subsequently occur over the next several centuries, reaching a best estimate 'climate sensitivity' of about 3°C (likely in the range of 2.1-4.3°C). The horizontal arrow in Figure S.4 depicts such a transition from transient to equilibrium warming. {2.2, 2.4, 3.2, 3.3}

Climate sensitivity remains subject to considerable uncertainty. The estimated "likely" range presented in this report corresponds to the range of model results in the CMIP3 global climate model archive, and is roughly consistent with paleoclimate evidence. However, the possibility of climate sensitivities substantially higher than this range cannot at present be ruled out. This

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[7] The transient climate response is defined as the warming at the time of doubling of CO_2 concentration (compared to a pre-industrial value of 278 ppm this is about 550 ppm). Scaled by radiative forcing, the same relationship characterizes warming that has occurred during the 20th century as well as further warming that is projected to continue with growing CO_2 concentrations in the 21st century for a broad range of plausible scenarios.

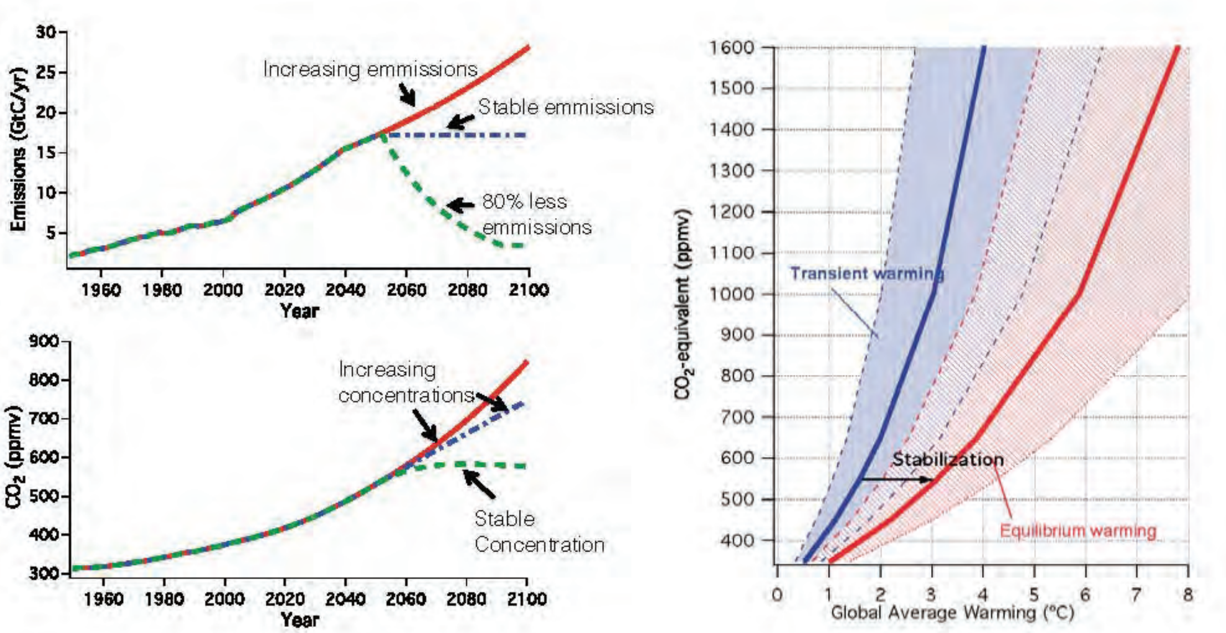

FIGURE S.4 The left panel shows illustrative examples (from calculations using the Bern Earth Model of Intermediate Complexity, see Chapter 2 and Methods) of how carbon dioxide concentrations would be expected to evolve depending upon emissions. Stable emissions (blue lines) do not result in stable concentrations because the source of carbon is much larger than the sink. Emission reductions larger than about 80% are required if concentrations are to be stabilized (green lines). The right panel shows the best estimates and likely ranges of global warming projected for various levels of carbon dioxide concentration in the transient (blue) and equilibrium states, or climate sensitivity (red); see Table 3.1. As carbon dioxide emissions increase, average global warming is projected to follow the blue curve. If concentrations of carbon dioxide were to be stabilized, the global warming is expected to increase from the blue to the red curve, as depicted by the arrow. Note that the equilibrium warming indicated in the figure incorporates only feedbacks from water vapor, clouds sea ice or snow changes; the slower acting feedbacks incoroporated in Earth System Sensitivity may increase the warming (by about 50% over the values shown according to one study by Lunt *et al.* 2009) {2.1, 3.2, 3.3}

TABLE S.1 Estimated likely ranges and best estimate values for transient and equilibrium global averaged warming verus carbon dioxide equivalent concentrations.

CO_2-equlvalent concentration (ppmv)	Best estimate transient warming (°C)	Estimated likely range of transient warming (°C)	Best estimate equilibrium warming (°C)	Estimated likely range of equilibrium warming (°C)
350	0.5	0.4-0.7	1	0.7-1.4
450	1.1	0.9 -1.5	2.2	1.4-3.0
550	1.6	1.3-2.1	3.1	2.1-4.3
650	2	1.6-2.7	3.9	2.6-5.4
1000	3	2.4-4.0	5.9	3.9-8.1
2000	4.7	3.7-6.2	9.1	6.0-12.5

report should be read with this proviso in mind, as these high sensitivities, if realized, would amplify many of the impacts discussed and associated risk. (3.2, 3.3, 6.1)

3. Climate Changes, Future Impacts, and Choices among Stabilization Targets

Increases in global mean temperature caused by higher anthropogenic greenhouse gas concentrations would be expected to lead to a diverse range of changes in potentially damaging climate-related parameters and impacts, affecting many aspects of human society and the natural environment.

The magnitude of some near-term (next few decades and centuries) climate changes and impacts can be estimated for specific levels of global mean temperature change experienced, illustrating how stabilization at different levels of greenhouse gas forcing would be expected to alter our world (see Figure S.5). Approximate estimates of these effects, per degree C of global warming, include:

- 5-10% changes in precipitation in a number of regions
- 3-10% increases in heavy rainfall[8]
- 5-15% yield reductions of a number of crops[9]
- 5-10% changes in streamflow in many river basins worldwide, including several in the U.S.
- about 15% and 25% decreases, in the extent of annually averaged and September Arctic sea ice, respectively

In addition, effects at particular levels of warming include:

- Increases in the number of exceptionally warm summers (i.e., 9 out of 10 boreal summers that are “exceptionally warm” in nearly all land areas for about 3°C of global warming, and every summer “exceptionally warm” in nearly all land areas for about 4°C, where an “exceptionally warm” summer is defined as one that is warmer than all but about 1 of the 20 summers in the last decades of the 20th century).
- 200-400% increases per degree in wildfire area burned in several western North American regions for 1-2°C
- Increased coral bleaching, and net erosion of coral reefs, due to warming and changes in ocean acidity (pH) for carbon dioxide levels corresponding to about 1.5-3°C of global warming.
- Sea level rise in the range of 0.5 to 1.0 m in 2100 (reached in a scenario corresponding to about 3±1°C of global warming) and an associated increase in the number of people at risk from coastal flooding by 5-200 million[10] as well as global wetland and dryland losses of more than 250,000 square kilometers.

