Projecting the future of the U.S. carbon sink

G. C. Hurtt*[†], S. W. Pacala[‡], P. R. Moorcroft[‡§], J. Caspersen[‡], E. Shevliakova[‡], R. A. Houghton[¶], and B. Moore III*

*Institute for the Study of Earth Oceans and Space, University of New Hampshire, Durham, NH 03824; [‡]Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ 08544; and [¶]Woods Hole Research Center, Woods Hole, MA 02543

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Atmospheric and ground-based methods agree on the presence of a carbon sink in the coterminous United States (the United States minus Alaska and Hawaii), and the primary causes for the sink recently have been identified. Projecting the future behavior of the sink is necessary for projecting future net emissions. Here we use two models, the Ecosystem Demography model and a second simpler empirically based model (Miami Land Use History), to estimate the spatio-temporal patterns of ecosystem carbon stocks and fluxes resulting from land-use changes and fire suppression from 1700 to 2100. Our results are compared with other historical reconstructions of ecosystem carbon fluxes and to a detailed carbon budget for the 1980s. Our projections indicate that the ecosystem recovery processes that are primarily responsible for the contemporary U.S. carbon sink will slow over the next century, resulting in a significant reduction of the sink. The projected rate of decrease depends strongly on scenarios of future land use and the long-term effectiveness of fire suppression.

Atmospheric- and ground-based studies indicate that the carbon sink in the coterminous United States accumulated 0.37–0.71 Pg C$\cdot$y^{-1} on average during the decade of the 1980s (1). Inventory-based estimates indicate that the carbon sink has several causes including net forest growth, the accumulation and encroachment of woody vegetation caused by fire suppression, and other terms related to land use and land-use history (1). In addition, a study using U.S. Forest Inventory Analysis data indicates that the carbon sink in forests is caused largely by ecosystem recovery from prior land use, as opposed to fertilization or climate change (2). Knowledge of the magnitude and primary causes of the contemporary U.S. carbon sink leads to questions about its magnitude in the future and thus the future of U.S. net emissions.

Projecting the future of the U.S. carbon sink is difficult because of potentially complex interactions between climatic, environmental, and land-use conditions. During the relevant past, these conditions and their effect on ecosystems are not perfectly known, and important terms must be estimated in reconstructions. For the future, the relevant conditions themselves have yet to be determined, and the responses of ecosystems to novel sets of conditions are uncertain. However, it is clear that such projections are needed, and that mechanistic ecosystem models are an essential tool. It is also clear that these models must account both for contemporary land use and fire management, as well as the history of these practices, because the magnitude of these effects are large and there are long time scales associated with ecosystem recovery.

Here we use two such models, the Ecosystem Demography (ED) model and a second simpler empirically based model (Miami Land Use History, Miami-LU), to estimate ecosystem carbon stocks and fluxes in the coterminous U.S. from 1700 to 1990 and then to make projections to 2100. The ED model (3, 4) is a mechanistic ecosystem model built around established submodels of leaf level physiology, organic matter decomposition, hydrology, and functional biodiversity. ED differs from most other large-scale terrestrial models by formally scaling up physiological processes through vegetation dynamics to ecosystem scales, while simultaneously modeling natural disturbances, land use, and the dynamics of recovering lands. To run efficiently over large spatial and long temporal scales, the model uses a new scaling method analogous to techniques used in statistical physics (see Appendix 1, which is published as supporting information on the PNAS web site, www.pnas.org for additional information.). Miami-LU (described below) is a far simpler empirically based ecosystem model that tracks the history of disturbance, land use, fire, and ecosystem recovery similar to ED.

