

FROM FORESTLAND TO HOUSE LOT:
Carbon Stock Changes and Greenhouse Gas Emissions from Exurban Land
Development in Central New Hampshire

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B.A., Middlebury College 1997

Thesis

Submitted in partial fulfillment of the requirements for the
Degree of Master of Arts in the Center for Environmental Studies at
Brown University

PROVIDENCE, RHODE ISLAND
MAY 2006

This thesis by Adam Cory Wienert is accepted in its present form
by the Center for Environmental Studies as satisfying the
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Acknowledgements

My thesis would not have been possible without the support and guidance of my advisor, Steve Hamburg. He is the other half of the “we” I refer to throughout the manuscript, and I feel very fortunate to have had the opportunity to work with him on this and other projects during my time at Brown. I would also like to thank my readers Neil Sampson and Skee Houghton for their interest in and encouragement of my work during the final editing stages. Finally, I must thank my beautiful and wonderful partner, Maya, for her support throughout my two years as a student. It wasn’t always easy, and I wasn’t always kind, but I always knew I could do it with her love and support.

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Abstract

Increasing interest in enhancing terrestrial carbon sequestration to mitigate rising atmospheric CO² levels requires a solid understanding of the terrestrial carbon cycle and how human activities, especially land-use change, impact carbon storage. One of the most important land-use changes in the northeastern United States is exurban expansion, with the conversion of forestlands into low-density housing lots. In order to understand the implications of this changing land-use within one of the strongest carbon sinks in the world – the eastern forest biome of North America – we quantified carbon stock losses due to increasing human disturbance associated with home construction within second-growth forests of central New Hampshire.

We studied the development impacts of 148 house lots using lot characteristics derived from on-site measurements and tax data, in addition to regional ecological data, to construct lot-level carbon budgets. The development of a house lot results, on average, in the loss of nearly 60 Mg C lot⁻¹ over 50 years, with a range of 35 to 94 Mg C. If each of the 6,500 homes built in New Hampshire each year causes this same scale of loss, the total carbon flux from home development equals nearly 8% of the state's total carbon emissions from fossil fuels each year. Policies to reduce sprawl associated with this development should be encouraged to reduce carbon emissions and promote climate-friendly land-use policies that allow for mitigation of rising atmospheric CO² concentrations.

Introduction

Fossil fuel burning and human-induced land-use change has driven the dramatic increase in atmospheric carbon dioxide concentrations over the past 50 years (Keeling and others 1995; Schlamadinger and others 2000). With increasing confidence, scientists believe these elevated concentrations, along with higher levels of other heat-trapping greenhouse gases, are the leading cause of climate change (Houghton and others 2001). If CO₂ levels continue to rise during the next century as predicted, the consequences to fragile ecosystems and the world economy could be devastating (McCarthy and others 2001). There is a need to better understand the global carbon cycle and how it can be managed in order to effectively mitigate climate change and its possible consequences.

In addition to efforts to reduce direct anthropogenic releases of CO₂ by limiting fossil fuel emissions, there is interest in enhancing terrestrial carbon sequestration as a way to slow net carbon accumulation in the atmosphere. Sequestration efforts, however, can conflict with increasing human use of the landscape for activities such as urban expansion and fiber and agricultural production (Foley and others 2005). More study is necessary to understand human land-use change and its influence on terrestrial carbon sequestration, both for fostering climate friendly land-use policy and for facilitating compliance with the Kyoto Protocol or other future carbon reduction programs.

Net terrestrial carbon sequestration in aggrading forests plays an important role in slowing the increasing level of CO₂ in the atmosphere by removing carbon dioxide through photosynthesis and storing net production in forest biomass and soil. The northern-latitude temperate forests of North America, Europe, and Asia sequester vast stores of carbon and are considered a major terrestrial “sink” (Goodale and others 2002).

In the United States, annual terrestrial carbon sequestration offsets approximately 24% of annual CO₂ emissions (USDA Forest Service 2001). The US terrestrial carbon sink is dominated by the presence of second-growth forests on abandoned agricultural land (Compton and Boone 2000), which is most common in the northeastern United States, especially New England.

The history of the New England landscape is one of continuous change. Development of extensive agriculture during European settlement in the 18th and early 19th centuries followed by farm abandonment in the late 19th and early 20th centuries has resulted in second-growth forests dominating what had been a largely non-forested landscape (Foster 1992; Foster and others 1998). By the middle of the 20th century, the forested area of New England returned to levels similar to those of the pre-settlement era (Foster and others 1998). Much of this forest is still aggrading and has further potential for carbon storage if managed with sequestration as a goal (Sampson and Hair 1996). Carbon accumulation, however, will likely be governed by future patterns of land-use (Caspersen and others 2000). One human-induced change increasingly influencing the current New England landscape is low-density home development. Accelerated by increased highway development over the past 30 years, previously isolated areas – those most heavily forested – have seen increasing rates of home development.