{4.1, 4.2, 4.5, 4.6, 4.7, 4.8, 4.9, 5.1, 5.2, 5.3, 5.4}

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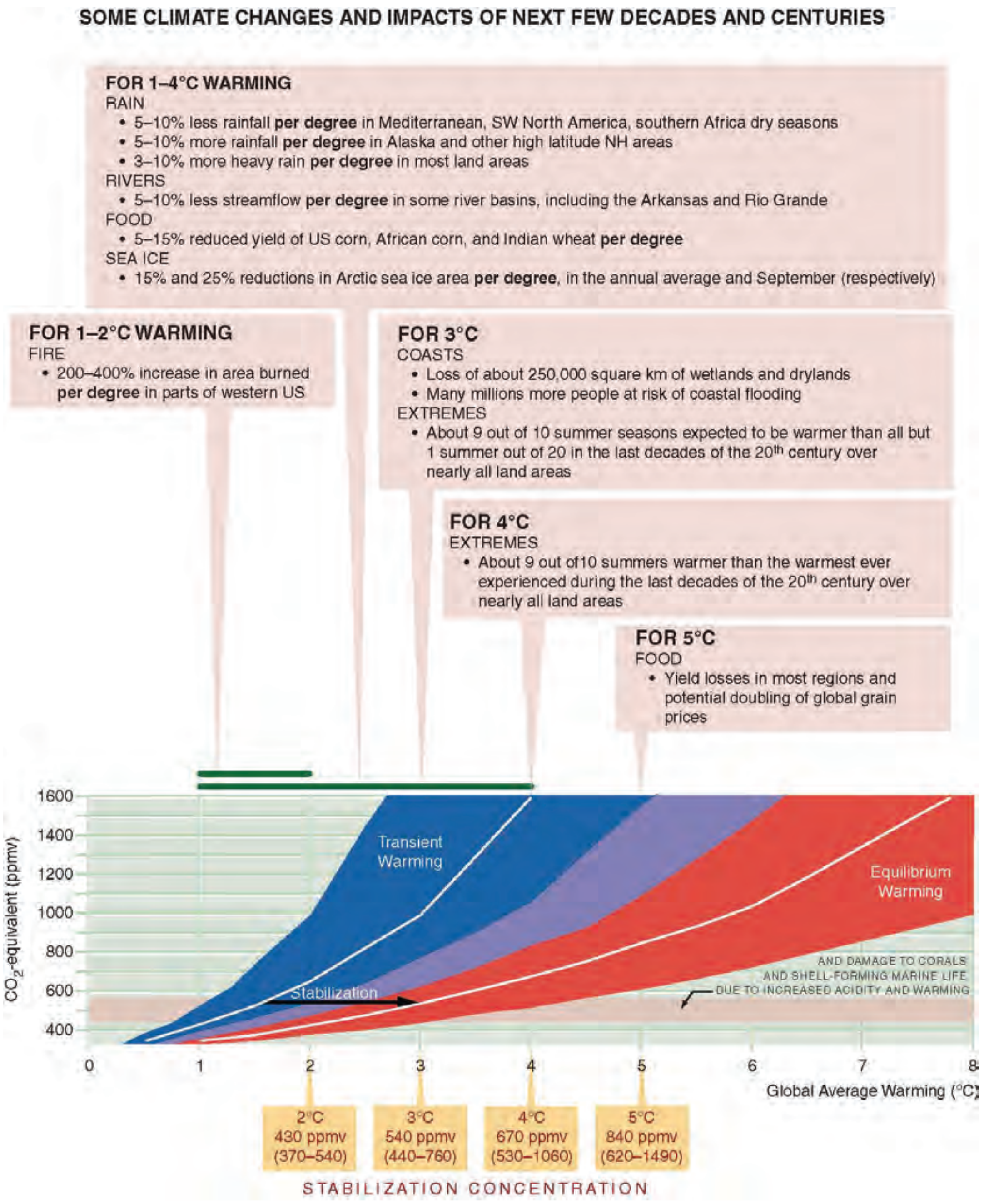
[8] heaviest 15% of daily falls

[9] unless adaptation measures not presently in hand become available

[10] with the range depending mainly on uncertainty in adaptation measures undertaken



SOME CLIMATE CHANGES AND IMPACTS OF NEXT FEW DECADES AND CENTURIES

FOR 1–4°C WARMING

RAIN
- 5–10% less rainfall **per degree** in Mediterranean, SW North America, southern Africa dry seasons
- 5–10% more rainfall **per degree** in Alaska and other high latitude NH areas
- 3–10% more heavy rain **per degree** in most land areas

RIVERS
- 5–10% less streamflow **per degree** in some river basins, including the Arkansas and Rio Grande

FOOD
- 5–15% reduced yield of US corn, African corn, and Indian wheat **per degree**

SEA ICE
- 15% and 25% reductions in Arctic sea ice area **per degree**, in the annual average and September (respectively)

FOR 1–2°C WARMING

FIRE
- 200–400% increase in area burned **per degree** in parts of western US

FOR 3°C

COASTS
- Loss of about 250,000 square km of wetlands and drylands
- Many millions more people at risk of coastal flooding

EXTREMES
- About 9 out of 10 summer seasons expected to be warmer than all but 1 summer out of 20 in the last decades of the 20th century over nearly all land areas

FOR 4°C

EXTREMES
- About 9 out of10 summers warmer than the warmest ever experienced during the last decades of the 20th century over nearly all land areas

FOR 5°C

FOOD
- Yield losses in most regions and potential doubling of global grain prices

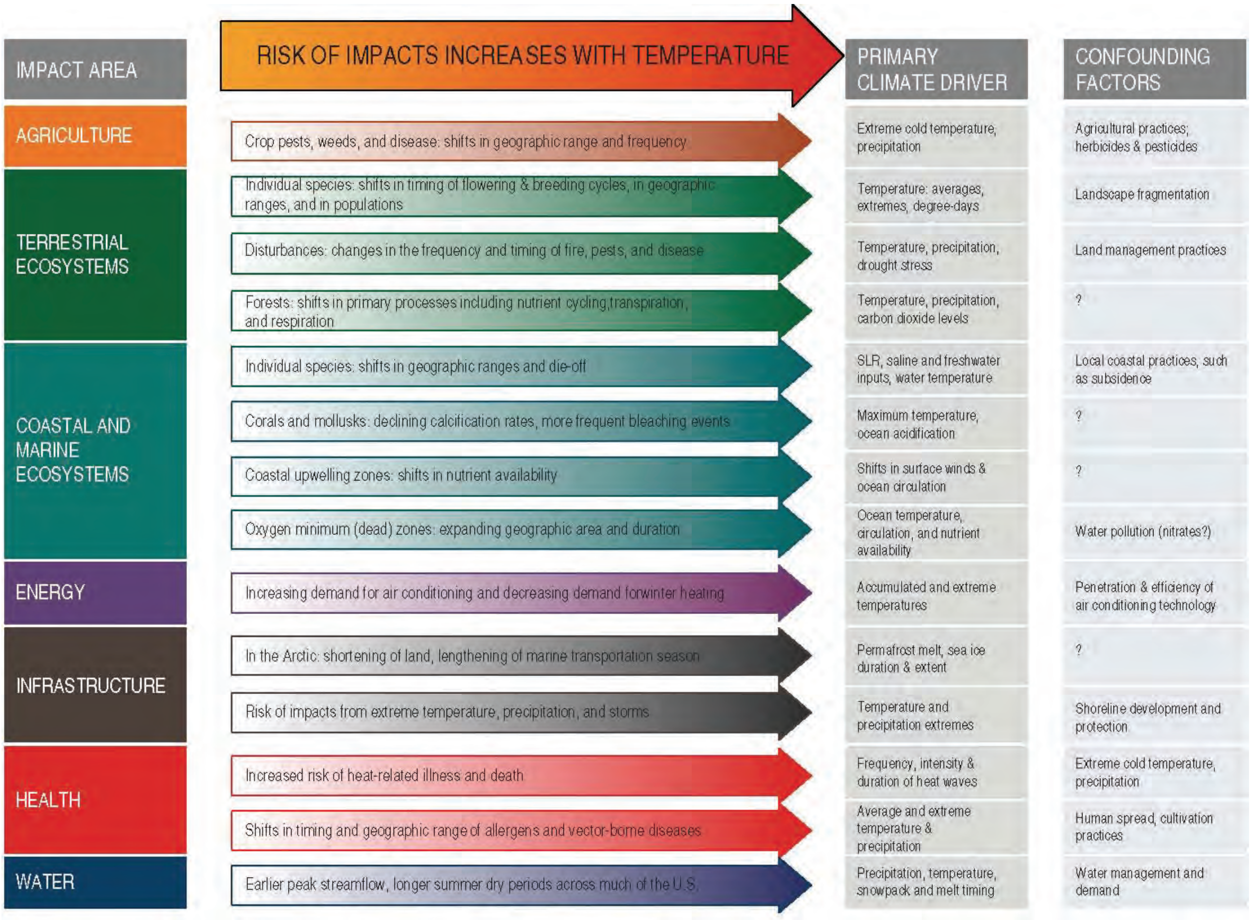
FIGURE S.5 Climate changes and climate impacts as a function of global warming (not in priority order or implied importance). These anticipated effects are projected to occur in the 21st century following the transient warming for a given CO_2 equivalent concentration, followed by further warming to the equilibrium value for stabilization at a given target concentration. As in previous figures, for discussion of transient and equilibrium warming see chapter 3, where it is noted that the probability distribution of climate sensitivity is uncertain; larger or smaller warmings than the estimated likely value for a given carbon dioxide equivalent concentration cannot be ruled out. Ranges are shown for climate impacts over the globe or over large regions; specific regions, crops, river basins, etc. and their uncertainties are discussed in detail in the full report. {3.2, 3.3, 4.2, 4.5, 4.6, 4.7, 4.8, 4.9, 5.1, 5.2, 5.3, 5.4, 5.7, 5.8}

Many important impacts of climate change are difficult to quantify for a given change in global mean temperature, but the risk of adverse impacts is likely to increase with global mean temperature change.

