A Contemporary Carbon Balance for the Northeast Region of the United States

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Ⓢ *Supporting Information*

ABSTRACT: Development of regional policies to reduce net emissions of carbon dioxide (CO_2) would benefit from the quantification of the major components of the region's carbon balance—fossil fuel CO_2 emissions and net fluxes between land ecosystems and the atmosphere. Through spatially detailed inventories of fossil fuel CO_2 emissions and a terrestrial biogeochemistry model, we produce the first estimate of regional carbon balance for the Northeast United States between 2001 and 2005. Our analysis reveals that the region was a net carbon source of 259 Tg C/yr over this period. Carbon sequestration by land ecosystems across the region, mainly forests, compensated for about 6% of the region's fossil fuel emissions. Actions that reduce fossil fuel CO_2 emissions are key to improving the region's carbon balance. Careful management of forested lands will be required to protect their role as a net carbon sink and a provider of important ecosystem services such as water purification, erosion control, wildlife habitat and diversity, and scenic landscapes.

INTRODUCTION

General interest is growing in how humans are disrupting the global cycles of life-sustaining elements including carbon, nitrogen, sulfur, and phosphorus. Human alteration of these cycles at regional scales can be even more dramatic. Policy makers across the globe are demanding spatially detailed scientific information to guide their climate-change policy decisions. As an example, we combine high-resolution, georeferenced data on regional fossil fuel emissions with model-based estimates of carbon sequestration by land ecosystems to develop a contemporary carbon balance for the Northeast region of the United States for the period 2001–2005.

The human-dominated region of the Northeast (NE) is a large, multistate environment defined by a complex amalgam of urban, suburban, and rural ecosystems.[1−3] This region, running from Maine in the north to Virginia in the south (Figure 1), is home to about 69 million people, which is almost one-fifth of the nation's population.[4] This large fraction of the U.S. population inhabits 54.5 million hectares, which is only about 7% of the area of the conterminous United States. The high-density urban/suburban coastal corridor from Boston to Washington, DC is the quintessential urban environment.

The region's population centers are energy-use hotspots. For the period 2001−2005, the region was an emitter of a large amount of CO_2 annually from fossil fuel burning, with the mean emissions[5] estimated at 275 Tg C/yr. The Northeast's landscape is dominated by forests (60%, Table 1), but the region also has grasslands, coastal zones, beaches and dunes, wetlands, and agricultural areas that include pastures, orchards, and croplands (Figure 1). The natural areas contribute important ecosystem services to people, including protecting water supplies, wildlife habitat and biodiversity, landscape stabilization, and sequestering carbon in vegetation and soils.[1,2,6,7]

Recent advances in our understanding of fossil-fuel CO_2 emissions at regional to local scales, combined with process-based biogeochemistry models, enable construction of annual regional carbon budgets that can provide decision makers with important information to guide policy. The spatial quantification of net land-atmosphere exchange of carbon allows budgets
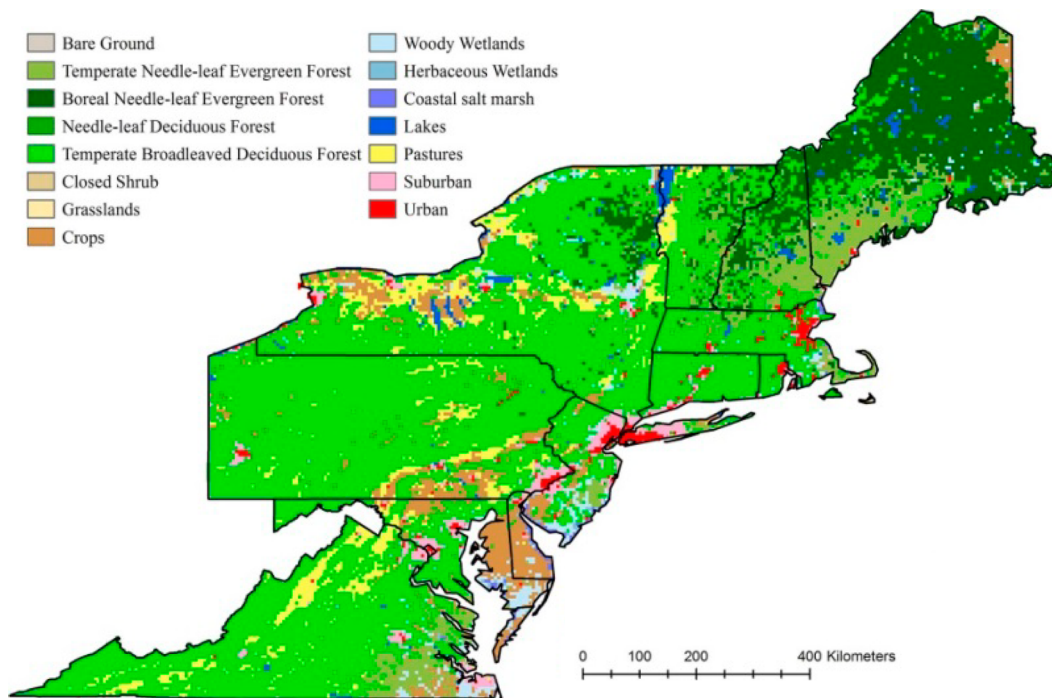
Figure 1. Dominant land cover across the northeastern United States. The resolution is 0.05° latitude × 0.05° longitude.

