Ecological Applications

Running Head: Carbon storage and forest management

February 11, 2009

Forest carbon storage in the northeastern United States: effects of harvesting frequency and intensity including wood products

Jared S. Nunery[1*]

William S. Keeton[1]

[1] 343 Aiken Center

Rubenstein School of Environment and Natural Resources

University of Vermont

Aiken Center,

Burlington, VT 05405

[*]Corresponding author: email: jnunery@uvm.edu

Phone: (207) 712 - 4406

ABSTRACT

Temperate forests are an important carbon sink, yet there is debate regarding the net effect of forest management practices on carbon storage. Few studies have investigated the effects of different silvicultural systems, and the relative strength of in-situ forest carbon versus wood products pools remains in question. Our research (1) describes the impact of harvesting frequency and degree of post-harvest structural retention on carbon storage in northern hardwood-conifer forests, and (2) tests the significance of including harvested wood products in carbon accounting at the stand scale. We stratified Forest Inventory and Analysis (FIA) plots to control for environmental, forest structural, and compositional variables, resulting in 32 FIA plots distributed throughout the northeastern US. We used the USDA Forest Vegetation Simulator to project stand development over a 160 year period under nine different forest management scenarios. Simulated treatments represented a gradient of increasing structural retention and decreasing harvesting frequencies and included a "no harvest" scenario. The simulations incorporated carbon flux between aboveground forest biomass (dead and live pools) and harvested wood products (including carbon storage in landfills). Mean carbon storage over the simulation period, including carbon stored in harvested wood products, was calculated for each silvicultural scenario. We investigated tradeoffs among scenarios using a factorial treatment design and two-way ANOVA. The predictive strength of management scenarios relative to site-specific variables was evaluated using Classification and Regression Trees. Mean carbon sequestration was significantly (a = 0.05) greater for "no management" compared to any of the active management scenarios. Of the harvest treatments, those favoring high levels of structural retention and decreased harvesting frequency stored the greatest amounts of carbon. In order to isolate the effect of in-situ forest carbon storage and harvested wood products, we did

not include the emissions benefits associated with substituting wood fiber for other construction materials or energy sources. Our results show that harvesting frequency and structural retention significantly affect mean carbon storage. Results from this study illustrate the importance of both post-harvest forest structure and harvesting frequency in carbon storage, and are valuable to land owners interested in managing forests for carbon sequestration.

Key Words: Carbon, sequestration, uptake rates, wood products, structural retention, harvesting frequency

INTRODUCTION

While deforestation accounts for 20 to 30% of total global CO_2 emissions, due primarily to tropical deforestation (IPCC 2007), forests in United States forests are currently a carbon (C) sink (Goodale et al. 2002), sequestering approximately 10% of US annual CO_2 emissions (Birdsey et al. 2006). Recognizing the important role forests play in the terrestrial C cycle and climate change mitigation efforts, developing cap and trade C markets are considering inclusion of sustainable forest management as an option for slowing rates of atmospheric CO2 accumulation (Alig and Bair 2006, Canadell and Raupach 2008, Ray et al. 2009). The working hypothesis is that “improved forest management” could achieve higher levels of C storage compared to “business as usual” or a baseline condition (Ruddell et al. 2007). While forest management clearly impacts terrestrial C storage (Birdsey et al. 2007), little information is available describing how specific forest management alternatives might affect C storage and sequestration. Yet this understanding is vital, because the dynamics of storage and fluxes among the different sinks impacted by management (e.g. forest C versus wood products) are complex, rendering accounting of net effects on C storage very challenging (Birdsey et al. 2006, Ray et al. 2009). The purpose of this study is to inform forest C management using empirical data coupled with forest stand development modeling. In particular, we investigate the impact of harvested wood products in the accounting of net C sequestration in managed forests in the northeastern US.

Some researchers have suggested that sustainably managed forests sequester more C than unmanaged forests, stressing the high tree growth rates achieved in harvested stands (Ruddell et al. 2007), and C stored in wood products (Malmsheimer et al. 2008b). However, other studies have demonstrated that unmanaged forests, such as old-growth forests in the US Pacific Northwest, sequester greater amounts of C than managed forests (Krankina and Harmon 1994, Harmon and Marks 2002). These authors have argued that intensified forest management actually leads to a net flux of C to the atmosphere due to lower biomass in harvested stands and the often short lifespan of wood products. However, these conclusions are based primarily on studies involving conversion of old-growth forest to young plantations (Harmon et al. 1990) and the effects of intensive harvesting practices, such as clearcutting (Krankina and Harmon 1994). Net effects on C dynamics across a range of silvicultural systems, including modified even-aged and less intensive uneven-aged practices, remain poorly explored and thus are a focus of this paper. In addition, we believe this is the first such study pertaining to northern hardwood-conifer ecosystems in particular.

Recently interest has developed in the use of “extended rotations” (Curtis 1997) and post-harvest structural retention (Franklin et al. 1997, Keeton 2006) as approaches favoring maintenance and development of high levels of in-situ forest C storage. However, efforts to analyze the effects of extended rotation were restricted to even-age forest management (Liski et al. 2001, Harmon and Marks 2002, Balboa-Murias et al. 2006). Each of these studies did not address the coupled effects of variations in harvesting frequency and post-harvest structural retention in uneven-age and even-age forests. Decreased harvesting frequency is correlated with increased C sequestration (Liski et al. 2001, Balboa-Murias et al. 2006); however, the increased total C storage as a result of decreased harvesting frequency is less than C storage in unmanaged forests, even when natural disturbance is accounted for (Krankina and Harmon 1994). Conversely, the inclusion of C stored in durable, long-lived wood products in C accounting increases net C storage in intensively managed forests where more biomass is being allocated to post-harvest wood products rather than being stored in the forest (Perez-Garcia et al. 2005b). In this study we explore C sequestration tradeoffs among harvesting frequency and structural retention in both even and uneven-age forests, while also incorporating fluxes to wood products.

We address a fundamental research question facing forest managers, namely: what is the most effective way to store C through forest management? Is effectiveness greater in more intensive approaches favoring high rates of update and C transfer to wood products? Or are less intensive approaches, favoring in-situ forest C storage, more effective at maximizing C storage? We test two key variables with the potential to effect forest C sequestration: 1) harvesting frequency (rotation length in even-aged silviculture and entry cycle in uneven-aged silviculture), and 2) post-harvest structural retention.

In order to isolate the effect of in-situ forest C storage and harvested wood products, we did not include the emissions benefits associated with substituting wood fiber for other construction materials (Perez-Garcia et al. 2005a, Perez-Garcia et al. 2005b, Szabó et al. 2006) or energy sources (Malmsheimer et al. 2008a). Accounting for these emissions offsets can significantly change the net C effect of forest management (Hennigar et al. 2008), especially considering the potential for reduced availability of wood products associated with decreased harvesting (Ray et al. 2009). Comprehensive life-cycle analyses show that the substitution of steel and concrete with wood products decreases emissions of CO_2 to the atmosphere, due to the energy intensive manufacturing processes of concrete and steel (Lippke et al. 2004). However, uncertainties in transportation related emissions and methane emissions attributable to decomposition of forest products in landfills, make the incorporation of substitutive effects associated with life-cycle analyses unreliable and difficult (Miner and Perez-Garcia 2007). Studies focusing on the substitutive benefits associated with wood products suggest that if the sole goal of forest management is to sequester C (and not to restrict C storage to forest C pools), both short-rotation intensive management and long-rotation less intensive management can be equivalent under certain conditions (Malmsheimer et al. 2008b). However, these conclusions are not based on analysis across a spectrum (encompassing both uneven-aged and even-aged silviculture) of forest management scenarios, but rather rely heavily on a synthesis of studies focused on uncertain wood product life-cycle assessments. Moreover, C markets currently award credits only for C stored in the forest and in wood products due to the complexities involved with broader energy accounting (Ruddell et al. 2007). Consequently for the purpose of this study, we define C sequestration as the total C stored in both aboveground forest biomass (live and dead) and the entire life-cycle of harvested wood products; sequestration thus relates not just to uptake rates but also storage.

Quantifying C storage necessitates a temporal scale of a minimum of one complete harvesting cycle, in order to obtain accurate and realistic results. For this reason, simulation modeling is often used as a means for quantifying C sequestration in forested ecosystems. Numerous process-based, empirical, and hybrid (combination of process-based and empirical) models have been developed to project forest C dynamics at a variety of scales. Examples include the European CO_2Fix model (Masera et al. 2003), the Pacific Northwest US models STANDCARB (Harmon and Marks 2002) and HARVEST (Harmon et al. 1996), the process-based FOREST-BGC (Running 1994), the northeast process-based model PnET (Aber and Federer 1992), and empirically based NE-TWIGS (Hilt and Teck 1989). While absolute predictions generated by empirical and hybrid models can be subject to a high degree of uncertainty, they are useful for comparing relative differences among alternate management and forest development scenarios (Zenner 2000, Eriksson et al. 2007, Seidl et al. 2007). These models represent a variety of empirical and mechanistic approaches; however in this study we employ another model in order to address all of our research questions with the use of one model. In this study, we used the USDA Forest Service's Forest Vegetation Simulator (FVS, Dixon 2002), a model derived from the Prognosis Model for Stand Development (Stage 1973). FVS has the ability to simultaneously simulate stand development in multiple biomes, model at multiple scales, model silvicultural treatments in uneven-aged mixed species composition forests, and incorporate C stored in wood products from timber harvests. In addition FVS is one of several simulation models identified by North American voluntary C markets for estimating C sequestration in managed forests as a part of climate change mitigation projects.