For some impacts, this difficulty arises because temperature is a primary, but not necessarily the only, driver of change. Quantification can also be difficult due to uncertainty in observing and modeling the response of a given system to temperature changes or other climate and non-climate factors, and additional complexity due to the influence of multiple environmental and other anthropogenic factors. It is clear from many scientific studies documenting projected impacts across numerous sectors and regions, however, that a number of impacts do scale approximately with global temperature. Hence, these are expected to intensify in response to a greater temperature change. An illustrative set of temperature-dependent impacts are summarized in Figure S.6. These include shifts in terrestrial and marine species ranges and abundances (including die-off in some cases), increased risk of heat-related human health impacts, loss of infrastructure in coastal regions (due to sea level rise) and the Arctic (due to sea level rise, retreat of sea ice and associated coastal erosion, and permafrost loss). This summary of temperature-related impacts is intended to be indicative rather than comprehensive. Figure S.6 does not include all possible temperature-sensitive impacts, such as projected extinctions due to climate change and increased risks to national security. {4.7, 4.9, 5.5, 5.6, 5.7, 5.8}

Uncertainty in the cumulative carbon or stabilized carbon dioxide concentration that corresponds to a given temperature target is large. It follows that choices about stabilization targets depend upon judgments regarding the degree of acceptable risk.

The likely range of cumulative carbon emissions corresponding to a given warming level is estimated to lie between -30% to +40% of the best estimate. This range is due mainly to uncertainties in the carbon cycle response to emissions and the climate response to increased radiative forcing. For a cumulative anthropogenic emission of 1000 GtC, our best estimate of the warming remains below 2°C, but there is about an estimated 17% probability that the warming could exceed 2°C for more than 1500 years. When cumulative emissions are increased to 1500 GtC, the best estimate of the anthropogenic warming remains above 2°C for over 3500 years, and the very likely upper end warming is still over 2.5°C for more than 10,000 years. Higher values cannot be excluded, implying additional risk which cannot presently be quantified. On the other hand, at the lower end of carbon-climate likely uncertainty range, there may be about an 17% chance that warming could remain below 2°C even if as much as 1700 GtC are emitted. Figure S.3 and S.5 provide some scientific reasons why global warming of a few degrees could be considered dangerous to some aspects of nature and society, but the corresponding uncertainty ranges should be emphasized here. For example, while the best estimate of a stabilization target corresponding to a long-term warming of 2°C is 430 ppm, the likely uncertainty range for this value spans from 380 (below current observed levels) to 540 ppm (almost a doubling of carbon dioxide relative to pre-industrial times). {3.4, 6.1}



IMPACT AREA	RISK OF IMPACTS INCREASES WITH TEMPERATURE	PRIMARY CLIMATE DRIVER	CONFOUNDING FACTORS
AGRICULTURE	Crop pests, weeds, and disease: shifts in geographic range and frequency	Extreme cold temperature, precipitation	Agricultural practices; herbicides & pesticides
TERRESTRIAL ECOSYSTEMS	Individual species: shifts in timing of flowering & breeding cycles, in geographic ranges, and in populations	Temperature: averages, extremes, degree-days	Landscape fragmentation
	Disturbances: changes in the frequency and timing of fire, pests, and disease	Temperature, precipitation, drought stress	Land management practices
	Forests: shifts in primary processes including nutrient cycling,transpiration, and respiration	Temperature, precipitation, carbon dioxide levels	?
COASTAL AND MARINE ECOSYSTEMS	Individual species: shifts in geographic ranges and die-off	SLR, saline and freshwater inputs, water temperature	Local coastal practices, such as subsidence
	Corals and mollusks: declining calcification rates, more frequent bleaching events	Maximum temperature, ocean acidification	?
	Coastal upwelling zones: shifts in nutrient availability	Shifts in surface winds & ocean circulation	?
	Oxygen minimum (dead) zones: expanding geographic area and duration	Ocean temperature, circulation, and nutrient availability	Water pollution (nitrates?)
ENERGY	Increasing demand for air conditioning and decreasing demand forwinter heating	Accumulated and extreme temperatures	Penetration & efficiency of air conditioning technology
INFRASTRUCTURE	In the Arctic: shortening of land, lengthening of marine transportation season	Permafrost melt, sea ice duration & extent	?
	Risk of impacts from extreme temperature, precipitation, and storms	Temperature and precipitation extremes	Shoreline development and protection
HEALTH	Increased risk of heat-related illness and death	Frequency, intensity & duration of heat waves	Extreme cold temperature, precipitation
	Shifts in timing and geographic range of allergens and vector-borne diseases	Average and extreme temperature & precipitation	Human spread, cultivation practices
WATER	Earlier peak streamflow, longer summer dry periods across much of the U.S.	Precipitation, temperature, snowpack and melt timing	Water management and demand

FIGURE S.6 Our understanding of the impacts of climate change is still evolving and quantitative information is currently too limited to provide numerical estimates of the scale, scope, and timing of some impacts. This figure illustrates a number of such possible impacts along with their primary drivers as well as available information on confounding factors. {5.1-5.8, 2.4}

Many important aspects of climate change and its impacts are expected to be approximately linear and gradual, slowly becoming larger and more significant relative to climate variability as global warming increases.

This report highlights the importance of 21st century choices regarding stabilization targets and how they can be expected to affect many aspects of Earth's future. Progressively warmer temperatures are expected to slowly lead to larger and more significant changes for impacts including wildfire extent, decreases in yields of some (but not all) crops, streamflow changes, decreased Arctic sea ice extent, increases in heavy rainfall occurrence, and other factors presented. However, it should be noted that many climate changes and impacts remain poorly understood at present. For example, the record of past climates suggests that major changes such as dieback of the Amazon forests or substantial changes in El Nino behavior can occur. This report identifies some areas where recent science suggests reduced effects compared to earlier studies (including e.g., projected future changes in hurricane activity). This report does not identify any specific projections of abrupt climate changes that the committee considers to be robustly established, e.g. based on clear physical understanding of processes and multiple models. However, it is clear that the risk of surprises can be expected to increase with the duration and magnitude of the warming. Finally, this report shows throughout that present emissions represent commitments to growing current and future impacts, including the very long-term future over many thousands of years. {2.4, 3.4, 4.3, 4.4, 5.8, 6.1, 6.2}

2

Emissions, Concentrations, and Related Factors

2.1 CONTRIBUTION OF DIFFERENT CHEMICALS TO CO_2 EQUIVALENT LEVELS AND CLIMATE CHANGES

A range of anthropogenic chemical compounds contribute to changing the Earth's energy budget, thereby causing the planet's global climate to change. For example, increases in greenhouse gases absorb infrared energy that would otherwise escape to space, acting to warm the planet, while some types of aerosol particles can contribute to cooling the planet by reflecting incoming visible light from the Sun. These components of our atmosphere are emitted from a variety of human activities, including for example fossil fuel burning, land use change, industrial processes such as cement production, and agriculture. The gases and particles involved are frequently referred to as drivers of climate change, or radiative forcing agents. A detailed review of radiative forcing is presented in Forster et al. (2007) and Denman et al. (2007). Radiative forcing due to various climate change agents can be converted to equivalency with the concentration of CO_2 (CO_2 equivalent), one frame of reference for this report (see Figure 2.1). Here we briefly summarize how major forcing agents contribute to current and future CO_2 equivalent target levels and explore implications for global mean temperature increases.

