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Assessing net carbon sequestration on urban and community forests of northern New England, USA

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ABSTRACT

Urban and community forests play an important role in the overall carbon budget of the USA. Accurately quantifying carbon sequestration by these forests can provide insight for strategic planning to mitigate greenhouse gas effects on climate change. This study provides a new methodology to estimate net forest carbon sequestration (FCS) in urban and community lands of northern New England using ground based forest growth rates, housing density data, satellite derived land cover and tree canopy cover maps at the county level. We estimated that the region's urban and community forests sequestered 603,200 tC/yr ($38.7 million/yr value), contributing 8.2% of regional net forest ecosystem carbon sequestration. The contributions at the state level varied from 2.3% in Vermont to 16.6% in New Hampshire with substantial variation at the county level up to 73.3%. Spatially, contribution rates from urban and community forests at the county level were much higher and concentrated in southeast portion of NH and southwest portion of ME along the coast, and decreased toward inland areas. Our estimated net FCS compared reasonably with gross FCS in the region reported by a previous study. On average, the net FCS was 34.2% lower (varying from 41.9% lower in Vermont to 28.1% lower in Maine) than the corresponding gross FCS mainly because of a lower regional average net growth rate used in this study, compared to the national average gross carbon sequestration rate used in the previous study.

Introduction

Urban and community forests play an important role in carbon cycle by sequestering atmospheric CO_2 to mitigate climate change (Moulton and Richards, 1990; Nowak and Crane, 2002). Accurately quantifying carbon sequestration by these forests can improve our current understanding and aid strategic planning for greenhouse gas mitigation. Forest carbon sequestration (FCS) is usually estimated as a function of forest area, forest type, and forest age. Over large scales variation in forest area is likely the most influential factor affecting calculation of overall budget of FCS (Houghton et al., 1999; Woodbury et al., 2006). However, most approaches for calculating FCS are designed with rural forests in mind, rather than urban and community forests in which other land covers are intimately intermingled.

Urban areas in the conterminous US have doubled in the past a few decades, and account for 3.5% of the land base on average (Dwyer et al., 2000). By region, the Northeast and Southeast have the greatest proportions of urban areas in the lower 48 states (Nowak and Crane, 2002). For example, urban and community lands accounted for 2.9%, 4.2%, and 10.3% of total land area in Vermont, Maine, and New Hampshire, respectively, with an average of 5.0% in the northern New England region, and much of this land base includes trees and forests (Nowak and Greenfield, 2008). Urban and community forests are valuable because of many ecological and social benefits they can provide, such as mitigating the impacts of climate change by reducing the levels of atmospheric CO_2 through sequestration. Nowak and Greenfield (2008) estimated the gross FCS in urban and community trees of northern New England at the state level based on forest area determined from percentage tree canopy and a constant forest growth rate (3 tC/ha/yr per hectare of tree cover) across the region. This study is designed to estimate net FCS of urban and community trees in northern New England using ground-based USDA Forest Service Forest Inventory and Analysis (FIA) growth data, along with data from the National Land Cover Change map, housing density data, and percentage tree canopy data at the county level. We use net FCS to better represent the overall contribution of urban and community forests to regional carbon budgets and to atmospheric carbon dioxide mitigation.

Zheng et al. (2012) found that land cover maps alone at moderate resolution (e.g., 30 m) may not capture low-density housing development characteristic of the urban–rural interface. Thus, FCS in these areas may be overestimated. We hypothesize that additional housing density data could be useful for refining FCS estimation

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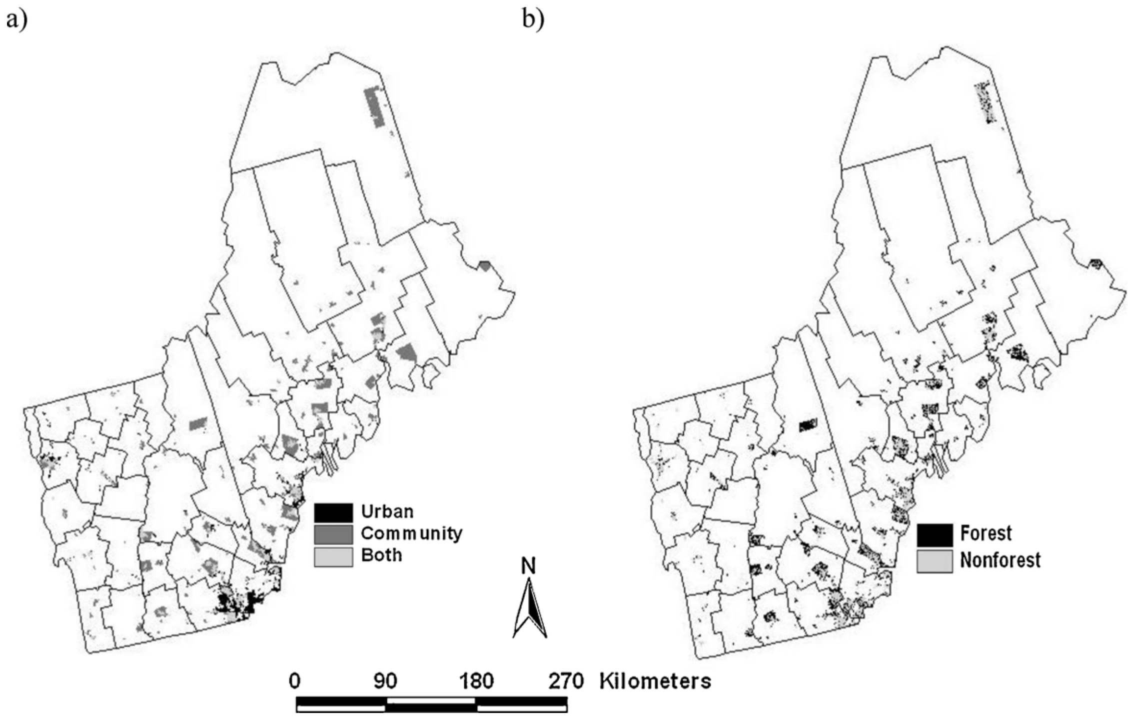