We first ran ED from an estimate of the state of ecosystems in 1700 to an estimate of the state of ecosystems in 1990 using climate data, soil data, and a gridded land-use history reconstruction as inputs. Our land-use history reconstruction provided estimates of land-use transition rates for each grid cell through time and was based on several sources of information including: the spatial distribution of potential vegetation in 1700 (5), the spatial patterns of cropland from 1700 to 1990 (5), regional estimates of land use and logging from 1700 to 1990 (ref. 6 and see ref. 1 for updated estimates and interpretation), and data on the current age distribution of forest stands from the U.S. Forest Inventory Analysis database. Both the implementation of land use in ED and the land-use history reconstruction product itself are described in Appendices 1 and 2, which are published as supporting information on the PNAS web site. We also included the effects of fire suppression, a process that resulted in an order of magnitude reduction in area burned during the period (6, 7). To simulate fire suppression, estimates of fire using ED's fire sub-model were constrained to give an area burned in 1700 of more than 800,000 km$^2\cdot$y^{-1}, and subsequently reduced in intensity to less than 30,000 km$^2\cdot$y^{-1} in 1990 to match estimates of the relevant history. Additional information on ED's fire sub-model is described in Appendices 1, 3, and 4 and Figs. 4 and 5, which are published as supporting information on the PNAS web site. For climate and soils, we used data from a 1° × 1° global data set (8, 20). Atmospheric CO_2 concentrations and climatic conditions were held constant throughout the runs presented here to focus on the consequences of land-use and fire-management changes—factors hypothesized to be of primary importance for explaining the current sink.

The estimated historical patterns of land use and total carbon stocks (above and below ground) are shown in Fig. 1 at four time intervals: 1700, 1850, 1920, and 1990 (see Appendix 4). Each land-use map shows the fraction of each grid cell in each of four categories: crop, pasture, primary vegetation, and secondary vegetation. Each map of total carbon shows the average total carbon density for each grid cell, including all above- and below-ground carbon stocks both in and out of agriculture. Changes in total carbon between time periods are the net result of gains from growth and losses that include respiration, decomposition, fire, and removals from land clearing, harvesting, grazing, and logging.

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Abbreviations: ED, Ecosystem Demography; Miami-LU, Miami Land Use History.

[†] To whom reprint requests should be addressed. E-mail: george.hurtt@unh.edu.

[§] Present address: Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA 02138.

