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Local-Scale Carbon Budgets and Mitigation Opportunities for the Northeastern United States

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Economic and political realities present challenges for implementing an aggressive climate change abatement program in the United States. A high-efficiency approach will be essential. In this synthesis, we compare carbon budgets and evaluate the carbon-mitigation potential for nine counties in the northeastern United States that represent a range of biophysical, demographic, and socioeconomic conditions. Most counties are net sources of carbon dioxide (CO_2) to the atmosphere, with the exception of rural forested counties, in which sequestration in vegetation and soils exceed emissions. Protecting forests will ensure that the region's largest CO_2 sink does not become a source of emissions. For rural counties, afforestation, sustainable fuelwood harvest for bioenergy, and utility-scale wind power could provide the largest and most cost-effective mitigation opportunities among those evaluated. For urban and suburban counties, energy-efficiency measures and energy-saving technologies would be most cost effective. Through the implementation of locally tailored management and technology options, large reductions in CO_2 emissions could be achieved at relatively low costs.

Keywords: carbon, energy, climate change, land use

Despite overwhelming scientific evidence of the risks associated with global climate change, limited progress toward binding global agreements to reduce greenhouse-gas emissions has been achieved (Bodansky 2010). In the United States, public support for immediate federal government action to address this problem declined between 2006 and 2010 (Pew Research Center 2010), and the political climate in Congress makes near-term climate change abatement legislation a remote possibility. Nevertheless, a variety of local and regional initiatives, such as the Regional Greenhouse Gas Initiative (RGGI; *www.rggi.org*) and the Western Climate Initiative (*www.westernclimateinitiative.org*), have been undertaken in the United States to reduce greenhouse-gas emissions. Although the feasibility or even desirability of such fragmentary approaches to climate change mitigation has been questioned (Victor et al. 2005, Wiener 2007), at present they are the only game in town. Moreover, cogent arguments, both theoretical and practical, for multilevel governance on this issue have been made (e.g., Trisolini 2010). For example, local governance plays a key role in a variety of economic activities that significantly influence greenhouse-gas emissions: building codes, zoning regulations, property taxes, public transportation, proprietary functions (heating, lighting), and waste disposal. Furthermore, Kuh (2009) argued for the need to design policies aimed at influencing individual consumer behavior and lifestyle, and local governments may be well suited to influence greenhouse-gas-emission behaviors. However, the knowledge to most effectively engage local governments in this arena is inadequate (van Staden and Musco 2010), although some significant initiatives and approaches to address this limitation have been undertaken (e.g., van Staden and Klas 2010). Economic realities present challenges for financing an aggressive climate change–abatement campaign; therefore, it is imperative to identify and pursue cost-effective strategies for reducing greenhouse-gas emissions. This task is made more difficult by the complex suite of local and regional factors that influence the abatement potential and cost-effectiveness of various mitigation approaches. These factors include biophysical features, such as climate, soils, topography, and vegetation; demographic factors, such as population density and distribution; features of the existing infrastructure, including transportation networks, heat and power supplies, housing, commerce, and industry; and the governance structures in which policies must be positioned.

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Our objective in this study is to describe how variation in this suite of factors influences the current carbon balance (i.e., net carbon dioxide [CO_2] fluxes) and the feasibility of approaches for reducing CO_2 emissions in the northeastern United States. We compare carbon budgets and mitigation opportunities across nine representative northeastern counties to illustrate some of the key features influencing the choice of strategies in this region. We chose the county scale because it is the smallest political unit for which nationally consistent data sets related to energy and emissions are commonly collected (Parshall et al. 2010). We focus on CO_2, which accounts for 77% of anthropogenic greenhouse-gas emissions (Pachauri and Reisinger 2007) and 85% of US greenhouse-gas emissions (USEPA 2011a), as the key greenhouse-gas involved in the climate change threat. A major emphasis in our analysis is the contribution of land use to CO_2 emissions, sinks, and mitigation opportunities. Recent analyses illustrate that land-use options may provide cost-effective carbon sequestration in the United States (Lubowski et al. 2006). Although several CO_2-emissions analyses have been conducted at national and global scales (Metz et al. 2001, Houghton 2007, USEPA 2011a), few have been done at the local scale. We hope that this synthesis stimulates a productive dialogue among policymakers, educators, and society at large and offers motivation and guidance for municipalities who will set goals to decrease CO_2 emissions in response to regional and international initiatives.

The region chosen for this study encompasses the states involved in the RGGI, an early cap-and-trade system designed to decrease CO_2 emissions from the northeastern United States. Under the RGGI, a cap on CO_2 emissions from the electric power sector has already been applied, with the goal of a 10% decrease by 2018 (*www.rggi.org*). The Northeast region is heavily populated and urbanized and currently emits more greenhouse gases than all but five nations: China, Russia, India, Japan, and the United States (USEIA 2009). Within this region, we chose eight counties, plus the independent city of Baltimore, for detailed study (figure 1). Baltimore is the third-largest city (by population and land area) in the region, although it is substantially smaller than New York City (the largest) and may not represent the most densely populated areas of that city (e.g., Manhattan). Metropolitan areas outside of major cities are represented by Essex and Middlesex Counties (Boston metropolitan area) and Baltimore County (Baltimore–Washington metropolitan area). Worcester County, Massachusetts, contains the medium-sized city of Worcester. The four remaining counties do not contain any cities with a population of more than 50,000 people. Hereafter, the eight counties and the independent city of Baltimore will all be referred to as *counties*. These counties exhibit a wide range of demographic and land-use characteristics from highly urbanized to heavily forested (table 1). They also encompass a moderate range of climatic variation and biotic production potential. Together, these factors were expected to result in highly contrasting profiles of energy use, carbon budgets, and mitigation potential across the region. Six of the counties encompass intensive research sites in the National Science Foundation's Long Term Ecological Research Network (*www.lternet.edu*).

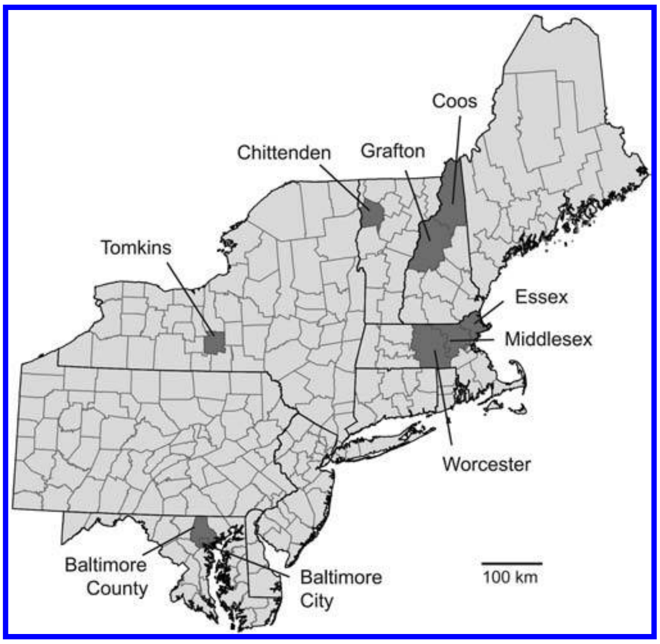

Figure 1. Map of the study area, which includes the states participating in the Regional Greenhouse Gas Initiative. Detailed carbon budgets and mitigation analyses were conducted for the highlighted counties.

A brief description of our methods

In general, we followed the protocols developed by Vadas and colleagues (2007) to circumscribe boundary conditions and to make emissions and sequestration estimates for the counties. Because utility data on heat and power supplies are not generally available at the county scale, we adjusted state-level data on the basis of population, employment, housing statistics, and typical energy-usage profiles for each housing type (Vadas et al. 2007). For residential electricity emissions, for example, we assigned total state-level emissions to the counties in weighted proportion both to the number of housing units in each county and to the relative energy usage of the housing types in each county (e.g., the proportion of single-family detached or single-family attached homes). Electricity emissions for the residential sector were obtained from the US Energy Information Administration's (USEIA) state-level data (USEIA 2010). Relative energy usage for each housing type was obtained from the USEIA Residential Energy Consumption Survey (USEIA 2005). The number and types of housing units in each county were obtained from the US Census Bureau (2011). Our analysis excludes CO_2 emissions from air travel and indirect CO_2 emissions associated with the manufacture of imported goods and with the extraction and transport of fossil fuels,

Table 1. Demographic and land-use information for the eight selected counties and Baltimore City.