Fig. 1. (a) Distribution of urban and community lands defined by the GIS dataset provided by USDA Forest Service in three northern New England states (http://www.nrs.fs.fed.us/data/urban/); and (b) distribution of forested and nonforest urban and community lands determined using the Retrofit change map 1992–2001 in the region. Methods to calculate net forest carbon sequestration for forested and nonforest land cover types within the urban and community lands differ.

calculated from land cover maps in urban and suburban areas as well. Moreover, capturing regional variability in forest growth rates could also improve estimation, especially if development patterns happen to be correlated with patterns of forest growth (e.g., coastal vs. inland or north–south variability).

Specific objectives of this study are to (1) develop an approach for estimating FCS in urban and community forests that has consistent growth rates with approaches used for rural forests; (2) identify the influence of housing density on FCS in these forests; and (3) explore the resulting spatial pattern in urban and community FCS for the region.

Study area, approach, and datasets

Our study area comprises three states in northern New England, USA: Maine, New Hampshire, and Vermont. This study integrates four major datasets from various sources through a combination of geo-spatial, modeling, and statistical analyses. The 5 datasets are: (1) Urban and community forests map that defines our study area; (2) Land cover change map (1992–2001) to ensure all areas being studied were forested in 2001, and to allow separation of forests that were continuously forested between 1992 and 2001 from those that were recently afforested; (3) Housing density data to calculate occupied areas of residential houses within the forested pixels; (4) National Land Cover Database (NLCD) tree cover map for estimating treed area in nonforest lands; and (5) Net growth-rate tables based on the FIA data for various forest types to estimate carbon effects at county level.

Urban and community land

The definition of community in this dataset is based on jurisdictional or politic boundaries delimited by U.S. Census definitions of places (U.S. Census and Bureau, 2007). Community lands are places of established human settlement that may include all, some, or no urban land within their boundaries (Nowak and Greenfield, 2008). Urban is defined by population density as delimited using the U.S. Census Bureau's (2007) definition: all territory, population, and housing units located within urbanized areas or urban clusters (Nowak and Greenfield, 2008). According to the definitions, "community" and "urban" areas can overlay each other (Fig. 1a). The urban and community forests map (http://www.nrs.fs.fed.us/data/urban/) is produced across the United States based on top-down aerial approaches and bottom-up field data collection.

Land cover change map

We used the National Land Cover Database (NLCD) 1992–2001 Retrofit Land Cover Change Product derived from 30-m Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) satellite data to identify forest status in 2001. The change product contains eight primary classes (no cover change between 1992 and 2001) at Anderson Level I (Anderson et al., 1976): (1) open water, (2) urban, (3) barren, (4) forest, (5) grass/shrub (G/S), (6) agriculture, (7) wetland, and (8) ice/snow. Other secondary classes indicate changes of land cover from one type to another during the period. For example, class 34 indicates the land was changed from barren in 1992 to forest in 2001 and so on. For our purposes, we considered all pixels with codes of 4 (forest remaining forest), 14, 24, 34, 54, 64, and 74 within the urban and community lands as forested in 2001 whereas all the remaining pixels (excluding water, which was treated separately) were considered nonforest. As a first step in analysis, we reclassified all urban and community lands into (1) forested pixels, and (2) nonforest pixels (Fig. 1b) because the methods to be implemented below for calculating net FCS in these two categories of lands differ.

As a test example, we overlaid the map resulting from the above procedures with fine-resolution imagery for a corresponding area located in Cumberland County, Maine from the National

Fig. 2. Overlaying a house (with cleared lots and driveways) built before 2001 located in Cumberland County, Maine obtained from the National Agricultural Inventory Program (http://www.maine.gov/megis/catalog/) at finer resolution with a 3 × 3 window obtained from the NLCD 30-m land cover change map suggests that houses located in the forested urban and community lands may not be proportionally reflected by remotely sensed land cover map alone at moderate resolution. All nine pixels for the corresponding area were classified as forest cover in 2001.