Just as thousands of individual decisions made in the late 19th century led to farm abandonment and reforestation of the New England landscape, thousands of small-scale land-use decisions made by developers and private forest owners are fragmenting and deforesting the region (Foster and others 2005). The number of private forest owners in the US and New England is steadily increasing and most land-use decisions are being

made with little thought for the services provided by forests (Sampson and DeCoster 2000), thus threatening the role of these second-growth forests in mitigating climate change.

Nearly 180,000 km² of private forestland is expected to experience substantial increases in housing density by 2030, with the Eastern US facing some of the highest development pressure (Stein and others 2005). The resulting sprawl from this development would result in water quality degradation, ecosystem fragmentation, and loss of biodiversity. The literature that examines sprawl, however, pays no attention to terrestrial carbon stock changes that result from land transformation from forestland to housing lot. As a consequence, the impact of increased land clearing and soil disturbance from home development on New England's terrestrial carbon budget is unknown.

A number of studies recognize the importance of including the human built environment in larger carbon budgets (Nowak and Crane 2002; Jenkins and Riemann 2003; Pouyat and others 2002). We seek to expand on this work by looking at the carbon implications of rural and exurban growth in forested areas of New England. The research reported in this study examines how home development impacts the carbon budget of the forests of central New Hampshire, one of the fastest growing and most heavily forested regions in the country. When choosing which impacts of development to study, we focused solely on changes to terrestrial carbon stocks. We have not included other elements such as long-term storage of carbon in wood products used to construct a home and CO₂ emissions from the creation of building materials and from construction vehicles.

We focused our research in the exurban communities (Theobald 2004) of Campton (20.2 people / km²) and Thornton (15.0 people / km²), two towns in central New Hampshire that have grown substantially since 1970, in part from recreational-driven development. Regional tourism has been made easier by the completion of Interstate 93 (I-93) in the early 1970s, which runs through the center of these towns and provides easy access between central New Hampshire and the Boston Metropolitan region. Population increased in Campton between 1970 and 2000 from 1,170 to 2,720 residents (132% growth) and in Thornton from 590 to 1,950 residents (230% growth) (USCB 2000).

Between 1970 and 2004, Campton grew from approximately 350 to 1,330 single-family homes (280% increase) while Thornton grew from approximately 170 to 1,080 (535% increase), well above the pace of population growth (USCB 1970; NHOEP 2005). Landscape development and deforestation from this growth are quickly transforming some of the most rural counties in New Hampshire and have factored in a decrease of the state's forested area from 87% to 83% between 1983 and 1993, with a further projected decline to 80% by 2020 (SPNHF 2005).

In our study, we ask the following questions: 1) What is the impact of lot-level home development on carbon stocks? and 2) What is the significance of this development on a regional scale? To measure development impacts, we constructed lot-level carbon budgets by measuring carbon stocks (expressed as fluxes) on lots of varying ages post development using the following measurements:

Above Ground Biomass Removal – To prepare a forested lot for development, aboveground biomass (AGB) is removed to create space for the home, open landscape features around it, and connecting road networks (in future, collectively referred to as the

“disturbance area”). We measure carbon loss resulting from tree slash decomposition, biomass burning, and wood product creation processes.

Soil Disturbances – During AGB clearing and later during home construction, light and heavy machinery repeatedly disturbs the soil as a result of harvesting, lot grading, and septic system, road, and house construction. We measure carbon loss due to increased soil respiration from a variety of disturbances that vary in magnitude and geographic extent, while accounting for increases of carbon, such as those from grass growth after soil disturbance.

Lost Sequestration Potential – When a forested lot is developed, the cleared area of the lot and associated road area will not return to a natural state of vegetation. There is little to no return of AGB in the disturbance area as it is typically a managed landscape of lawn and small woody plants, and there is no regrowth of vegetation on paved surfaces. We measure this loss of carbon sequestration potential, defined as the difference between the AGB left standing in the disturbance area during initial clearing and the AGB that would be present in the disturbance and road areas if the lot had remained undeveloped.

Materials and Methods

Site Description

We studied 148 house lots and the carbon stock changes associated with development of these lots in the towns of Campton (135 km²) and Thornton (130 km²), located along the eastern edge of Grafton County (4,535 km²) in central New Hampshire, USA (Figure 1). Both towns abut southern portions of the White Mountain National Forest (WMNF) and lie just to the southeast of the Hubbard Brook Experimental Forest. Campton and Thornton are approximately 110 km northwest of the Atlantic Ocean and 200 km north of Boston, Massachusetts.