Our primary research objective was to inform forest C management by testing two hypotheses. The first hypothesis was that even with the inclusion of C storage in durable wood products in C accounting, unmanaged (passive) forests would sequester greater amounts of C than actively managed forests. Our second hypothesis focused on the effects of management intensity on C sequestration. We hypothesized that silvicultural prescriptions with increased structural retention coupled with decreased harvesting frequency would sequester the greatest amount of C. In order to test these hypotheses, we evaluated a wide spectrum of silvicultural prescriptions (Table 1), spanning nine different even-age and uneven-age forest management scenarios.

METHODS

Study area and selection of study sites

Our study area spanned the northern hardwood region of the northeastern US, encompassing portions of upstate New York, Vermont, New Hampshire, and Maine. The study area is dominated by northern hardwood-conifer forests, in which *Acer saccharum* (sugar maple), *Fagus grandifolia* (American beech), *Tsuga canadensis* (eastern hemlock), and *Betula alleghaniensis* (yellow birch) form the major late-successional species. We used Mapmaker 2.1 (CITATION) to stratify the study area by eco-subregions following (Cleland et al. 1997), and then selected Forest Inventory and Analysis (FIA) plots (or sites) from within these to ensure that our sample was representative and well-distributed (Figure 1.). We used the most recent FIA inventory data available at the time of this study for each state to avoid potential discrepancies among different FIA survey periods (Maine: 2003, New Hampshire: 2005, New York: 2004, Vermont: 2005). We controlled for other sources of variability by further stratifying plots based on several site-specific variables as defined in the FIA database. These included stand age (80-100 years old), slope (0 to 50%), forest type (maple-beech-birch), stand origin ("natural"), site productivity (site class 1-5 out of 7), physiographic class (mesic classes 21-25) basal area (BA > 23 m^2/ha), and total merchantable cubic volume (> 57 m^3). The stratification process resulted in a total of 32 FIA plots meeting these criteria (14 plots in the White Mountain Region and western Maine, 3 plots in the Green Mountain Region, and 15 plots in the Adirondack Mountain

Region); these were selected for further analysis and are hereafter referred to as our “study sites” (Table 2).

Model description

Site specific stand structure and composition data were input into FVS to project stand development under alternate management scenarios. The FVS model has been used by North American forest managers for over 30 years in a variety of applications (Teck et al. 1996, Crookston and Dixon 2005). FVS is effective at simulating forest growth under alternative management scenarios (Crookston and Dixon 2005). FVS is a distant-independent, individual-tree based forest growth model, specifically designed for and applicable to even and uneven-aged stands with simple to mixed species composition (Crookston and Dixon 2005). Aboveground biomass estimates are based on species group-specific allometric equations developed by Jenkins et al. (2003). The temporal scope of model projections ranges from five to several hundred years, with five to ten year resolution. Projections begin with a summary of current stand conditions based on original forest inventory data and then follow a sequential command order (Dixon 2002). Multiple validation studies of various aspects of FVS have proven the model’s accuracy in simulating forest growth in North America at decadal time steps (Robinson and Froese 2004, Froese and Robinson 2007) and in numerous species (Froese and Robinson 2007). Component models (variants) are used to adjust models to reflect specific regional climatic conditions and growth rates. In this study we used Northeast Variant (NE-FVS) for all simulations. NE-FVS uses growth and yield equations from NE-TWIGS (Hilt and Teck 1989), with embedded height equation and bark ratios specific to northeastern species. Regional validation studies of NE-FVS have shown reasonable predictions of forest growth in a variety of species within the region (Bankowski et al. 1996, Yaussy 2000). FVS also has the ability to track C flux in wood products between pools throughout the product life history from production to landfill following methodologies developed by the USDA Forest Service (Smith et al. 2006). To simulate C flux in wood product pools, FVS identifies pulp and sawlogs (Dixon 2002), and applies product-specific life span curves based on recent data specific to North American forest types (Smith et al. 2006).

Silvicultural simulations

In total, we simulated nine different management scenarios, including one passive (i.e. a reserve-based) no management scenario and eight active management scenarios. The latter were representative of silvicultural systems used commonly in the Northeast, but were modified to encompass a range of harvesting intensities. Specific parameters of prescriptions were derived from experience and studies in the Northeast (Seymour 1995, Nyland 1996, 1998). Silvicultrual prescriptions used in this study included four even-age scenarios and four uneven-age scenarios. Within these broad silvicultural groups, individual treatments were derived by factoring two "levels" for each of two categories: harvesting frequency and degree of structural retention (Table 1).

To test the effect of harvesting frequency on C sequestration, the four active management scenarios were run under two different harvesting intervals, one long (120 years for even-age management scenarios, and 30 years for uneven-age management scenarios) and one short (80 years for even-age management scenarios, and 15 years for uneven-age management scenarios). To analyze the effect of structural retention we developed two different even-aged management scenarios representing different levels of structural retention. A clearcut represented low structural retention, with a complete removal of all trees greater than five centimeters in diameter at breast height (DBH), and all harvesting residue (slash) removed from the site. A shelterwood represented high structural retention, with the preservation of six legacy trees (canopy trees never harvested) per hectare and all slash left on site. In uneven-aged scenarios, two individual tree selection (ITS) systems were used. In ITS systems, harvesting was based on a pre-defined diameter distribution (q factor) that directed harvesting towards diameter classes with stem densities above target levels. The first ITS represented low retention, where at each entry the stand was harvested to a residual basal area of 15 m^2/ha, with no legacy trees left and 50 cm diameter used to define the maximum diameter size retained post-harvest. The second ITS represented high retention, where at each entry the stand was harvested to a residual basal area of 19 m^2/ha, with 12 legacy trees per hectare and 61 cm diameter used to define the maximum post-harvest tree size.

We ran all scenarios for 160 years on five year cycles, in order to capture a minimum of one complete rotation length. Each projection cycle represented the five year period of time for which increments of tree characteristics (i.e. growth and mortality) were predicted (Dixon 2002). As NE-FVS does not have a regeneration sub-model, user-defined regeneration parameters (including species, distribution, total number per acre, and size of expected new trees) must be defined in order to simulate non-stump sprout regeneration. Natural regeneration rates in northern hardwood forests were acquired from the literature (Graber and Leak 1992), and field data (Keeton unpublished data). These natural regeneration rates were used to develop "background" regeneration rates based on average site species composition, which were input into all simulations on every other simulation cycle (or every ten years) (Table 3). Background regeneration rates were used to emulate natural regeneration within stands, independent of forest management activities. In active management scenarios, we used adapted regeneration data specific to northern hardwood even-age forest management (Leak 1987, 2005), and uneven-aged forest management (Mader and Nyland 1984, Leak 1987). Regeneration in response to harvesting activities was input into model simulations the cycle following harvesting activities. Background regeneration, in addition to post-harvest regeneration, was included every other simulation cycle as previously described.

Data analysis

Simulation outputs from the 32 different sites were averaged to produce mean values for each scenario. We calculated the mean C stock in aboveground biomass (live and dead) and wood products during the simulation period, as a way to compare C sequestration between different management scenarios (Eriksson et al. 2007). In order to test our first hypothesis examining the tradeoffs in C sequestration between active and passive management scenarios, we used SPSS 16.0 (2008) statistical software to run single-factor ANOVA and post-hoc Bonferroni multiple comparisons to test for significant differences (a = 0.05) between management scenarios. In order to address our second hypothesis we used two-way ANOVA to test for the significance of harvesting frequency and structural retention and interaction between the two relative to mean C sequestration. We also preformed a sensitivity analysis to help identify subtle differences in the effects of harvesting frequency on C sequestration. We did this by adjusting the low and high harvesting frequency scenarios applied to each of the four original silvicultural prescriptions. The original high harvesting frequency (80 years in even-age and 15 years in uneven-age management scenarios) was decreased by 25% to create two additional harvesting frequencies (60 years for even-age and 11 years for uneven-aged management scenarios). The original low harvesting frequency (120 years in even-age and 30 years in uneven-age management scenarios) was increased by 25% to create two additional harvesting frequencies (150 years for even-age and 38 years for uneven-aged management scenarios). The adjusted models were again tested using two-way ANOVA to test for the effects of harvesting frequency and post-harvest structural retention on mean C sequestration.