Table 1. Contemporary (2001-2005) Carbon Fluxes (Tg C/yr) among Land Covers in the Northeastern United States[a]

land cover	area (10^6 ha)	net primary production	heterotrophic respiration	resource management and consumption	net carbon exchange
food crops	3.75 (0.04)	21.8 (2.4)	16.0 (0.3)	6.1 (0.6)	−0.3 (2.7)
pastures	6.23 (0.02)	6.4 (0.5)	4.6 (0.3)	3.4 (0.4)	−1.6 (1.1)
urban	1.10 (<0.01)	1.0 (0.1)	0.9 (<0.1)	<0.1 (<0.1)	0.1 (0.1)
suburban	4.53 (0.26)	10.4 (1.0)	9.2 (1.1)	4.5 (1.2)	−3.3 (1.4)
forests	32.77 (0.14)	208.2 (10.5)	185.7 (10.1)	1.5 (<0.1)	21.0 (18.4)
shrublands	1.75 (0.04)	4.8 (1.0)	4.9 (0.2)	<0.1 (<0.1)	−0.1 (0.9)
grasslands	0.57 (0.01)	1.6 (0.7)	1.9 (0.1)	<0.1 (<0.1)	−0.3 (0.8)
wetlands	3.68 (0.05)	19.8 (2.9)	18.9 (0.4)	0.2 (0.1)	0.7 (2.8)
total	54.38	274.0 (11.4)	242.1 (11.8)	15.7 (1.9)	16.2 (22.4)

[a]Values in parentheses represent standard deviations of the variation among years during the five-year study period.

to be constructed that define the degree to which carbon sequestration by land ecosystems could offset fossil-fuel CO_2 emissions regionally. In addition, it can identify areas where important atmospheric carbon sinks occur that may need protection from development in the future.

MATERIALS AND METHODS

The regional carbon balance, which focuses on CO_2 only, is determined by subtracting fossil-fuel CO_2 emissions from model estimates of the net carbon exchange between land ecosystems and the atmosphere. The regional fossil CO_2 emissions data for the NE are from two sources: the DOE's Energy Information Administration (DOE-EIA),[5] and the Vulcan Project.[8] The DOE emissions inventory data is reported for the period 2001−2005 at the state level for each of the 12 states in the region. The Vulcan emissions inventory data is reported for only 2002, but at a higher spatial resolution (10 km by 10 km). The DOE and Vulcan data sets account for the same sources of CO_2−C emissions, which include transportation, industrial and residential energy uses within the region. Extra-regional fossil fuel emissions associated with electricity imported to the region are not included in the DOE

and Vulcan analyses. When the Vulcan high-resolution emissions estimates for 2002 are aggregated to the state level, the aggregated values agree well (Supporting Information (SI) Table S13) with the DOE-EIA state-level estimates.

The Terrestrial Ecosystem Model (TEM) is a process-based biogeochemistry model that uses spatially referenced information on climate, elevation, soils, and vegetation to estimate vegetation and soil carbon fluxes and pool sizes. The TEM is well documented and has been used to examine patterns of land carbon dynamics across the globe including how they are influenced by multiple factors such as CO_2 fertilization, climate change and variability, land-use change, atmospheric nitrogen deposition, and ozone pollution.[9−12] For this study, the model has been modified to also account for the effects on regional carbon dynamics of the large area of impervious surfaces found in urban and suburban areas, which are assumed to be a mosaic of impervious surfaces, lawns, and trees (SI Table S2). While lawns and urban/suburban trees are allowed to gain and lose carbon, no such fluxes are assumed to occur in areas covered by impervious surfaces. Because of their higher population density, urban areas contain more impervious surfaces per unit area, whereas suburban areas contain more open spaces covered with

grasses and trees. The relative proportion of these four land covers comprising urban and suburban areas, however, vary spatially as prescribed by a land cover data set.[13]

Representation of the Carbon Budget. To estimate the contribution of natural processes to a region's carbon budget, TEM estimates the uptake of atmospheric carbon dioxide by land vegetation through photosynthesis, also known as gross primary productivity (GPP), and the release of carbon dioxide from land ecosystems back to the atmosphere from plant respiration, also known as autotrophic respiration (R_A), and heterotrophic respiration (R_H) associated with the decomposition of detritus and soil organic matter.[14] This version of the model also estimates the loss of dissolved organic carbon from land ecosystems to neighboring river networks.[12] Net primary production (NPP), which represents the production of vegetative biomass, is estimated by subtracting R_A from GPP. Ecosystem respiration (ER) is estimated as the sum of R_A and R_H. Net ecosystem production (NEP) is the net uptake or release of carbon dioxide associated with ecosystem metabolism and is estimated either by subtracting R_H from NPP or by subtracting ER from GPP.