Agricultural Inventory Program (Fig. 2). This example illustrates that housing development in the forested pixels may not be appropriately reflected in 30-m land cover map alone (Zheng et al., 2012). Thus, additional housing density data are needed for the adjustment.

Housing density map

Housing development within forestlands can create additional canopy gaps and also alter the vertical structure of the canopy to increase light transmittance to forest floor (Ellsworth and Reich, 1993; Parker et al., 2001). These effects could reduce the capability of lands otherwise mapped as forests to sequester carbon. Therefore, areas occupied by houses and associated nonforest cover should be deducted from the areas of forestlands identified by land cover maps at moderate resolution for the purposes of FCS estimation because these areas make no contribution to carbon sequestration by trees. Our housing density data were a subset of the national dataset at decennial intervals from 1940 to 2030 at partial block group level (http://silvis.forest.wisc.edu/Library/HousingData.asp). We used the housing density data in 2000 (units per squared kilometer) to estimate numbers of houses in the forested pixels across the region (Fig. 1b). The number of houses in the forested pixels of urban and community lands for a given county was calculated using a mean housing density value multiplied by the corresponding area.

NLCD percentage tree canopy

This dataset provides estimates of percentage tree canopy in 2001 for the conterminous US for all pixels at 30-m resolution (http://www.mrlc.gov/nlcd01_data.php). We subset the dataset for our study area. The information is needed to estimate tree canopy cover to be used as a proxy for treed area in nonforest urban and community pixels. This allows us to apply forestland area FIA-based growth rates for estimating net FCS in these areas (Nowak and Greenfield, 2008).

Estimation of net FCS in forested and nonforest pixels of urban and community lands

Previous studies suggested that separating forest status of afforestation from forest remaining forest would improve the accuracy of FCS because forest growth rates between these two general categories differ (Smith et al., 2006, Zheng et al., 2011). However, a preliminary analysis of the urban and community forests in our region indicated that forest remaining forest accounted for 99.3% of the total forested area in 2001. Because of the miniscule amount of afforestation, we treated all forested area as forest remaining forest and applied the same net growth rates of forest remaining forest to all forested lands to simplify the analyses.

We applied the FIA-based net forest growth rates differently in forested as compared to nonforest urban and community lands to estimate net carbon sequestration. The FIA growth-rate tables include all nonsoil components: live trees, understory, standing dead trees, down dead wood, and forest floor (Smith et al., 2006). For a given county, the growth rate of forests was determined from mean forest age that was inferred from the mean carbon density (t/ha) of all live trees in that county, based on the FIA data. First, forest growth rates were used directly by multiplying forest areas (areas of all forested pixels minus areas occupied by houses) in the corresponding counties to estimate FCS because the FIA-based growth rates are carbon per unit forest land area. Therefore, regional averaged growth rates can be used for a collective land area of all forested pixels within a county given the scope and objectives of our study, although specific rates may be more appropriate subject to a particular study. We further refined the collective land area estimation by deducting effective area occupied by houses in all forested pixels. To convert the number of houses to the area occupied by houses, we applied a factor of 0.2 ha per house (treating this as an average effective cleared area associated with a single-family dwelling; Zheng et al., 2012). This factor is based on the facts that (1) the recommended minimum lot sizes for single family residence in NH (New Hampshire Department of Environmental Services, 2008) ranged from 0.28 ha to about 0.81 ha; (2) the mean sizes of housing lots in the rural zoning under Maine law varied from about 0.2 ha to 0.5 ha (Growsmart, 2005). Many of these zoning recommendations reflect areas that must be permanently cleared of woody vegetation, including the footprint of the house itself, driveways and other access, and septic fields. Houses from these 2 states accounted for 87% of the regional total of cleared area for housing. While county-level means for house lot size would have been preferred, such data are not available. The effective cleared area incorporates areas from which trees are entirely or largely removed (the foundation, driveways, and lawns), recognizing that while there may be some woody regrowth in lawns there may be other indirect negative effects on FCS in associated road improvements or power line improvements (Zheng et al., 2012).

Second, forest growth rates were adjusted for estimating FCS in all nonforest pixels. This adjustment was necessary because the information about trees available in nonforest pixels was a canopy coverage, not a direct land area. We employed equation 1 below to calculate FCS in nonforest pixels (FCS_{nonf}) of urban and community lands based on tree canopy coverage expressed as an area, at the county level:

$$FCS_{nonfi} = \left[\left(\frac{FIA_{ratei}}{FOREST_{mean-pcti}} \right) \times NONF_{mean-pcti} \right] \times NONF_{areai} \tag{1}$$

where i was for a given county, FIA_{rate} was net forest growth rate for the most common type group in county i (Smith et al., 2006), $FOREST_{mean-pct}$ was a mean canopy cover percentage for all forested pixels in the county i, $NONF_{mean-pct}$ was a mean canopy cover percentage for all nonforest pixels in county i, and $NONF_{area}$ was area sum of all nonforest pixels in county i. The sum of FCS in both forested and nonforest pixels was the total net FCS by urban and community trees in county i. We note that FCS includes contributions of trees from both forested and nonforest lands but retain the label FCS for simplicity.