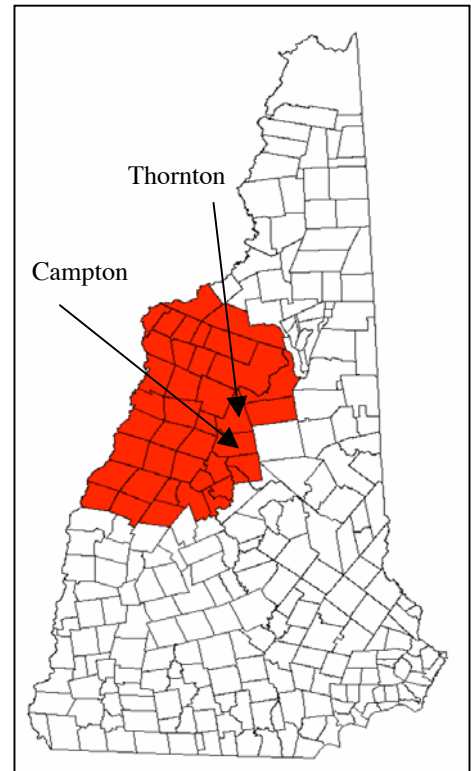


Figure 1 - Grafton County, New Hampshire

Annual precipitation in eastern Grafton County averages 140 cm, of which about one third to one quarter is snow. Winters are long and cold, with an average January temperature of -9°C. Summers are generally short and cool, with an average July temperature of 18°C. The average number of days without killing frost is approximately 145. Soils in our study area are predominantly well-drained Spodosols, derived from glacial till, with sandy loam textures (HBES). Elevations range from 160 m along the valley of the Pemigewasset River to nearly 800 m in the mountainous areas of the two towns.

The house lots we measured in Campton and Thornton represent the range of ages,

lot sizes, physical landscapes, and development styles (subdivisions versus large lot single-family homes) in numbers proportional to the distribution of lots with respect to each of these variables. We limited our analysis to lots less than 2 hectares in size and developed after 1970 to best represent current building trends in the area.

Carbon Budget Data Sources

AGB Calculations

To determine carbon released from clearing of AGB during lot development and to quantify the loss of carbon sequestration potential, we must estimate forest biomass both at the time of initial clearing and 50 years into the future. We assume that a lot is developed when the age of the forest is 70 years old – the average forest age in the study region – and estimate the characteristics of the forest at age 120, assuming no disturbances.

To estimate AGB of the forest at age 70, we used the biomass of 11 plots in the WMNF region between 60 and 80 years old (Hamburg 1984; Siccama unpublished; Leak and Smith 1996). Plots are located in Campton, the Hubbard Brook Experimental Forest (Woodstock, NH), and the Bartlett Experimental Forest (Bartlett, NH). Biomass for the Hubbard Brook plots was calculated using both allometric equations and direct measurements (Arthur and others 2001). The mean AGB for these plots is 160 ± 19 Mg/ha. The average plot age is approximately 70 years old.

To estimate AGB of the forest at age 120, we used biomass calculations from 15 plots between 110 and 140 years old, also in the WMNF region (Rhoads unpublished). All plots are former pastures and are located in the towns of Campton, Warren, Landaff,

Easton, Benton, and Sandwich, New Hampshire. The mean AGB for these plots is 220 ± 27 Mg/ha. The average plot age is approximately 125 years old.

Although much of the AGB in the disturbance area of a lot is removed during initial clearing, some trees may be left for landscaping and aesthetic purposes. To estimate the growth of this remaining biomass 50 years into the future – used in the calculation of lost sequestration potential – we first measured diameter at breast height (DBH) for each tree in the disturbance area greater than 10 cm in diameter. DBH was then converted to AGB using species-specific allometric equations (Jenkins and others 2003). Lastly, we multiplied the remaining AGB by a factor of 3, 3.5, and 4 to estimate future growth of this biomass under different loss scenarios. These factors were not determined by direct measurement, but were assumed to be reasonable estimates of growth rates.

To determine carbon content for all AGB measurements used in our budget, we assume carbon content to be 50% of total mass (Hamburg and others 1997).

Soil Carbon Calculation

To quantify soil carbon stocks and measure baseline carbon concentrations from which we could calculate flux, we collected soil cores at seven house lots in our study area with 3.1 cm diameter twist auger, sampling to the C layer (60 – 75 cm). We collected O, Ap, E, and B layer samples, recorded layer depth, and stored each layer separately for chemical analysis. At each site, we took one reference core in an undisturbed location – a forested area or the most remote area of the site – and one to three cores in the disturbance area around the home.

In the lab, we air-dried all samples at room temperature for 72 hours. We sieved each sample to 2 mm and redried the sample at 105°C for three days. We pulverized the samples in a SPEX 5300 mixer mill and stored them in a desiccator until ready for chemical analysis. Carbon concentrations were determined using a Carlo Erba NC2100 model C/N analyzer (Carlo Erba Instruments, Milan, Italy). Acetanilide, Cyclohexane, Mag1, and Montana Soil were used as reference material. 90 soil samples from the seven lots were analyzed. Analyzer results were paired with O ($0.19 \pm 0.06 \text{ g/cm}^3$), Ap ($0.83 \pm 0.07 \text{ g/cm}^3$), and B ($1.03 \pm 0.09 \text{ g/cm}^3$) layer bulk density calculations from similar Spodosol soil profiles from Campton (Hamburg unpublished (a)).

We compared our baseline soil carbon concentration results with soil carbon concentrations from 14 forested sites in the WMNF region that we assume to be similar to the pre-development landscapes of our house lots (Hamburg unpublished (b)). Sites range in age from 14 to 200 years old with a mean age of 61. Three full quantitative pits were taken at each of the 14 sites. We disregarded carbon in the C horizon of these pits to make the profiles consistent with our samples and then averaged the total carbon present. The mean carbon concentration for the 14 sites is $12 \pm 7 \text{ kg C/m}^2$.