A logical criticism of attributing predicted C sequestration effects solely to management scenario is that certain site characteristics, such as productivity, pre-harvest stand volume, and species composition (e.g. percent conifer), might also affect forest growth rates and C sequestration potential. To evaluate this, we used a classification and regression tree (CART) to test the predictive strength of management scenario relative to other site-specific environmental, structural, and compositional characteristics, modeled as independent variables. CART analysis is recognized as a powerful tool for analyzing complex ecological data (De'ath and Fabricius 2000). CART is a robust, nonparametric, binary method that partitions variance in a response variable through a series of repeated splits (branches) based on the values of independent variables (Breiman et al. 1984, Keeton et al. 2007). CART was chosen for its ability to explain the variation of a single response variable (in this case, mean C sequestration) based on multiple categorical or continuous independent variables (De'ath and Fabricius 2000). We used both categorical and continuous independent variables from original FIA plot measurements (Table 4). To avoid redundancy among predictor variables, independent variables exhibiting strong collinearity ($r^2 > 0.60$) were dropped from further analyses. CART analysis was performed using S-Plus software (Statistical Sciences 2002). Cost-complexity pruning was used to eliminate non-significant nodes and reduce tree size.

RESULTS

Mean C sequestration under alternate forest management scenarios

Simulation modeling output

We averaged C sequestration in both forest aboveground live and dead biomass as well as C stored in wood products (both in use and in landfills) over the 160 year time period for all 32 stands under each of the nine different management scenarios. All values, unless stated otherwise, are presented as mean C sequestration over the 160 year simulation period. Simulation results showed a clear gradient of C sequestration ranging from high intensity forest management (clearcut) to low intensity management (ITS_HighLow and No Management) (Figure 2). Ten year means of C sequestration were used to create chronosequences of management scenarios to illustrate C temporal dynamics in management scenarios. Sharp declines in active management scenarios are caused by the removal of C from the forest following a scheduled harvest. The amplitude of these declines is muted by the flux of C into storage pools in wood products as well as the averaged 10-year C sequestration values. Generally, management scenarios with decreased harvesting frequency show greater accrual of C as a result of accretion of C in dead wood pools and increased live biomass (Figure 3). Clearcut scenarios sequestered less C than all other management scenarios (simulation mean: 72.9 metric tons C/ha). Shelterwood scenarios sequestered similar amounts of C as ITS scenarios that favored low structural retention (simulation means: Shelterwood = 90.2 metric tons C/ha and ITS_Low = 90.3 metric tons C/ha). Of the active management scenarios, ITS scenarios that favored high structural retention sequestered the greatest amount of C (simulation mean: ITS_High = 110.0 metric tons C/ha). Results from post-hoc Bonferoni multiple comparisons of means following the one-way ANOVA confirmed that mean C sequestration in the no management scenario was significantly higher ($p < 0.01$) than all other management scenarios (simulation mean: 157.1 metric tons C/ha) (Figure 3).

Effects of harvesting frequency and intensity

We found that harvesting intensity significantly affected C sequestration ($p < 0.01$), based on the results of the two-way ANOVA. Harvesting frequency was also significant ($p = 0.081$); however at a lower significance level than retention (Table 5). The interactive effect of harvesting frequency and retention was not significant ($p = 0.584$). In order to further investigate the nuance effects of harvesting frequency and retention within silvicultural prescriptions, we re-ran the two-way ANOVA, separating treatments into two groups: even-age (clearcut and shelterwood scenarios) and uneven-age treatments (ITS scenarios) (Table 5). The second iteration of the two-way ANOVA showed that in uneven-age management scenarios harvesting frequency significantly affected C sequestration ($p = 0.010$). On the contrary, in even-age management scenarios, given our chosen harvesting frequency comparisons (80 and 120 year harvesting cycles), harvesting frequency did not significantly affect C sequestration ($p = 0.658$). In both uneven and even-age management scenarios, retention significantly affected C sequestration ($p < 0.01$). Furthermore, the interactive effects of harvesting frequency and retention were not significant in either uneven-age ($p = 0.716$) or in even-age ($p = 0.554$) management scenarios.

In order to test the model sensitivity to harvesting frequency, we performed a secondary analysis where we adjusted harvesting frequency in all active management scenarios. We tested the effect of the following four harvesting frequencies on each active management scenario (simulations: n =16): 1) the original high harvesting frequency (80 years in even-age; 15 years in uneven-age), 2) 25% below the original high frequency (60 years even-age; 11 years uneven-age), 3) the original low frequency (120 years even-age; 30 years uneven-age), and 4) 25% above the original low frequency (150 years even-age; 38 years uneven-age). Restrictions of current FVS activity storage limits resulted in the model's inability to project extremely high harvest frequencies (harvesting frequency < 15) in uneven-aged scenarios over the entire 160 year simulation period. For this reason, the 25% below original high frequency (11 year entry cycles) for uneven-aged management are computed in FVS the same as the original high frequency (15 year harvesting frequency), and the sensitivity analysis in uneven-aged scenarios is restricted to three different harvesting frequencies (15, 30, and 38 years). A third two-way ANOVA analysis was done to test the effects of the adjusted harvesting frequencies on mean C sequestration within management scenarios (Table 6). Harvesting frequency significantly ($a = 0.05$) affected C sequestration in all scenarios ($p = 0.01$) except the original frequencies (80 and 120 years) in even-age scenarios ($p = 0.658$). In all scenarios interactive effects between harvesting frequency and structural retention were not significant ($p > 0.01$), except in scenarios using the 25% below original high harvesting frequency (60 year) for even-age scenarios ($p < 0.01$). In these two scenarios, the interaction is driven by a combination of extremely high harvesting frequencies (relative to typical silvicultural practices in the Northeast), and very low structural retention that is notably different than other scenarios.

Effects of management versus site-specific factors

Our results strongly supported our second hypothesis that harvesting frequency and intensity significantly affect C sequestration in actively management forests. In order to confirm that this result was not a relic of pre-existing environmental or stand variables, we used a CART analysis to confirm the predictive strength of the management scenarios in explaining mean C sequestration relative to other site variables. We identified eleven independent variables to reflect environmental, structural, and compositional components that may affect forest growth (Table 4). Of eleven variables included in the initial model, four variables were incorporated in the final CART model. Management scenario was the most important predictor of mean C sequestration in CART models, with active management scenarios (B through I) generally having a mean C sequestration of <130 metric tons C/ha (Figure 4). The CART model identified several secondary predictor variables explaining lesser amounts of variance among sites following the partitioning of sites by management scenario, which explained a significantly greater proportion of deviance. In the passive (no management) scenario (A), sites with initial basal areas greater than 36.4 m^2/ha generally sequestered the greatest amount of C in all of the tested scenarios in the CART analysis (N = 288). Within the active management scenarios, the CART model identified management scenario as the variable explaining the second greatest amount of deviance. At this "branch" in the CART model, management scenarios were partitioned by even-age (shelterwood and clearcut) and the most intensive ITS scenario (ITS_LowHigh). Following secondary partitioning, the CART model identified two environmental (site index) and compositional (percent conifer) variables as the tertiary nodes. At this point, uneven-age management practices with lower percentages of conifer (< 15% basal area/ha) sequestered generally more C than stands with greater initial conifer compositions. Furthermore, even-age management scenarios and the one high intensity ITS scenario were partitioned by site index, where stands with better growing conditions (i.e. greater site index) generally sequestered greater amounts of C.

Effects of forest management scenarios on C uptake rates

We calculated C uptake rates three different ways (Table 7). When C uptake rates were averaged by harvesting frequency, clearcut scenarios had greater C uptake rates than all other scenarios (clearcut uptake rate: high harvesting frequency = 0.55 metric tons C/ha/year, and low harvesting frequency = 0.44 metric tons C/ha/year). In this same comparison of C uptake rates, C uptake rates in the no management scenario were the third greatest (no management uptake rate = 0.36 metric tons C/ha/year). In the calculation of uptake rates for the no management scenario uptake rates were averaged for the 160 year simulation period, as there were no harvesting cycles. When averaged over the 160 year simulation period without the inclusion of C stored in wood products, C uptake rates in three scenarios were negative (shelterwood_low = -0.02 metric tons C/ha/yr, ITS_LowHigh = -0.04 metric tons C/ha/yr, ITS_LowLow = -0.04 metric tons C/ha/yr). When calculating C uptake rates, the inclusion of C stored in wood products resulted in positive uptake rates for all scenarios. It should be noted that mean C uptake rates for the 160 year simulation period include harvesting activities, when significant amounts of C is lost from forest pools.

