A Preliminary Investigation of Forest Carbon Changes Associated with Land-Use Change in Northern New England

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Abstract: *Maine (ME), New Hampshire (NH), and Vermont (VT) are three of the four most heavily forested states in the United States. In these states, we examined how land-use change, at the Anderson Level I classification, affected regional forest carbon using the 30-m Multi-Resolution Land Characteristics Consortium 1992/2001 Retrofit Land Cover Change product coupled with county-level forest carbon stock densities and changes based on U.S. Forest Service, Forest Inventory and Analysis data during the 9-year period. Results indicate that about 1,100 km^2 of forests were newly developed from other land-cover types during 1992 and 2001 across the region, and about 3,100 km^2 of forests were converted to other cover types in the same period, resulting in an apparent net loss of 2,000 km^2 of forest. Thirty percent of land-cover changes occurred within 1.5 km of major roads. Forest land converted to nonforest land area change resulted in apparent carbon (C) loss of 26 million metric tons (10^{12} grams – teragrams (Tg)), nonforest land becoming forest land sequestered 1 TgC and forest land remaining forest land sequestered approximately 154 TgC. Consequently, the regional forests functioned as a carbon sink of 129 TgC over the entire 9-year period. All counties functioned as C sinks during the period, ranging from 0.07 Tg in Grand Isle, VT, to 12.5 Tg in Aroostook, ME. Spatially, 8 of the top 10 counties identified as C sinks were in ME and the other two in NH. In terms of forest carbon loss from deforestation alone, 8 of the top 10 counties were located in ME while the other two were in southeastern NH, where relatively high deforestation rates were detected.*

Keywords: NLCD land-cover maps, land-use change, afforestation, forest land remaining forest land, change detection.

Introduction

Global forests play a dominant role in the terrestrial carbon (C) cycle. They contain 86 percent of the earth's aboveground C and about 73 percent of the C in the world's soil (Post et al. 1982, Olson et al. 1983). Changes in land-use patterns affect C dynamics and balance (Dixon et al. 1994, Houghton 1995). Various models have predicted that the amount of C released from forest ecosystems annually to the atmosphere is positively related to the global deforestation rate (Alcamo et al. 1996, Yamagata and Alexandrov 1999). Turner et al. (1996) estimated that 45 percent of the potential forest cover of the conterminous United States had been converted to other land-cover types. Furthermore, spatial and

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temporal dynamics of forest ecosystems can vary substantially with human-introduced disturbances (such as road accessibility and urbanization). Although ownership can also affect spatial and temporal dynamics of forest ecosystems, it is not the focus of this study.

The Forest Inventory and Analysis (FIA) Program has been using systematic sampling schemes for surveying forest lands across the nation with periodic updates since the early 1930s before changing the survey method to an annualized approach in the early 2000s (Bechtold and Patterson 2005). The FIA field data provide accurate ground measurements for conducting statistical analyses, and for model development and validation; however, these point-based measurements are less suitable for conducting spatially explicit analyses across entire landscapes (Cramer et al. 2001, Zheng et al. 2003). Combining satellite observations with field-based natural resources inventory data will provide more consistent, reliable, and comparable analyses across both spatial and temporal dimensions for national-scale forest and carbon related studies (Nelson et al. 2002, Liknes et al. 2004, McRoberts et al. 2006, Zheng et al. 2008). A previous study demonstrated how land-cover data from different sources could be used for studying regional greenhouse gas dynamics (Brown et al. 2007). Recent collaborations among NASA, FIA, and other Forest Service and university partners indicate that potential benefits from linking the information have begun to be recognized by colleagues, scientific communities, and governmental agencies (Healey et al. 2007).