Inferred Flux Rates

We assume a net loss of $60\% \pm 20\%$ of the carbon from soils removed to build the foundation. Our assumption is greater than a 30 - 40% carbon loss assumed for cultivated soils (Davidson and Ackerman 1993) because of the deeper intrusion into the soil profile and the time the soil may be exposed to sun and air during construction.

We assume a $50\% \pm 10\%$ loss of carbon from soils disturbed as part of the construction of the septic system. We estimate trench digging – the greatest area of septic system disturbance – is more disruptive than plowing, which we again assume to release approximately 30 - 40% of stored carbon. Because the area above the septic system remains clear of significant biomass in order to avoid root damage, return of soil carbon is projected to be minimal.

We assume a $35\% \pm 15\%$ respiration rate during road construction from soil disturbance approximately 10 cm deep. Although the depth is relatively shallow, this disturbance affects carbon-rich material in a second-growth forest, and because this material is almost always scraped away, there is a very rapid release of carbon into the atmosphere. After initial disturbance, a layer of asphalt caps the remaining carbon in the deeper profile underground, reducing the rate of decomposition.

The loss of carbon from AGB removal is assumed to be $85\% \pm 10\%$ over 50 years. We based this rate on a study of product flow in the Tongass National Forest (Leighty and others in press). Because site clearing in our study region is generally done on a very small scale through non-commercial operations, we decreased harvested material turned into sawtimber from 30% to 10%, which increases our flux rate due to AGB removal and the amount of carbon released to the atmosphere over time.

We used the analysis of our soil core data to determine respiration rates within the disturbance area. The difference between soils that were disturbed during clearing and soils on the same lot that were undisturbed during development showed an approximate 40% lower carbon level in the disturbance area after 50 years. From this result, we assume a 40% \pm 15% respiration rate. (See further discussion in the Results section).

House Lot Characteristics

To calculate the road area associated with a lot, we assume a road width of 9 m and a road frontage of 60 m, a minimum town requirement. We also assume each lot shares the road with a neighboring lot across the street, halving the overall width “charged” to the lot. These assumptions produce an average road area of 280 \pm 70 m².

The size of an individual septic system varies widely based on house size, slope, and soil conditions. The New Hampshire Department of Environmental Services (NHDES) describes systems ranging between 45 and 165 m². We believe an average home system would be in the lower end of this range and assume an area of 65 \pm 20 m².

To calculate foundation size, we took the “Effective Building Area” entry in the towns’ tax databases and divided by 1.5 to estimate the area of the largest floor (City of Fort Bragg). We added 15 m² to the result with the assumption that approximately 2 m on each side of the ultimate foundation is excavated and thus disturbed. The statistical average calculated from our 148 lots is presented in the Results section.

To quantify average lot disturbance area, we took in situ measurements using a Dell X50 handheld computer running ESRI’s ArcPad 6 software with an attached TeleType GPS receiver. At each house lot, data points were collected around the

perimeter of what was determined to be the initial cleared area. These data points were downloaded into ESRI's ArcGIS 9 software package and polygons representing the disturbance area of each lot were created and their size was calculated using the Area Calculator function in ArcGIS 9. The statistical average of this characteristic is presented in the Results section.

Statistical Analysis

We used STATA/SE 9.0 to run all summary statistics, confidence intervals, regression analysis, tests of significance, and distribution calculations. We used Microsoft Excel to obtain regression line slope calculations.

Results

House Lot Characteristics

The mean disturbance area of our 148 lots is $0.24 \pm .03$ hectares. A histogram of the disturbance area distribution in .05-hectare increments is shown in Figure 2. The smallest disturbance area measured was .03 hectares, while the largest disturbance was 1.74 hectares.