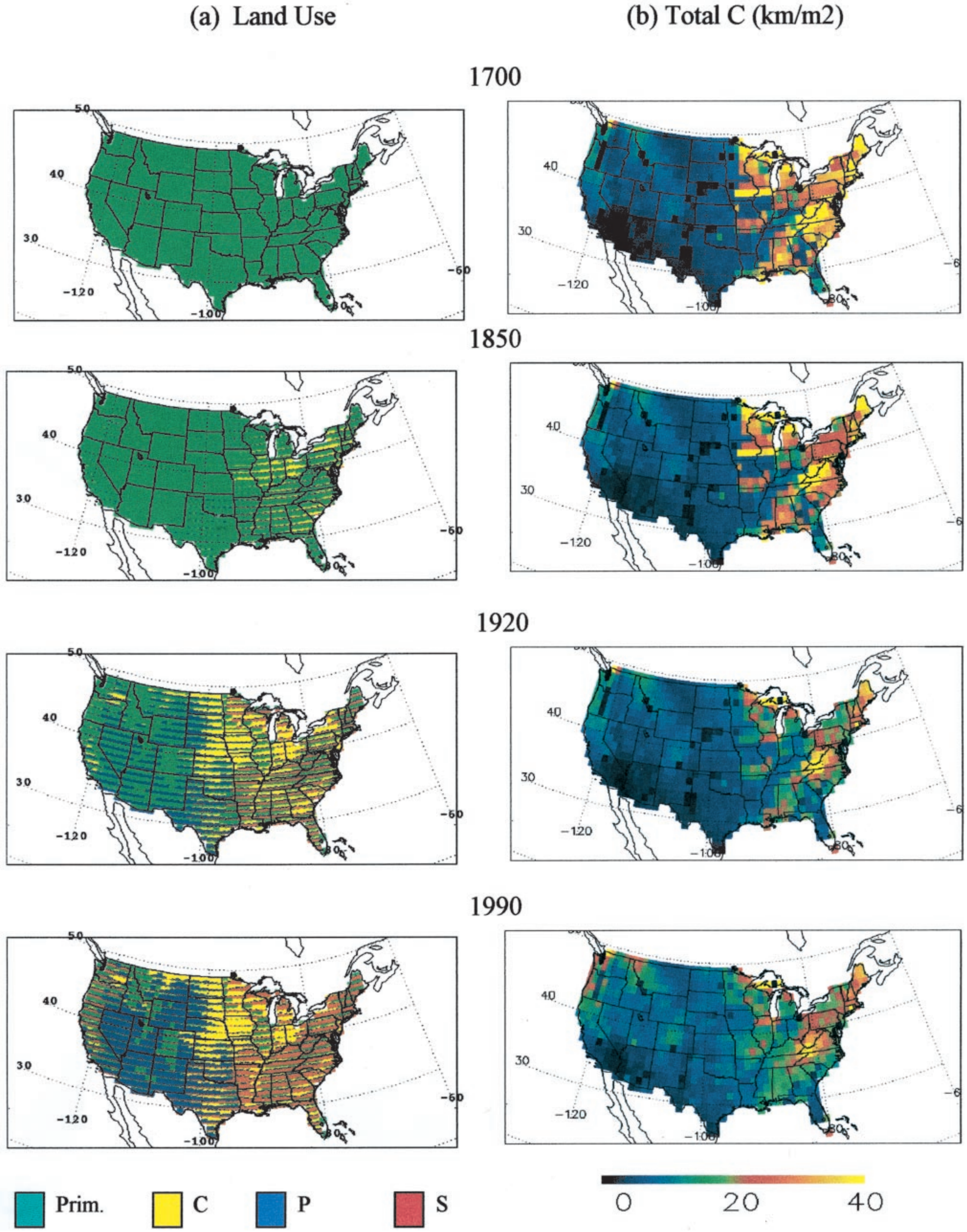

Fig. 1. ED tracks patterns of land use and carbon stocks throughout the simulation. Shown here are estimated patterns of land use and average total carbon stocks (kg C·m^{-2}) at four times in history: 1700, 1850, 1920, and 1990. In the land-use maps, each 1° × 1° grid cell is colored according to the fraction of the grid cell that is estimated to be in each of four land-use classes: primary vegetation (green), secondary vegetation (red), crop (yellow), and pasture (blue). In particular, each grid cell is shown as a stacked bar chart with colors in a fixed order. Spatial patterns of the relative amounts of land use in each of these four classes can be seen on each map. However, subgrid-scale spatial patterns and the impression of bands spanning a series of adjacent cells are the result of consistently applied coloring rules and do not illustrate spatial patterns of land use within grid cells or banded patterns of land use between grid cells.