DISCUSSION

Forest management intensity strongly affects C sequestration based on our results. While our findings tell a novel story, they build on previous studies conducted throughout the world's temperate forested regions (Roxburgh et al. 2006, Schmid et al. 2006, Eriksson et al. 2007, Seidl et al. 2007). Previous research showed that actively managed forests can sequester significant amounts of C and should be considered when developing terrestrial C management options (Roxburgh et al. 2006). Furthermore, research has shown the importance of considering wood products in C accounting (Schmid et al. 2006, Eriksson et al. 2007, Seidl et al. 2007). Unlike previous studies, our results showed there can be important interactive effects of post-harvest structural retention and harvesting frequency. These findings are relevant to ongoing debates regarding forest management and C sequestration, as addressed by our two hypotheses. The results supported our first hypothesis that passive management sequesters more C than active management, as well our second hypothesis that management practices favoring lower harvesting frequencies and higher structural retention sequester more C than intensive forest management. Currently, the incorporation of active forest management in climate change mitigation is widely debated. On one hand, intensively managed forests with high harvesting frequencies that produce wood products and biofuels are recognized as a viable option for preventing C emissions that would otherwise accrue from fossil fuel emissions used to produce substitute products or energy (Eriksson et al. 2007, Malmsheimer et al. 2008b). On the other hand, numerous studies have concluded that the replacement of older forests with younger forests results in a net increase in C released to the atmosphere (Cooper 1983, Harmon et al. 1990, Schulze et al. 2000). Our results support these latter findings, and show that a shift towards intensively managed forests does not increase C sequestration when C accounting is restricted to C sequestration in aboveground forest biomass and harvested wood products.

Effects of forest management on carbon sequestration

Our results showed that management practices that favor lower harvesting frequencies and higher structural retention sequester more C than more intensive forest management practices. In addition, we can conclude there are more nuanced effects of structural retention and harvesting frequency based on the results. In our first iteration of management scenario projections, structural retention had a greater effect on C sequestration than harvesting frequency. Similar to previous studies that showed the effect of decreased harvesting frequency

(Krankina and Harmon 1994, Liski et al. 2001, Balboa-Murias et al. 2006), we found that in most cases harvesting frequency significantly affected C sequestration. Unlike previous studies that focused on even-age management (Liski et al. 2001, Balboa-Murias et al. 2006) or did not include wood products in their analysis (Krankina and Harmon 1994), our analysis evaluated the effect of harvesting frequency on both even-age and uneven-age forest management practices with the inclusion of wood products. Our second iteration of simulations showed that C sequestration is sensitive to harvesting frequency in some cases. In the even-aged management scenarios C sequestration was significantly higher when harvesting frequencies were increased or decreased by more than 25%. Relative to even-age management, the effects of harvesting frequency in uneven-age scenarios is underrepresented in the extant literature. Our studied showed that in all uneven-aged management scenarios common to the Northeast, decreased harvesting frequency significantly increased C sequestration, independent of post-harvest structural retention. These findings suggest that in the Northeast, decreasing harvesting frequency alone may not be effective for managing for C. Furthermore, there was a significant interaction effect with harvesting frequency and post-harvest structural retention in high harvesting frequency even-age stands. Thus, simultaneous consideration of both structural retention and harvesting frequency is necessary in order to optimize forest C sequestration in the northern hardwood ecosystems.

Carbon uptake rates versus storage

An important issue is the relative importance of C uptake rates versus in-situ storage (or biomass) in terms of effects of total ecosystem sequestration (Fahey et al. 2005). Our results showed that increased management intensity was positively correlated with increased C uptake rates. Younger forests have high C uptake rates, though they store significantly less C than older forests (Harmon et al. 1990, Harmon 2001, Luyssaert et al. 2008). Carbon uptake rates vary depending on the scale (spatial, temporal, and process resolution) at which they are measured or extrapolated to (Harmon 2001). To clarify the relative importance of uptake rates versus storage in our estimates of total predicted sequestration, we examined C uptake rates three different ways (Table 7). When the temporal scope was restricted to one harvesting cycle, the greatest C uptake rates were in clearcut scenarios (0.55 metric tons C/ha/yr and 0.44 metric tons C/ha/yr), representing the highest intensity management scenario. These findings are consistent with previous research on relationships between forest management and C uptake rates (Hoover and Stout 2007). However, with the exception of the two clearcut scenarios, the no management scenario had greater C uptake rates (0.36 metric tons C/ha/yr) than all other management scenarios (Range of uptake rates per harvesting cycle: -0.02 to 0.55 metric tons C/ha/yr). We believe this is a result of two factors: 1) model sensitivity to regeneration inputs; 2) net increase in C sequestered in dead wood pools. We examined the first factor by testing model sensitivity to varying regeneration inputs; confirming the model's high sensitivity to user-defined regeneration inputs. Model sensitivity to regeneration was tested by re-running all 32 stands in two randomly selected management scenarios with no regeneration inputs. Results from these two additional simulations showed large increases in C uptake rates (up to 12.5 times greater). Mortality and stand developmental dynamics within FVS are largely a function of stand density; hence accurate regeneration inputs are vital to realistic simulation outputs. Simulations run without user-defined regeneration inputs do not realistically reflect stand developmental processes of the Northeast. Regeneration sub-models have been incorporated into several western variants of FVS; however, most variants (including NE-FVS) require user-defined regeneration rules. It is critical that FVS variants lacking well developed regeneration extensions or sub-routines account for model sensitivity to regeneration inputs. One possibility is to develop regionally standardized regeneration inputs in order to maintain consistently among modeling efforts.

To address the second factor affecting uptake rates, we analyzed model partitioning of C within forest pools (Figure 3). Continued recruitment of dead wood in the no management scenarios accumulated at greater rates than the simulated decay of dead wood, resulting in a net increase of C in these pools. Allocation of C to dead wood pools increases with forest stand development and, in some cases, compensates for declining growth rates in older trees in terms of total ecosystem biomass accumulations (Harmon 2001, Franklin et al. 2002, Goodale et al. 2002). For this reason, in our results no management had C accrual rates similar to the greatest C accrual rates of intensive active management scenarios, where rapid biomass accretion was closely related to increased growth rates. Excepting the most intensive management scenarios (i.e. clearcutting), our results did not show that higher frequency, intensively managed forests have greater C uptake rates than older, slower growing forests. We attribute this to a combination of model sensitivity to regeneration, projected net positive C additions in live trees (Hadley and Schedlbauer 2002, Keeton et al. 2007, Luyssaert et al. 2008), and the significantly greater dead wood C pool that develops over time under less intensive management scenarios Harmon (2001) suggested that the parameters used to address comparisons of C sequestration can influence the results. Our results confirm that the parameters used to measure C uptake rates have a significant effect on calculated C uptake rates.

Accounting for carbon stored in harvested wood products

The inclusion of C stored in harvested wood products in C accounting is essential for quantifying forest C sequestration (Schmid et al. 2006). Furthermore, unmanaged forests sequester greater amounts of C than managed forests (Harmon et al. 1990, Thornley and Cannell 2000, Seidl et al. 2007). One of the objectives of this study was to test the effect of the inclusion of harvested wood products in C accounting relative to management intensity, and quantify the role of harvested wood products in net C sequestration at the forest stand scale. We recognize that substitutive benefits in C accounting can alter GHG mitigation benefits of management scenarios (Perez-Garcia et al. 2005b, Eriksson et al. 2007). However, in order to isolate the effect of wood products in C accounting, we did not include substitutive benefits of avoided combustion of fossil fuels from the use of forest biomass in construction or energy production. It is critical to understand the individual impacts of fluxes between pools in order to inform broader studies addressing substitutive benefits of forest products. Carbon flux between forest and various wood products pools is well documented in the Northeast (Smith et al. 2006).

Model assumptions

We simulated stand development in NE-FVS based on three primary assumptions: 1) natural disturbance is not included in simulations; 2) climate is held constant throughout simulations; 3) C storage in soils is constant throughout simulation. Fine-scaled canopy disturbance is the dominant disturbance type in the Northeast (Seymour et al. 2002), and occur on return intervals of 50 to 200 years (Runkle 1982). Disturbance regimes impact C sequestration through rapid flux of C from living biomass to dead wood pools following large-scale disturbance (McNulty 2002), or more gradual flux of C between pools as a result of intermediate and small-scale disturbances (Thurig et al. 2005). However, we did not include natural disturbances in model simulations in order to isolate the effects of forest management practices, and minimize natural stochastic variability within sites.

Individual species range shifts (Beckage et al. 2008), community compositional changes (Xu et al. 2009), increased mortality from drought and disease (van Mantgem et al. 2009) as a result of climate change are likely to impact North American forests. However, due to the uncertainties in the magnitude of regional climate change (Hayhoe et al. 2006), forest response to climate change (Pitelka et al. 1997, Dale et al. 2001), and future CO_2 emissions driving anthropogenic climate change (IPCC 2007), climate was held constant at the current climate throughout simulations. Soils in temperate hardwood forests sequester approximately 50 % of the total C stock (Lal 2005); however, uncertainties in C assimilation in stable mineral soils (Jandl et al. 2007) make modeling C sequestration in soils difficult. In order to insulate C flux to biomass pools, C sequestration measurements were restricted to aboveground live biomass, standing dead trees, coarse woody debris, and harvested wood products.