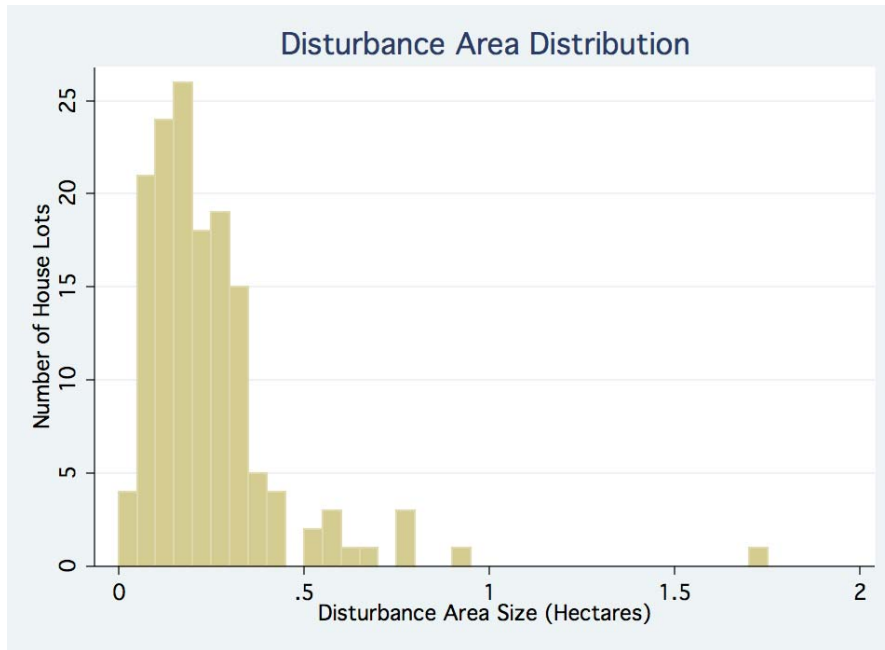


Figure 2 – Histogram showing the distribution of disturbance area measurements

On average $36\% \pm 20\%$ of each lot was disturbed during initial development. The wide range of this result is due to the high variability in the relationship between disturbance area and lot size (Average lot size is $0.7 \pm .06$ hectares with a minimum of .06 ha and a maximum of 2.09 ha). Figure 3 shows disturbance area plotted against lot size and suggests that a three-fold increase in lot size will lead to a doubling of disturbance area size, though variability increases with lot size greater than one hectare.

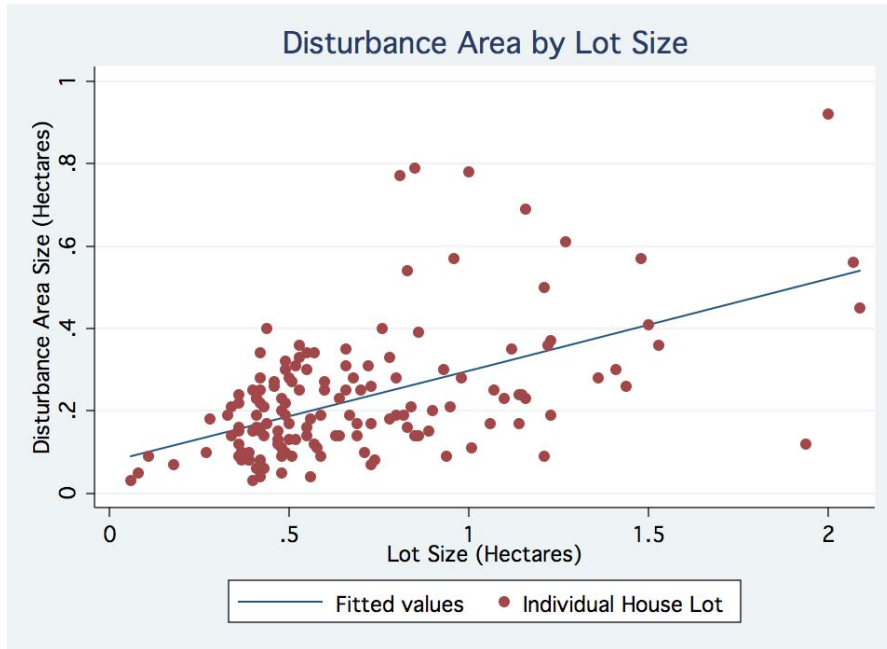


Figure 3 – Lot disturbance area size plotted against total lot size in hectares with added regression line
 R^2 value = .315; $y = .2225x + .1864$; $p < .001$

For all 148 lots, mean AGB left in the disturbance area is 3 ± 1 Mg/ha, with a minimum of 0 and a maximum of 43 Mg/ha (Figure 4). 52% of our lots ($n = 77$) had some AGB in the disturbance area while the disturbance areas of the remaining lots were completely cleared. 35% of the lots were developed between 0 – 10 years ago, 25% between 10 – 20 years ago, and 40% between 20 – 35 years ago, with development occurring an average of 15 years ago.

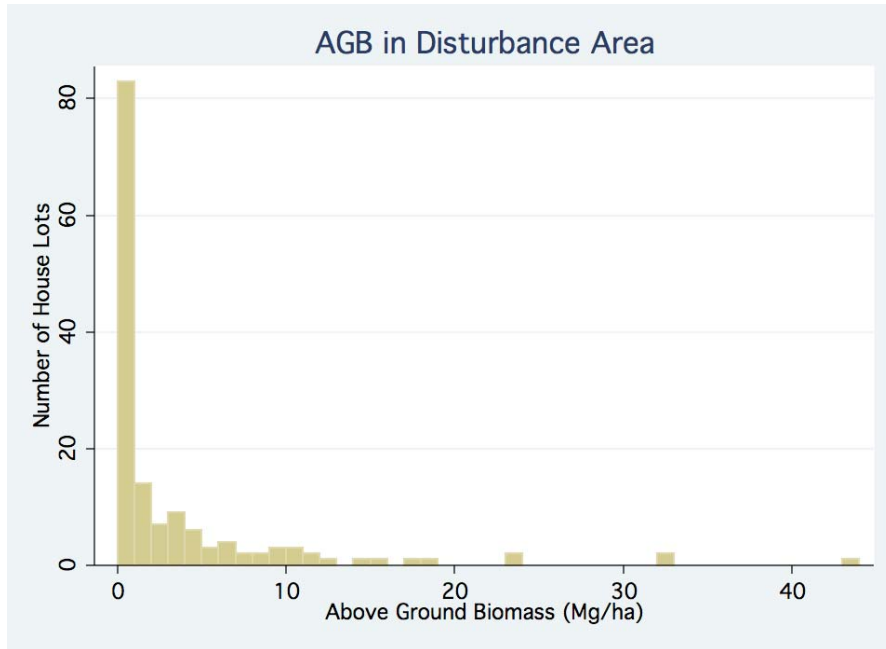


Figure 4 – Histogram showing the distribution of AGB measurements
 NOTE: Lots with no AGB in the disturbance area are included in the 0 – 1 Mg/ha distribution