To estimate monetary value associated with net FCS by urban and community lands, the FCS was multiplied by \$17.47/t CO_2, or \$64.11/tC, based on recent weighted-average global carbon dioxide prices (Point Carbon, 2011). We recognize that carbon markets are highly volatile, and that the value of a unit of sequestered carbon depends not only on the actual sequestration but also on the documentation of that sequestration and its conformance to the regulations governing specific markets. We also recognize that efforts to value carbon sequestration can yield a wide range of results depending on assumptions about future social choices and policy decisions; recent estimates bracket the market price used here (e.g., Gutrich and Howarth, 2007). Thus, the price used here should be taken as an approximation based on recent market prices and not an indication of the actual monetization that could be achieved in any particular market.

We further examined contribution rates of annual net FCS by the region's urban and community forests to the region's annual net forest ecosystem carbon sequestration by all forests estimated for the period of 1992–2001 at the county level from a previous study (Zheng et al., 2011). The county-level estimates were tallied to state and regional levels as necessary.

Results

Housing effects on net FCS in forested urban and community lands

Forested urban and community lands were estimated to be 3050 km^2, or 48.1% of the total urban and community lands in the region (Table 1). Proportions of forested and nonforest urban and community lands were similar in the states of Maine (48.5%) and New Hampshire (51.3%), but only 35.2% of urban and community lands were identified as forested in Vermont (Table 1).

Table 1
Proportion (in %) of forested urban community areas determined from the NLCD change map in relation to total urban and community lands and the housing effect within these identified forestlands by county in northern New England. ME, Maine; NH, New Hampshire; VT, Vermont.

County	State	Forested (ha)	Occupied # houses	Occupied area (ha)[a]	Occupied area in %	Forested proportion in %
Androscoggin	ME	13,959	7251	1450	10.4	50.8
Aroostook	ME	15,757	2977	595	3.8	31.8
Cumberland	ME	15,730	14,393	2879	18.3	36.8
Franklin	ME	1378	1637	327	23.7	50.7
Hancock	ME	17,524	3355	671	3.8	74.4
Kennebec	ME	22,412	9246	1849	8.3	56.9
Knox	ME	2559	1501	300	11.7	42.5
Lincoln	ME	2486	1572	314	12.6	61.9
Oxford	ME	4778	2205	441	9.2	58.3
Penobscot	ME	16,607	8021	1604	9.7	45.4
Piscataquis	ME	3148	2031	406	12.9	54.5
Sagadahoc	ME	3140	1611	322	10.3	51.6
Somerset	ME	5785	2567	513	8.9	46.2
Waldo	ME	7201	1866	373	5.2	59.8
Washington	ME	6283	902	180	2.9	68.1
York	ME	19,998	13,877	2775	13.9	48.5
Belknap	NH	4786	5141	1028	21.5	54.6
Carroll	NH	2065	2251	450	21.8	56.4
Cheshire	NH	8053	3981	796	9.9	61.2
Coos	NH	14,625	2216	443	3.0	82.0
Grafton	NH	12,403	6557	1311	10.6	67.2
Hillsborough	NH	19,291	21,456	4291	22.2	37.8
Merrimack	NH	18,481	10,477	2095	11.3	58.1
Rockingham	NH	20,583	23,445	4689	22.8	39.9
Strafford	NH	11,213	9619	1924	17.2	42.5
Sullivan	NH	10,376	3801	760	7.3	69.8
Addison	VT	935	495	99	10.6	21.9
Bennington	VT	2052	1833	367	17.9	34.6
Caledonia	VT	2063	1065	213	10.3	49.7
Chittenden	VT	3906	6784	1357	34.7	22.2
Essex	VT	666	357	71	10.7	59.8
Franklin	VT	588	500	100	17.0	22.0
Grand Isle[b]	VT	10	16	3	30.0	6.2
Lamoille	VT	761	788	158	20.8	46.6
Orange	VT	1053	336	67	6.4	52.3
Orleans	VT	1141	1158	232	20.3	32.6
Rutland	VT	1473	1601	320	21.7	25.2
Washington	VT	4208	4058	812	19.3	47.3
Windham	VT	3632	2379	476	13.1	57.3
Windsor	VT	1597	2333	467	29.2	37.7
ME		158,745	75,012	14,999	9.4[c] (5.5)	48.5
NH		121,876	88,944	17,787	14.6 (7.2)	51.3
VT		24,085	23,703	4742	19.7 (8.3)	35.2
Overall		304,706	187,659	37,528	12.3 (7.7)	48.1

[a] Area occupied by the houses in the forested urban and community lands was estimated using a conversion factor of 0.2 ha per house unit on average.
[b] Containing higher estimation uncertainty due to relatively small amount of urban and community lands (total of 162 ha, see Table 2).
[c] Area weighted. Numbers in the parentheses are standard deviation in %.

Table 2
Net carbon sequestration rate (tC/yr) of urban and community lands in northern New England by county. ME, Maine; NH, New Hampshire; VT, Vermont.