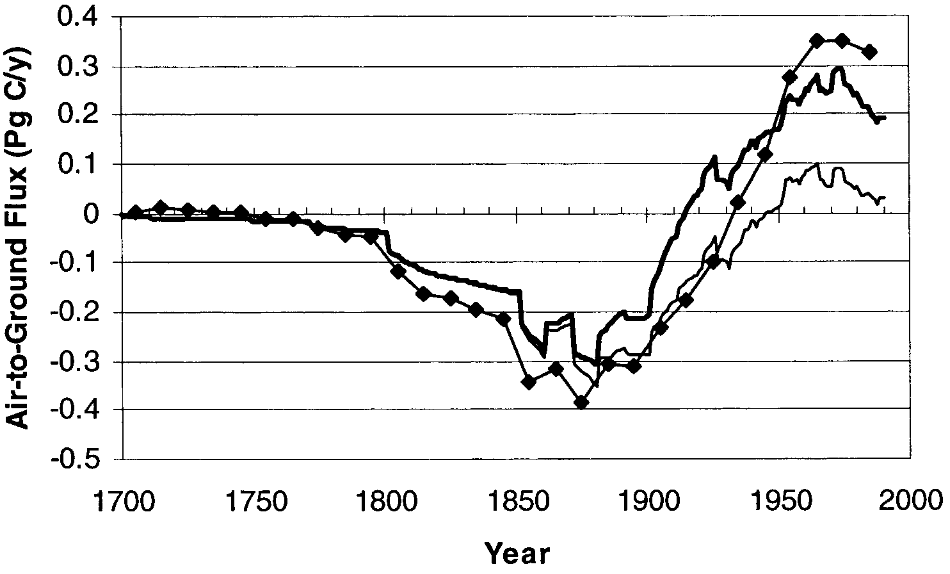

Fig. 2. Estimated average annual air-to-ground net flux in Pg C·y^{-1} from 1700 to 1990. Positive values indicate a land sink and negative values indicate a source to the atmosphere. Light line, ref. 6 without fire suppression. Dark line, ref. 6 with fire suppression. Dark line with ◆, ED.

Our calculations indicate that changes in land use and fire management have had large effects on the historical patterns of carbon stocks (Fig. 1) and fluxes (Fig. 2). Beginning in approximate carbon balance in 1700, we find that by 1900 the region lost ≈26 Pg C because of the expansion of agriculture and logging. By the mid-1900s and late 1900s, the migration of agriculture to the West primarily displaced grasslands and led to the net regrowth of Eastern forests, and fire suppression led to woody encroachment and vegetation thickening in fire-prone ecosystems predominantly in the West. Because of these factors, ecosystems of the coterminous U.S. are estimated to have been a significant carbon sink in the 20th century. These historical patterns are broadly consistent with earlier estimates (6), but differ importantly in the causes and spatial distribution of the pattern during the 20th century. Our estimates of recent gains in Eastern forests are closer than those in Houghton *et al.* (6) to estimates based on Forest Service data (10, 11) and are consistent with the mechanism of net ecosystem recovery suggested by ref. 2. However, we may overestimate the consequences of fire suppression on some Western lands. Fine-scale edaphic and topographic factors are important determinants of the structure of ecosystems in the West and are not well represented with 1° resolution. Our overall fire suppression sink term is similar to that from Houghton *et al.* (6).

Estimates of recent net fluxes from land-use change and fire suppression compare favorably to detailed estimates based largely on inventory methods (Table 1). For the decade of the 1980s, the estimated average annual carbon sink for the coterminous U.S. was 0.33 Pg C·y^{-1}. Forested lands [defined in ED as all primary and secondary lands where the primary vegetation exceeds 20 t C·ha^{-1}—a definition that corresponded to a total forested area in the coterminous U.S. of 2.48×10^6 km^2 in 1990, which is comparable to independent estimates (17) accumulated a net 0.10 Pg C·y^{-1} in biomass and 0.13 Pg C·y^{-1} in soils and litter for a total of 0.23 Pg C·y^{-1}. The biomass sink was mostly in the East where it was caused primarily by forest growth exceeding removals. Other organic matter accumulated more in the West as a result of fire suppression. Pastures and naturally nonforested vegetation accumulated a net 0.11 Pg C·y^{-1} in biomass and 0.02 Pg C·y^{-1} in soils and litter, for a total of 0.13 Pg C·y^{-1}, primarily because of the effects of fire suppression. These gains were partially offset by net decreases in cropland soils of -0.03 Pg C·y^{-1}. Estimates of net carbon storage from mechanisms that ED does not simulate must be added to these estimates to obtain a comprehensive estimate. The processes modeled in this study represent approximately 45–90% of the total U.S. terrestrial carbon sink in the 1980s. Additional sinks caused by such factors as the accumulation of wood products, improved agricultural soil

Table 1. Estimated land-use areas in 1990 and average net fluxes of carbon to the land for the 1980s

	Area, 10^4 km^2	B	S	Total
Forest	248	0.10 (0.11–0.15)	0.13 (0.03–0.15)*	0.23 (0.14–0.30)
Nonforest and pasture	336	0.11 (NA)	0.02 (NA)	0.13 (0.12–0.13)*
Cropland	183	0.00 (NA)	−0.03 (0.00–0.04)	−0.03 (0.00–0.04)†
Total	767	0.21	0.12	0.33 (0.26–0.47)‡

Positive values indicate carbon sinks on land. B is for live biomass. S is other organic matter in litter, necromass, and soils. Numbers in parentheses are lower and upper bounds from ref. 1. NA, not available.