County	Area (km²)	Population	Population density (people per km²)	Heating degree-days (base 18.3° Celsius)	Cooling degree-days (base 18.3° Celsius)	Percentage land use†		
						Forest	Agriculture	Developed
Coos, NH	4740	33,111	7	7500	440	87	6	3
Grafton, NH	4532	81,743	18	7500	440	87	6	4
Tompkins, NY	1273	96,500	76	6800	550	43	31	7
Chittenden, VT	1605	146,571	91	7700	490	73	14	13
Worcester, MA	4090	750,963	184	6800	370	68	9	17
Baltimore County, MD	1573	786,547	501	4700	1220	34	37	24
Essex, MA	1297	735,959	567	6400	560	44	8	37
Middlesex, MA	2133	1,467,016	688	6400	550	46	8	42
Baltimore City, MD	207	639,493	3055	4700	1220	8	2	87

†Land uses not shown include water, bare ground, wetlands, and nonforest vegetation.
km², square kilometers.

which would be challenging to incorporate without violating our county-level boundary conditions (designed to prevent double counting of CO_2 emissions across geographic areas); we consider some implications of this approach for informing national policy in a later section discussing wider applications and implications. For land areas classified as *forested* by the US Department of Agriculture Forest Service, Forest Inventory and Analysis (FIA) data (*http://fia.fs.fed.us*) were used to estimate changes in forest carbon stocks, except for Baltimore City and Baltimore County, where more detailed forest and nonforest biomass data were available (Nowak and Crane 2002, Jenkins and Riemann 2003). To estimate the potential for carbon sequestration by afforestation, we assumed that all inactive agricultural land (USDA 2009) is available for afforestation. We used FIA estimates of forest carbon storage for 26–30-year-old forest plots in each state (using data from between 2002 and 2008) and divided the total biomass by the median age of the forest to provide an estimate of mean annual sequestration.

For the carbon budgets, we used common, widely available data sources when that was possible in order to standardize our comparisons across counties and to ensure that our calculations would be easily repeatable, so that they might serve as a model for calculating carbon budgets and mitigation opportunities for other counties. All of the mitigation opportunities evaluated use mature, current technologies and can be separated into 10 categories: (1) space and water heating (e.g., improved building insulation, sealed air leaks, programmable thermostats, lower thermostat temperature settings, boiler maintenance or replacement, geothermal heating); (2) lighting (compact florescent lamps [CFLs] and LED [light-emitting diode] exit signs); (3) computers and appliances (energy star refrigerators and air-conditioning units, and computer energy-saving features); (4) fuelwood harvest for electricity generation; (5) wind power (land-based, utility-scale facilities); (6) bioenergy crops (switchgrass and willow for electricity generation, soybeans for biodiesel, corn for ethanol); (7) afforestation; (8) residential, commercial, and industrial photovoltaics; (9) transportation (for Tompkins County only, including increasing personal-vehicle fuel efficiency to 35 and 50 miles per gallon [mpg], increased bus ridership and carpooling to work, traffic signal upgrades, hybrid electric buses, waste oil as fuel, production and use of ethanol and biodiesel); and (10) combined heating and power (CHP). Near-future technologies, including carbon capture and storage, high-efficiency solar photovoltaics, and fuel-cell vehicles, were not evaluated. Nuclear power, offshore and small-scale wind power, and energy efficiency in industrial processes were outside of the scope of the analysis. We did not include embedded energy (e.g., manufacture, transport, installation of equipment) in our calculations; life cycle assessments of solar and wind power indicate that these emissions are small relative to their carbon offsets and the total energy generated (Pehnt 2006, Fthenakis et al. 2008). Detailed methods and data sources can be found in Vadas and colleagues (2007), which we followed in general but with major adjustments; we describe these adjustments below.

Solid bioenergy for electricity generation and liquid biofuels for on-road transportation. For bioenergy crops (see box 1)—we used a scenario in which solid bioenergy (switchgrass and willow) would be used in place of coal for electricity generation and in which liquid biofuels (ethanol and biodiesel) would be used in place of gasoline or diesel in vehicles. All scenarios were based on published life-cycle analyses (Ney and Schnoor 2002 for switchgrass, Keoleian and Volk 2005 for willow, Wang M 2005 for ethanol, and Sheehan et al. 1998 for biodiesel). We used statistical and geospatial methods to estimate land availability for bioenergy production using switchgrass, short-rotation willow, soybeans, and corn without competition with current agricultural production. On the basis of the total area of pasture, hay, and grassland

Box 1. Land cover, albedo, and climate.

The potential climate benefits of carbon sequestration in forests and of replacing fossil fuels with solid biofuels are widely acknowledged. Less appreciated, however, are the concomitant effects of land-use changes on radiative forcing associated with differences in albedo, evapotranspiration, and surface roughness between native vegetation and bioenergy crops. For example, conversion from herbaceous vegetation to forest in boreal regions likely has a net warming impact on the climate, whereas similar conversion in broadleaf temperate regions can range from net warming to net cooling (Bala et al. 2007). The differing climate impacts of afforestation in boreal and temperate forests result especially from the fact that the albedo of deciduous forests is higher than that of evergreen forest, and that of herbaceous vegetation can be particularly high, especially when the area is snow covered (Bonan 2008). From south to north across the northeastern United States, forest cover changes from predominantly broadleaf deciduous to evergreen conifer, the duration of snow cover increases markedly, and the potential yield of biofuel crops and the growth of forests declines. Each of these differences contributes to the regional variation in the effects of land-use change on radiative forcing. To illustrate the magnitude of these effects, we compared the climate forcing associated with afforestation and biofuel crops in Baltimore County, Maryland, and Coos County, New Hampshire (figure 1). We used climate data specific to each location (NCDC 2009), together with albedo estimates for these land-cover types (Bonan 2008, Jackson et al. 2008) to calculate the annual albedo difference between forest (hardwood or conifer) and cropland in the two locations. The albedo difference between bioenergy crops and forest is much greater for the northern location (Coos County; see table 2).

This difference indicates that albedo change has a much greater effect on the climate forcing associated with land-use conversion to bioenergy crops at northern than at southern locations, even within the relatively restricted Northeast region. In fact, a simple conversion of the change in albedo to carbon dioxide (CO_2) equivalents (see Betts 2000; assuming the change in radiative forcing at the Earth's surface is equal to the change in radiative forcing at the tropopause) suggests that the albedo effect of land-use change in Coos County may greatly exceed the climate forcing associated the effects of bioenergy crops and afforestation on atmospheric CO_2 at decadal time scales. In contrast, in Baltimore County, these effects are more comparable. Moreover, the differences in productivity and carbon sequestration between the northern and southern locations are overshadowed by the contrast in albedo effects. These observations are meant to illustrate the fact that evaluations of land-use change for climate benefits need to account for forcings other than carbon sequestration and that these other forcings can vary markedly even within relatively restricted geographic ranges (e.g., the northeastern United States). A complete quantitative assessment of the climate forcing associated with the land-use change would need to include surface roughness, evapotranspiration, climate model runs to simulate how radiative forcing at the Earth's surface influences radiative forcing at the tropopause (i.e., the layer in the atmosphere at which the radiative forcing by CO_2 is determined), and other factors. Research is needed to better address this important problem.

Table 2. Differences between Baltimore County, Maryland, and Coos County, New Hampshire, for solar radiation, number of days of snow cover, albedo, and dominant afforestation cover type.