The mean foundation footprint size is $127 \pm 9 \text{ m}^2$ with a minimum of 31 m^2 and a maximum of 380 m^2 (Figure 5).

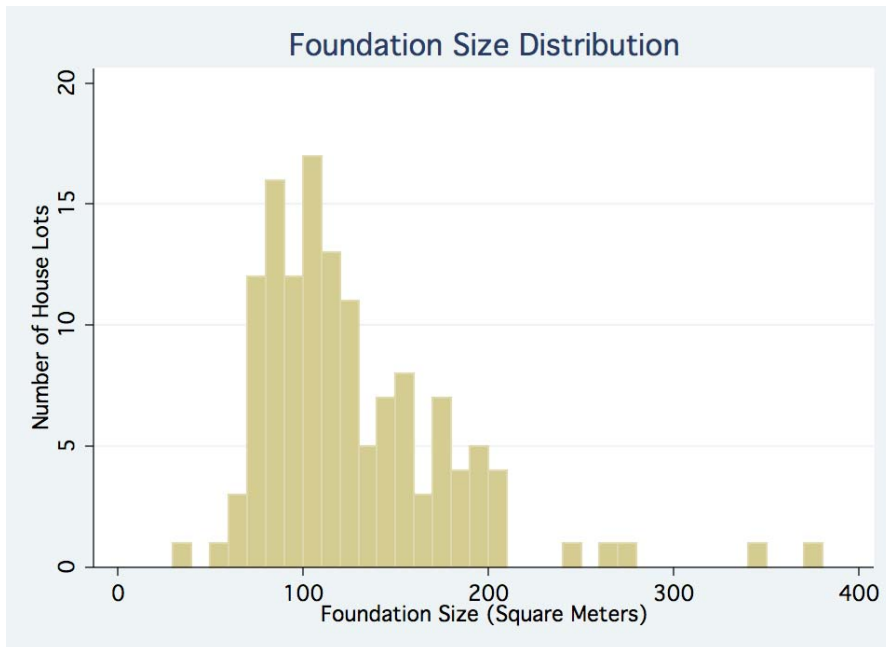


Figure 5 – Histogram showing the distribution of foundation size.

Soil Samples

The mean soil carbon concentration for the seven reference cores we collected is $12 \pm 7 \text{ kgC/m}^2$. Average O layer content was 2 kgC/m^2 , average Ap layer content was 4 kgC/m^2 , and average B layer content was 6 kgC/m^2 . Results for one of our seven sites lies outside of the 95% confidence interval ($5 - 19 \text{ kgC/m}^2$) of the 14 WMNF sites. This outlier (29 kgC/m^2) is a dense pine stand with very high carbon content in the O and B layers. Our reference core results match the range of the more extensive pits analyzed in the WMNF (Hamburg unpublished (b)).

Disturbance Area Carbon Loss

The difference between reference core carbon concentrations and the average of the cores taken within the disturbance area shows a chronosequence of carbon stock loss and recovery over time (Figure 6). Average decline in soil stocks within disturbance areas of varying ages (in comparison to the reference locations) suggest that there is 74% (n=2) less carbon during the first 0 – 20 years, 59% (n=4) less carbon at 20 – 40 years, and 25% (n=1) less during years 40 – 60. Soil carbon content at age 50 is approximately 35% below the reference core's carbon concentration. We rounded this loss up to 40% to account for assumed heavier disturbances today than those 50 years ago and used it as our assumed disturbance area flux rate.