*Upper-bound in ref. 1 based, in part, on the use of the ED model.

†The estimates using ED do not include the effects of modern agricultural techniques, such as conservation tillage, that help sequester soil carbon as do the estimates in ref. 1.

‡Estimates of carbon sinks that ED does not simulate must be added to these estimates to obtain a comprehensive estimate (see text).

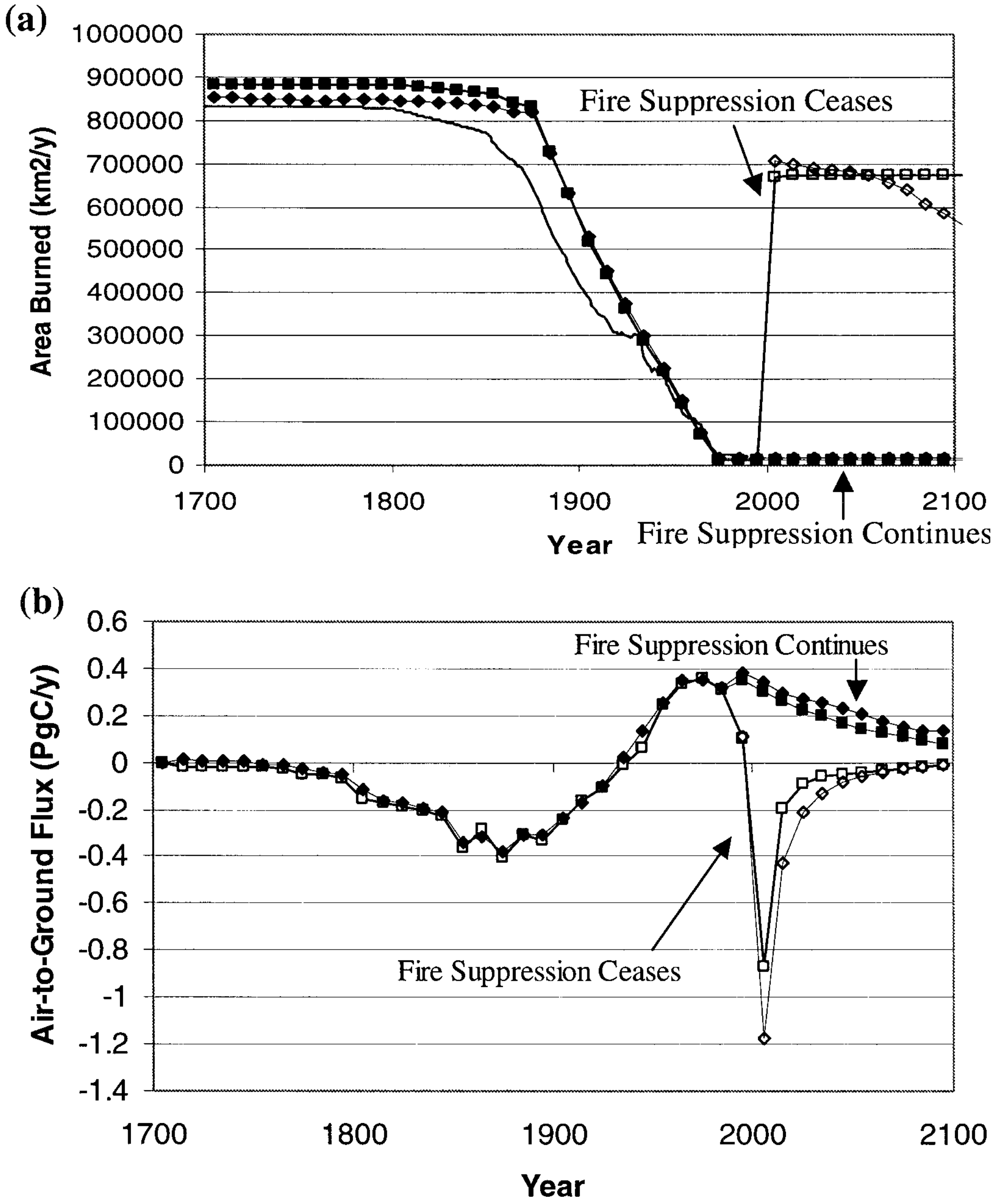

Fig. 3. (a) Estimated average annual area burned in km^2·y^{-1} from 1700 to 2100. (*b*) Projected average annual air-to-ground net flux in Pg C·y^{-1} from 1700 to 2100. Positive values indicate a land sink and negative values indicate a source to the atmosphere. Diamonds represent ED; squares represent Miami-LU. Solid symbols represent cases assuming continued fire suppression. Empty symbols represent cases assuming fire suppression ceases.

management practices, and carbon storage in reservoirs are in the range of 0.1 to 0.2 Pg C·y^{-1} (1), putting an estimate of the sink in the coterminous U.S. based largely on ED at approximately one-half Pg C·y^{-1} for the 1980s.

We then used ED to project the future of the modeled portion of the U.S. carbon sink under two scenarios that span a wide range of future conditions. In both scenarios, we held climate and CO_2 patterns constant so as to focus on the future of the mechanisms estimated to be responsible for the current carbon sink. We also assumed that there are no future land-use conversions and no significant changes in the intensity of land use, and that the harvesting of secondary forests continues with current estimated age-specific harvesting rates. These assumptions reflect the comparative stability of land use over the past 50 years. Since 1950, there has been little change in the total area of forest, pasture, cropland, or nonforested vegetation. Also forest management has produced a stable increase in forest tree carbon of 0.10 ± 0.02 Pg C·y^{-1} (9–11), most of which is in the East, because regrowth consistently exceeds harvest by this amount. The two scenarios differ in their treatment of fire, because fire dynamics are difficult to anticipate and because effective fire suppression is estimated to be such an important part of the current sink (refs. 1, 6, 7, and 12; this study).