The National Land Cover Database (NLCD) provides national land-cover maps for 1992 and 2001 using 30-m Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) satellite data (Vogelmann et al. 2001, Homer et al. 2004). Although the classification methods and systems were not identical between the 2 years, one of the guiding principles in the NLCD 2001 map was to ensure that the second generation land-cover product maintained reasonable compatibility with NLCD 1992 map (Homer et al. 2004). Thus, the products are the best resources currently available for detecting land-cover changes between these years at regional and national scales. While direct pixel-to-pixel comparison between two datasets is not recommended (U.S. EPA 2008), the U.S. Geological Survey NLCD design team initiated research to devise an optimal way to compare the products. As a result, the team generated the NLCD 1992/2001 Retrofit Land Cover Change Product using a multistage processing method on the NLCD 1992 and 2001 datasets (MRLC 2008). We obtained the retrofit change product at the Anderson Level I (broader classification categories than those at the Level II used in the original NLCD 1992 and 2001 datasets; Anderson et al. 1976) for use in our regional study.

The states of Maine (ME), New Hampshire (NH), and Vermont (VT) are three of the four most heavily forested states in the country, about 73 percent forested in 1992 and 72 percent in 2001 based on the Retrofit product. While the three states accounted for 1.7 percent of the total land area in the conterminous United

States, they contained 4.6 percent of the total forest land. Therefore, the area has disproportionate importance in the nation's forest ecosystem carbon estimates. The overall goal of this study is to establish baseline information for area changes in land-cover types and forest carbon dynamics in the region. The specific objectives are to: 1) quantify land-use changes at the Anderson Level I in the three northern New England states between 1992 and 2001 focusing on the forest sector; and 2) illustrate how these changes affect countywide and regional forest area and carbon dynamics, as well as their spatial distributions (that is, related to distribution of roads).

Methods and Materials

Study area

The study area contains three northern states (ME, NH, and VT) of the New England area in the United States, with a total land area of 133,100 km^2. About 73 percent of the area is forested. The area is characterized by rolling hills, mountains, and a jagged coastline resulting from retreating ice sheets that shaped the landscape thousands of years ago. Elevation ranges from sea level to 1,917 m at Mount Washington in NH. Dominant forest types include: 1) spruce-fir in northern ME and at high elevation; 2) white/red/jack pine along the coast of southern ME and southeast of NH; and 3) maple/beech/birch in southwestern NH and western VT (Irland 1999). The area is classified as humid continental short and relatively cool summers and long, cold winters. Long-term annual mean temperature is about 4.4 ^{o}C. The average annual rainfall ranges from 500 to 1,000 mm.

Digital maps and data analyses

We downloaded the NLCD 1992/2001 Retrofit Land Cover Change Product provided by the Multi-Resolution Land Characteristics Consortium (MRLC) (MRLC 2008), and extracted the data for our study area. We compared our satellite-based forest area change estimates with those developed from FIA data during the corresponding period at the state level.

To simplify the calculation in carbon dynamics, we based carbon changes on area change categories of nonforest land becoming forest land, forest land remaining forest land, and forest land becoming nonforest land, by county. Because forest carbon is related to forest type, the most common forest type was identified for each county for carbon-related calculations. Since there was a 9-year interval for the area change estimates, we assumed the average age of new forests was 5 years, but a total of 9 years of growth occurs for the area of forest land remaining forest land. To calculate C loss for deforestation, we used the county-level change in forest area, multiplying the county mean forest C densities obtained from the most recent FIA data by a conversion factor of 0.8. This factor is based on the assumption that 80 percent of the nonsoil forest C (including live tree, stand dead, understory, down dead wood, and forest floor) would be lost during conversion to nonforest (Smith and Heath 2008).

To examine the relationship between land-cover change and road distribution, we used the 2004 national major-road map from ESRI (2008). The map represents interstate, U.S. and state highways, major streets, and other major thoroughfares within the country. We clipped the roads for our study area and created a polygon cover identifying buffer zones within a distance of 1.5 km (one side) from all roads using the GIS function. The buffered roads were overlaid with the Retrofit change map to quantify the relationship.