County	State	Growth rate[a]	Forest[b] (ha)	Forest (tC/yr)	Forest (Cano%[c])	Nonf[d] (ha)	Nonf (tC/yr)	Nonf (Cano%)	Total (ha)	Total (tC/yr)
Androscoggin	ME	1.8	13,959	22,516	76.0	13,530	4710	14.7	27,489	27,226
Aroostook	ME	1.6	15,757	24,259	72.9	33,728	7794	10.5	49,485	32,053
Cumberland	ME	1.7	15,730	21,847	77.3	27,056	10,183	17.1	42,786	32,030
Franklin	ME	2.2	1378	2311	76.2	1341	585	15.1	2719	2896
Hancock	ME	1.6	17,524	26,965	79.6	6030	3095	25.5	23,554	30,060
Kennebec	ME	1.8	22,412	37,013	79.1	16,977	6493	16.8	39,389	43,506
Knox	ME	1.6	2559	3614	78.2	3456	1218	17.2	6015	4832
Lincoln	ME	1.8	2486	3909	79.0	1530	379	10.9	4016	4288
Oxford	ME	1.8	4778	7807	80.0	3417	1414	18.4	8195	9221
Penobscot	ME	2.2	16,607	33,006	79.0	19,953	13,029	23.5	36,560	46,035
Piscataquis	ME	2.2	3148	6032	75.3	2625	1621	21.1	5773	7653
Sagadahoc	ME	1.7	3140	4790	74.9	2940	1167	17.5	6080	5957
Somerset	ME	2.2	5785	11,597	77.1	6729	3230	16.8	12,514	14,827
Waldo	ME	1.8	7201	12,290	79.9	4842	1985	18.2	12,043	14,275
Washington	ME	1.6	6283	9764	78.7	2949	2048	34.2	9232	11,812
York	ME	1.8	19,998	31,001	79.6	21,228	11,356	23.7	41,226	42,357
Belknap	NH	1.7	4786	6388	85.4	3980	1960	24.7	8766	8348
Carroll	NH	1.5	2065	2422	81.3	1599	485	16.4	3664	2907
Cheshire	NH	1.5	8053	10,885	90.3	5106	2555	30.1	13,159	13,440
Coos	NH	2.2	14,625	31,200	87.4	3219	1985	24.5	17,844	33,185
Grafton	NH	1.7	12,403	18,856	84.7	6060	1782	14.6	18,463	20,638
Hillsborough	NH	1.5	19,291	22,500	79.4	31,719	14,124	23.6	51,010	36,624
Merrimack	NH	1.5	18,481	24,578	82.0	13,339	5850	24.0	31,820	30,428
Rockingham	NH	1.7	20,583	27,020	78.3	31,041	17,642	26.2	51,624	44,662
Strafford	NH	1.7	11,213	15,792	80.8	15,151	6663	20.9	26,364	22,455
Sullivan	NH	1.7	10,376	16,347	90.8	4493	1627	19.3	14,869	17,974
Addison	VT	1.8	935	1505	88.8	3338	727	10.7	4273	2232
Bennington	VT	1.4	2052	2359	85.5	3879	1213	19.1	5931	3572
Caledonia	VT	1.8	2063	3330	75.3	2087	394	7.9	4150	3724
Chittenden	VT	1.7	3906	4334	80.4	13,680	3699	12.8	17,586	8033
Essex	VT	2.2	666	1308	73.9	448	313	23.5	1114	1621
Franklin	VT	1.7	588	830	75.5	2088	342	7.3	2676	1172
Grand Isle	VT	1.7	10	12	70.9	152	28	7.7	162	40
Lamoille	VT	1.7	761	1026	76.0	873	81	4.2	1634	1107
Orange	VT	1.8	1053	1774	77.6	960	122	5.5	2013	1896
Orleans	VT	1.8	1141	1637	74.8	2358	412	7.3	3499	2049
Rutland	VT	1.7	1473	1960	87.9	4361	1542	18.3	5834	3502
Washington	VT	1.7	4208	5774	78.2	4681	765	7.5	8889	6539
Windham	VT	1.4	3632	4419	86.4	2707	682	15.5	6339	5101
Windsor	VT	1.7	1597	1922	81.9	2637	957	17.5	4234	2879
ME		1.8	158,745	258,721	77.7[e]	168,331	70,307	18.8[e]	327,076	329,028
NH		1.7	121,876	175,988	84.0	115,707	54,674	22.4	237,583	230,662
VT		1.7	24,085	32,190	79.5	44,249	11,277	11.8	68,334	43,467
Overall		1.8	304,706	466,899	79.9	328,287	136,258	17.3	632,993	603,157

[a] tC/ha/yr.
[b] Sum of area for all forested pixels in urban and community lands that were determined using the NLCD change map at the ending year of 2001.
[c] Percentage canopy cover (CANO%) data were used for converting canopy cover based area to land based area so FIA tree growth data measured at ground can be used for estimating net carbon sequestration in nonforest pixels (excluding water) of urban and community lands based on tree canopy cover area (see Eq. (1)).
[d] Sum of area for all nonforest pixels in urban and community lands that were determined using the NLCD change map at the ending year of 2001.
[e] County mean.