County	Solar radiation (in megajoules per square meter per day)	Snow duration (days)	Albedo difference between biofuels and forest (percentage)	Afforestation cover type
Baltimore County, MD	17.26	13	17.5	deciduous
Coos County, NH	15.29	122	45.5	evergreen

in each county (Homer et al. 2004), we discounted land in federal ownership, land with slopes greater than 15%, and land currently in pasture or hay production, determined on the basis of the 2007 Census of Agriculture (USDA 2009). We assumed that only 20% of the total available land area would actually be used for bioenergy feedstock production. Yield data for dedicated bioenergy feedstocks are only available from a few locations in the Northeast, and these data are not sufficient by themselves to predict yields across our study region. Therefore, to estimate potential feedstock yields, we used measured crop-yield data for all of the counties and an integrated index of soil and climate characteristics called the National Commodity Crop Productivity Index (Dobos et al. 2008). This index incorporates key soil and climatic characteristics that influence crop yields and is available for the locations in our study region. We also used corn yield data from the National Agricultural Statistical Service. We developed regression equations to predict corn yield on the basis of this index ($r^2 = .65$; NYSERDA 2011). Assuming a one-to-one relationship between grain and stover (Graham et al. 2007), this regression relationship was modified to predict the aboveground biomass yield of corn, which was used as a conservative proxy for the potential switchgrass and willow yield (NYSERDA 2011). This regression equation was used to predict switchgrass and willow yield on the land identified to be potentially available in each county as was described above. We performed further regression analyses to quantify the trends from 1960 to 2007 in 35 major crops for each state. For crops with strong evidence of linear increases in yield, we predicted the yield increases from 2007 to 2020 and estimated the area of land that would become available for each crop for each county. This land could be available either for increased crop production or for the production of bioenergy feedstocks. We assumed that all of this land could be available for feedstock production.

Sustainable fuelwood harvest for electricity generation. Sustainable harvest rates from forests were calculated from FIA data for the years between 2002 and 2008 using the following criteria: (a) The live-forest biomass that accounts for all types of harvest and removals must be maintained or increased; (b) at least 35% of logging residue (branches and tops) must be left on site, therefore allowing a maximum of 65% to be removed for feedstock; (c) all dead trees must be left on site; (d) no more than 3% of noncommercial and commercial standing biomass from trees greater than 12.7 centimeters (cm; about 5 inches) in diameter may be harvested and all residue from these trees must be left on site; and (e) 50% of "other removals" should be added from the FIA-estimated timber product output. The sum of these criteria provides an estimate of the available biomass that can be harvested indefinitely (Perlack et al. 2005). Finally, an ownership factor of 50% was applied in order to account for the likelihood that only a portion of forest landowners would be interested in biomass harvest. In New York State, this factor has been estimated to range from 10% to 90% (NYSERDA 2011).

Commercial-scale wind energy. For this category, we used 200-meter- (m) resolution simulated wind-resource data to evaluate the potential for commercial wind power generation across the counties in New England. Our analysis was focused on terrestrial wind resources. Areas with class 3 (6.4 m per second mean speed at 50 m height) or greater wind power potential were considered commercially viable sites for wind power generation. Developed areas were excluded as potential sites. The information on land availability for wind power generation was determined using the 2001 national land-cover database of Homer and colleagues (2004). The wind-resource data, obtained from MassGIS (the Massachusetts Office of Geographic Information, Boston), were originally developed by AWS Truepower (Albany, New York) as part of a project funded by the Connecticut Clean Energy Fund (now part of the Clean Energy Finance and Investment Authority), the Massachusetts Technology Collaborative, and Northeast Utilities.

Combined heating and power. For CHP, we evaluated the potential CO_2-emission reductions that would result if natural-gas-powered CHP systems were installed in all high-potential buildings in each county: hospitals, educational facilities, office buildings, and lodging (hotels, motels, resorts, assisted-care facilities, and dormitories). The total square footage of each building type in each county was estimated by scaling regional building square footage estimates (USEIA 2003) by county population or by student population for educational buildings (US Census Bureau 2011). The average electrical, heating, and hot-water usage per square foot (USEIA 2003) were used to calculate the annual energy usage for each building type. The fuel required for each CHP system was estimated using the total electrical load and a conservative heat rate (Midwest CHP Application Center 2010). These energy requirements were converted to CO_2 emissions (USEPA 2011a). The net CO_2 reduction was obtained by summing the current electrical and thermal CO_2 emissions and then subtracting the CO_2 released from hypothetical CHP systems.

Light bulb replacement. We assumed a mean total usage of 30 bulb-hours per day for CFL replacement bulbs in an average housing unit (USEIA 2005).

Residential photovoltaics. We assumed that half of all single-family dwellings would be realistic candidates for photovoltaic systems (Anders and Bialek 2006).

Electric fuel grid mix. For all electricity-based energy savings and new renewable power generation, we assumed that emission reductions would displace emissions from the current mix of fuels in the regional electricity grid (USEPA 2011b).

Carbon budgets

The counties included in this study span a wide range of population densities, from 7 people per square kilometer (km^2) in Coos County, New Hampshire, to over 3000 people per km^2 in Baltimore City, Maryland. The net CO_2 fluxes from the counties were strongly and positively correlated with population density (figure 2), despite moderate differences in per capita CO_2 emissions among the counties (figure 3). The current rates of carbon sequestration in vegetation and soils were inversely related to population density ($r^2 = .63$); however, this pattern was not robust at the lower population densities, because the counties with population densities of less than about 200 people per km^2 differed little from each other in sequestration rates. According to the national land-cover database, all counties with population densities in this lower range have developed less than 12% of their total land area, and most of that developed area falls into the *open space* and *low-intensity development* land-use categories (Homer et al. 2004). These data suggest that opportunities for sequestration in vegetation and soils are not greatly diminished until the developed proportion of the landscape exceeds about 10%–15%.

Most of the counties were net sources of CO_2 to the atmosphere, since emissions from fossil-fuel combustion exceeded sequestration in vegetation and soils (figure 2). The exceptions were the two most rural, forested counties in northern New Hampshire, where the carbon sequestration in growing forests exceeded CO_2 emissions. Therefore, much of the northeastern United States is a source of atmospheric

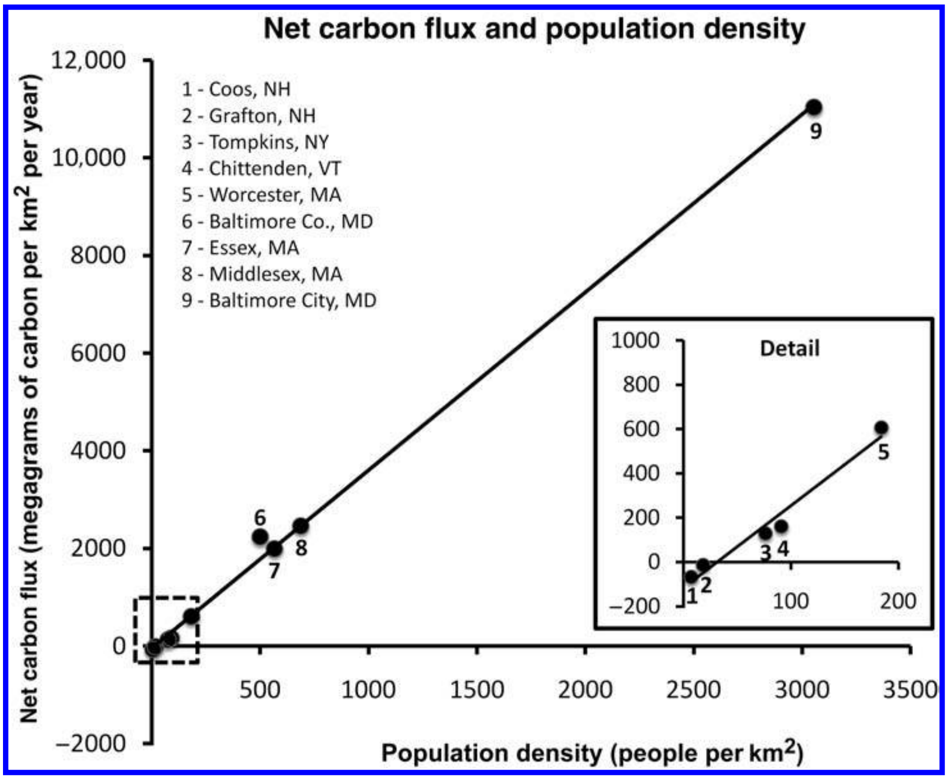

Figure 2. Net carbon flux plotted against population density. Net-zero emissions, where anthropogenic emissions are roughly in balance with sequestration in vegetation and soils, coincides with a county population density of about 30 people per square kilometers (km^2; see the inset). Our analysis excludes emissions from air travel and indirect emissions associated with the manufacture of imported goods and the extraction and transport of fossil fuels.