Some greenhouse gases and aerosols are retained for days to years in the atmosphere after emission. The concentrations of such compounds in the atmosphere are tightly coupled to the rate of emission. Their concentrations would drop rapidly if emissions were to cease. Increasing emissions lead to increases in concentrations of such gases, while constant emissions are required for their concentrations to be stabilized. Methane is a key greenhouse gas with an atmospheric lifetime of about 10 years whose concentration has approximately doubled since the pre-industrial era (1750), and it is the second most important greenhouse gas, currently contributing about 25 ppmv of CO_2 equivalent (see Figure 2.1). Over the period from about 1998 to 2007, methane concentrations remained nearly constant (Forster et al., 2007). Methane has, however, begun increasing after about 2007. In the absence of mitigation, methane is expected to continue to make significant contributions to climate change over the 21st century (see Section 2.2).

In sharp contrast, some greenhouse gases have biogeochemical properties that lead to atmospheric retention times (lifetimes) of centuries or even millennia. These gases can accumulate in the atmosphere whenever emissions exceed the slow rate of their loss, and concentrations would remain elevated (and influence climate) for timescales of many years even in the complete absence of further emission. Like the water in a bathtub, concentrations of carbon dioxide are building up because the anthropogenic source substantially exceeds the natural net sink. Even if human emissions were to be kept constant at current levels, concentrations would still increase, just as the water in a bathtub does when the water comes in faster than it can flow out the drain. The removal of anthropogenic carbon dioxide from the atmosphere involves multiple loss mechanisms, spanning the biosphere and ocean (see Section

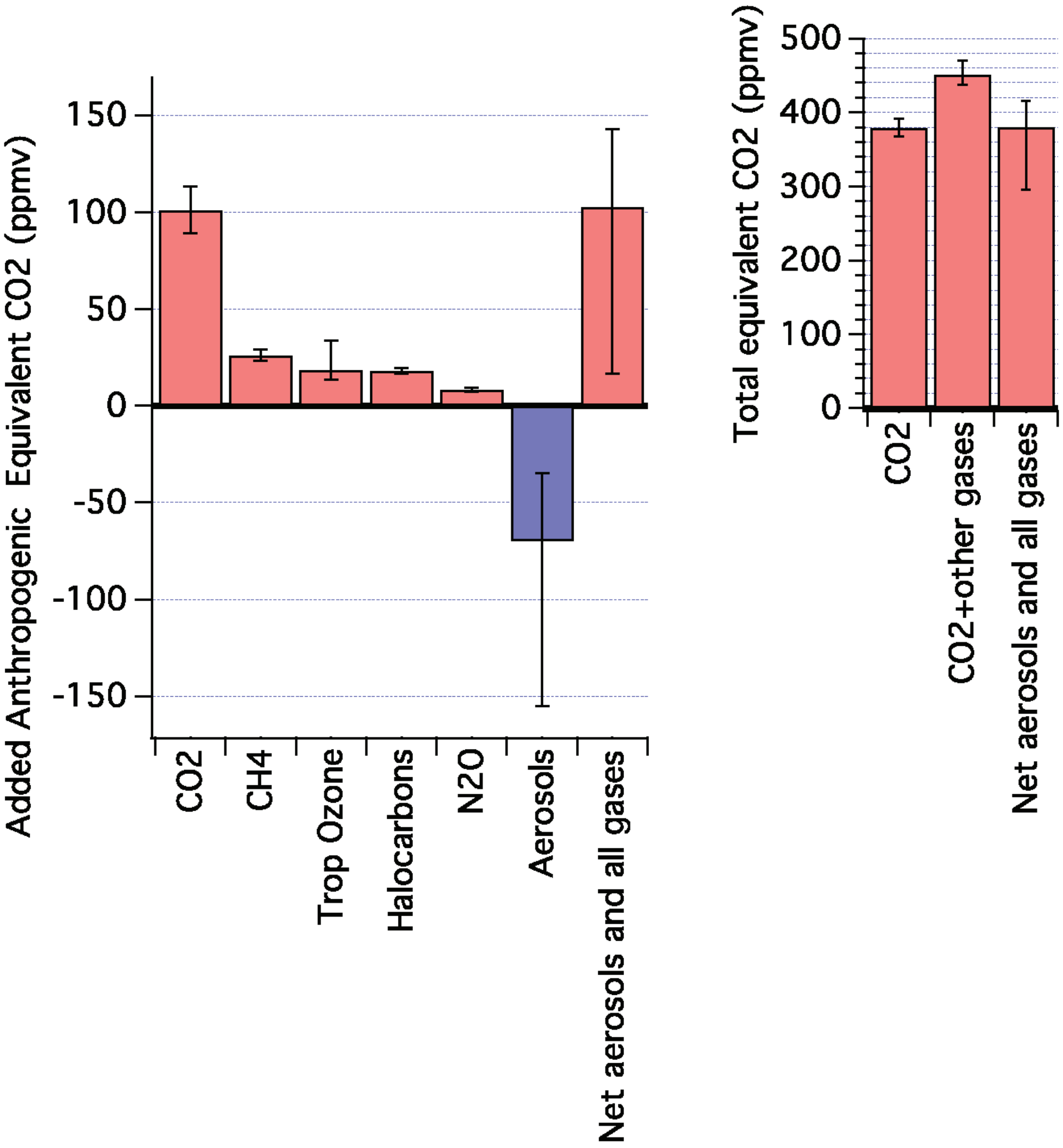


FIGURE 2.1 (left) Best estimates and very likely uncertainty ranges for aerosols and gas contributions to CO_2-equivalent concentrations for 2005, based upon the radiative forcing given in Forster et al. (2007). All major gases contributing more than 0.15 W m^{-2} are shown. Halocarbons including chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, and perfluorocarbons have been grouped. Direct effects of all aerosols have been grouped together with their indirect effects on clouds. (right) Total CO_2 equivalent concentrations in 2005 for CO_2 only, for CO_2 plus all gases, and for CO_2, plus gases plus aerosols.

2.4), and carbon dioxide removal cannot be characterized by any single lifetime. While some carbon dioxide would be lost rapidly to the terrestrial biosphere and to the shallow ocean if human emissions cease, some of the enhanced anthropogenic carbon will remain in the atmosphere for more than a thousand years, influencing global climate (Archer and Brovkin, 2008). The warming induced by added carbon dioxide is expected to be nearly irreversible for at least 1000 years (Matthews and Caldeira, 2008; Solomon et al., 2009), see Section 3.4.

Figure 2.1 shows that carbon dioxide is the largest driver of current anthropogenic climate change. Other gases such as methane, nitrous oxide, and halocarbons also make significant contributions to the current total CO_2 equivalent concentration, while aerosols (see Section 2.3) exert an important cooling effect that offsets some of the warming. The best estimate of net total CO_2 equivalent concentration of the sum across these forcing agents in the year 2005 is about 390 ppmv (with a very likely range from 305 to 430 ppmv). Global carbon dioxide emissions have been increasing at a rate of several percent per year (Raupach et al., 2007). If there were to be no efforts to mitigate its emission growth rate, scenario studies suggest that carbon dioxide could top 1000 ppmv by the end of the 21st century. Carbon dioxide alone accounts for about 55% of the current total CO_2 equivalent concentration of the sum of all greenhouse gases, and increases to between 75 and 85% by the end of this century based on a range of future emission scenarios (see Section 2.2). Thus carbon dioxide is the main forcing agent in all of the stabilization targets discussed here, but the contributions of other gases and aerosols to the total CO_2-equivalent remain significant, motivating their consideration in analysis of stabilization issues.