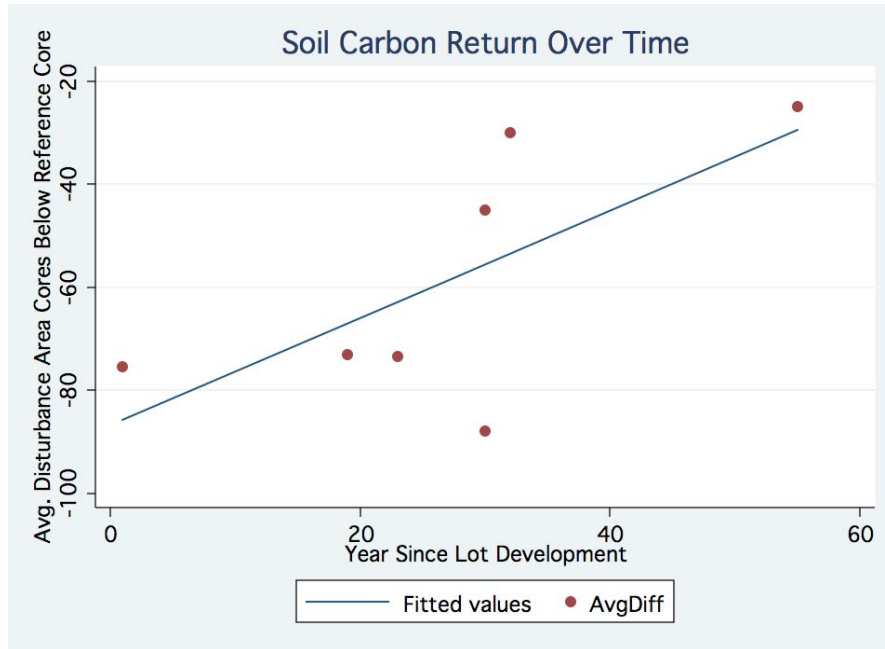


Figure 6 – Soil Carbon Return Over Time. Each data point represents the average of one to three cores taken at each lot in the disturbance area compared to the carbon concentration of the reference core (0%)
 $R^2 = 0.464$; $y = 1.0428x - 86.875$; $p = .09$

House Lot Budget

Using the mean value for our inputs of inferred flux rates, baseline ecological data, and house lot statistics, an average house lot development results in the net loss of 59 Mg C during the 50 years post construction initiation, compared with no development (Table 1). We calculate that 13 tons (22%) are released through carbon respiration due to soil disturbance, 18 tons (31%) of carbon are released through processes associated with AGB clearance, and 28 tons (47%) of carbon dioxide in the atmosphere will not be stored on-site as AGB in the disturbance and road areas.

	Cause of Disturbance	Inferred Flux Rate	Carbon Stock Loss over 50 years
Soil Carbon Flux			
	Footprint	60%	1 Mg C
	Leach Field	50%	1 Mg C
	Road Area	35%	1 Mg C
	Disturbance Area	40%	10 Mg C
	Total		13 Mg C
AGB Removal			
	Road	85%	2 Mg C
	Disturbance Area	85%	16 Mg C
	Total		18 Mg C
Lost Sequestration Potential			
	Road		3 Mg C
	Disturbance Area		25 Mg C
	Total		28 Mg C
Complete Lot	Total		59 Mg C

Table 1 – Mean lot level carbon budget

The low-flux scenario uses the lower bound of the 95% confidence interval or lowest assumed range for all input variables and estimates a net loss of 35 Mg C over 50 years. The high-flux scenario uses the upper bound of the 95% confidence interval or highest assumed range for all input variables and estimates a net loss of 94 Mg C over 50 years. The large range between the two values suggested by these scenarios is due to the assumption that every input variable for each calculation in the budget is the extreme low value in the low-flux scenario and the extreme high value in the high-flux scenario.

Discussion

House Lot Budget Results

Results of the mean house-lot carbon budget suggest that the construction of a single home has significant impacts on the landscape's carbon stocks. Of the 49 Mg C that we assume are present in the AGB (19 Mg C) and soil (30 Mg C) of an average disturbance area (.24 hectares) at the time of house lot development, 61% (30 Mg C) is released into the atmosphere over the 50 years following construction. In addition, the area of the lot cleared of AGB is unable to sequester approximately 28 Mg C that would have been stored if left to continue to grow. The three components in our budget that have the most influence on carbon flux are carbon respiration in the disturbance area, CO² emissions from the AGB that is harvested, and the cleared area's lost potential to sequester additional AGB in the future.

Disturbance Area Carbon Loss

Our analysis of soil carbon content in the disturbance area suggests forest clearing and home construction activities cause a large initial flux of carbon at the time of development. This heavy initial loss is in contrast to the idea that development activities create a disturbance that releases carbon slowly over a period of decades after development before levels begin to increase. Because home developers often must level a lot to create a flat area for construction, we believe it is reasonable to assume that a large percentage of the sequestered soil carbon is blown off through the scraping away of carbon-rich topsoil during tree removal and construction.

The regression line fit to our seven sites suggests the return of soil carbon to pre-development levels will take more than 80 years. A low level of carbon inputs coming from minimal vegetation growth, such as grass and decorative woody plants, would cause carbon return to be much slower than in a regrowing forest. We believe, however, that recovery will likely take at least 100 years, longer than the regression line suggests, because the data points in our analysis do not represent a true chronosequence. Disturbances during lot clearing and construction 60 years ago would likely have been much lighter than disturbances today. Today's more powerful earth moving equipment is able to clear areas that may have been left forested in the past, and larger-scale subdivision development that affects multiple lots at once may also lead to heavier soil disturbances during clearing. Additionally, our regression analysis assumes a linear function; whereas it is more likely that the rate of carbon return will slow and begin to plateau as it approaches pre-development levels.