CO_2, with the strength of the source varying primarily with human population density and with only sparsely populated forested counties acting as net CO_2 sinks.

Net-zero emissions of CO_2 in the northeastern region coincide with a population density of about 30 people per km^2, a figure that is based on the regression between net CO_2 emissions and population density (r^2 = .99; figure 2). This value represents the population density at which CO_2 emissions in the Northeast are roughly in balance with the sequestration in vegetation and soils. Contrast this value with the mean population density of the region of 134 people per km^2 (US Census Bureau 2011). The implication of our results is that sequestration in forests and soils cannot offset existing emissions from the region. Note that our analysis ignores air travel, which constitutes nearly 3% of US CO_2 emissions (USDOE 2009a), as well as CO_2 emissions associated with the production and transportation of imported food and goods, which are at least 10% of the total emissions for the United States (Davis and Caldeira 2010).

The future potential for natural sequestration to offset regional CO_2 emissions is less promising when the patterns of forest regrowth in the Northeast are examined. Forests in the region are maturing, and their ability to sequester additional CO_2 will likely decline unless policies and practices shift considerably (Hurtt et al. 2002). Furthermore, sequestration in northeastern forests is threatened by a number of invasive pests and pathogens (Lovett et al. 2006) that could significantly reduce forest biomass over the coming decades. Finally, forest cover in the region is declining as real estate development expands in both suburban and rural areas (Stein et al. 2010). Therefore, if current trends in land use continue, future carbon sequestration potential will be reduced and some previously stored carbon in vegetation and soil will be released to the atmosphere as CO_2.

Per capita CO_2 emissions

Per capita CO_2 emissions among the counties ranged from 2900 kilograms (kg) of carbon per person for Chittenden County, Vermont, to 4670 kg of carbon per person for Baltimore County, Maryland (figure 3). This range in per capita emissions is smaller than international variation (Aldy 2006), but it is still quite large, which suggests that local factors may exert considerable influence on per capita CO_2 emissions.

The transportation sector accounted for the largest share of CO_2 emissions from every county (35%–47%), except for Baltimore City, Maryland (26%; figure 3). Per capita transportation CO_2 emissions ranged from 920 kg of carbon per person in Baltimore City to 1640 kg of carbon per person in neighboring Baltimore County. The greater availability of public transportation and the closer proximity to places of employment play a role in Baltimore City's lower transportation CO_2 emissions. More than 28% of working Baltimore City residents used public transportation, walked, or used alternate means of transportation (19.4%, 7.1%, and 1.6%, respectively) to get to work (US Census Bureau 2011). Compare these values with those for neighboring Baltimore County, where fewer than 8% of working residents used these forms of transportation for their daily commute. A lower average income combined with more convenient access to public transportation probably contributes to the lower vehicle ownership rates in Baltimore City, where 30% of households have no personal vehicle (US Census Bureau 2011). The other county with comparatively low per capita transportation

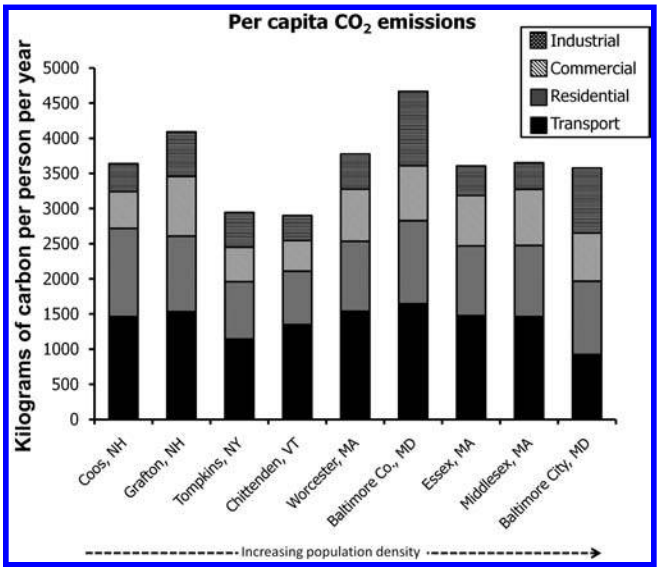

Figure 3. Annual per capita carbon dioxide (CO_2) emissions for nine northeastern counties in four sectors. The county population densities increase from left to right. Our analysis excludes emissions from air travel and indirect emissions associated with the manufacture of imported goods and the extraction and transport of fossil fuels.

CO_2 emissions is Tompkins County, New York, which is dominated by the small city of Ithaca. Ithaca is itself dominated by Cornell University, which provides strong incentives to discourage single-occupancy vehicle commuting. More than 8% of Tompkins County commuters use public transportation, and an even greater percentage (19.4%) walk or use other alternative means of transit. Still, a most-striking pattern is the similarity in per capita transportation CO_2 emissions across counties with dramatically different population densities and landcover patterns.

The residential sector accounted for the second-largest share of CO_2 emissions in each of the counties (except Baltimore City, where it ranked first), accounting for 25%–35% of the total CO_2 emissions. CO_2 emissions ranged from 760 kg of carbon per person in Chittenden County, Vermont, to 1260 kg of carbon per person in Coos County, New Hampshire. Factors such as local climate, housing mix, and the carbon intensity (the amount of carbon released per unit of energy produced) of fuels used for heating and electricity generation contribute to this wide range in residential CO_2 emissions. For instance, Baltimore City has lower per capita CO_2 emissions than Baltimore County, despite similar climate and fuel mixes for heating and electricity generation. The greater proportion of attached houses, multifamily dwellings, and apartment buildings in Baltimore City (86% of housing units) is a major driver of these trends, because these smaller, attached housing units require less energy to heat, cool, and light than do detached, single-family houses (USEIA 2005).

Electricity usage constituted a large and highly variable percentage of residential CO_2 emissions across the counties and influenced many of the patterns in residential CO_2 emissions. Chittenden County, Vermont, has unusually low per capita residential CO_2 emissions because of its extensive reliance on renewable energy (50%, mostly hydroelectric) and nuclear power (34%) for electricity generation (VTDPS 2011). These low-carbon-intensity electricity sources result in residential electricity emissions of only 82 kg of carbon per person or just 11% of the total residential CO_2 emissions. On the other hand, Baltimore City and Baltimore County had the highest per capita residential electricity use (0.049 and 0.056 billion British thermal units [Btu] per person, including system losses) and the highest accompanying CO_2 emissions from electricity use, at 750 and 850 kg of carbon per person, respectively—10 times higher than that in Chittenden County, Vermont. The warmer climate in Maryland and the state's heavy reliance on coal for electricity generation may explain this sharp contrast. Baltimore City averages 1220 cooling degree-days (CDD) per year versus just 370–560 CDD per year for the other counties (table 1; NCDC 2009), which leads to higher electricity use for home cooling. The milder climate also stimulates a greater proportion of homeowners to rely on electric heat, which is a relatively inefficient source; more than 36% of Maryland residents heat their homes with electricity compared with fewer than 10% in the New England states (USEIA 2005).

Fossil-fuel burning for space and hot-water heating accounted for the largest proportion of residential CO_2 emissions in the upstate New York and New England counties, making up 59%–89% of emissions compared with less than 35% of residential emissions in the Maryland counties. Natural gas and heating oil are favored in the colder climate of New England (more than 6000 heating degree-days [HDD] per year, compared with 4700 HDD per year in Baltimore City and County; see table 1).

Per capita industrial CO_2 emissions were much greater in Baltimore City and Baltimore County (927 and 1058 megagrams [Mg] of carbon per person) than in other counties (355–636 Mg carbon per person). Baltimore is home to a major port and has historically been a center for industry in the region, despite a major industrial decline in the second half of the twentieth century. Finally, the differences in per capita CO_2 emissions from the commercial sector are not explained by any obvious factor; for example, the highest and lowest per capita commercial sector CO_2 emissions were observed in the two northernmost rural counties in our study. Detailed study of this variation is warranted.