Human activities modify these natural carbon fluxes by enhancing the loss of land carbon from burning slash when converting land to agriculture or urban areas (i.e, conversion emissions or E_C), by removing vegetation biomass from the ecosystem for food, fiber, or fuel, and by applying fertilizers to enhance NPP. In TEM, the fate of carbon in food and wood products is tracked separately from ecosystem carbon dynamics.[15] Carbon stored in food products is assumed to be returned back to the atmosphere from decay within a year after harvest. Carbon in wood products is stratified between paper and paper products, which decay within 10 years after timber harvest, and longer-lasting wood products (e.g., construction materials, wood furniture), which decay within 100 years after timber harvest. No horizontal transport of food or wood products is assumed to occur among grid cells. In this study, the net carbon exchange between the atmosphere and land ecosystems (NCE) is estimated as

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

where E_P represents the sum of carbon emissions associated with the decomposition of food and wood products. A positive value of NCE represents a net sink of atmospheric carbon by land ecosystems whereas a negative value of NCE indicates that land ecosystems represent a net source of carbon dioxide to the atmosphere. The net ecosystem carbon balance (NECB)[16] is then estimated as the difference between NCE and the amount of organic carbon flushed from the land to freshwater systems in dissolved form (i.e., dissolved organic carbon, DOC). As NECB represents the amount of carbon sequestered or lost by land ecosystems, it may also be calculated from changes in the associated carbon pools:

$$NECB = \Delta VEGC + \Delta SOILC + \Delta PRODUCTC \tag{2}$$

where $\Delta VEGC$ is biomass increment, $\Delta SOILC$ is the change in the standing stock of soil organic carbon, and $\Delta PRODUCTC$ is the change in standing stocks of agricultural and wood products. Finally, the atmospheric net carbon balance (NCB) is determined by subtracting fossil fuel emissions described above from NCE.

Land-Use Legacy. The contemporary carbon dynamics in terrestrial ecosystems of the NE have been affected by the legacy of centuries of land-use and climate change. This legacy of past land-use change is considered in our simulations by using a disturbance cohort approach[17] to track the effects of land-use change and climate on terrestrial carbon stocks and fluxes from 1700 to 2005. Land-use transition data from Hurtt et al.[18] are used to prescribe the timing and locations of land conversions, which are used to modify the land cover of existing cohorts or to create new land cover cohorts in a grid cell based on the area required by the prescribed conversion (see SI text for more details). During conversion of land to food crops, pastures, urban or suburban areas, all vegetation within a cohort is killed. As described in McGuire et al.,[15] the amount of carbon lost to the atmosphere from burning vegetation or slash to clear the land, left on or in the soils as slash to decompose, or harvested as wood products varies with the type of vegetation cover present during conversion For example, 40% of the carbon in the tree biomass in a forested cohort is assumed to be lost to the atmosphere from the burning of slash or fuel wood, 33% of the biomass carbon is assumed to be added to the soil as detritus, and 27% of the biomass carbon is assumed to be converted to wood products. In a nonforested cohort, 50% of the carbon in the vegetation biomass is assumed to be lost to the atmosphere from burning and 50% is assumed to be added to the soil as detritus.

After conversion, the carbon dynamics of food crops are simulated using a generic crop parametrization where both planting and harvest dates are determined using growing degree days.[19] Upon harvest, we assume 40% of the crop biomass is transferred to an agricultural product pool and the remaining biomass enters the soil organic carbon pools. In this study, we assume that all crops are rain-fed, grown under no-till conditions, and are optimally fertilized such that the NPP of the crop plant is never nitrogen-limited. Pastures are simulated basically as grasslands, but 5% of the standing plant biomass is assumed to be consumed by livestock each month. Of the forage consumed by livestock, 83% of the carbon is assumed to be released to the atmosphere as animal respiration each month and 17% of the carbon is added to reactive soil organic carbon as manure.[20] For the corresponding nitrogen in forage, 50% is added to reactive soil organic nitrogen as manure and 50% is added to the soil ammonium pool as urine. For urban/suburban areas, new temperate broadleaved deciduous trees and temperate needle-leaf evergreen trees are assumed to grow from seedlings based on the comparable parametrizations of the natural forest types. Lawns are established and simulated as grasslands, but 10% of the grass biomass is assumed to be clipped when monthly net primary production rates are greater than zero to mimic mowing. The carbon and nitrogen in the grass clippings are added to the respective reactive soil organic carbon and nitrogen pools. In areas covered with impervious surfaces, no carbon fluxes are assumed to occur except those related to land conversion. All precipitation and atmospheric nitrogen deposition falling on impervious surfaces are assumed to be redirected to neighboring river networks without entering the soil.