About 187,700 houses were estimated to lie within the forested urban and community lands across the region based on housing density data in 2000. The total effective cleared area associated with these houses was 375 km^2, and ranged from 47 km^2 in Vermont to 178 km^2 in New Hampshire (Table 1). Effective cleared area as a fraction of total forested urban and community land ranged from 9.4% in Maine to 19.7% in Vermont, averaging 12.3% for the region (Table 1). This cleared area would translate to a 9.0% reduction in net FCS estimation by all urban and community trees, compared to the estimation without considering housing effects. After deduction of effective areas occupied by houses, forested urban and community lands generated a net carbon sequestration of 466,900 tC/yr, which accounted for 77% of FCS by all urban and community trees (Table 2). Ninety-three percent of this net carbon sequestration (466,900 tC) came from forested urban and community forests in Maine and New Hampshire (Table 2).

Net forest carbon sequestration in nonforest urban and community lands

Nonforest urban and community lands were estimated to be 3280 km^2 with an average tree canopy cover of 17.3% across the region (Table 2). Tree canopy cover percentages by state in nonforest urban and community lands varied from 11.8% in Vermont to 22.4% in New Hampshire. We estimated that about 136,300 tC were sequestered by urban trees per year in the region using Eq. (1), accounting for 23% of net FCS by all urban and community forests (Table 2). Ninety-two percent of this urban-tree sequestration (136,300 tC) was from Maine and New Hampshire. If the net FCS were stratified by forested and nonforest urban and community lands, contributions of FCS by urban trees to the carbon sequestration by all urban and community forests accounted for 21.4%, 23.7%, and 25.6% in the states of Maine, New Hampshire, and Vermont, respectively. The highest contribution rate (25.6%)

Table 3
Comparison between forest carbon sequestration (FCS, tC/yr) of urban and community forests obtained from this study (NEW) and urban and community FCS reported from a previous study (PRE) (Nowak and Greenfield, 2008) by state. Differences in FCS were calculated as (NEW/PRE − 1) × 100 in percentage.

State	This NEW study[a]		PRE study		Diff.	Contribution[d]
	Area[b] (km^2)	FCS	Area (km^2)	FCS[c]		
ME	3271 (4.1[e])	329,028	3367	457,571	−28.1	8.2
NH	2376 (10.2)	230,662	2397	383,610	−39.9	16.6
VT	683 (2.9)	43,467	685	74,781	−41.9	2.3
Overall	6330 (5.0)	603,157	6449	915,961	−34.2	8.2

[a] Carbon sequestrations in this study were calculated using aggregated regional net forest growth rates for varying forest types while carbon sequestrations in the previous study were calculated using a constant national average gross sequestration rate.
[b] Land area (excluding water) was tallied from county-level analysis based on the NLCD land cover change map in 2001. Relatively larger difference (−2.8%) in land area observed in state of Maine between the two studies was due to exclusion of small islands along the coast lines in this study.
[c] Reported gross carbon sequestration by urban community forests were adjusted slightly based on area difference between the two studies at the state level. This justification is valid because gross carbon sequestration was estimated using a single rate of 3 tC/ha/yr across the region (Nowak and Greenfield, 2008). In other words, gross carbon sequestration is solely a function of area change.
[d] State-level contributions (in percent) of FCS by urban and community forests as compared to the net ecosystem carbon gains by all forestlands estimated from a previous study (Zheng et al., 2011).
[e] Area percentage of urban community lands in relation to total land area.

by trees in nonforest lands in Vermont was due to 65% of the total urban and community lands in the state were identified as nonforest area, the highest percentage among the three states (Table 1).

Overall net FCS in urban and community lands and its spatial pattern

We estimated that net FCS in the region's urban and community lands was 603,200 tC per year, accounting for 8.2% of the net forest ecosystem carbon gains in the region estimated from a previous study (Zheng et al., 2011). Ninety-three percent of the net FCS came from Maine and New Hampshire (Table 2). The contribution of urban and community net FCS to the net forest ecosystem carbon gains by all forests varied substantially at state level, from 2.3% in Vermont, 8.2% in Maine, to 16.6% in New Hampshire (Table 3). These contribution percentages included trees from nonforest pixels within the community and urban lands that were not counted in the study of Zheng et al. (2011). On average, carbon sequestration by trees in the nonforest pixels accounted for 22.6% of total carbon sequestered by all forested lands (pixels) and trees within the urban and community lands in the study area. The total monetary value of net FCS by urban and community forests was $38.7 million per year.