Mitigation opportunities

The nine counties in this study represent a wide variety of biophysical, demographic, political, and economic conditions, which in turn influence the feasibility of various approaches for reducing CO_2 emissions. In counties in which forests and inactive agricultural land are abundant, a variety of land-based strategies offer opportunities to sequester CO_2 in vegetation and soils and provide feedstocks for biofuel production or space to accommodate alternative energy technologies. In more urbanized counties, in which available land is limited and expensive, the most cost-effective carbon-mitigation strategies will include energy-efficiency practices and energy-saving technologies. In all cases, a range of locally tailored management and technology options can offer substantial CO_2-emission reductions at high rates of return on investment, as is described below.

Low-cost mitigation opportunities. We identified and evaluated a range of low-cost mitigation opportunities (i.e., those that entail a rapid return on investment; figure 4) that were based on the criterion that they pay for themselves with income generated or through energy-cost savings over the lifetime of the strategy. For simplicity, we have assumed a simple payback period, such that the payback time in years is equal to the initial investment divided by the annual savings. The actual return on investment may be slower than is represented here, since the potential interest earned from alternative investments and the interest paid on loans are not considered. However, if CO_2 emissions are priced and energy prices subsequently rise, the return on investment may be faster than we have estimated. Our suite of low-cost mitigation opportunities includes land-intensive alternative power sources such as electricity production from sustainably harvested fuelwood and utility-scale wind power. In the residential sector, low-cost opportunities include energy-efficient lighting (replacing incandescent bulbs with CFL bulbs), increased home insulation, programmable thermostats, lowered thermostat temperature settings for heating, sealing air leaks, boiler maintenance or replacement, and US Environmental Protection Agency Energy Star–certified refrigerators and air-conditioning units (Vadas et al. 2007). We focused our analysis on the residential sector, together with land-use change and alternative-energy opportunities. Mitigation strategies were applied to commercial and industrial sectors in cases in which they were readily transferable and for which supporting data were available.

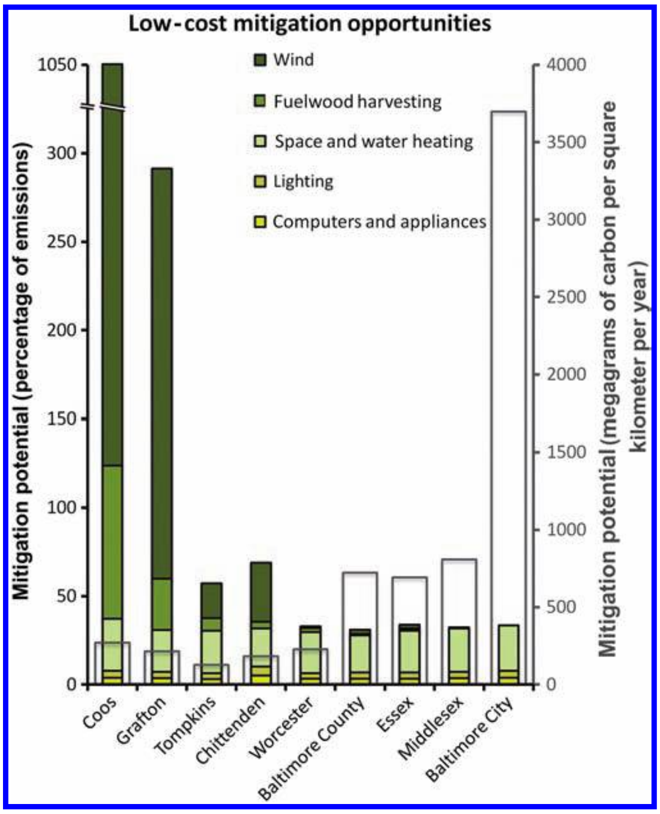

Figure 4. Low-cost mitigation opportunities pay for themselves over time through income generated or energy-cost savings over the lifetime of the strategy. The shaded bars (primary y*-axis) show low-cost mitigation potential as a percentage of the current gross county emissions. The open bars (secondary* y*-axis) show the absolute mitigation potential normalized by area. County population densities increase from left to right.*

Rural counties in our study area (less than 100 people per km²) could offset 27%–1000% of the current emissions at low cost through the sustainable harvest of fuelwood from existing forests and through the installation of commercial-scale wind-energy farms at favorable sites (figures 4 and 5). Our wind-energy analysis was focused on terrestrial wind resources, which are most abundant in hilly and mountainous terrain; however, the region also possesses abundant offshore wind resources (figure 5 inset). Because of low population densities, abundant forest cover, and favorable topography for wind energy, these land-based strategies could provide cost-effective reductions in greenhouse-gas emissions in rural areas. In suburban counties, these strategies are also favorable (they would, e.g., reduce emissions up to 116,000 Mg of carbon per year in Essex County, Massachusetts), although they could mitigate a smaller proportion of total county CO_2 emissions (0.4%–3.3%).

Regardless of population density and available land area, the suite of low-cost residential, commercial, and industrial energy-saving opportunities could be substantial and represent a potential 29%–37% reduction in the CO_2 emissions of the counties in this study. The largest potential for low-cost residential energy savings was for space and water heating, for which a combined 9%–13% reduction in county CO_2 emissions could be achieved by sealing air leaks, by increasing insulation in older homes, by lowering thermostats to 65° Fahrenheit, by using programmable thermostats, through boiler maintenance, and through the replacement of outdated boilers. Other space- and water-heating upgrades would bring even greater energy savings but would require greater upfront costs. For instance, augmenting conventional home-heating systems with geothermal systems could reduce heating energy

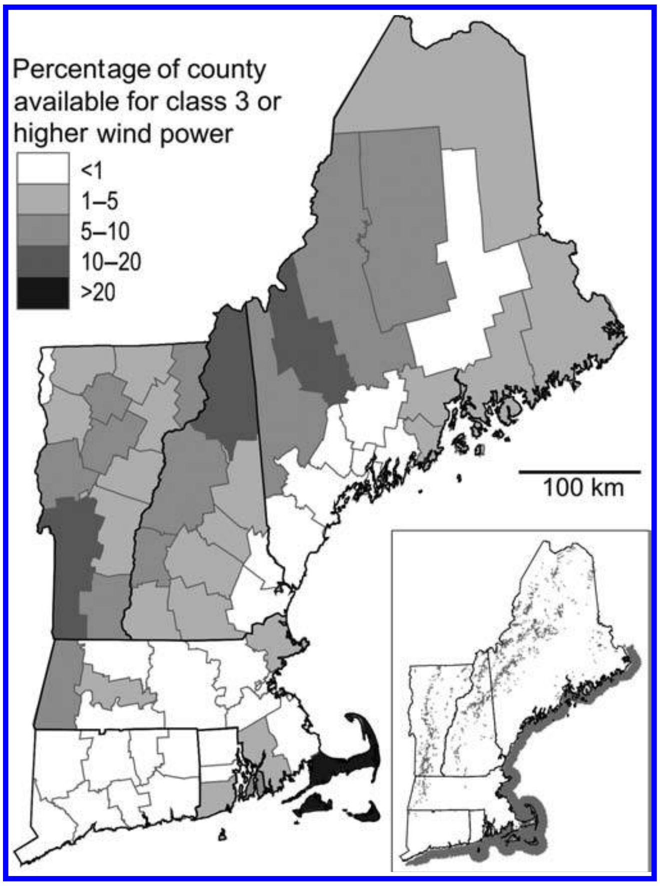

Figure 5. The large map shows the percentage of each county's undeveloped land area with class 3 (6.4 meters per second at 50 meters height) or greater wind potential. The inset map shows the spatial distribution of these land areas. The information on land availability (i.e., developed or undeveloped) was based on the 2001 national land-cover database (Homer et al. 2004). Our analysis was focused on terrestrial wind resources, which are greatest in hilly and mountainous regions, but offshore wind resources are also abundant (see the inset map).

expenditures by about 50% (USOGT 1998), which would lead to an 8%–11% reduction in county CO_2 emissions. Such systems would cost approximately $18,750 for a typical house (Hughes 2008, SBI Energy 2009) and have a simple payback period of 18–20 years, as determined from 2008 energy prices in the region. Similarly, residential solar hot-water systems (flat plate collectors) could decrease water-heating costs by about 50%, with upfront costs of $3250 (USDOE 2010) and a payback period of 14–22 years for a typical home. This could reduce county CO_2 emissions by another 1.7%–2.3%. Replacing the 28 remaining incandescent light bulbs contained in the average home (USDOE 2009b) with more-energy-efficient lighting is the next largest low-cost opportunity to reduce CO_2 emissions in the residential sector; county CO_2 emissions could be reduced by another 2.4%–3.4% with CFL bulbs. Enabling computer energy-saving features on the nearly 50% of commercial-sector computers that are currently set to run constantly (Alliance to Save Energy and 1E 2009) would decrease total county CO_2 emissions by another 1.1%–2.4%.