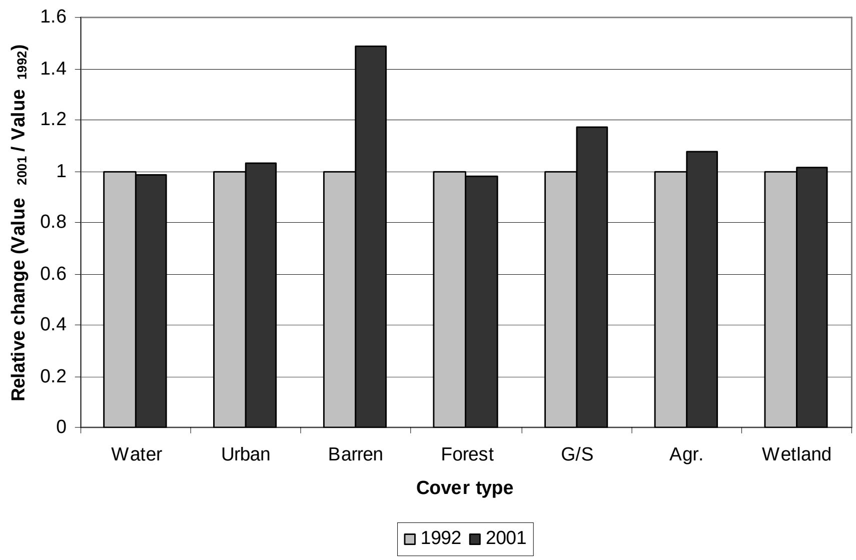

Figure 1. - Relative changes in area between 1992 and 2001 by the seven broad Anderson Level I cover categories from the Retrofit change product using 1992 values as reference (= 1). G/S = Grass/Shrub.

Results and Discussion

Area dynamics and spatial pattern

The most significant relative changes by land-cover types between 1992 and 2001 were found in barren (increased by 49 percent), followed by grass/shrub (17 percent), agriculture (7 percent), urban (3 percent), and forest (-2 percent) (Fig. 1). Across the region, area of water was estimated to decrease by 0.1 percent of total land area (Table 1). Percentage of forest land decreased from 73.3 percent in 1992 to 71.8 percent in 2001 by 1.5 percent of the total land area, at an annual rate of less than -0.2 percent. During the 9-year period, about 3.5 percent of total land area experienced cover-type change. About 91 percent of the land experiencing the change was related to forest. Although these changes occurred across the region and did not exhibit a specific pattern, we found 30 percent of these cover-type changes occurred within 1.5 km of major roads (Fig. 2). Such information is useful for future regional resource planning.

Table 1. - Statistics in 1992 and 2001 for the seven land-cover categories from the Retrofit change product of MRLC, in terms of percentages of total regional land area.

Cover Type	1992 (%)	2001 (%)
Water	4.5	4.4
Urban	4.4	4.5
Barren	0.3	0.4
Forest	73.3	71.8
Grass/Shrub	4.7	5.5
Agriculture	5.6	6.0
Wetland	7.3	7.4

During the 9-year period, about 3,100 km^2 of forest land changed to other types (Table 2). Most of the type changes, in order of amount of area changed, were from forest to grass/shrub (G/S), agricultural land, wetland, and urban (Table 3). About 1,100 km^2 of other types were converted to forests (Table 2), most of these conversions came from G/S, wetland, and agricultural land (Table 3). Other cover types with smaller percentage changes during the period were wetland (2 percent) and water (-1 percent). Overall, the region experienced an apparent net loss of 2,000 km^2 of forests during the 9-year period, at an annual rate of 220 km^2, which is less than 0.2 percent of total land area including water. Considering that all these cover types contain vegetation to some degree, potential uncertainties could be caused by mapping errors in satellite based products. For example, wetlands have proven difficult to map with satellite data because they may be rare in occurrence (4.6 percent in the region, (Stehman et al. 2003)) and their spectral and spatial characteristics are highly context-dependent (Wright and Gallant 2007). Among the 7 Anderson Level I categories in the 1992 NLCD map, wetlands have the lowest user accuracies using center pixel and mode agreement definitions (Stehman et al. 2003).