How large a reduction of emissions is required to stabilize carbon dioxide concentrations, and does it depend upon when this is done, or on the chosen target stabilization concentration? Studies over the past five years of so using many different carbon cycle models have improved our understanding of requirements for carbon dioxide stabilization. This is because of more detailed treatments of carbon-climate feedbacks, including the ways in which warming decreases the efficiency of carbon sinks as compared to earlier work (e.g., Jones et al., 2006; Matthews, 2006). Figure 2.2 shows an example of stabilization for two different Earth Models of Intermediate Complexity (EMICs), the University of Victoria model and the Bern model (see Methods section for descriptions of these two models; see also Plattner et al., 2008 and references therein for a model intercomparison study). In this example test case, carbon dioxide emissions increase at current growth rates of about 2% per year to a maximum of about 12 GtC per year, followed by a decrease of 3%/year down to a selected total reduction of 50, 80, or 100%. The rate of decrease of 3%/year used here is derived from scenario analysis described in the next section. This section together with the next section aims to probe what plausible rates of emission reduction based upon scenario studies imply for the future evolution of carbon dioxide concentrations. The rate of possible emission reductions of carbon dioxide depends upon factors including e.g., commitments to existing infrastructure and development of alternatives, see Section 2.2. It is interesting to note that even in the case of the phaseout of ozone-depleting substances under the Montreal Protocol, emission reductions were about 10% per year initially but stalled at a total reduction of about 80% of the peak, with some continuing emissions of certain gases occurring due for example to the challenge of finding alternatives for fire-fighting applications (see IPCC, 2005).

Figure 2.2 shows that carbon emission reductions of 50% do not lead to long-term stabilization of carbon dioxide, nor of climate, in either of these models, as has also been shown in previous studies (e.g., Weaver et al., 2007). . . It is noteworthy that the Bern model has weaker carbon-climate feedbacks than the UVIC model; nevertheless both models show the need for emissions reductions of at least 80% for carbon dioxide stabilization even for a few decades, while longer-term stabilization requires nearly 100% reduction. Very similar results were obtained in other test cases run for this study considering peaking at higher values, or decreasing at rates from 1 to 4% per year (see also Weaver et al., 2007, Meehl et al., 2007). Figure 2.3 shows sample calculations evaluated in Meehl et al. (2007) using three different models, for various stabilization levels. Figure 2.3 shows that stabilization levels of 450, 550, 750, or 1000 ppmv require eventual emission reductions of 80% or more (relative to whatever peak emission occurs) in all of the models evaluated. Thus current representations of the carbon cycle and carbon-climate feedbacks show that anthropogenic emissions must approach zero eventually if carbon dioxide concentrations are to be stabilized in the long term (Matthews and Caldeira, 2008). This is a fundamental physical property of the carbon cycle and is independent of the emission pathway or selected carbon dioxide stabilization target. Box 2.1 discusses how emissions of non-CO_2 greenhouse gases could affect attainment of stabilization targets.

Figures 2.2 and 2.3 illustrate a fundamental change in understanding stabilization of climate change that has been prompted by the scientific literature of the past two years or so (see Jones et al., 2006; Matthews and Caldeira, 2008). Early work on stabilization using relatively simple models suggested that slow reductions in emissions could lead to eventual stabilization of climate (e.g., Wigley et al., 1996). But recent studies using more detailed models of key feedbacks in the ocean, biosphere, and cryosphere, have underscored that while a quasi-equilibrium may be reached for a limited time in some models for some scenarios, stabilizing radiative forcing at a given concentration does not lead to a stable climate in the long run. Cumulative emitted carbon can more readily be linked to climate stabilization, due to the irreversible character of the induced warming driven by carbon dioxide (see Section 3.4).

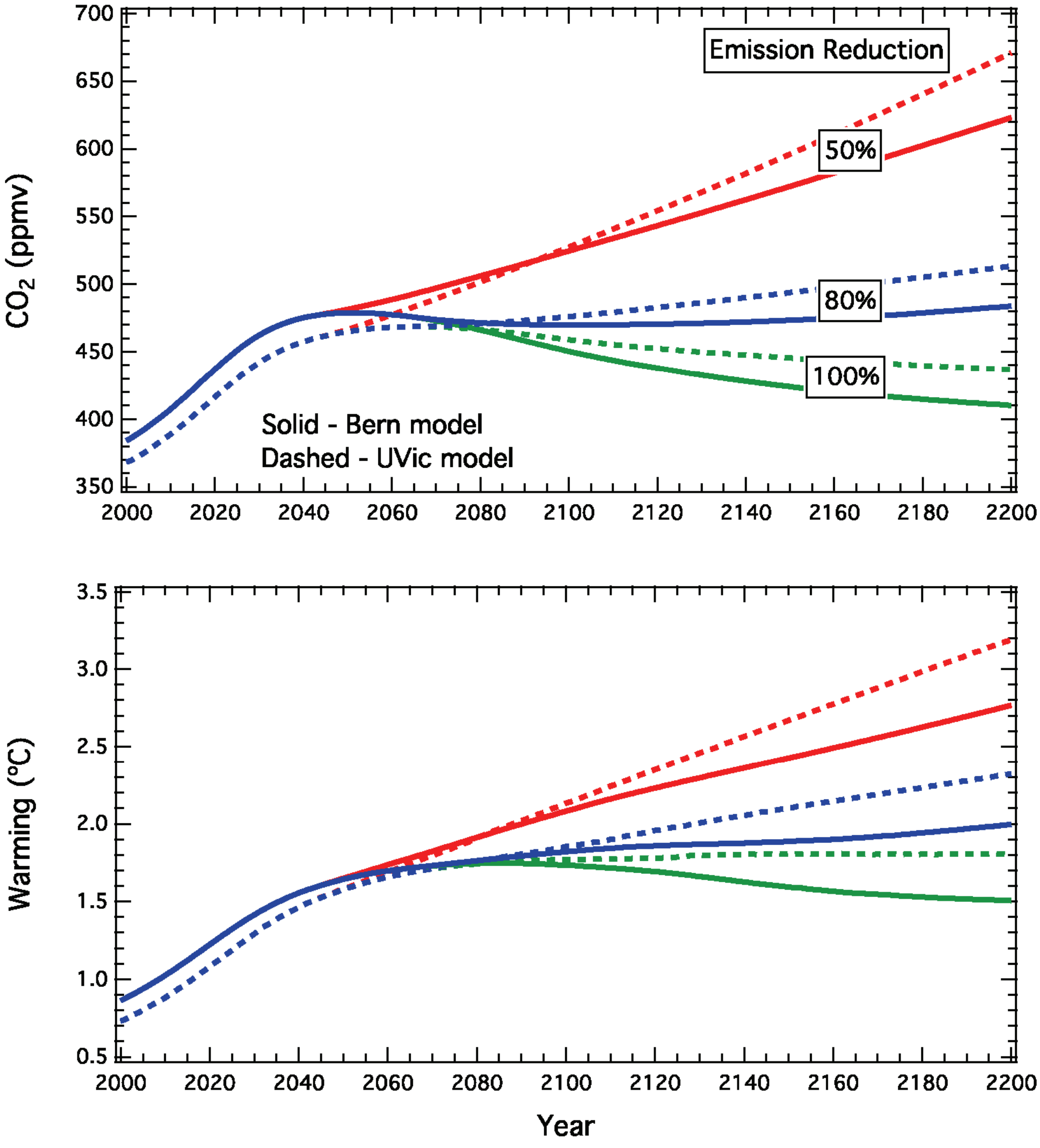


FIGURE 2.2. Illustrative calculations showing CO_2 concentrations and related warming in two EMICS (the Bern model and the University of Victoria model, see Methods) for a test case in which emissions first increase, followed by a decrease in emission rate of 3% per year to a value 50%, 80%, or 100% below the peak. The test case with 100% emission reduction has 1 trillion tonnes of total emission and is also discussed in Section 3.4.