In the first scenario, we assume that fire suppression efforts continue to be effective at reducing fires to their 1980s levels throughout the 21st century. This scenario is optimistic, because it excludes any future significant increases in fire despite the ongoing build-up of fuel in fire-prone ecosystems. In the second scenario, we assume that fire suppression ceases in 2000. Although, this second scenario is obviously a worst-case scenario for fire, it is reasonable to expect that fire risk will increase as ecosystems accumulate carbon. Together, the two scenarios span a broad range of possible futures for the dominant portion of the current U.S. sink in the absence of dramatic changes in land use or ecosystem dynamics in response to future climate change or fertilization.

Even with continued fire suppression, the modeled U.S. sink is projected to decline to 0.21 Pg C$\cdot$y^{-1} by 2050 and to 0.13 Pg C$\cdot$y^{-1} by 2100, having stored a total of 25 Pg C in the 21st century (Fig. 3). The reason the sink decreases is that woody encroachment from fire suppression approaches its maximum extent and forest ecosystem recovery slows and begins to equilibrate with forest harvesting and natural mortality. If fire suppression efforts were to completely fail, the modeled U.S. sink would be rapidly replaced by a source caused by extensive burning from large-scale fires (Fig. 3). In this case, U.S. terrestrial ecosystems would be a source during the entire 21st century, losing a net 20 Pg C to the atmosphere.

The results presented here are not overly dependent on the submodels and scaling algorithms in ED. To illustrate this, we developed and parameterized a second simpler model for comparison, Miami-LU (see Appendix 5, which is published as supporting information on the PNAS web site). Miami-LU is driven by the same climate data and land-use history reconstruction as ED, and it tracks the subgrid-scale heterogeneity resulting from land-use changes in a similar way. However, the submodels in Miami-LU are far simpler and less mechanistic than those in ED. Miami-LU is driven by the empirically based Miami model of net primary production (13), has prescribed mortality rates, and has greatly simplified decomposition and fire submodels. As Fig. 3 illustrates, this model has similar aggregate dynamics to ED over the entire period.[‖] Additional calculations with Miami-LU suggest that model results are not qualitatively affected by alternative assumptions about fire frequency in the distant past when the uncertainty is greatest (see Appendix 6 and Fig. 6, which are published as supporting information on the PNAS web site).