Input Data Sets. In addition to land cover, the primary driving variables for TEM are meteorological data (precipitation, cloudiness and average air temperature), atmospheric chemistry data (CO_2 concentrations, ozone concentrations, and nitrogen deposition), soil texture, and elevation. The TEM simulations have been run at a monthly time step and a spatial resolution of 0.05° latitude × 0.05° longitude. The development of the input data sets is described in the SI.

■ RESULTS AND DISCUSSION

Regional Carbon Balance. The NE is estimated to be a net carbon source to the atmosphere that averaged 259 ± 29 Tg C/yr for the period 2001 through 2005, with the error estimates representing the standard deviation of the variations in the regional carbon balance among years. Fossil fuel emissions are the dominant term in the region's carbon balance with 275 ± 7 Tg C/yr released to the atmosphere. Concurrently, land ecosystems are estimated to take up, on average, 16 ± 22 Tg C/yr of atmospheric CO_2 over the study period or about 6% of the fossil fuel emissions. This is a much lower percentage than the values (range 19−35%, SI Table S14) estimated for that of the conterminous U.S. or the whole North American continent.[21−25]

The annual carbon budget of land ecosystems has several components (see also SI Figure S2). The NPP of terrestrial vegetation in the region takes up an average of 274 Tg C of atmospheric CO_2 per year (Table 1), which is almost identical to the amount of C released to the atmosphere in fossil fuel emissions (275 Tg C/yr) across the region. Much of this C uptake, however, is counterbalanced by microbial respiration associated with the decomposition of plant litter and soil organic matter, which releases an average of 242 Tg C/yr back to the atmosphere each year. Another 16 Tg C/yr of the NPP is consumed by people for food, fuel, fiber, and related management activities, and is ultimately oxidized and returned to the atmosphere as CO_2 (SI Table S4). As a result, the net carbon exchange between land ecosystems and the atmosphere is only 16 Tg C/yr. However, not all of this carbon taken up from the atmosphere by vegetation remains on land. About 2 Tg C/yr is transferred from land ecosystems to neighboring river networks as DOC such that 14 Tg C/yr is accumulating in the land ecosystems of the region.

Land Patterns of Fossil Fuel Emissions. The densely populated urban/suburban coastal corridor from Boston, Massachusetts to Washington, DC. where net carbon losses may be as high as 725 Mg C ha^{-1} yr^{-1}, is mostly responsible for the NE being a net carbon source (Figure 2). In addition to the concentrated use of large amounts of fossil fuels, a large portion of this urban/suburban corridor is covered with impervious surfaces (68.2% for urban and 16.9% for suburban), which prevents vegetation from growing and taking up atmospheric CO_2. In contrast, many areas outside of the urban/suburban coastal corridor are net carbon sinks, including the northern parts of New York, Vermont, New Hampshire, and Maine, western Pennsylvania, southern New Jersey, southeastern Maryland, and Virginia. Within these more rural areas dominated by carbon sink activity (Figure 3b), however, fossil fuel emissions from the interstate highway system (e.g., I-81 and I-95 in Virginia, I-80 and I-76 in Pennsylvania, I-90 in New York) show the important role of on-road transportation on emissions patterns[26] (Figure 3a) and how expansion of urban/suburban areas may threaten the ability of land in this region to sequester atmospheric CO_2 in the future. While fossil fuel emissions dominate the flux of carbon to the atmosphere in every state, land carbon emissions associated with the expansion of suburban areas also enhance state-level carbon emissions in several states (Figure 2).

Land Carbon Sources and Sinks. Forests represent the largest sink of atmospheric CO_2 in the NE (Table 1), sequestering on net 21.0 Tg C/yr. Wetlands and urban areas are much smaller sinks sequestering 0.7 Tg C/yr and 0.1 Tg C/
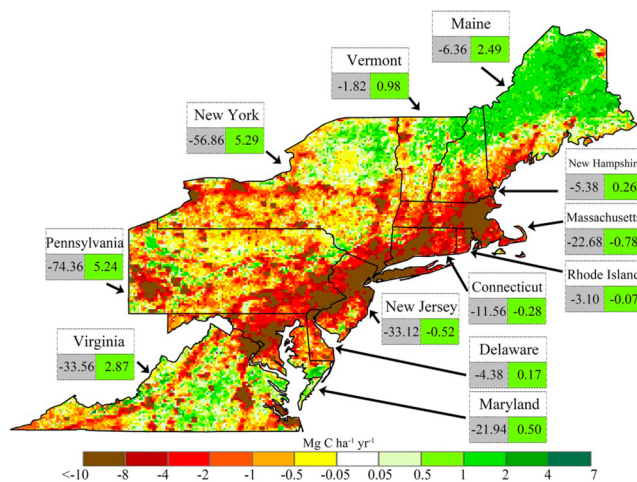