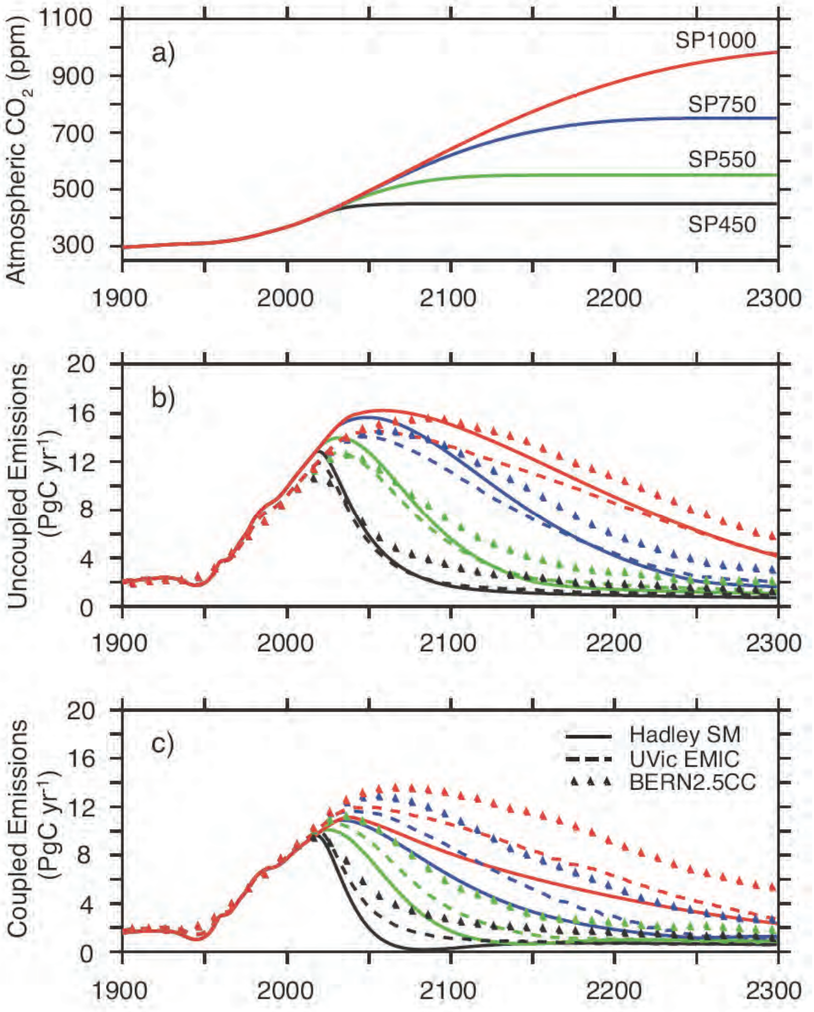


FIGURE 2.3 (a) Atmospheric Illustrative atmospheric CO_2 stabilisation scenarios for 1000, 750, 550, and 450 ppmv; SP1000 (red), SP750 (blue), SP550 (green) and SP450 (black), from Meehl et al. (2007). (b) Compatible annual emissions calculated by three models, the Hadley simple model (solid), the UVic EMIC (dashed) and the BERN2.5CC EMIC (triangles) for the three stabilisation scenarios. Panel (b) shows emissions required for stabilization without accounting for the impact of climate on the carbon cycle, while panel (c) included the climate impact on the carbon cycle, showing that emission reductions in excess of 80% (relative to peak values) are required for stabilization of carbon dioxide concentrations at any of these target concentrations.

BOX 2.1
STABILIZATION AND NON-CO_2 GREENHOUSE GASES.

Because carbon emissions reductions of more than 80% are required to stabilize carbon dioxide concentrations, small continuing emissions of carbon dioxide, or emissions of CO_2-equivalent through other gases, could have surprisingly important implications for stabilizing climate change. For example, emissions of the hydrofluorocarbons (HFCs) currently used as substitutes for chlorofluorocarbons make a small contribution to today's climate change. However, because emissions of these gases is expected to grow in future if they are not mitigated, and because of the stringency of the requirement of near zero emissions of CO_2-equivalent emissions, these gases could represent a significant future impediment to stabilization efforts. For example, the Figure below shows that in the absence of mitigation, the HFCs could represent as much as a third of the allowable CO_2-equivalent emissions in 2050 required for a stabilization target of 450 CO_2-equivalent. Thus, the analysis presented here underscores that stabilization of climate change requires consideration of the full range of greenhouse gases and aerosols, and of the full suite of emitting sectors, applications, and nations.

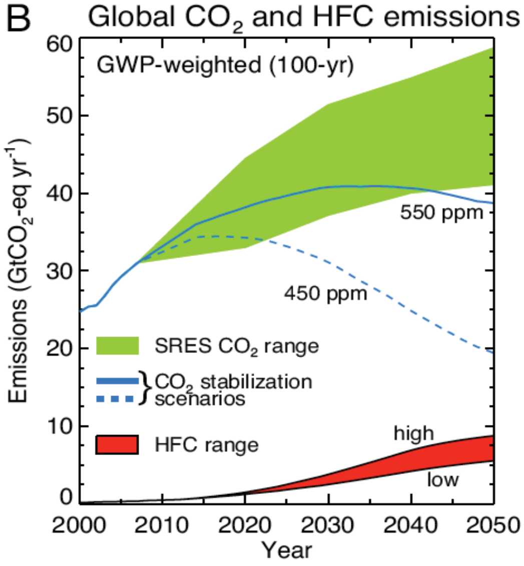


FIGURE 2.4 Global CO_2 and HFC emissions expressed as CO_2-equivalent emissions per year for the period 2000 –2050. The emissions of individual HFCs are multiplied by their respective GWPs (direct, 100-year time horizon) to obtain aggregate emissions across all HFCs expressed as equivalent $GtCO_2$ per year. A high and low estimated range based on analysis of likely demand for these gases and assuming no mitigation of HFCs is shown. HFC emissions are compared to emissions for the range of SRES CO_2 scenarios, and two 450-and 550-ppm CO_2 stabilization scenarios. The estimated CO_2-equivalent emissions due to HFCs in the absence of mitigation reach about 6 $GtCO_2$-equivalent in 2050, or about a third of the emissions due to CO_2 itself at that time in the 450 stabilization scenario. From Velders et al. (2009).

2.2 INFORMATION FROM SCENARIOS

Figure 2.5 shows the emissions of man-made greenhouse gases from various sectors of the U.S. economy (U.S. E.P.A., 2008). For highly industrialized countries such as the United States, the difficulty in reducing emissions will depend in large part on the lifetimes of the *existing* capital stock associated with the major emitting sectors. The electric sector is the largest source of man-made emissions in the United States, primarily due to the carbon dioxide emitted during the combustion of fossil fuels. The lifetime of coal-fired power plants is measured in decades. The next largest source of U. S. greenhouse gases is the transportation sector, again due to the combustion of fossil fuels. Here the lifetime of the capital stock is typically a decade or two.

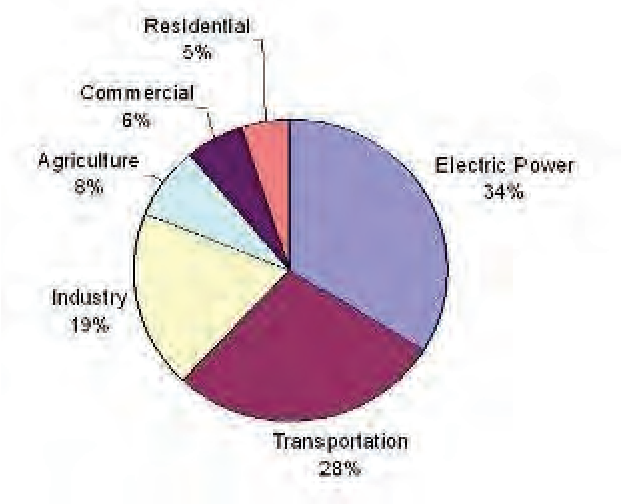


FIGURE 2.5 U.S. Greenhouse Gas Emissions by Sector in 2006 (Source, U.S. EPA (2008))

While historically, developed countries have been the major emitter of greenhouse gases, developing countries are on track to overtake them in the next few years. In their case, the issue becomes one of the capital stock put in place in the *future* to support their industrialization process. With the huge economic growth projected for developing countries and in the absence of incentives to act otherwise, these countries will likely turn to the cheapest energy sources to fuel their growth. These fuels currently are fossil based: coal, oil and gas. A recent study by the Energy Modeling Forum, based on eight Energy-Economy models, projected an annual growth rate of CO_2 emissions globally from the burning of fossil fuels and industrial uses, to be of the order of 1 to 2 percent per year over the remainder of the century, in the absence of intervention (EMF 22, 2009). The study attributes much of the growth to developing countries.