Although previous modeling studies have either inferred (6) or predicted (14) a significant role of ecophysiological mechanisms such as fertilization or climate change in explaining the current U.S. carbon sink, this study estimates reasonable values of the sink without these mechanisms.[**] This is an important distinction, because different sink mechanisms can lead to substantially different projections of the future of the sink in models. While the evidence is mounting that the contemporary sink is dominated by ecosystem recovery resulting from land-use history and fire suppression,[††] continued research to eliminate uncertainties and to estimate the responses of ecosystems to past and future environmental change is critical. The projected decline of the current U.S. carbon sink as ecosystem recovery progresses increases the need to evaluate alternative land-use practices that may prolong the sink and to confirm any expectations of an increasing sink caused by future environmental changes.

This study builds on previous studies that have anticipated the decline in global carbon sinks generally (15) and that of the U.S. forest sink in particular (11, 16). The projections here include all lands (both forested and nonforested) and highlight the uncertainties associated with the long-term effectiveness of fire suppression. We find that without dramatic increases in the area of forests, without substantially positive changes in land-use practices, without large net positive effects of CO_2 or climate change in the future, or without some other new significant carbon storage mechanism, the U.S. carbon sink itself will decrease substantially over the 21st century. If realized, the decreases projected here would be significant. Total U.S. fossil fuel emissions would need to be reduced by an additional 7–30% to compensate for the declining sink and stabilize net emissions at 1990 levels throughout this century.[‡‡]

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[‖] The dynamics of ED and Miami-LU are very similar. However, there are differences at finer scales. Miami-LU recovers faster from prior land use than ED, as evidenced in Fig. 3, probably because it lacks mechanisms responsible for the longertime scales of succession.

[**] Unlike previous studies, reasonable estimates of the sink on decadal time scales are obtained here without ecophysiological mechanisms. This does not preclude the importance of ecophysiological mechanisms in influencing the sink on seasonal and interannual time scales, or over longer time scales under future environmental change. The estimates in this study are similar to estimates from Houghton *et al* for agricultural lands and fire suppression (ref. 6, but see revision to cropland estimate in ref. 1.) and estimates of the magnitude and cause of the forest sink based on U.S. Forest Inventory Analysis data (1, 2).

[††] The hypothesis that the sink in the coterminous U.S. on decadal time scales is primarily caused by net ecosystem recovery and other factors associated with land use and land-use history is consistent with the following lines of evidence: the inconsistency of substantially enhanced forest vital rates with forest inventory data (2), fertilization experiments that suggest that resource limitation may limit the enhancement of carbon sequestration in forests (18), the documentation of sink terms such as woody encroachment that are relatively unambiguously related to factors such as fire suppression (1, 6), the stability of the forest sink over last 40 years based on forest inventories (9–11), and the stability of the U.S. sink generally over last 15 years based on recent atmospheric inversions (1).

[‡‡] To maintain constant net emissions, fossil fuel emissions must be reduced by an amount equal to declines in the carbon sink. Thus it is possible to convert model estimates of the decline in the sink into estimates of how much fossil fuel emissions would have to be reduced to compensate. In the calculation presented here, net emissions from the coterminous U.S. in 1990 were estimated by subtracting a sink of 1/3–2/3 Pg C$\cdot$y^{-1} (1) from fossil fuel emissions of 1.337 Pg C (19).

The decline in the sink was estimated by using ED (this study). For simplicity, the necessary cuts in emissions cited in the text are calculated such that the total net emissions over the interval (1990–2100) equal those from maintaining constant 1990 net emissions over the same interval. Holding net emissions to 1990 levels on a year-by-year basis would require cuts in fossil fuel emissions that vary through time and that range from lower to higher than the average values cited. The low estimate (7%) is derived from the scenario in which fire suppression efforts continue. The high estimate (30%) is derived from the scenario in which fire suppression efforts fail. These requirements are in addition to the reduction in fossil fuel emissions currently needed to achieve 1990 net emissions.