The net sequestration rate of urban trees across the region was about 0.98 tC/ha/yr, on average, or 46% lower than that of FIA based

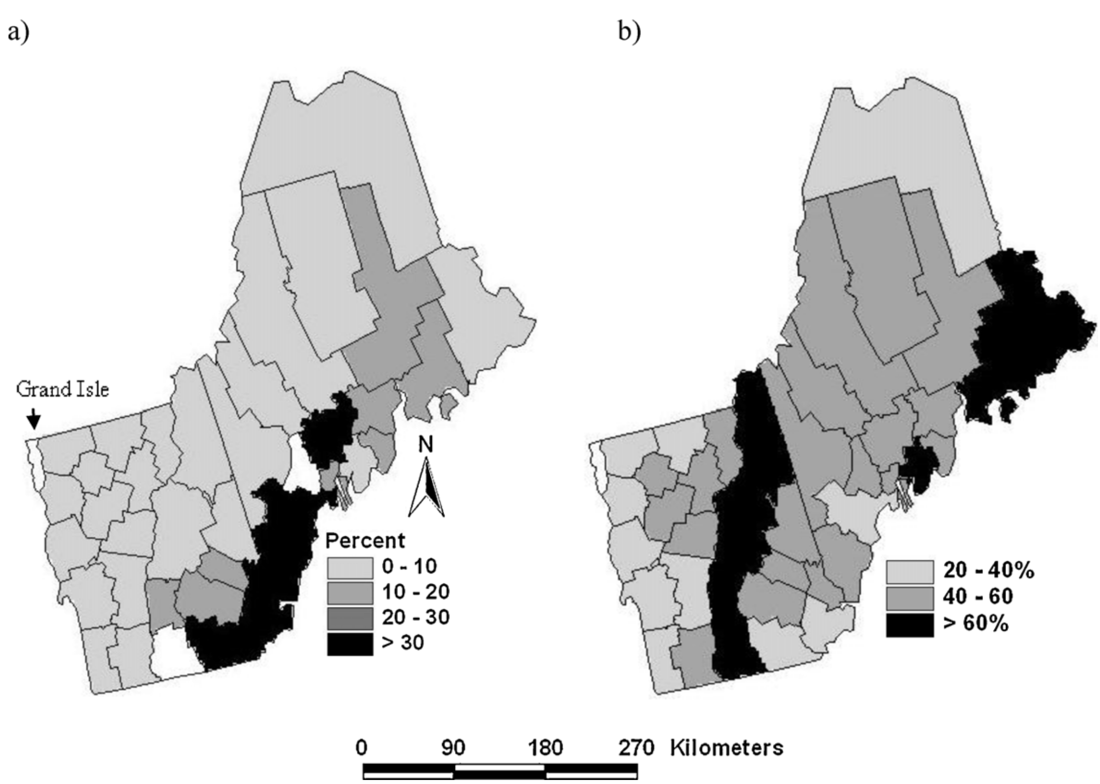

Fig. 3. (a) Spatial variations in contribution (percent) of net forest carbon sequestration (FCS) by urban and community forests in relation to net FCS by all forests at the county level in the three states. Grand Isle county in Vermont was excluded due to its high uncertainty possibly caused by: (1) majority of the county's territory is covered by water; and (2) small amount of urban and community land area involved in the analysis (Table 2). The contribution assessment for another two counties (in white) are not applicable because their annual mean carbon removals from harvests on forestland were larger than their annual net forest carbon sequestrations so the denominators become negative; and (b) county-level proportion (in percent) of forested pixels determined using the NLCD change map in relation to its total urban and community lands at the county level for the year of 2001.

net growth rate for forest stands. However, it should be borne in mind that the area basis for this calculation is total urban and community area, which includes some substantial nonforest areas, especially in urban lands. By comparison, it has previously been reported that national average urban forest carbon storage density was 53% lower than that in forest stands (Nowak and Crane, 2002).

The county-level analyses showed clearly that the contributions of net FCS by urban and community forests to total forest ecosystem carbon gains varied substantially across the region ranging from 0.8% in Franklin County, Maine to 73.3% in Hillsborough County in New Hampshire. Counties with higher contribution rates were concentrated in southeast portion of New Hampshire and southwest portion of Maine along the coast, whereas the contribution rates decreased rapidly toward inland counties in general (Fig. 3a). For example, average contribution rate for the 6 counties classified in the highest category was 59.3% while no county was identified in the 20–30% category, the second highest class.

Discussion

Contribution of region's FCS by urban and community forests and its spatial patterns

Zheng et al. (2011) estimated net forest ecosystem carbon gains in the region by incorporating disturbances from forest harvests and fires. Although our estimates of net FCS by urban and community forests in this study do not include components of carbon emissions from forest harvests and fires, it is reasonable to assume that commercial harvests are very limited in urban and community lands. In addition, forest fires are very rare across the region (Zheng et al., 2011). Comparison between the two studies suggested that net FCS by urban and community forestlands including trees in nonforest pixels identified from land cover map and tree cover percentage map in this study accounted for approximately 8% of net ecosystem carbon exchanges on annual basis by all forestlands (excluding trees in nonforest pixels, Zheng et al., 2011) in the region.

Two counties, Androscoggin in Maine and Cheshire in New Hampshire, had net FCS for their entire forest ecosystem carbon exchanges that were negative (i.e., annual carbon removals from harvest were larger than annual carbon sequestrations by all forests in these two counties) (Fig. 3a). Thus, data from these counties were not applicable for assessing contributions of net FCS by urban and community forests in relation to total ecosystem FCS. For example, forest area in these two counties accounted for 2.4% of total forest area in the region, whereas their annual harvest carbon removal accounted for 11.1% of the region's total based on the data we used.