Figure 2. Distribution of net sources (negative values) and sinks (positive values) of atmospheric carbon dioxide across the northeastern United States for the year 2002 based on spatially explicit Vulcan[8] fossil fuel emissions and TEM estimates of net carbon exchange in 2002. State-level summaries represent averaged rates of fossil fuel emissions (Tg C/yr, values are highlighted in gray) and TEM-estimated net carbon exchange between land ecosystems and the atmosphere (Tg C/yr, values are highlighted in green) over five years (2001−2005).
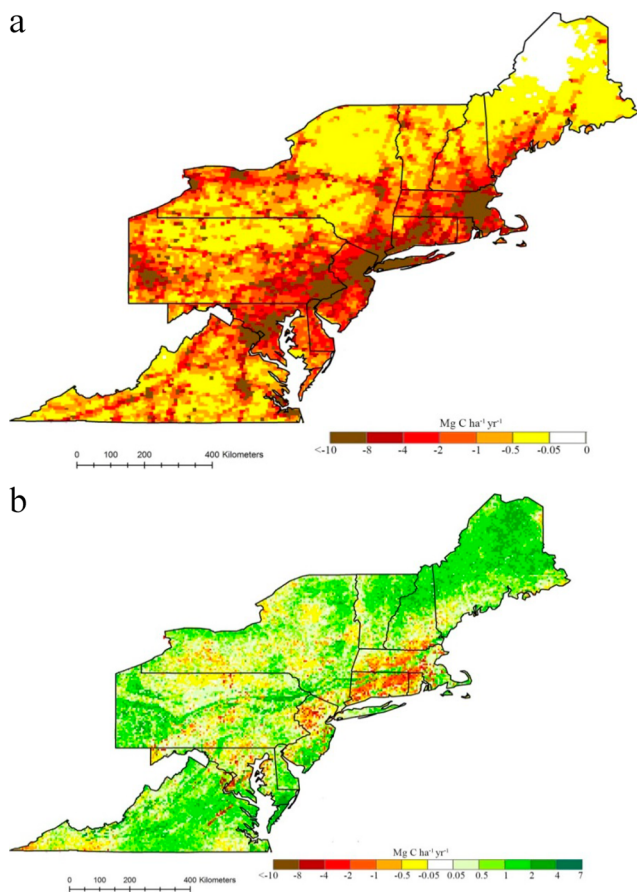

Figure 3. Carbon fluxes across the northeastern United States in 2002 including Vulcan[8] fossil fuel emissions (a) and TEM-estimated net carbon exchange between land ecosystems and the atmosphere (b).

yr, respectively. All other land ecosystems, on the other hand, are carbon sources. Suburban areas represent the largest carbon

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Table 2. Contemporary (2001-2005) Forest Carbon Characteristics among States in the Northeastern United States[a]

state	forest area (10^6 ha)	net primary production (g C m^{-2} yr^{-1})	net carbon exchange (g C m^{-2} yr^{-1})	state/regional net carbon exchange (Tg C/yr)
Connecticut	0.74 (0.01)	648 (205)	40 (194)	0.3 (1.0)
Delaware	0.08 (<0.01)	848 (389)	80 (378)	0.1 (0.1)
Maine	5.70 (<0.01)	525 (219)	41 (215)	2.3 (6.8)
Maryland	0.81 (0.01)	763 (268)	73 (221)	0.6 (0.4)
Massachusetts	1.10 (0.02)	594 (166)	21 (162)	0.2 (0.9)
New Hampshire	1.88 (0.01)	530 (176)	30 (195)	0.6 (1.9)
New Jersey	0.638 (0.01)	752 (221)	53 (174)	0.3 (0.3)
New York	6.68 (0.02)	642 (184)	87 (206)	5.8 (3.3)
Pennsylvania	7.17 (0.04)	684 (180)	88 (189)	6.3 (2.4)
Rhode Island	0.13 (<0.01)	620 (201)	46 (161)	0.1 (0.1)
Vermont	1.78 (<0.01)	577 (179)	56 (214)	1.0 (1.6)
Virginia	6.06 (0.02)	699 (264)	56 (188)	3.4 (2.5)
Total	32.77 (0.14)	635 (221)	64 (201)	21.0 (18.4)

[a]Values in parentheses represent standard deviations of the variation among years during the study period for area and state/regional fluxes and standard deviations of the variation among cohorts across years of the five-year study period for areal fluxes.