Even if wealthier countries like the United States were to reduce their emissions to zero immediately, it is unlikely that global CO_2 emissions would be stabilized, much less global atmospheric concentrations (Blanford et al., 2009). Being in their post industrial phase of development, the economic growth rates in developed countries are expected to be lower than those of developing countries and their mix of goods and services less carbon intensive. The cumulative reductions of developed countries, even with aggressive emission reduction programs, are expected to be low when compared to those of developing countries.

One important contribution that developed countries can make to global emission reductions is to develop the technological wherewithal that would not only be necessary for their own emission reductions, but is also essential for developing countries to meet their economic development goals with affordable climate friendly technologies.

As noted above, both the existing capital stock and that put in place in the future are critical to understanding the difficulty of transitioning away from the current path of growth in greenhouse gas emissions. Figure 2.6 shows representative carbon pathways (RCP) for limiting radiative forcing (watts per m^2) at two alternative levels. These are referred to as the RCP 2.6[14] and RCP 4.5 scenarios. These are among a suite of pathways being developed for use in the IPCC 5th Assessment. The pathways shown in the figure were developed by the IMAGE and MiniCAM models, respectively (Moss, 2010).

Figure 2.6 highlights the importance of the carbon budget. That is, the area under the allowable emissions curve associated with a particular radiative forcing target. Being much lower in RCP 2.6 scenario than the RCP 4.5 scenario, we see the rate of growth first slow and then rapidly decline beginning in 2020. In the case of the higher CO_2 budget, emissions rise for another two decades before peaking. Notice that the maximum rate of decline is comparable in the two scenarios (about 3.5% per year); however, in the later it is shifted out in time. The reason for this shift are both the higher carbon budget and a greater array of low-carbon, economically competitive alternatives which are assumed to become available in the future.

We stress that there is a great deal of flexibility regarding the rate at which new technologies are substituted for existing ones, both on the supply and demand sides of the energy sector. The rate of retirement of existing carbon-intensive plant and equipment and their replacement with more climate friendly alternatives will depend upon a number of factors. These include the stabilization target, reference case emissions in the absence of a price on CO_2 (either explicit or implicit), the availability and costs of alternatives, and the *willingness* to pay the costs of the transition to a low-carbon economy. The latter will depend on society's perception of the benefits (reduction in damages due to climate change). From a purely physical perspective, decline rates much higher than those shown here are feasible. It is a matter of the perceived urgency and the motivation to decarbonize.

Figure 2.7 shows the CO_2-equivalent concentrations for these two scenarios at three points in time. Notice that in the case of the tighter radiative forcing goal, there is some "overshoot". That is, the target is exceeded in the middle part of the century and then gradually approached. This is due to the assumption that there will be a "negative" emitting technology, Bioenergy with Carbon Capture and Sequestration (BECS). Otherwise a faster decline rate of the capital stock would be required.

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[14] Although Moss (2010) refers to this as the RCP2.6 scenario, this is the one RCP scenario that peaks and then declines. For this reason it is also referred to as the RCP3-PD scenario. The RCP3-PD has a unique shape. The radiative forcing of RCP3-PD peaks and declines (PD), while the radiative forcing of the other RCPs stabilize or rise towards their higher 2100 levels. Specifically, the final RCP3-PD prepared for climate modeling peaks at 2.99 W/m^2 in 2050 and then declines to 2.71 W/m^2 in 2100 with the decline continuing beyond 2100. The decline is due to the availability later in the century of a negative emitting technology, biomass with carbon capture and storage (BECs).

Figure 2.6 CO2 Mitigation Paths for Meeting RCP2.6 and RCP4.5 Goals

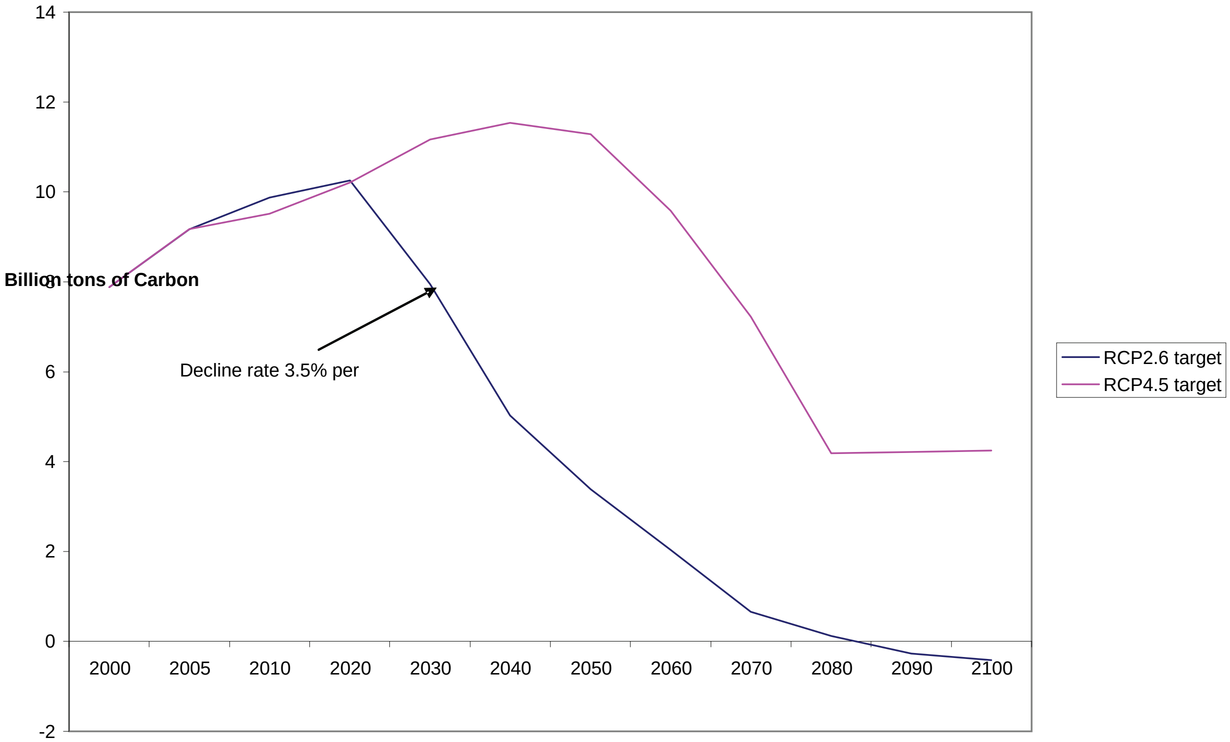
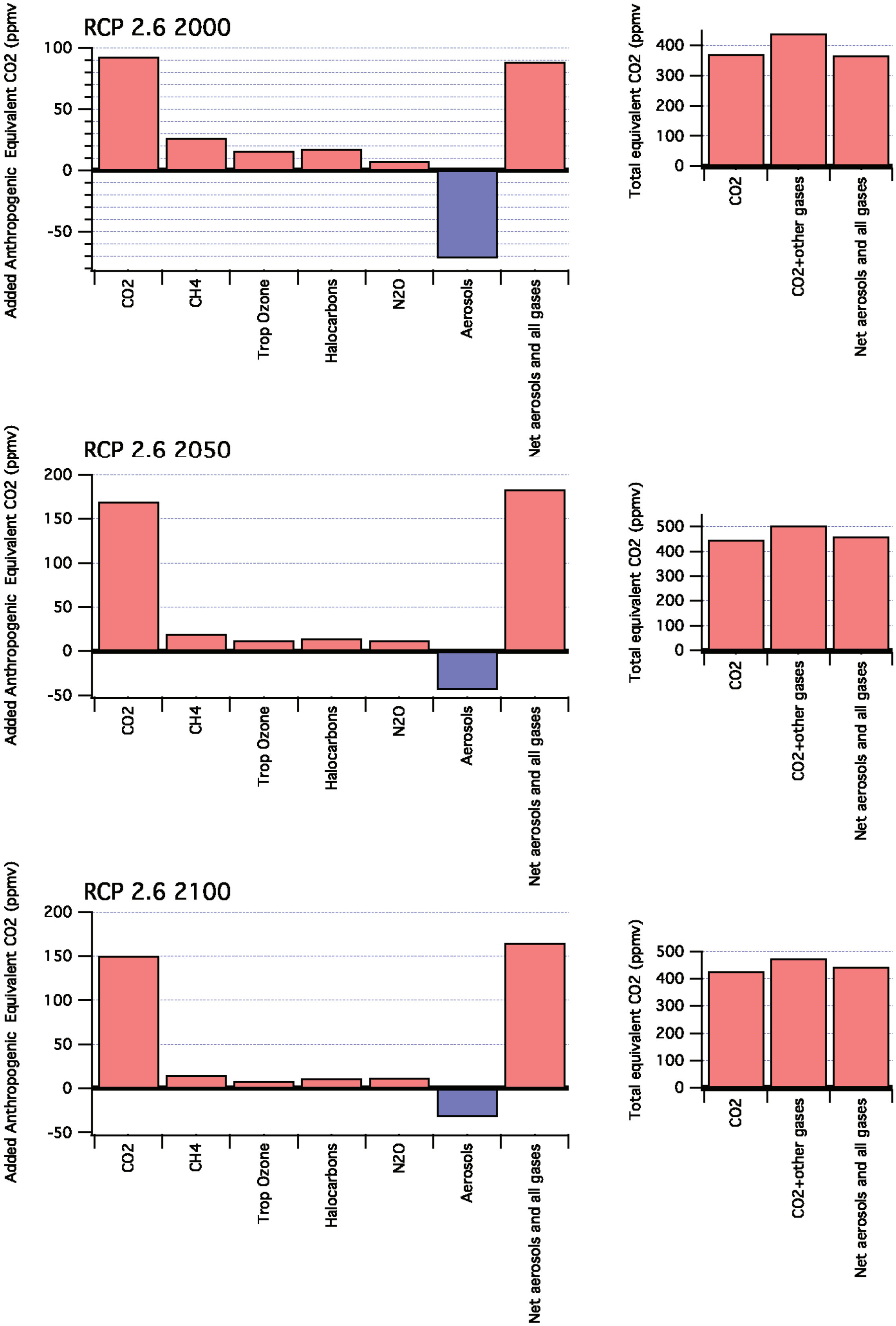