Estimation of net FCS by urban and community forests at the county level were affected by spatial variations of several factors: (1) total amounts of urban and community lands involved in calculations; (2) proportions of forested urban and community lands to the totals; and (3) net forest growth rates associated with most-common-forest type. For example, most of the region's urban and community lands (89.2%) are located in New Hampshire and Maine. Furthermore, proportions of counties with forested urban and community lands over 40% were 46%, 80%, and 88%, respectively, for the states of Vermont (excluding Grand Isle county), New Hampshire, and Maine (Fig. 3b). In other words, a higher proportion of forested (rather than nonforest) urban and community lands for a given county indicated more of the county's urban and community lands whose FCS were calculated using the higher forest growth rate per unit total land area on average, compared to that applied to the county's nonforest urban and community lands, mainly because of higher tree density per unit cover on forestlands (Nowak and Crane, 2002).

Net forest carbon sequestration vs. gross FCS

We summarized our county level net FCS estimates to the state level for comparison with gross FCS estimates that were available only at the state level for entire urban and community forests in the region by Nowak and Greenfield (2008). Overall, our estimated net FCS was 34.2% lower than its gross FCS in the region varying from 41.9% lower in Vermont to 28.1% lower in Maine (Table 3). The main explanation for difference in carbon sequestration between the two studies is that this study used regional net growth rates for varying forest types, which is about 40% lower, on average, than the national average gross sequestration rate of 3 tC/ha/yr that was used in the previous study. Within region variation was mainly caused by (1) 6% higher forest growth rate in Maine (1.8 tC/ha/yr) than that in Vermont (1.7 tC/ha/yr) (Table 2); (2) 59% higher canopy cover percentage in nonforest urban and community lands in Maine (18.8%) than that in Vermont (11.8%) (Table 2); and (3) higher proportion of nonforest urban and community lands in Vermont (64.8%) than that in Maine (51.5%) (Table 1). In other words, there are relatively more urban and community lands in Vermont, but the FCS for those lands was calculated using lower growth rates (after adjustment for canopy area and housing) than that in Maine based on our methodology.

Uncertainty assessments

There are four major error sources in our FCS estimation. First, there are always mapping errors from remote sensing derived products. For example, the NLCD 1992–2001 Retrofit change map contained some classification errors although it was improved using a set of new technologies (Fry et al., 2009). It was reported that the overall classification error at Anderson Level I was 20% in the New England region (Stehman et al., 2003). Also, the NCLD tree cover map generally underestimated canopy cover by 9.7% nationwide with reported errors ranging from 6% to 22% (Homer et al., 2004; Nowak and Greenfield, 2010). These errors would affect the accuracy in separation of forested urban and community lands from nonforest lands, and also the calculation of growth rates in nonforest lands. Second, we used a constant factor (0.2 ha per house) to convert numbers of houses to the effective cleared areas within the forested urban and community lands across the region. As true mean size of housing lots undoubtedly varies with regional variation in topography, house size, and construction practices, the resulting FCS estimation would differ. But the effect of this kind of systematic error can be bounded. For instance, effective area occupied by houses in the forested urban and community lands would be increased by 50% if the mean size of effective cleared area per house unit increased from 0.2 ha to 0.3 ha, with straightforward consequences for estimates of FCS. Third, a possible overestimation in housing density occurs within the forested urban and community lands due to data precision, because the housing density map was developed based on the census data following partial block group divisions, rather than the divisions between forest and nonforest. Thus, the allocation of housing units between forested and nonforest urban and community lands is inherently imprecise. We believe our approach may allocate too many housing units to the forested areas in some instances; however, our use of an 0.2 ha effective cleared area for housing units in forested areas is probably on the small side so that these inaccuracies may be partially or wholly compensating (Zheng et al., 2012). And finally, although we identified most common forest types at the county level in the region, the growth rates for these types were still regional averages and not specific to the individual county. Therefore, while the estimates for all of the urban and community forests combined would likely produce a reasonable estimate for the whole region studied, any estimates specific to one of the counties would not likely be accurately represented by the average. Therefore, any comparison among or between individual counties should be assessed cautiously. Future improvements should endeavor to compile estimates directly from the FIA database for the specific areas of study, rather than using the pre-calculated values from Smith et al. (2006).

This study presented a new methodology to estimate net FCS by urban and community lands using FIA land-area based forest growth rates, which provides a direct link and assessment of roles and contributions of urban and community forests in relation to region's net forest ecosystem carbon sequestration and mitigation to climate change. Our estimates compared well with gross FCS in the region reported by a previous study, and also allow for greater spatial variability in growth rates. Our approach also bridges ecological properties (e.g., carbon sequestration) with social sectors (e.g., housing development) that can be influential in forest dominant urban and community areas. Overall, the value of net FCS by urban and community lands in the region is new value is approximately $38.7 million/yr, based on recent international carbon markets. By comparison, the total gross domestic product associated with all forestry, fisheries, and related activity in the three-state area was $620 million/yr in 2009 (Bureau of Economic and Analysis, 2011). Thus the value of one ecosystem service (carbon sequestration) provided by these urban and community lands is nontrivial in comparison with the market-based delivery of goods and services by all forests over the entire region.

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