Integrating natural stand developmental processes into forest management

Our research showed that deceased harvesting frequency and increased post-harvest structural retention can effectively increase C sequestration. Silvicultural tools have already been developed that utilize these concepts and would be applicable for land manager interested in managing for increased C sequestration. In the Pacific Northwest, shifts in forest management techniques have increased the focus on variable retention forestry (Franklin et al. 1997), and the incorporation of stand developmental dynamics in silvicultural prescriptions (Zenner 2000, Franklin et al. 2007). In the Northeast, attention on emulating frequency and scale of natural disturbance dynamics (Seymour et al. 2002, Seymour 2005), and increased post-harvest structural retention (Keeton 2005, Keeton 2006) have been proven as viable forest management options. Using the two variables identified in this study as important to increased C sequestration in forest management, we can identify existing silvicultural techniques that will optimize C sequestration. Furthermore, less intensive management strategies may correlate with other management goals. Based on previous research, we can infer that in addition to sequestering more C, less intensively managed forests have multiple co-benefits, such as enhanced late successional wildlife habitat (McKenny et al. 2006), hydrologic regulation (CITATION), riparian functionality (Keeton et al. 2007). More intensively managed forests with extremely high harvesting frequency may have negative impacts on biodiversity (Huston and Marland 2004), and forest structural development (Rudolphi and Gustafsson 2005).

Implications for forest management and carbon markets

Though C sequestration in forests has been shown as a potential contribution to climate change mitigation efforts (Lindner and Karjalainen 2007), this contribution is small relative to other abatement options, but can have a significant impact on C market dynamics (Tavoni et al. 2007). However, sustainably managed forests sequester significant amounts of C and should be recognized as a focal point as North American forestry sectors identifies climate change mitigation projects (Ruddell et al. 2007). Numerous methodologies for measuring and managing for C in forests are being discussed, ranging from individual stand monitoring protocols (Hoover et al. 2000), to larger international programs developed in accordance the Kyoto Protocol (Lindner and Karjalainen 2007). The parallel development of mandatory and voluntary C markets over the last decade has lead to a wide array of climate change mitigation programs. The establishment of standardized protocols for both managing and measuring C in forests is necessary in order to maintain accurate C estimates (Lindner and Karjalainen 2007), while maintaining socially (Agrawal et al. 2008) and ecologically (Chazdon 2008) responsible mitigation projects. A secondary research objective of this project was to develop a methodology that can be applied to other regions of North America. We did this by using data sources that are available nationally (i.e. Forest Inventory and Analysis [FIA] data), and a widely accessible simulation model (FVS).

Emerging voluntary C markets may provide a potential source of revenue for forest owners interested in practicing sustainable forest management. Several different extant or developing C markets within the US already incorporate or are considering sustainable forest management as a means of mitigating CO_2 emissions (e.g. Chicago Climate Exchange, California Climate Action Registry, and the Regional Greenhouse Gas Initiative). Our results show that if the management objective of a land owner in the Northeast is strictly to manage for high levels of C sequestration, passive management with no harvesting is the most effective management technique. However, passive management in temperate forests is not currently recognized as a viable project under present day C markets. Our results inform forest based C sequestration projects, showing that both decreased harvesting frequency and increased post-harvest structural retention are effective management techniques for increasing C sequestration. Furthermore, coupling these two techniques results in the greatest C sequestration in actively managed northern hardwood-conifer forests.

CONCLUSIONS

Results from this study will inform forest managers and policy makers in understanding the effects of forest management on C sequestration and the role forests can play in climate change mitigation. We showed that with the inclusion of C sequestered in harvested wood products, unmanaged northern hardwood forests will sequester greater amounts of C (157.1 metric tons C/ha) than managed forests(72.5 to 112.8 metric tons C/ha). Moreover, less intensively managed forests, such as selection harvest systems, sequester greater amounts of C than intensively managed forests, such as even-aged systems with low structural retention, despite lower C uptake rates. This is largely a result of the significant initial loss of C incurred in intensive management scenarios as a result of the removal of large quantities of C stored in live and dead biomass in the forest, followed by slow post-harvest accretion of C in dead wood pools.

ACKNOWLEGEMENTS

Thank you GEOL 371 class for reading this manuscript!

LITERATURE CITED

Aber, J. D. and C. A. Federer. 1992. A generalized, lumped-parameter model of photosynthesis, evapotranspiration and net primary production in temperate and boreal forest ecosystems. Oecologia **92**:463-474.

Agrawal, A., A. Chhatre, and R. Hardin. 2008. Changing governance of the world's forests. Science **320**:1460-1462.

Alig, R. J. and L. S. Bair. 2006. Forest environmental investments and implications for climate change mitigation. Journal of Environmental Quality **35**:1389-1395.

Balboa-Murias, M. A., R. Rodriguez-Soalleiro, A. Merino, and J. G. Alvarez-Gonzalez. 2006. Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives. Forest Ecology and Management **237**:29-38.

Bankowski, J., D. Dey, E. Boysen, M. Woods, and J. Rice. 1996. Validation of NE-TWIGS for tolerant hardwood stands in Ontario. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, Ontario.

Beckage, B., B. Osborne, D. G. Gavin, C. Pucko, T. Siccama, and T. Perkins. 2008. A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. Proceedings of the National Academy of Sciences of the United States of America **105**:4197-4202.

Birdsey, R., K. Pregitzer, and A. Lucier. 2006. Forest carbon management in the United States: 1600-2100. Journal of Environmental Quality **35**:1461-1469.

Birdsey, R. A., J. C. Jenkins, M. Johnston, E. Huber-Sannwald, B. Amero, B. d. Jong, J. D. E. Barra, N. French, F. Garcia-Oliva, M. Harmon, L. S. Heath, V. J. Jaramillo, K. Johnsen, B. E. Law, E. Marín-Spiotta, O. Masera, R. Neilson, Y. Pan, and K. S. Pregitzer. 2007. North American Forests. In: The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research Asheville, NC, USA.

Breiman, L., J. H. Friedman, R. Olshen, and C. Stone. 1984. Classification and Regression Trees. Wadsworth International Group, Belmont, California, USA.

Canadell, J. G. and M. R. Raupach. 2008. Managing forests for climate change mitigation. Science **320**:1456-1457.

Chazdon, R. L. 2008. Beyond deforestation: Restoring forests and ecosystem services on degraded lands. Science **320**:1458-1460.

Cleland, D. T., P. E. Avers, W. H. McNab, M. E. Jensen, R. G. Bailey, T. King, and W. E. Russell. 1997. National Hierarchical Framework of Ecological Units. Yale University Press, New Haven & London.

Cooper, C. F. 1983. Carbon Storage in Managed Forests. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere **13**:155-166.

Crookston, N. L. and G. E. Dixon. 2005. The forest vegetation simulator: A review of its structure, content, and applications. Computers and Electronics in Agriculture **49**:60-80.

Crookston, N. L. and A. R. Stage. 1999. Percent canopy cover and stand structure statistics from the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-24., U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT.

Curtis, R. 1997. The role of extended rotations. Pages 165-170 *in* K. Kohm and J. Franklin, editors. Creating a forestry for the twenty-first century: The science of ecosystem management. Island Press, Washington, D.C.

Dale, V. H., L. A. Joyce, S. McNulty, R. P. Neilson, M. P. Ayres, M. D. Flannigan, P. J. Hanson, L. C. Irland, A. E. Lugo, C. J. Peterson, D. Simberloff, F. J. Swanson, B. J. Stocks, and B. M. Wotton. 2001. Climate change and forest disturbances. Bioscience **51**:723-734.

De'ath, G. and K. E. Fabricius. 2000. Classification and regression trees: A powerful yet simple technique for ecological data analysis. Ecology **81**:3178-3192.

Dixon, G. E. 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. US Forest Service, Forest Management Service Center, Fort Collins, CO.

Eriksson, E., A. R. Gillespie, L. Gustavsson, O. Langvall, M. Olsson, R. Sathre, and J. Stendahl. 2007. Integrated carbon analysis of forest management practices and wood substitution. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere **37**:671-681.

Fahey, T. J., T. G. Siccama, C. T. Driscoll, G. E. Likens, J. Campbell, C. E. Johnson, J. J. Battles, J. D. Aber, J. J. Cole, M. C. Fisk, P. M. Groffman, S. P. Hamburg, R. T. Holmes, P. A. Schwarz, and R. D. Yanai. 2005. The biogeochemistry of carbon at Hubbard Brook. Biogeochemistry **75**:109-176.

Franklin, J. F., D. R. Berg, D. A. Thornburh, and J. C. Tappeiner. 1997. Alternative silvicultural approaches to timber harvesting: Variable retention harvest systems. Pages 165-170 *in* K. A. Kohm and J. F. Franklin, editors. Creating a forestry for the 21st century: The science of ecosystem management. Island Press, Washington, D.C.

Franklin, J. F., R. J. Mitchell, and B. J. Palik. 2007. Natural disturbance and stand development principals for ecological forestry, Gen. Tech. Rep. NRS-19. Pages 1-44. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newton Square, PA.