1. Pacala, S. W., Hurtt, G. C., Baker, D., Peylin, P., Houghton, R. A., Birdsey, R. A., Heath, L., Sundquist, E. T., Stallard, R. F., Ciais, P., *et al*. (2001) *Science* **292,** 2316–2320.
2. Caspersen, J. P., Pacala, S. W., Jenkins, J. C., Hurtt, G. C., Moorcroft, P. R. & Birdsey, R. A. (2000) *Science* **290,** 1148–1151.
3. Hurtt, G. C., Moorcroft, P. R., Pacala, S. W. & Levin, S. A. (1998) *Global Change Biol.* **4,** 581–590.
4. Moorcroft, P. R., Hurtt, G. C. & Pacala, S. W. (2001) *Ecol. Monogr.* **71,** 557–586.
5. Ramankutty, N. & Foley, J. A. (1999) *Global Biogeochem. Cycles* **13,** 997–1027.
6. Houghton, R. A., Hackler, J. L. & Lawrence, K. T. (1999) *Science* **285,** 574–578.
7. Houghton, R. A., Hackler, J. L. & Lawrence, K. T. (2000) *Global Ecol. Biogeogr.* **9,** 145–170.
8. Meeson, B. W., Corprew, F. E., McManus, J. M. P., Myers, D. M., Closs, J. W., Sun, K. J., Sunday, D. J. & Sellars, P. J. (1995) *ISLSCP Initiative I: Global Data Sets for Land-Atmosphere Models 1987–1988* (National Aeronautics and Space Administration, Washington, DC), Vols. 1–5, CD.
9. Birdsey, R. A. (1992) *Forest Service General Technical Report WO-59* (U.S. Department of Agriculture, Washington, DC).
10. Birdsey, R. A. & Heath, L. S. (1995) in *Forest Service General Technical Report RM-GTR-271*, ed. Joyce, L. A. (U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO), pp. 56–70.
11. Birdsey, R. A., Plantinga, A. J. & Heath, L. S. (1993) *Forest Ecol. Management* **58,** 33–40.
12. Tilman, D., Konops, J., Reich, P., Peterson, D., Phillips, H., Menton, M., Patel, A. & Vos, E. (2000) *Ecology* **81,** 2680–2685.
13. Leith, H. (1972) *Nat. Resources* **8,** 277–282.
14. Schimel, D., Melillo, J., Tian, H., McGuire, A. D., Kicklighter, D., Kittel, T., Rosenblum, N., Running, S., Thorton, P., Ojima, D., *et al.* (2000) *Science* **287,** 2004–2206.
15. Falkowski, P., Scholes, R. J., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Hogberg, P., Linder, S., *et al*. (2000) *Science* **290,** 291–296.

16. Turner, D. P. & Koerper, G. J. (1995) *Tellus* **47B,** 232–239.
17. Turner, D. P., Koerper, G. J., Harmon, M. E. & Lee, J. J. (1995) *Ecol. Appl.* **5,** 421–436.
18. Oren, R., Ellsworth, D. E., Johnsen, K. H., Phillips, N., Ewers, B. E., Maier, C., Schafer, K. V. R., McCarthy, H., Hendrey, G., McNulty, S. G. & Katul, G. G. (2001) *Nature (London)* **411,** 469–472.
19. U.S. Department of Energy Energy Information Administration (1997) *International Energy Outlook 1997* (U.S. Department of Energy, Washington, DC).
20. Sellers, P. J., Meeson, B. W., Closs, J., Collatz, J., Corprew, F., Dazlich, D., Hall, F. G., Kerr, Y., Kostes, R., Los, S., *et al.* (1995) in *ISLSCP Initiative I-Global Data Sets for Land-Atmosphere Models, 1987–1988* (National Aeronautics and Space Administration, Washington, DC), Vol. 1, CD.