Combined heating and power, which uses a generator to produce electrical power while applying the waste heat for another purpose, is a viable mitigation strategy in all of the counties. Using waste heat for space heating or absorption refrigeration can result in energy efficiencies as high as 85%, compared with 35% for conventional heating and power systems (Midwest CHP Application Center 2009). CHP also offers opportunities to switch to lower-carbon fuels (such as natural gas or biofuels), which can provide additional reductions in CO_2 emissions. The price difference between electricity and a chosen combustible fuel (typically less expensive per unit of energy than electricity) is a widely accepted indicator of the economic feasibility for CHP systems for a given area (Midwest CHP Application Center 2009). We compared natural gas and electricity prices in the counties and found that the resulting price differences were high in all of the counties (between $25.08 and $34.56 per million Btu), with the exception of Baltimore City and Baltimore County, where it was moderate ($12.66 per million Btu). For buildings in the latter locations to have acceptable payback periods for CHP systems, other factors would have to be favorable, such as a good balance of thermal and electrical load, high heat and electricity demand, or long operating hours (Midwest CHP Application Center 2009). Our analysis indicates that installing CHP systems in all high-potential buildings in each county (hospitals, educational facilities, office buildings, and lodging) could reduce CO_2 emissions by 0.6%–2.4% (table 3). The use of biofuels as CHP feedstocks could provide even greater CO_2-emission reductions than would the use of natural gas (Eriksson et al. 2007).

In total, the low-cost mitigation options that we evaluated could decrease or offset a high proportion of the CO_2 emissions in the studied counties. For example, the rural counties that contain small cities, represented here by Tompkins County, New York, (which includes Ithaca) and Chittenden County, Vermont, (which includes Burlington), could offset more than half of their CO_2 emissions. At higher population densities, energy-efficiency strategies and technologies are the most cost-effective options and could offset as much as 34% of county CO_2 emissions.

Higher-cost mitigation opportunities. The higher-cost opportunities that we evaluated (figure 8) include terrestrial sinks (e.g., afforestation of inactive agricultural land) and bioenergy crops (willow and switchgrass for solid fuels, corn ethanol and soybean biodiesel for transportation fuels). We also evaluated the potential for photovoltaic systems in the residential, commercial, and industrial sectors.

The rural counties (those with populations under 100 people per km^2) could offset a significant portion of current CO_2

Table 3. Potential carbon dioxide (CO2)–emission reductions (megatons of carbon) that would result if natural-gas powered combined heating and power systems were installed at all high-potential buildings (hospitals, educational facilities, office buildings, and lodging) in each county.

County	Educational facilities	Hospitals	Office buildings	Lodging	CO_2–emissions reduction (percentage of gross county emissions)
Coos County, NH	129	705	321	994	1.78
Grafton County, NH	1565	1410	1682	1679	1.89
Tompkins County, NY	4699	235	1354	583	2.42
Chittenden County, VT	2518	235	2503	1371	1.56
Worcester County, MA	7498	3759	8579	2125	0.77
Baltimore County, MD	9346	1645	9926	1611	0.61
Essex County, MA	6526	4229	8061	2296	0.80
Middlesex County, MA	18,365	7989	24,500	4078	1.02
Baltimore City, MD	7484	3994	8314	1234	0.92

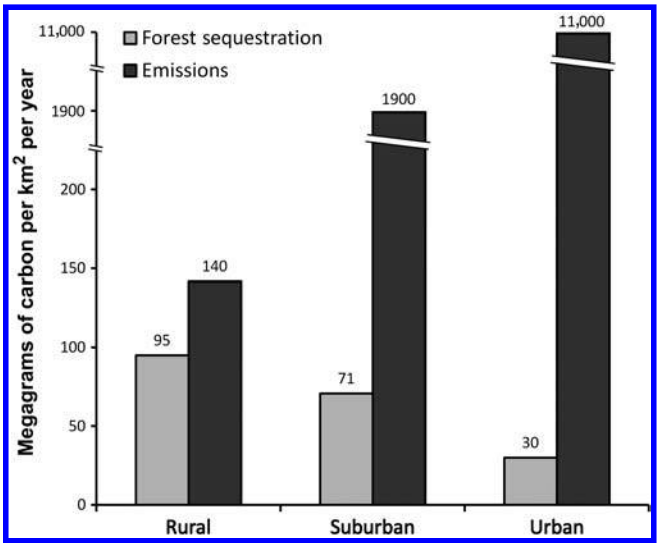

Figure 6. Forest sequestration (light gray) compared with CO_2 emissions (dark gray) on a per-area basis for rural (<100 people per square kilometer [km²]), suburban, and urban (i.e., Baltimore City) counties.

emissions (up to 42%) by expanding forest CO_2 sinks and, in some cases, by growing bioenergy crops, but protecting existing forests from overharvest and land-use conversion will be critical. Forests are the largest potential CO_2 sinks in rural counties (figure 6) and sequester 18%–420% of annual CO_2 emissions in the studied counties (77,000–511,000 Mg of carbon per year). Forest loss would turn these present-day sinks into large sources of CO_2 emissions. Unfortunately, these forests face strong development pressure. For instance, the Maryland Department of Planning predicts that if past trends continue, the state will lose 9% of its forest cover by 2020 (Weber et al. 2006). This trend holds true for the entire Northeast region, where approximately 9% of existing forests are predicted to be subsumed by urban development between 2000 and 2050 (Nowak and Walton 2005). At present, forest preservation and afforestation are higher-cost strategies because of relatively high land values in the region, the low value of carbon offsets in existing markets, and the challenges of meeting additionality and verifiability requirements under emerging carbon-accounting frameworks (Fahey et al. 2010).

Growing willow and switchgrass for electric generation could provide relatively large reductions in CO_2 emissions (table 4) but at a higher price per unit of energy than coal (Vadas et al. 2007). Cofiring willow or switchgrass could offset up to 15% of CO_2 emissions in rural and suburban counties (up to 75,000 Mg of carbon per year) without competing with current agricultural production or forestland. Together, afforestation and bioenergy could offset 0.3%–28% of the CO_2 emissions in rural counties. Afforestation is limited by the availability of inactive agricultural land, whereas bioenergy feedstocks are also limited by climate, soil quality, and their proximity to potential markets or processing facilities (Potter et al. 2007). In the suburban counties (those with fewer than 180 people per km², excluding Baltimore City), the potential for afforestation and bioenergy is significant (4700–101,000 and 7600–149,000 Mg of carbon per year, respectively) and could offset 0.3%–6.8% of current CO_2 emissions. However, it is likely that land prices and development pressure in these areas will be highest. For instance, Nowak and Walton (2005) predicted that more than 60% of the land area of four of the most-developed northeastern states (Rhode Island, New Jersey, Massachusetts, and Connecticut) will be urban by the year 2050.

In the residential, commercial, and industrial sectors, grid-connected rooftop photovoltaic systems have the potential to reduce county-level CO_2 emissions by 9.5%–19%, but the initial costs are high, and the payback periods exceed the lifetimes of the systems unless large subsidies are available to reduce the costs. The initial system costs are approximately $40,000 for 5-kilowatt (kW) residential systems and $115,000 for 15-kW commercial systems (Barbose et al. 2010). The associated energy-cost savings ranged from $800 to $1000 per year and from $1900 to $2800 per year for 5-kW and 15-kW systems, respectively, on the basis of local energy-generation potential and retail electricity prices (NREL 2010). At current electricity prices, and assuming no government subsidies or feed-in tariffs, this would mean a payback period of 37–63 years, depending on the county and

Table 4. Summary of the technical potential for switchgrass and forest biofuels, including estimated yields and carbon offsets.