Studies examining soil carbon loss over time after timber harvest generally conclude that there is no measurable long-term loss (Johnson and Curtis 2001). Many of these studies, however, quantify the return of soil carbon in an environment initially less disturbed than landscapes subject to the effects of house construction and that is left to naturally regrow. Without the return of substantial AGB in these developed landscapes, inputs of carbon to soil will be far less than in an aggrading forest, thus greatly lengthening the time of carbon recovery to pre-clearing levels.

Studies examining nitrogen fertilization effects on soil carbon (Qian and Follett 2002; Schlesinger 2000) suggest that fertilization can increase carbon sequestration rates. Because 30 – 40% of the homes in our study area are second homes, which do not

generally receive intensive lawn care, as well as the exurban characteristics of these communities that don't promote the desire to grow lush, green lawns, we do not believe fertilization is a strong factor to consider for soil carbon return in the disturbance area.

AGB Carbon Loss

When house lots are prepared for development in our study area, independent loggers, with limited ability to market the stumpage for timber, typically clear the AGB. Thus, we assume more biomass is left on-site as slash and less wood ends up in the sawtimber stream where it has the best chance to be stored in long-term products. Most of the tree biomass removed during the development of sites we visited was sold as firewood or burned as biomass fuel. This quick release of CO₂ from burning along with higher slash levels and less material going to the long-term stream leads to an estimate that over 16 of the 19 Mg C removed from a typical disturbance area is released back into the atmosphere within 50 years of clearing.

Lost Sequestration Potential

In all three scenarios of our lot-level budget, the loss of sequestration potential accounts for the largest flux over time. After the disturbance area of the lot is cleared, this portion of the lot will not naturally regrow back to forest, a process which was vital to the creation of the New England carbon sink after farm abandonment over 100 years ago. As more and more homes are built on the landscape each year that are unlikely to be abandoned and support aggrading forests in the future, this new pattern of land-use change will likely have long-lasting carbon stock implications well into the 21st century.

Scaling Up the Budget

Approximately 6,500 single-family homes have been built each year in New Hampshire during the first five years of the 21st century (NHOEP 2005). Estimating a loss of 35 to 94 Mg C over a 50-year period for each one of these homes, the total loss of carbon due to yearly home construction is between 227,500 and 611,000 Mg. Our mean scenario predicts a loss of 383,500 Mg C or 1,410,000 Mg of CO₂ equivalent (MGCDE). This loss is equal to approximately 8% of the net 18 million MGCDE released from fossil fuels yearly by New Hampshire (NHDES 2001). Because the carbon loss from home development suggested by our study is not listed as an itemized part of the larger state carbon emissions budget, it is important to understand how land-use change used in state budget calculations represents the carbon loss from home development we are examining in our study.

Inclusion in Larger Budgets

Because many of our house lots are located in areas where the Forest Service actively studies the landscape through Forest Inventory and Analysis (FIA) data points, we assume that some of the landscape changes we have detailed are also included in budgets that use FIA data points to quantify land-use change, including the New Hampshire carbon emissions budget. There are, however, elements of the current FIA system that may lead to exclusion of some of the carbon stock change we have detailed.

Many of the studies that attempt to quantify large-scale carbon budgets use remote sensing techniques to assist in the analysis of land cover and to quantify change over time. Land-use change in rural and exurban communities is less likely to be

detected by using these methodologies (Ward and others 2000), although these techniques can be successful (Tyrrell and others 2004). As we have detailed, a house lot development in the forests of New Hampshire can heavily disturb a small piece of land, releasing dozens of Mg C into the atmosphere. This same area, however, could seem forested and unchanged through use of aerial photography or satellite imagery alone, and may lead to the belief that the landscape is in fact sequestering carbon, not releasing carbon as our budget shows.

In contrast to the possible exclusion of lot-level changes due to the use of remote sensing, land-use change that is observed and quantified through FIA data points is likely overestimating carbon flux by focusing on net land-use change, which assumes all stored carbon is lost if land changes from “forest” to “developed”. Because of the likely underestimation of land-use change occurring in rural and exurban regions, but the overestimation of carbon loss from the change that is recorded, it is difficult to say how much of the net carbon flux detailed as part of our average house lot development is ultimately reported in larger budgets.

Conclusion

As pressure on New England's private forestland continues during the next several decades, it is important to further our knowledge of lot-level carbon impacts and integrate them into regional planning that values the role of the forests as a carbon sink. Concepts such as cluster development, which allows for development to continue while reducing road area and increasing common open space, could minimize disturbance area size on lots and allow for greater carbon sequestration over time. If carbon-trading markets continue to develop and if the science of land-use change can more precisely quantify carbon loss from development, could reducing disturbance become a marketable, tradable commodity that mitigates terrestrial carbon sequestration loss?

We believe an analysis of lot-level carbon stock change is essential to understanding the future of New England forests and human impacts on carbon sequestration patterns. Our study suggests there are significant carbon stock changes occurring due to increases in home development rates in New Hampshire. This kind of development is not unique to the state and will pressure private forestland throughout New England (Stein and others 2005) in the decades ahead. Without regional thinking or incentive programs designed to manage landscapes for carbon storage, increased development will continue to reduce the capabilities of the region to mitigate the rising CO₂ concentrations in the atmosphere.

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