FIGURE 2.6 shows representative carbon pathways (RCP) for limiting radiative forcing (watts per m^2) at two alternative levels. The tighter the limit, the earlier the reductions must take effect. With the RCP 2.6 scenario, the rate of growth first slows and then rapidly declines beginning in 2020. In the case of the less stringent constraint, emissions rise for another two decades before peaking. Here the decline is shifted out in time


RCP 2.6 2000
Added Anthropogenic Equivalent CO2 (ppmv
100
50
0
-50
CO2
CH4
Trop Ozone
Halocarbons
N2O
Aerosols
Net aerosols and all gases
Total equivalent CO2 (ppmv
400
300
200
100
0
CO2
CO2+other gases
Net aerosols and all gases
RCP 2.6 2050
Added Anthropogenic Equivalent CO2 (ppmv)
200
150
100
50
0
-50
CO2
CH4
Trop Ozone
Halocarbons
N2O
Aerosols
Net aerosols and all gases
Total equivalent CO2 (ppmv)
500
400
300
200
100
0
CO2
CO2+other gases
Net aerosols and all gases
RCP 2.6 2100
Added Anthropogenic Equivalent CO2 (ppmv)
200
150
100
50
0
-50
CO2
CH4
Trop Ozone
Halocarbons
N2O
Aerosols
Net aerosols and all gases
Total equivalent CO2 (ppmv)
500
400
300
200
100
0
CO2
CO2+other gases
Net aerosols and all gases

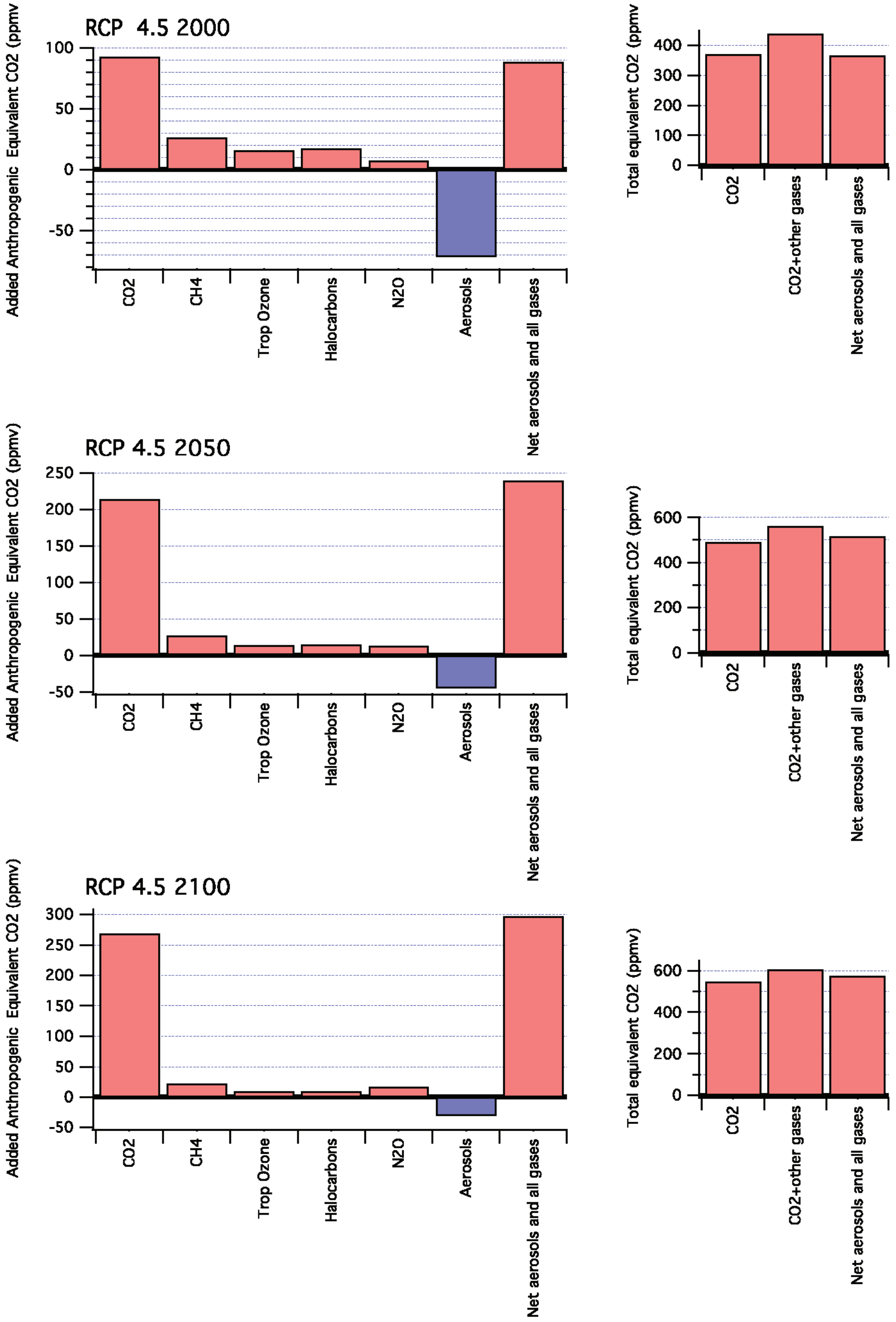


FIGURE 2.7 This figure illustrates components of radiative forcing (in CO_2-equivalent concentration units) for the RCP 2.6 (a) and RCP 4.5 (b) scenarios (see Moss et al., 2010). RCP 2.6 peaks at 3 W/m^{-2} before 2100 and then declines. There is some "overshoot" where the target is exceeded and is then gradually approached (see footnote 1). RCP 4.5 stabilizes at 4.5 W/m^{-2} after 2100.