Spatial heterogeneity in net forest loss across the region between 1992 and 2001 was observed among the states. About 85.9 percent of regional net forest loss occurred in ME, followed by 8.4 percent in NH, and 5.7 percent in VT; this is due to relatively higher deforestation rates in ME, as well as its larger area (Fig. 3; Table 4). On a state basis, forest loss accounted for 2.1 percent, 0.7 percent, and 0.5 percent of the total areas in ME, NH, and VT, respectively, from 1992 to 2001. All counties in ME except Washington and Hancock in eastern ME exhibited some degree of forest loss, from 1 percent to 7 percent (Fig. 3). The other three counties in the region gaining forest area during the period were one in NH (Coos) and two in VT (Caledonia and Essex) (Fig. 3). All five counties gaining forest area exhibit small percentage gains (less than 1 percent) with the maximum of 0.7 percent in Washington County of ME. Two counties, Grand Isle and Lamoille, in VT showed no changes in forest area. Most of the remaining counties in VT and NH (excluding 3 counties with forest gains) had relatively low rates of forest loss (between 0 and 1 percent). The exceptions were two counties in southeastern NH: Hillsborough with 3 percent loss and Rockingham with 5 percent loss (Fig. 3).

Table 2. - Forest area change and carbon (C) dynamics during a 9-year period (1992-2001) in ME, NH, and VT by county (sorted by C sum). The numbers for total areas may slightly differ to those in Table 3 that were derived from regional summary due to rounding.

County	State	Area Status (km^2)			C Status (1000 ton)			C Sum
		Gained	Lost	Remain	Gained[a]	Lost[b]	Remain[c]	
Aroostook	ME	224	649	12119	291	5103	17342	12531
Piscataquis	ME	153	460	7889	196	3908	15620	11908
Penobscot	ME	122	282	6248	156	2148	12371	10379
Somerset	ME	162	696	7141	207	5477	14139	8870
Coos	NH	12	4	4136	15	34	8189	8170
Oxford	ME	25	40	4432	32	378	7339	6993
Franklin	ME	28	114	3611	36	995	7150	6190
Washington	ME	105	72	4469	137	519	6476	6093
Grafton	NH	10	16	3883	13	167	5766	5612
Hancock	ME	76	63	2842	99	520	4067	3646
Essex	VT	6	2	1517	8	17	3004	2995
Carroll	NH	7	9	2091	9	106	2860	2763
York	ME	0	38	1655	0	355	2741	2385
Orange	VT	3	5	1420	4	49	2352	2306
Rutland	VT	6	27	1739	8	298	2582	2292
Windsor	VT	4	46	2045	5	518	2798	2284
Merrimack	NH	14	32	1886	18	371	2580	2227
Caledonia	VT	4	3	1322	5	26	2189	2168
Washington	VT	2	5	1456	3	52	2162	2112
Orleans	VT	3	6	1278	4	57	2116	2063
Kennebec	ME	8	59	1497	10	545	2479	1945
Waldo	ME	9	51	1337	12	449	2214	1776
Cheshire	NH	8	25	1504	10	299	2057	1768
Cumberland	ME	4	37	1429	5	360	2122	1767
Windham	VT	3	27	1730	4	342	2086	1748
Bennington	VT	4	13	1447	5	168	1745	1582
Addison	VT	5	16	1001	6	156	1658	1508
Sullivan	NH	4	21	1141	5	226	1694	1474
Hillsborough	NH	15	57	1544	19	672	2112	1459
Lamoille	VT	1	1	966	1	11	1435	1425
Franklin	VT	3	4	943	4	42	1400	1363
Chittenden	VT	3	6	853	4	64	1267	1207
Belknap	NH	5	8	826	6	81	1227	1152
Androscoggin	ME	6	22	761	8	199	1260	1069
Lincoln	ME	4	38	812	5	367	1345	983
Rockingham	NH	3	59	1017	4	630	1510	885
Strafford	NH	0	15	617	0	158	916	758
Knox	ME	9	27	484	12	228	693	477
Sagadahoc	ME	1	11	383	1	107	569	463
Grand Isle	VT	0	0	44	0	0	65	65
Total		1061	3066	93515	1366	26201	153699	128864

[a] Carbon gain was estimated using carbon accumulation tables for afforestation (Smith et al. 2006), assuming the average age of the new forests in this 9-year period was 5 years.

[b] County-level carbon loss was estimated using average nonsoil forest carbon density by county from the latest FIA data, assuming that 20 percent of the nonsoil carbon remained after forest land became nonforest land.