Franklin, J. F., T. A. Spies, R. Van Pelt, A. B. Carey, D. A. Thornburgh, D. R. Berg, D. B. Lindenmayer, M. E. Harmon, W. S. Keeton, D. C. Shaw, K. Bible, and J. Q. Chen. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management **155**:399-423.

Froese, R. E. and A. P. Robinson. 2007. A validation and evaluation of the Prognosis individual-tree basal area increment model. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere **37**:1438-1449.

Goodale, C. L., M. J. Apps, R. A. Birdsey, C. B. Field, L. S. Heath, R. A. Houghton, J. C. Jenkins, G. H. Kohlmaier, W. Kurz, S. R. Liu, G. J. Nabuurs, S. Nilsson, and A. Z. Shvidenko. 2002. Forest carbon sinks in the Northern Hemisphere. Ecological Applications **12**:891-899.

Graber, R. E. and W. B. Leak. 1992. Seed Fall in an Old-growth Northern Hardwood Forest. USDA Forest Service, Northeastern Forest Experimental Research Station Resarch Paper, NE-663.

Hadley, J. L. and J. L. Schedlbauer. 2002. Carbon exchange of an old-growth eastern hemlock (Tsuga canadensis) forest in central New England. Tree Physiology **22**:1079-1092.

Harmon, M. E. 2001. Carbon Sequestration in Forests: Addressing the Scale Question. Journal of Forestry **99**:24-29.

Harmon, M. E., W. K. Ferrell, and J. F. Franklin. 1990. Effects on Carbon Storage of Conversion of Old-Growth Forests to Young Forests. Science **247**:699-702.

Harmon, M. E., S. L. Garman, and W. K. Ferrell. 1996. Modeling historical patterns of tree utilization in the Pacific Northwest: Carbon sequestration implications. Ecological Applications **6**:641-652.

Harmon, M. E. and B. Marks. 2002. Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, USA: results from a simulation model. Canadian Journal of Forest Research **32**:863-877.

Hayhoe, K., C. Wake, B. Anderson, J. Bradbury, A. DeGaetano, T. Huntington, X. Liang, L. Luo, E. Maurer, M. Schwartz, J. Sheffield, D. Wolfe, D. Wuebbles, and E. Wood. 2006. Climate Change in the U.S. Northeast: A Report of the Northeast Impacts Assessment. Union of Concerned Scientists, Cambridge, USA.

Hennigar, C. R., D. A. MacLean, and L. J. Amos-Binks. 2008. A novel approach to optimize management strategies for carbon stored in both forests and wood products. Forest Ecology and Management **256**:786-797.

Hilt, D. E. and R. M. Teck. 1989. NE-TWIGS: An individual-tree growth and yield projection system for the northeastern United States. The Compiler **7**:10-16.

Hoover, C. and S. Stout. 2007. The carbon consequences of thinning techniques: Stand structure makes a difference. Journal of Forestry **105**:266-270.

Hoover, C. M., R. A. Birdsey, L. S. Heath, and S. L. Stout. 2000. How to estimate carbon sequestration on small forest tracts. Journal of Forestry **98**:13-19.

Huston, M. A. and G. Marland. 2004. Carbon management and biodiversity. Journal of Environmental Management **67**:77-86.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jandl, R., M. Lindner, L. Vesterdal, B. Bauwens, R. Baritz, F. Hagedorn, D. W. Johnson, K. Minkkinen, and K. A. Byrne. 2007. How strongly can forest management influence soil carbon sequestration? Geoderma **137**:253-268.

Jenkins, J. C., D. C. Chojnacky, L. S. Heath, and R. A. Birdsey. 2003. National-Scale Biomass Estimators for United States Tree Species. Forest Science **49**:12-35.

Keeton, W. S. 2005. Managing for old-growth structure in northern hadwood forests. Pages 107-111 *in* C. E. Peterson and D. A. Maguire, editors. Balancing ecosystem values: innovative experiments for sustainable forestry. USDA Forest Service, Gen. Tech. Rep PNW-GTR-635.

Keeton, W. S. 2006. Managing for late-successional/old-growth characteristics in northern hardwood-conifer forests. Forest Ecology and Management **235**:129-142.

Keeton, W. S., C. E. Kraft, and D. R. Warren. 2007. Mature and old-growth riparian forests: Structure, dynamics, and effects on Adirondack stream habitats. Ecological Applications **17**:852-868.

Krankina, O. N. and M. E. Harmon. 1994. The impact of intensive forest management on carbon stores in forest ecosystems. World Resource Review **6**:161-177.

Lal, R. 2005. Forest soils and carbon sequestration. Forest Ecology and Management **220**:242-258.

Leak, W. B. 1987. 50 Years of Compositional Change in Deciduous and Coniferous Forest Types in New-Hampshire. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere **17**:388-393.

Leak, W. B. 2005. Effects of small patch cutting on sugar maple regeneration in New Hampshire northern hardwoods. Northern Journal of Applied Forestry **22**:68-70.

Lindner, M. and T. Karjalainen. 2007. Carbon inventory methods and carbon mitigation potentials of forests in Europe: a short review of recent progress. European Journal of Forestry **126**:149-156.

Lippke, B., J. Wilson, J. Perez-Garcia, J. Bowyer, and J. Meil. 2004. CORRIM: Life-cycle environmental performance of renewable building materials. Forest Products Journal **54**:8-19.

Liski, J., A. Pussinen, K. Pingoud, R. MSkipSS, and T. Karjalainen. 2001. Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere **31**:2004-2013.

Luyssaert, S., E. D. Schulze, A. Borner, A. Knohl, D. Hessenmoller, B. E. Law, P. Ciais, and J. Grace. 2008. Old-growth forests as global carbon sinks. Nature **455**:213-215.

Mader, S. F. and R. D. Nyland. 1984. Six-Year Response of Northern Hardwoods to the Selection System. Northern Journal of Applied Forestry **1**:87-91.

Malmsheimer, R. W., P. Heffernan, S. Brink, D. Crandall, F. Deneke, C. Galik, E. Gee, J. A. Helms, N. McClure, N. Mortimer, S. Ruddell, M. Smith, and J. Stewart. 2008a. Preventing GHG Emissions through Biomass Substitution. Journal of Forestry **106**:136-140.

Malmsheimer, R. W., P. Heffernan, S. Brink, D. Crandall, F. Deneke, C. Galik, E. Gee, J. A. Helms, N. McClure, N. Mortimer, S. Ruddell, M. Smith, and J. Stewart. 2008b. Preventing GHG Emissions through Wood Substitution. Journal of Forestry **106**:132-135.

Masera, O. R., J. F. Garza-Caligaris, M. Kanninen, T. Karjalainen, J. Liski, G. J. Nabuurs, A. Pussinen, B. H. J. d. Jong, and G. M. J. Mohrenf. 2003. Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. Ecological Modelling **164**:177-199.

McKenny, H. C., W. S. Keeton, and T. M. Donovan. 2006. Effects of structural complexity enhancement on eastern red-backed salamander (Plethodon cinereus) populations in northern hardwood forests. Forest Ecology and Management **230**:186-196.

McNulty, S. G. 2002. Hurricane impacts on US forest carbon sequestration. Environmental Pollution **116**:S17-S24.

Miner, R. and J. Perez-Garcia. 2007. The greenhouse gas and carbon profile of the global forest products industry. Forest Products Journal **57**:80-90.

Nyland, R. D. 1996. Silviculture : concepts and applications. McGraw-Hill, New York.

Nyland, R. D. 1998. Selection System in Northern Hardwoods. Journal of Forestry **96**:18-21.

Perez-Garcia, J., B. Lippke, D. Briggs, J. B. Wilson, J. Bowyer, and J. Meil. 2005a. The environmental performance of renewable building materials in the context of residential construction. Wood and Fiber Science **37**:3-17.

Perez-Garcia, J., B. Lippke, J. Comnick, and C. Manriquez. 2005b. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood and Fiber Science **37**:140-148.

Pitelka, L. F., R. H. Gardner, J. Ash, S. Berry, H. Gitay, I. R. Noble, A. Saunders, R. H. W. Bradshaw, L. Brubaker, J. S. Clark, M. B. Davis, S. Sugita, J. M. Dyer, R. Hengeveld, G. Hope, B. Huntley, G. A. King, S. Lavorel, R. N. Mack, G. P. Malanson, M. McGlone, I. C. Prentice, and M. Rejmanek. 1997. Plant migration and climate change (vol 85, pg 464, 1997). American Scientist **85**:501-501.

Ray, D. G., R. S. Seymour, N. A. Scott, and W. S. Keeton. 2009. Mitigating Climate Change with Managed Forests: Balancing Expectations, Opportunity, and Risk. Journal of Forestry **107**:50-51.

Robinson, A. P. and R. E. Froese. 2004. Model validation using equivalence tests. Ecological Modelling **176**:349-358.