source of atmospheric CO_2 releasing 3.3 Tg C/yr as vegetation, particularly trees, are cleared during the expansion of suburban areas (+0.89 million ha) into forests (−0.43 million ha), wetlands (−0.14 million ha), and other natural vegetation (−0.08 million ha). At first glance, the expansion of suburban areas into croplands (−0.16 million ha) and pastures (−0.08 million ha) has had small direct effects on the region's contemporary carbon balance and may help to enhance future carbon sequestration as vegetation regrow in these areas.[27,28] However, this expansion has additional indirect effects by the displacement of croplands (0.03 million ha) and pastures (0.08 million ha) into natural areas (SI Table S15). Consideration of livestock respiration (2.7 Tg C/yr, SI Table S4) in addition to microbial decomposition and the conversion of 0.12 million ha natural land (0.7 Tg/yr) causes pastures to represent the second largest carbon source, whereas attribution of the carbon released from the consumption of food produced in the region (6.0 Tg C/yr) to croplands causes this land cover to be the third largest carbon source.

Role of Forests. Because forests store a large amount of carbon in wood and cover 60% of the NE, this land cover has a dominant influence on carbon dynamics in this region (Table 1). Thus, variations in the ability of various states to sequester carbon are largely influenced by the extent and productivity of forests found in these states (Table 2). Pennsylvania and Delaware have the largest and smallest forest areas, respectively. While Delaware has less forested land than Rhode Island, the net primary productivity rate of the Delaware forests is about 1.4 times greater than the Rhode Island forests so that the net amount of atmospheric CO_2 taken up by forests is about the same for the two states. While a slightly warmer climate may account for some of this difference in productivity, past land use may also be a factor. Some forests that develop on land abandoned by agriculture, especially where manure has been applied, may grow faster than undisturbed forests.[29]

Validation and Sensitivity Analyses. We evaluate model performance by comparing TEM estimates of carbon fluxes to other types of estimates at three spatial scales. At the finest spatial scale, we compare model estimates to two types of stand-level estimates, one based on increment measurements and allometry, and the other based on eddy covariance measurements of carbon exchange between land and the atmosphere at the Harvard Forest. At the state-level, model

results are compared to biomass increment estimates of forests based on data from the U.S. Forest Service Forest Inventory and Analysis (FIA)[30] program. Finally, at the watershed-scale, model estimates of terrestrial DOC loading of river networks are compared to field-based estimates of riverine DOC export. Below, we present a summary of these comparisons (see SI text for more details).

At the stand level, the TEM estimates of biomass increment (1.1 Mg C ha^{-1} yr^{-1}) and changes in soil carbon (0.2 Mg C ha^{-1} yr^{-1}) at the Harvard Forest compare well with the 1.0 Mg C ha^{-1} yr^{-1} biomass increment and 0.2 Mg C ha^{-1} yr^{-1} change in soil carbon reported by Barford et al.[31] The TEM estimates, however, do not account for the 0.4 Mg C ha^{-1} yr^{-1} increase in dead wood reported by Barford et al.[31] so that the TEM NEP estimate of 1.3 Mg C ha^{-1} yr^{-1} is less the 1.6 Mg C ha^{-1} yr^{-1} derived from biometric measurements, but is still within the 95% confidence limits (±0.4) of the biometric estimate (SI Table S5). The mean TEM estimate of −1.3 ± 1.4 Mg C ha^{-1} yr^{-1} for net ecosystem exchange (NEE) at the Harvard Forest is also less than the previously reported[31] NEE of −2.0 ± 0.4 Mg C ha^{-1} yr^{-1} from eddy covariance measurements at this site (SI Table S7). However, it should be noted that the NEE estimate of −1.6 Mg C ha^{-1} yr^{-1} based on corresponding biometric measurements of NEP for the same time period is also lower than the eddy covariance estimate although the eddy covariance estimate is still within the 95% confidence limits of the biometric estimate. The TEM estimates of −12.6 ± 1.4 Mg C ha^{-1} yr^{-1} for gross ecosystem exchange (GEE) and 11.3 ± 0.6 Mg C ha^{-1} yr^{-1} for ecosystem respiration (ER) are also similar to the previously reported[31] estimates of −13.0 ± 1.0 Mg C ha^{-1} yr^{-1} for GEE and 11.0 ± 0.9 Mg C ha^{-1} yr^{-1} for ER (SI Table S6). Unlike Albani et al.,[32] consideration of CO_2 fertilization does not cause TEM to overestimate NEE (SI Table S7) nor does consideration of atmospheric nitrogen deposition effects. This may be partially due to the additional consideration of concurrent ozone pollution effects, which tends to reduce plant uptake of atmospheric carbon dioxide.[19]