		Switchgrass				Fuelwood	
County	Land rent[a] (US dollars per ha per year)	Crop area (ha)	Yield[b] (Mg of carbon per ha per year)	Offset[c] (Mg of carbon per year)	Forest area (ha)	Yield (Mg of carbon per ha per year)	Offset (Mg of carbon per year)
Coos County, NH	48	2791	3.8	0	210,707	0.52	104,245
Grafton County, NH	60	623	4.3	0	200,283	0.51	96,747
Tompkins County, NY	47	11,310	9.6	107,840	27,584	0.77	20,054
Chittenden County, VT	59	340	7.6	2584	43,631	0.38	15,695
Worcester County, MA	123	4749	5.2	24,250	134,749	0.48	61,813
Baltimore County, MD	102	20,553	9.2	184,815	22,963	1.25	27,198
Essex County, MA	176	1532	6.5	9822	27,765	1.11	29,171
Middlesex County, MA	178	2546	5.4	13,343	42,076	0.49	19,395

[a] Agricultural land rents were not available at the county level. Instead, we estimated county-level land rents based on county-level land prices using the state-level relationship between land values and agricultural rents for the study states ($r^2 = .99$). All land-rent and land-value data were from the US Department of Agriculture (2009).

[b] The estimated switchgrass and willow yields for Coos and Grafton counties were too low to be commercially viable (less than 4.5 megagrams [Mg] per hectare [ha]).

[c] Based on substituting biomass for coal in electricity generation.

the application. If the capital costs associated with small-scale photovoltaic systems were to decrease or if the energy prices, carbon credits, or efficiency of photovoltaic cells were to increase, photovoltaic systems would become a more cost-effective opportunity for the region.

Transportation-sector mitigation opportunities: Tompkins County. To illustrate the potential mitigation opportunities in the transportation sector, we highlight the case of Tompkins County, New York, largely on the basis of the Ithaca-Tompkins County Transportation Council's (2004) 2025 Long Range Transportation Plan. In the plan, the TransCAD (Caliper Corporation, Newton, Massachusetts) travel-demand model was used to generate and distribute trips along the road network, which included all state, county, and important local roads, and to simulate the results of proposed transportation upgrades.

A broad suite of mitigation opportunities applies to the transportation sector (table 5), including changes in land-development patterns to support mixed-use and other environment-friendly zoning practices (Banister 1999). The impact of these land-use-planning activities was tested with a number of indicators, including congestion and vehicle miles traveled. Under proposed land-use planning scenarios, the model predicted a 2% decrease in vehicle miles traveled at peak travel times. If this outcome is generalized to include off-peak travel times, it would mean a decline of approximately 2% in county CO_2 emissions relative to the business-as-usual scenario.

Table 5. Summary of transportation mitigation opportunities for Tompkins County, New York.

Transportation mitigation	Carbon offset (megagrams of carbon per year)	Percentage of transport emissions	Percentage of total gross emissions
Vehicle fuel efficiency to 50 mpg	20,774	18.90	7.30
Vehicle fuel efficiency to 35 mpg	7226	6.60	2.50
Increased carpooling to work	8200	7.40	2.90
Increased bus ridership	1417	1.30	0.50
Traffic signal upgrades	670	0.61	0.24
Biodiesel	472	0.43	0.17
Ethanol	391	0.35	0.14
Hybrid electric buses	189	0.17	0.07
Waste oil as fuel	73	0.07	0.03
Total range[†]	18,620–32,169	16.9–29.2	6.6–11.3

[†] This range is based on vehicle fuel efficiencies of between 35 miles per gallon (mpg) and 50 mpg.

Other mitigation opportunities in the transportation sector include improving passenger-vehicle fuel efficiency, producing transportation biofuels, increasing carpooling to work, increasing the use of public transit, upgrading traffic signals, upgrading the county bus fleet to hybrid electric drivetrains, and utilizing in-county waste oil for fuel (table 5). The opportunity with the largest potential to decrease CO_2 emissions (of those evaluated) is increasing passenger-vehicle fuel efficiency. Current passenger-vehicle fuel efficiency is estimated at 27 mpg, and an increase to 35 mpg would offset transportation-related CO_2 emissions by 6.6%. Increasing effective fuel efficiency to 50 mpg would lead to a 19% decrease in transportation-related CO_2 emissions. The county could provide some incentives to encourage the use of fuel-efficient vehicles, such as enhanced parking privileges or special travel lanes for hybrid, plug-in hybrid, and electric vehicles. Increased carpooling could reduce transportation-related CO_2 emissions by up to 7.4%, assuming that the majority of people who drive alone to work would participate. Increasing bus ridership in the county by approximately one third (or 1,000,000 annual rides) would decrease transportation-related CO_2 emissions by 1.3%. A mix of smaller upgrades, including traffic-signal upgrades in the city of Ithaca (0.6%), hybrid electric buses (0.2%), and using available county waste oil as fuel (0.1%) could further reduce transportation-related CO_2 emissions. These emissions could be offset by another 0.8% by growing corn and soybeans for ethanol and biodiesel, a figure based on a scenario that avoids deforestation and competition with existing agricultural production. Note that willow, switchgrass, or forest biofuels could provide larger emission benefits than ethanol or biodiesel, especially if they are used in place of carbon-intensive fuels such as oil (for home heating) or coal (for electricity generation). Taken in total, these improvements have the potential to decrease transportation-sector CO_2 emissions by 17%–29% and total county CO_2 emissions by 6.3%–11% (table 5). The transportation-related CO_2 mitigation portfolio for other counties would vary as a consequence of differences in current transportation systems and other factors, but clearly, incentives for increased passenger-vehicle fuel efficiency will dominate the mitigation opportunities regionwide.

Other patterns in mitigation cost and potential. A number of regional and local conditions contribute to the differences in potential mitigation costs and emission benefits (figure 7) among the counties—particularly, the mix of fuels used for heating and electricity generation, local climate (e.g., cooling and heating degree-days), and fuel prices. The payback period for photovoltaic systems; energy-efficient lighting, air-conditioning, and appliances; and commercial wind installations are all dependent on the market price of electricity (USEIA 2009), which is highest in New York and Massachusetts ($0.15–$0.16 per kilowatt-hour) and lowest in Maryland ($0.10–$0.11 per kilowatt-hour). These factors can combine to create dysfunction in the economic incentive structure for carbon abatement. For example, Baltimore County and City have the highest carbon intensity for residential heating systems in the region, yet they have the lowest economic incentive (slowest return on investment) for mitigation opportunities (figure 7). Clearly, correction of this sort of economic disincentive, such as through a rise in the cost of carbon credits under the RGGI, will be needed.

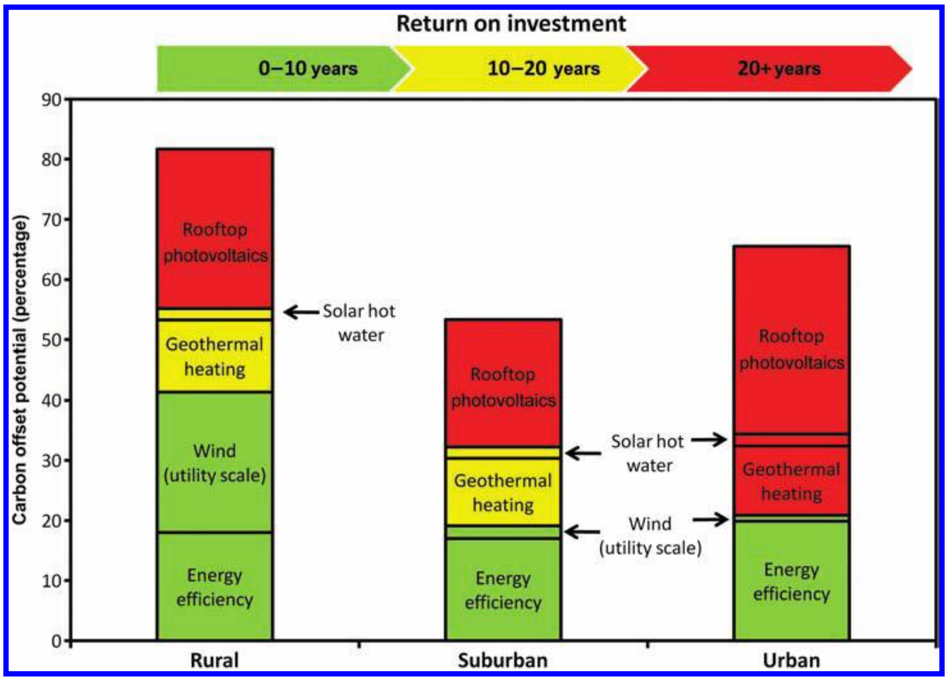

Figure 7. Return on investment for technological mitigation opportunities for rural (<100 people per square kilometer), suburban, and urban (i.e., Baltimore City) counties. The height of each bar indicates the mean carbon offset potential as a percentage of current emissions. The color indicates the expected payback period, with payback periods increasing from bottom to top. Note that several land-intensive mitigation strategies (including biofuels and afforestation) are not represented in this chart but could provide substantial carbon offsets in rural counties.