[c] Carbon for forest land remaining forest land was estimated using carbon accumulation tables for reforestation (Smith et al. 2006) for the most common forest type in the county. The county-level carbon density was used to estimate the expected carbon growth.

Table 3. - Detected land-cover change (km^2) using the Retrofit change product in three northern New England states, U.S.A. G/S = grass/shrub.

	Water	Urban	Barren	Forest	G/S	Agric.	Wetland	Sum1992
Water	5817	2	16	8	5	4	72	5924
Urban	2	5773	1	16	4	48	14	5858
Barren	0	0	340	0	0	0	0	340
Forest	14	233	143	94470	1855	530	326	97571
G/S	1	18	4	695	5462	68	62	6310
Agric.	2	12	1	85	10	7284	15	7409
Wetland	3	5	0	266	41	18	9358	9691
Sum2001	5839	6043	505	95540	7377	7952	9847	133103

We compared our forest area changes detected from NLCD with those calculated from FIA during the corresponding years. Regional estimates from these sources were substantially different from each other. While the NLCD detected a forest net loss of 2,000 km^2 across the region during the period, FIA data showed a loss of 22 km^2 (Table 4). Compared at the state level, the satellite-based results overestimated the forest net loss by 24 percent in ME while underestimating the loss by 73 percent in NH, compared to FIA-based losses. For Vermont, even the sign of the change was opposite. Such a discrepancy may be caused by differences in forest definition and mapping errors. For example, forests in NLCD were defined as areas dominated by trees generally greater than or equal to 5 m tall and greater than or equal to 20 percent of total vegetation cover (Homer et al. 2004), whereas forest lands defined by the FIA are at least 10 percent stocked by trees of any size (Bechtold and Patterson 2005). Reconciliation of this issue requires better coordination and integrity between ground forest inventory and remotely sensed information in future, including 1) increasing plot density; 2) measuring all cover types; and 3) improving remote sensing techniques to reduce mapping errors.

Forest carbon dynamics and spatial pattern

During the 9-year period, regional afforestation sequestered a net 1.4 million metric tons (10^{12} grams – teragrams (Tg)) of carbon (C) and forest land remaining forest land sequestered approximately 153.7 TgC. Regional deforestation resulted in a loss of 26.2 TgC. As a result, the regional forests functioned as a carbon sink sequestering a total of 128.9 TgC (Table 2).

Spatially, all 40 counties in the region functioned as C sinks during the period ranging from 12.5 Tg (Aroostook in ME) to 0.07 Tg (Grand Isle in VT). Eight of the top 10 counties were in ME and the remaining two were in NH (Table 2). The top 10 sink counties as a whole accounted for 62.4 percent of regional sequestered C during the period due to their larger size (on average 2.4 times larger than the regional mean) and higher forest cover percentages (on average 7 percent higher than the regional mean).