At the state-level, TEM estimates of biomass increment in forests are mostly within a standard deviation of the estimates based on FIA data, but TEM still tends to be at the low end of the biomass increments calculated from the FIA data (Figure 4). It should be noted that the FIA biomass increment estimates are based on a sampling of permanent plots whereas
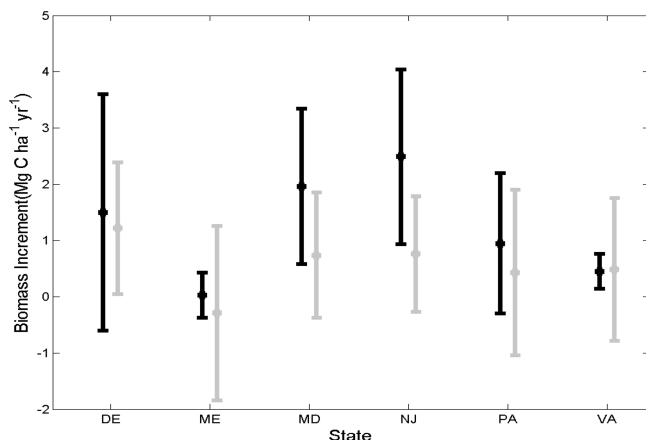
Figure 4. State-level biomass increment (Mg C ha^{-1} yr^{-1}) estimated using data from the U.S. Forest Service FIA program (black) and TEM (gray) for Delaware (DE), Maine (ME), Maryland (MD), New Jersey (NJ), Pennsylvania (PA), and Virginia (VA) . Error bars represent standard deviations of variation among plots for the inventory estimates and among cohorts for the TEM estimates.

the TEM estimates are based on the entire population of cohorts within a state or region that were forested during the time periods used to estimate the biomass increments from the FIA data.

At the watershed scale, the TEM estimates of riverine DOC export compares well with those estimates derived from field data if losses of DOC associated in-stream processing[33−36] are considered (SI Table S9). For example, if 63% of DOC is broken down by microbes to CO_2 in the Potomac River as Raymond and Bauer[34] found for the York River, then the 110 Gg C/yr of DOC estimated by TEM to be contributed by land to the Potomac River will result in a DOC export of 41 Gg C/yr, which compares well to the 42 Gg C/yr estimated by Hossler and Bauer.[37]

Our analyses are based on a number of assumptions, each of which introduces uncertainties into our model estimates. To explore the consequences of some of these assumptions, we have conducted several sensitivity analyses to examine the importance of assumptions related to forest age structure, disturbance effects related to the removal or nonremoval of trees during the creation of suburban areas, and how the fate of land-derived DOC transferred to rivers may influence regional estimates of net carbon exchange between the land surface and the atmosphere. Additional details of these sensitivity analyses are provided in the SI.

We find that driving TEM with a land cover data set prescribing a younger forest stand age structure that mimics the FIA data (SI Figure S1b) results in a 46% increase in the regional NCE (23.6 Tg C/yr) of the Northeast United States estimated by TEM (SI Table S11). Forest NEP almost doubles from 22.5 to 43.8 Tg C/yr, but increases in carbon losses to the atmosphere associated with the enhanced timber harvests and enhanced decomposition of wood products compensate for much of the enhanced CO_2 uptake by the younger regrowing forests. These forest NEP estimates by TEM bracket the comparable estimate of 32.0 Tg C/yr by Williams et al.[38]

The use of an assumption that all forests remain intact during the creation of suburban areas reduces the estimated carbon losses from suburban areas by 1 Tg C/yr, from −3.3 to −2.3 Tg C/yr. The loss of forest carbon from the creation of lawns and impervious surfaces still overwhelms any uptake of CO_2 by

forests in suburban areas whether they are disturbed or not (SI Table S12). In our simulations, lawns have not been considered to be watered or fertilized. Several studies[39,40] have suggested that turf grass, especially if watered and fertilized, may sequester substantial amounts of carbon. Based on the modeling analysis of Milesi et al.,[40] lawns in the Northeast United States may be able to sequester up to 2.3 Tg C/yr if they are all optimally fertilized and watered.

In our analyses, it is assumed that the carbon in DOC entering the river networks from land ecosystems is not released back to the atmosphere within the region, but is instead exported to the oceans either as DOC or dissolved inorganic carbon (DIC). The loss of riverine inorganic carbon by gaseous evasion of CO_2 to the atmosphere versus DIC export to the oceans as bicarbonate depends on a source of alkalinity within the transport waters, which can vary among rivers.[41] If all of the DOC transferred to river networks is remineralized to CO_2 and evaded to the atmosphere within the region, then the land surface will sequester only 14 Tg C per year.