Wider applications and implications

We chose the county scale as an effective level of analysis to inform local policies that could contribute to significant reductions in greenhouse-gas emissions (e.g., building and tax codes, public transit, proprietary functions). The application of analysis at this scale to policy development at larger scales deserves further attention. To avoid double counting, it seemed appropriate to define boundary conditions at the county scale; therefore, importation and cross-boundary transport were not considered, nor were large-scale energy-generation facilities. To inform policies at the regional and national levels, future development of this approach must be embedded in analyses at these larger scales. The contribution of local analysis to prescriptions for incentives and investments at larger scales also need to account for differences in the cost-effectiveness of mitigation activities at the larger scale; for example, the embedded energy in any material-intensive mitigation option would comprise a different proportion of the carbon offset, depending on the efficiency of the end use. We recommend that future researchers work toward a synthesis of local-, regional-, and national-scale analyses of carbon budgets and mitigation options; this would facilitate quantitative comparisons that could help direct policy decisions at various scales.

To put our results into a larger context, we used regression relationships between population density and per-area emissions ($r^2 = .97$) and mitigation potential ($r^2 = .96$) for the nine counties to extrapolate our results to the Northeast region on the basis of the population density of each county. We caution that this is a rough extrapolation because our nine-county comparison demonstrated large differences in the emissions and offset potential of the mitigation strategies (e.g., figures 3, 4, and 8, and table 4). Our scaling exercise results in net CO_2 emissions of 188 teragrams (Tg) of carbon per year, based on 228 Tg of carbon per year of gross emissions and 40 Tg of carbon per year of terrestrial sinks. Our extrapolation of gross regional emissions is within 5% of the USEIA emissions estimates for the region. Our estimate of terrestrial CO_2 sinks is within the range of published estimates for the region (e.g., 31 and 45 Tg of carbon per year for Turner et al. 1995 and Murdock et al. 2007, respectively). When we analyzed the relationship between low-cost mitigation opportunities and population density in the same way ($r^2 = .97$), we found that approximately 117 Tg of carbon per year (52% of the extrapolated annual CO_2 emissions) can be offset in the region at low cost (i.e., with a favorable payback period). These extrapolations provide a coarse estimate of the potential carbon mitigation for the region on the basis of the strategies and assumptions that we have outlined.

The magnitude and feasibility of the mitigation strategies rely, to a significant extent, on climate, energy usage patterns, and the level of carbon intensity of the local economy of the northeastern United States. We would expect similar emissions and mitigation profiles for the northern United States, southern Canada, and possibly northern Europe. Regions with warmer climates, largely nonforest vegetation, or lower affluence would be considerably different. For example, despite similar climate, potential vegetation, and human population density (Toth et al. 2003), the carbon balance of northeastern China would reflect the lower per capita income (Pedroni and Yao 2006), level of carbon intensity (UCS 2009), and forest carbon sequestration (Wang S et al. 2002)—the latter two of which could increase with continued economic development and afforestation (Shuifa et al. 2010).

Conclusions

Clearly, no single carbon-mitigation strategy will be cost-effective for all locations in the Northeast region; however, by implementing a range of locally tailored management and technology options, substantial CO_2-emission reductions can be achieved at low cost. For largely rural counties, afforestation, sustainable fuelwood harvest for electricity generation, and utility-scale wind power can provide the largest and most cost-effective mitigation opportunities. For urban and suburban counties, energy-efficiency measures and energy-saving technologies will be the largest and most cost-effective mitigation opportunities. Many of the mitigation strategies presented here are considered "low cost," because the energy saved or the income generated will equal or exceed the initial capital costs over the lifetime of the strategy. These low-cost options could effectively offset or decrease CO_2 emissions by as much as 31%–1100% in counties across the region. And if the higher-cost options are included, emissions can be reduced by another 14%–440%. In both cases, the greatest proportional CO_2-emission reductions are possible in rural counties in which the carbon sequestration in vegetation and soils may already exceed current

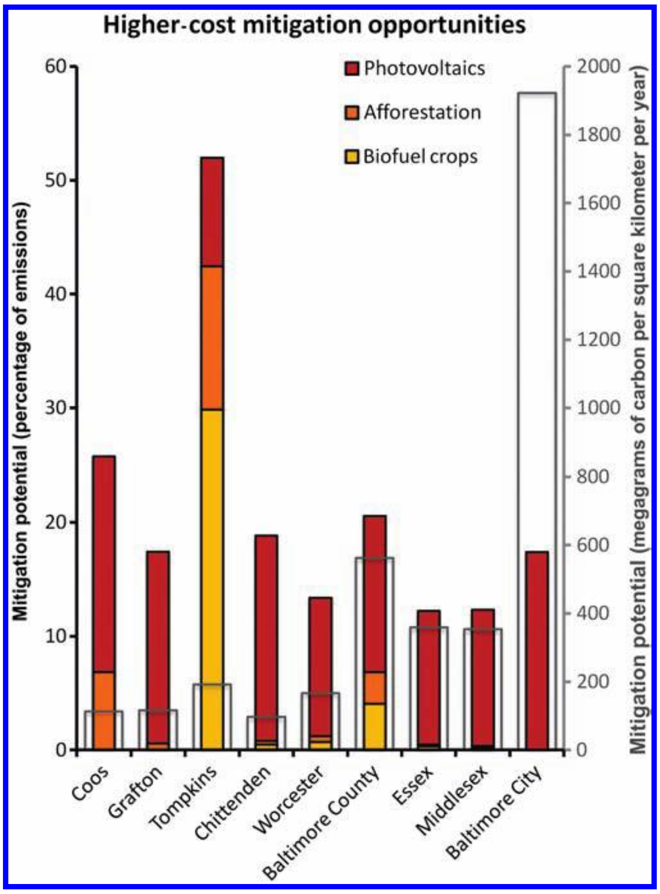

Figure 8. Higher-cost mitigation opportunities. At present (in the absence of government subsidies and strong carbon markets), these opportunities do not fully recoup their initial investment costs. The shaded bars (primary y*-axis) show higher-cost mitigation potential as a percentage of the current gross county emissions. The open bars (secondary* y*-axis) show the absolute mitigation potential normalized by area. County population densities increase from left to right.*

CO_2 emissions. If the transportation-sector opportunities explored in Tompkins County are indicative of what can be achieved in other counties, countywide CO_2 emissions could be reduced by an additional 6.6%–11%. Future work in which this approach is used should be embedded in the context of regional- and national-scale analyses in order to better inform policies for achieving cost-effective reductions in greenhouse-gas emissions in the US economy.

Despite the generally promising findings, implementing even the low-cost mitigation opportunities will be difficult without strong leadership, effective policies, and greater public support for reducing CO_2 emissions. The potential clearly exists to dramatically alter the carbon-mitigation landscape in the United States by taking advantage of a suite of existing technologies and future breakthroughs in such areas as building design, alternative-energy vehicles, biofuels and cellulosic ethanol, photovoltaics, and carbon capture. These changes can be implemented most efficiently at the local level, and the analysis presented in our study contributes to a blueprint for achieving this goal.

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