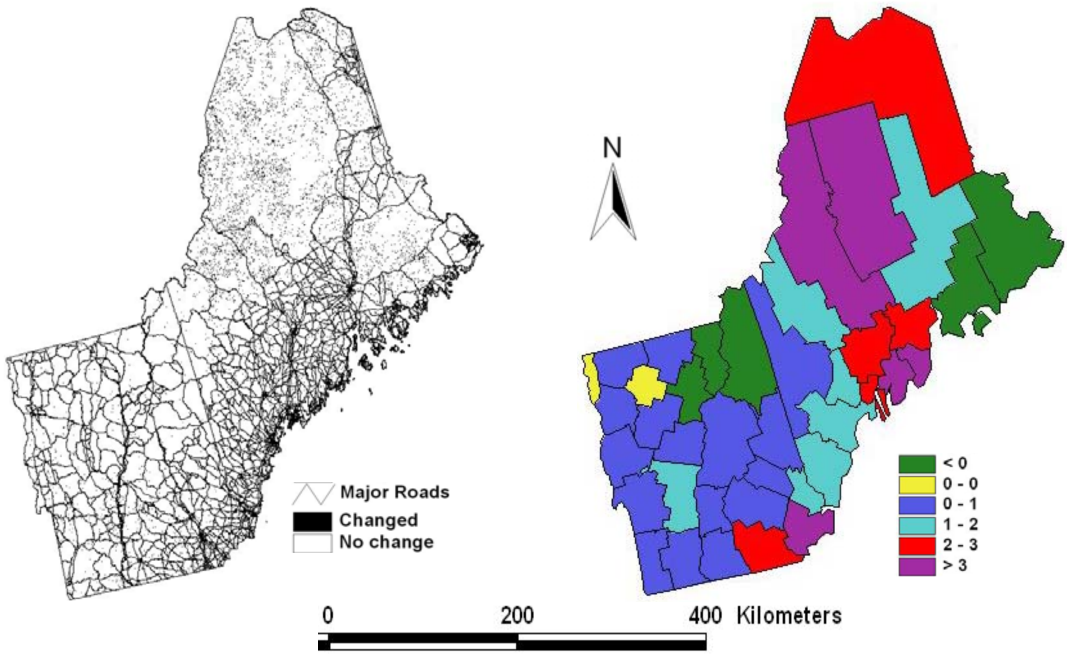

Figure 2. - Relationship of spatial distributions of the lands experiencing changes from one type to another (92-01) and the major roads distributions across the region.

Figure 3. - Spatial pattern of regional forest area changes (92-01) in percentage (%, round to a whole number) at county level. Negative percentages (< 0) indicated gains in forest area.

In terms of C loss due to deforestation, 8 of the top 10 counties were located in ME. The remaining two counties were in southeastern NH where a greater rate of urbanization occurred. For example, areas used for urbanization and development in Rockingham County, NH, accounted for 18.9 percent of its total land area in 2001 compared to that of 4.5 percent for the region according to the Retrofit change product. From the afforestation perspective, 8 of the top 10 counties were located in ME and the remaining two in NH. Only three of the five counties with net forest gains during the 9-year period (Fig. 3) were in the top 10 carbon-sink-county list (Table 2) because 1) all the net gains in area were relatively small; and 2) carbon density for young trees (afforestation) was much smaller than the carbon density in mature forests lost to deforestation.

At the state level, ME had the leading numbers in all categories, both in area and C status: forest gained, lost, and forest land remaining forest land (Table 5) because of its much larger size of forest land than those in the other two states. Maine accounted for 60.1 percent of total regional sequestered C during the 9-year period, followed by 20.4 percent for NH and 19.5 percent for VT.

Table 4. - State-level comparison of forest area changes (km^2) between FIA and NLCD Retrofit change product based calculations in Maine (ME), New Hampshire (NH), and Vermont (VT): 1992-2001.

State	FIA	NLCD
ME	-1388	-1723
NH	-631	-168
VT	1997	-114
Total	-22	-2005[a]

[a] County level based summary.

Table 5. - State-level statistics of forest area change and carbon (C) dynamics during a 9-year period (1992-2001) in Maine (ME), New Hampshire (NH), and Vermont (VT). Sums may not match exactly due to rounding.

State	Area Status (km^2)			C Status (1000 ton)			C Sum
	Gained	Lost	Remain	Gained[a]	Lost[b]	Remain[c]	
ME	936	2659	57109	1207	21658	97927	77475
NH	78	246	18645	99	2744	28911	26268
VT	47	161	17761	61	1800	26859	25118

See Table 2 for [a], [b], and [c].

Conclusions

This study illustrates an approach to associate carbon changes with specific categories of cover-type changes. Our results could be used as a reference for monitoring future emissions of CO_2 and forest removals in the region. Spatial patterns identified from this study can provide useful information for improving our existing forest management strategies related to where and how much carbon could be enhanced or reduced. Future management strategies might also need to consider the effects of forest accessibility on greenhouse gas emissions. Our method is simple and straightforward because we used a consistent national land cover change product. Current limitations of this study are that it included neither estimates of carbon in harvested wood products, nor carbon changes from the soil pool. Although further coordination and integrity between field observations and remotely sensed information are needed to reduce potential uncertainties, this spatially explicit approach provides a way to associate changes in carbon with land-cover categories.

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