Roxburgh, S. H., S. W. Wood, B. G. Mackey, G. Woldendorp, and P. Gibbons. 2006. Assessing the carbon sequestration potential of managed forests: a case study from temperate Australia. Journal of Applied Ecology **43**:1149-1159.

Ruddell, S., R. Sampson, M. Smith, R. Giffen, J. Cathcart, J. Hagan, D. Sosland, J. Godbee, J. Heissenbuttel, S. Lovett, J. Helms, W. Price, and R. Simpson. 2007. The role for sustainably managed forests in climate change mitigation. Journal of Forestry **105**:314-319.

Rudolphi, J. and L. Gustafsson. 2005. Effects of forest-fuel harvesting on the amount of deadwood on clear-cuts. Scandinavian Journal of Forest Research **20**:235-242.

Runkle, J. R. 1982. Patterns of Disturbance in Some Old-Growth Mesic Forests of Eastern North-America. Ecology **63**:1533-1546.

Running, S. W. 1994. Testing FOREST-BGC ecosystem process simulations across a climatic gradient in Oregon Ecological Applications **4**:238-247.

Schmid, S., E. Thurig, E. Kaufmann, H. Lischke, and H. Bugmann. 2006. Effect of forest management on future carbon pools and fluxes: A model comparison. Forest Ecology and Management **237**:65-82.

Schulze, E. D., C. Wirth, and M. Heimann. 2000. Climate change - managing forests after Kyoto. Science **289**:2058-2059.

Sciences, S. 2002. S-plus statistical software. Statistical Science, Seattle, Washington, USA.

Seidl, R., W. Rammer, D. Jager, W. S. Currie, and M. J. Lexer. 2007. Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. Forest Ecology and Management **248**:64-79.

Seymour, R. S. 1995. The northeastern region. Pages 31-80 *in* J. Barrett, editor. Regional Silviculture of the United States, 3rd Edition. John Wiley and Sons, Inc., New York, NY.

Seymour, R. S. 2005. Integrating natural disturbance parameters into conventional silvicultural systems: experience from the Acadian forest of northeastern North America. Pages 41-49 *in* C. E. Peterson and D. A. Maguire, editors. Balancing ecosystem values: innovative experiments for sustainable forestry. USDA Forest Service General Technical Report PNW-GTR-635.

Seymour, R. S., A. S. White, and P. G. deMaynadier. 2002. Natural disturbance regimes in northeastern North America - evaluating silvicultural systems using natural scales and frequencies. Forest Ecology and Management **155**:357-367.

Smith, J. E., L. S. Heath, K. E. Skog, and R. A. Birdsey. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. USDA Forest Service, Northeastern Research Station, General Technical Report NE-343.

SPSS. 2008. SPSS Base 16.0 User's Guide. SPSS Inc., Chicago, IL.

Stage, A. R. 1973. Prognosis Model for Stand Development. Res. Pa INT-137, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Szabó, L., I. Hidalgo, J. C. Ciscar, and A. Soria. 2006. CO2 emission trading within the European Union and Annex B countries: the cement industry case. Energy Policy **34**:72-87.

Tavoni, M., B. Sohngen, and V. Bosetti. 2007. Forestry and the carbon market response to stabilize climate. Energy Policy **35**:5346-5353.

Teck, R., M. Moeur, and B. Eav. 1996. Forecasting ecosystems with the forest vegetation simulator. Journal of Forestry **94**:7-10.

Thornley, J. H. M. and M. G. R. Cannell. 2000. Managing forests for wood yield and carbon storage: a theoretical study. Tree Physiology **20**:477-484.

Thurig, E., T. Palosuo, J. Bucher, and E. Kaufmann. 2005. The impact of windthrow on carbon sequestration in Switzerland: a model-based assessment. Forest Ecology and Management **210**:337-350.

van Mantgem, P. J., N. L. Stephenson, J. C. Byrne, L. D. Daniels, J. F. Franklin, P. Z. Fule, M. E. Harmon, A. J. Larson, J. M. Smith, A. H. Taylor, and T. T. Veblen. 2009. Widespread Increase of Tree Mortality Rates in the Western United States. Science **323**:521-524.

Xu, C., G. Z. Gertner, and R. M. Scheller. 2009. Uncertainties in the response of a forest landscape to global climatic change. Global Change Biology **15**:116-131.

Yaussy, D. A. 2000. Comparison of an empirical forest growth and yield simulator and a forest gap simulator using actual 30-year growth from two even-aged forests in Kentucky. Forest Ecology and Management **126**:385-398.

Zenner, E. K. 2000. Do residual trees increase structural complexity in Pacific northwest coniferous forests? Ecological Applications **10**:800-810.

Table 1. THIS TABLE WILL BE BROKEN INTO TWO TABLES WITH BETTER RESOLUTION. Description of the four different silvicultural prescriptions used as management scenarios. We ran each scenario with two different harvesting frequencies, and used a factorial design to test the independent effects of harvesting frequency and structural retention.

Even aged silvicultural prescriptions		Harvesting frequency: High (80 years)	Harvesting frequency: Low (120 years)
Residual structure	Low	*Clearcut_High* 1) Commercial thin: implement when stand reaches stocking density above normal 2) Clearcut: 2005 and 2085 No legacy trees *Whole tree harvest	*Clearcut_Low* 1) Commercial thin: implement when stand reaches stocking density above normal 2) Clearcut: 2005 and 2125 No legacy trees. *Whole tree harvest
	High	*Shelterwood_High* 1) Commercial thin: implement when stand reaches stocking density above normal. 2) Shelterwood: 2005 and 2085 residual BA 14 m²/ha -6 legacy trees/ha, smallest diameter removed at 6 cm *Slash left on site	*Shelterwood_Low* 1) Commercial thin: implement when stand reaches stocking density above normal. 2) Shelterwood: 2005 and 2125 residual BA 14 m²/ha -6 legacy trees/ha, smallest diameter removed at 6 cm *Slash left on site

Uneven aged silvicultural prescriptions		Harvesting frequency: High (15 years)	Harvesting frequency: Low (30 years)
Residual structure	Low	*US_LowHigh* Entry cycle length: 15yrs Q-value: 1.3 Residual BA: 15 m²/ha Min DBH class: 5 cm Max DBH class: 50 cm DBH class width: 5 cm Number of legacy trees/ha: 0	*US_LowLow* Entry cycle length: 30 yrs Q-value: 1.3 Residual BA: 15 m²/ha Min DBH class: 5 cm Max DBH class: 50 cm DBH class width: 5 cm Number of legacy trees/ha: 0
	High	*US_HighHigh* Entry cycle length: 15yrs Q-value: 1.3 Residual BA: 19 m²/ha Min DBH class: 5 cm Max DBH class: 61 cm DBH class width: 5 cm Number of legacy trees/ha: 12 Average legacy tree diameter: 41 cm	*US_HighLow* Entry cycle length: 30 yrs Q-value: 1.3 Residual BA: 19 m²/ha Min DBH class: 5 cm Max DBH class: 61 cm DBH class width: 5 cm Number of legacy trees/ha: 12 Average legacy tree diameter: 41 cm

Table 2. Descriptive information of environmental, structural, and compositional components of 32 FIA forest inventory plots used in simulation modeling. Eco-subregion codes are shown on figure one.