Looking to the Future. This study suggests that the ability of land in the northeastern United States to sequester carbon in the future will depend on protecting forests in the region. Conversion of forests to crops, pasture, urban, or suburban areas will release carbon to the atmosphere and may diminish the ability of the land to sequester carbon, especially if expansion of urban/suburban areas cover more of the landscape with impervious surfaces. As noted in this study, the expansion of urban/suburban areas may influence forests carbon stocks and fluxes either directly by converting forest lands to urban/suburban areas or indirectly by displacing pastures and croplands which then cause a loss of forests from land conversion to agriculture. Carbon sinks associated with forest regrowth from the abandonment of croplands, pasture, and urban/suburban areas will depend on the age of the forest stands with the highest rates of carbon sequestration occurring in intermediate-aged (30−120 years) stands.[42] However, even old-growth forests can sequester carbon.[43] Stand age information of forests in the NE region (SI Figure S1) implies that most secondary forests were established during the middle of last century, which suggests the current forest sink will tend to decrease over the next several decades even without further disturbances. These age-related declines in the forest carbon sink, however, might be compensated by enhanced forest growth from changes in atmospheric chemistry such as atmospheric nitrogen deposition,[44,45] although there may be limits to this enhanced growth.[46] While there is considerable vegetation in urban and suburban areas[3] that may also sequester atmospheric carbon, our analyses indicate this urban carbon sink will not overcome the loss of carbon associated with expanding urbanization (Table 1).

While forests of the region currently take up only 6% of the fossil-fuel CO_2−C emissions, their large carbon mass, estimated by us to be 8300 Tg C, make protecting forests a critically important task to ensure they do not become an additional source of emissions in the future. Currently, a small proportion of forests in the Northeast United States (5%) is officially designated as protected areas (SI Table S16). The largest protected area in the Northeast United States is in the Adirondack Mountains (Figure 5). Protected areas perform a variety of functions important to people including microclimate control, carbon storage, soil erosion control, pollination, watershed protection and water supply, soil formation, nutrient
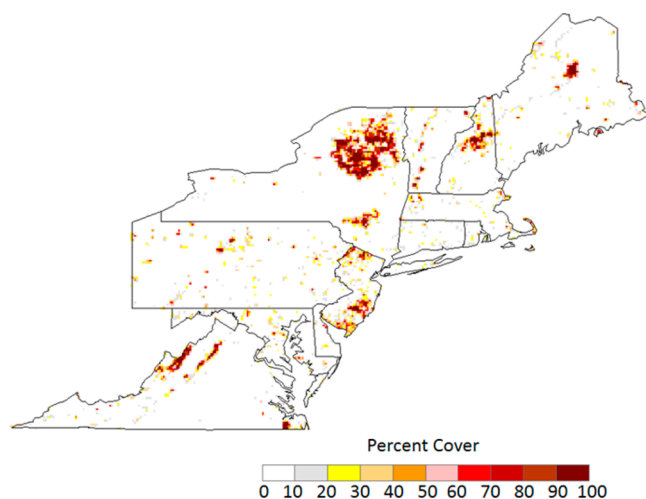
Figure 5. Distribution of protected areas[51] across the northeastern United States.

recycling, inspiration, and a sense of place.[47] Recently, these areas, especially forested ones, are being considered as a component of climate-change mitigation strategies that use land to reduce the atmospheric CO_2 burden.[48] In the Northeast United States, forests in the protected areas sequester 0.6 Tg C/yr (SI Table S17) or about 4% of the regional land carbon sink. These areas, however, also store about 2400 Tg C, which is about 30% of the carbon stored in all forests in the region. An imperative of future forest policy is maintaining the integrity of these protected areas.

Finally, it is clear from the biogeophysical limits highlighted by our analysis that lowering CO_2 emissions from fossil-fuel burning will be key to altering the carbon budget of the NE and moving it closer to zero net emissions. Furthermore, past century-scale legacy effects from land- use change have yet to fully dissipate through the carbon budgets of today, suggesting that current land management decisions will have consequences on regional carbon dynamics for decades or centuries into the future. The challenge is developing a viable strategy for phasing out the use of fossil fuels as a primary energy source for the region. One way forward is to pursue a "wedge strategy" for the region that identifies a set of options that can work together to first stabilize and then reduce CO_2 emissions.[49,50] The fact that the CO_2 emissions overwhelms the carbon sequestration suggests that the most effective wedge strategy to apply in the NE region will include energy-efficiency practices and energy-saving technologies, especially for the more urbanized areas. Some detailed wedge analyses have been done or a few local areas in the NE, which indicated that afforestation and fuel wood harvest for bioenergy might be tailored opportunities for some rural and suburban areas.[28]

ASSOCIATED CONTENT

⑤ Supporting Information

A description of the development of the input data sets used for TEM; a more detailed analysis about the influence of disturbances and land-water interactions on carbon sequestration by the region's land ecosystems; a comparison of biometry and eddy flux measurements at the Harvard Forest to TEM estimates of carbon fluxes and changes in carbon stocks; a comparison of simulated biomass increment to forest inventory data; a comparison of simulated terrestrial DOC loading to riverine DOC export; and sensitivity analyses of the importance of stand age distribution, impervious surfaces and the representation of suburban carbon dynamics on estimates of NCE. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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