FIA Plot Code	Starting Stand Age	Eco-subregion **	Site Index	Slope (%)	Elevation (meters)	Aspect (degrees)	Percent Conifer (% BA)	Basal Area (m2/ha)	SDI	Trees per Hectare	QMD	MAI (m3/ha/yr)	Number of Strata *	Canopy Height (m)	Percent Canopy Cover
2320030702501505	94	M211Af	44	14	518	195	13	37.6	510	10843	2.6	2.6	1	18.6	80
2320030702502686	97	M211Af	42	12	427	235	21	31.5	444	11125	2.4	1.6	1	19.5	82
2320030900702261	86	M211Af	34	8	549	215	34	33.1	506	17423	1.9	1.8	1	19.2	76
2320030900703046	80	M211Ae	42	9	701	100	18	30.5	480	18318	1.8	2.2	1	17.4	73
2320030900703313	87	M211Ag	51	12	183	2	50	35.1	430	5997	3.4	2.5	1	17.1	80
2320030900703677	89	M211Af	81	10	488	140	1	26.2	384	11191	2.1	1.6	1	19.5	79
2320030901700110	84	M211Ag	37	14	366	22	62	42.2	604	16032	2.3	3.2	2	21.3	72
2320030901700852	81	M211Af	37	13	823	248	42	29.4	372	6005	3.1	1.9	1	16.2	59
2320030901701013	96	M211Ae	41	14	610	124	17	34.7	450	8058	2.9	2.4	1	18.6	69
2320030901702963	85	M211Ag	65	27	274	65	0	24.6	334	7117	2.6	1.8	2	21.3	78
3320050200300163	82	M211Ad	81	17	274	250	0	30.5	398	7122	2.9	2.9	1	24.4	78
3320050200700781	80	M211Af	62	5	549	60	22	28.7	355	5300	3.3	2.3	1	21.9	71
3320050200900018	85	M211Ba	83	12	579	343	0	26.6	395	11826	2.1	2.8	1	26.8	73
3320050200900904	97	M211Ad	49	3	427	0	34	32.6	454	10939	2.4	2.1	1	23.5	82
3620040303506767	81	M211Db	62	0	335	0	44	47.8	477	2894	5.7	4.6	1	23.2	86
3620040304303762	80	M211Dd	60	12	457	179	3	38.1	465	6440	3.4	3.5	1	24.4	82
3620040304303966	80	M211Dd	43	6	549	256	27	33.1	403	5545	3.4	2.4	1	21.3	85
3620040403101088	95	M211Df	46	16	640	85	18	29.8	437	12639	2.2	2.1	1	24.4	71
3620040403102007	92	M211Df	88	20	549	81	4	30.5	354	4040	3.9	2.5	1	25.9	76
3620040403102851	97	M211Df	35	18	335	148	37	35.1	413	4982	3.7	2.4	1	20.1	79
3620040403105127	100	M211Df	50	13	701	287	7	24.6	330	6808	2.7	1.5	1	20.1	66
3620040403105218	90	M211Df	57	33	305	137	57	33.5	443	8599	2.8	2.1	1	21.0	75
3620040404102413	82	M211Dd	47	0	640	0	15	48.0	525	4663	4.5	4.8	1	25.3	75
3620040404102456	86	M211Dd	60	12	671	12	15	29.6	362	5115	3.4	2.3	1	25.0	73
3620040404102703	90	M211Dd	62	18	579	327	57	26.2	345	6588	2.8	2.0	2	21.9	57
3620040404104669	91	M211Dd	41	22	732	306	20	29.2	363	5488	3.2	2.1	1	20.1	72
3620040404106138	86	M211Dd	60	12	579	12	27	38.3	480	7480	3.2	3.2	1	22.6	80
3620040411302486	80	M211De	88	12	488	166	0	44.3	506	5382	4	5.0	1	33.8	90

3620040411305029	100	M211De	48	14	518	169	51	25.5	357	8819	2.4	1.8	1	23.5	59
5020050200900479	91	M211Ae	37	11	396	276	44	38.8	507	9160	2.9	3.0	2	21.3	81
5020050201701120	85	M211Ba	64	27	671	235	0	29.6	400	828	2.7	2.4	1	22.9	80
5020050202300275	81	M211Ca	89	47	183	10	0	23.0	261	2743	4.1	2.9	2	27.4	59

Note: All values were measured by USDA Forest Service Forest Inventory and Analysis Program, and retrieved through the stand list file in FVS.

* As defined in Crookston and Stage 1999

** As defined in Cleland et al. 1997

Table 3. Regeneration inputs used in model simulations. Seedling numbers are given as total seedlings per hectare.

Management Scenario	*Acer saccharum*	*Fagus grandifolia*	*Tsuga canadensis*	*Picea rubens*	*Fraxinus americana*	*Betula alleghaniensis*	*Acer rubrum*	*Populus tremuloides*	*Betula papyrifera*
Clearcut	4448	1730	432	432	8154	8093	8093	15320	15320
Shelterwood	4448	4695	62	62	618	556	1174	-	-
ITS	1977	2224	309	309	62	62	185	-	62
Background	494	247	62	62	-	62	62	-	-

Table 4. Description of independent variables used in CART analysis. The character of variables is denoted by A = Anthropogenic, S = Spatial, E = Environmental, C = Stand composition, T = Stand structure; and the type by N = numeric, O = Ordinal, or C = categorical

Variable	**Character**	**Type**	**Values**	**Description**
Scenario Code	A	C	A - I	A (Background), B (ITS_ HighHigh), C (ITS_ LowHigh), D (ITS_HighHigh), E (ITS_LowHigh), F (Clearcut_Low), G (Clearcut_High), H (Shelterwood_Low), I (Shelterwood_High)
Eco-subregion	S	C	10	Ecological subregions as defined by the USDA, 2005, Forest Service ECOMAP team, Washington D.C.
Site Index	E	N	30 < x < 90	Site indexat age 50
Aspect	E	N	0 < x < 359	Aspect of individual stands
Percent Conifer	C	N	0 < x < 63	Starting percent conifer, calculated as a percentage of basal area per hectare
Basal Area	T	N	23.0 < x < 24 < x < 49	Starting basal area (m²/ha),
Quadratic Mean Diameter	T	N	1.8 = x = 4.5	Starting QMD
Structure Class	T	O	0 - 6	0 (bare ground), 1 (stand initiation), 2 (stem exclusion), 3 (understory reinitiating), 4 (young forest, multi-strata), 5 (old forest, single stratum), 6 (old forest, multi-strata) (Crookston and Stage 1999)
Number of strata	T	O	0 - 3	Strata differentiated by 30% differentiation in tree height, with minimum threshold of 5% cover to qualify as a strata (Crookston and Stage 1999)
Slope	E	N	0 - 30	Slope of individual stands, measured as a percentage
Stand age	T	N	80 = x = 100	Starting stand age

Table 5. Treatment effects on the mean C sequestration over the 160 year simulation period, based on two-way ANOVA. Italicized p values are statistically significant.

Treatment	**Silviculture type**	**Mean Square Error**	**F**	**Significance (p)**
Harvesting Frequency* Retention (interaction)	Total	92.070	.300	.584
	Even-age	71.055	.352	.554
	Uneven-age	26.423	.133	.716
Harvesting Frequency	Total	940.159	3.066	.081
	Even-age	39.739	.197	.658
	Uneven-age	1373.349	6.907	*.010*
Retention	Total	17575.921	57.325	*.000*
	Even-age	9674.480	47.959	*.000*
	Uneven-age	7944.034	39.954	*.000*

Table 6. Two-way ANOVA results from sensitivity analysis. Results are divided by harvesting frequency and structural retention. Harvesting frequency adjustments are shown as percent above (+) or below (-) the original high and low harvesting frequencies used in simulation modeling. Four harvesting frequencies were used: 1) 25% below the original high frequency (60 years EA; 11 years UA); 2) the original high frequency (80 years EA; 15 years UA); 3) the original low frequency (120 years EA; 30 years UA); 4) 25% above original low frequency (150 years EA; 38 years UA).

Treatment	Silviculture type	Harvesting Frequency Adjustment	Mean Square Error	F	Significance (p)
Harvesting Frequency* Retention (interaction)	Even-age	- 25 %	14955.249	94.696	*.000*
		+/- 25%	17339.034	103.410	*.000*
		No change	71.055	.352	.554
		+ 25%	317.393	1.501	.223
	Uneven-age	- 25 % *	67.807	.326	.569
		+/- 25% *	67.807	.326	.569
		No change	26.423	.133	.716
		+ 25%	67.807	.326	.569
Harvesting Frequency	Even-age	- 25 %	17934.946	113.564	*.000*
		+/- 25%	29779.801	177.607	*.000*
		No change	39.739	.197	.658
		+ 25%	2020.570	9.555	*.002*
	Uneven-age	- 25 % *	3811.707	18.349	*.000*
		+/- 25% *	3811.707	18.349	*.000*
		No change	1373.349	6.907	*.010*
		+ 25%	3811.707	18.349	*.000*
Retention	Even-age	- 25 %	45037.826	285.179	*.000*

	+/- 25%	41142.063	245.372	*.000*
	No change	9674.480	47.959	*.000*
	+ 25%	7916.163	37.434	*.000*
Uneven-age	- 25 % *	7402.050	35.633	*.000*
	+/- 25% *	7402.050	35.633	*.000*
	No change	7944.034	39.954	*.000*
	+ 25%	7402.050	35.633	*.000*

Note: * = As a result of model limitations, 11 year harvesting frequencies in uneven-aged scenarios are simulated the same as 15 year entry cycles and values are identical.

Table 6. Description of independent variables used in CART analysis. The character of variables is denoted by A = Anthropogenic, S = Spatial, E = Environmental, C = Stand composition, T = Stand structure; and the type by N = numeric, O = Ordinal, or C = categorical

Variable	**Character**	**Type**	**Values**	**Description**
Scenario Code	A	C	A - I	A (Background), B (ITS_ HighHigh), C (ITS_ LowHigh), D (ITS_ HighHigh), E (ITS_LowHigh), F (Clearcut_Low), G (Clearcut_High), H (Shelterwood_Low), I (Shelterwood_High)
Ecoregion	S	C	10	Ecological subregions as defined by the USDA, 2005, Forest Service ECOMAP team, Washington D.C.
Site Index	E	N	30 < x < 90	Site indexat age 50
Aspect	E	N	0 < x < 359	Aspect of individual stands
Percent Conifer	C	N	0 < x < 63	Starting percent conifer, calculated as a percentage of basal area per hectare
Basal Area	T	N	23.0 < x < 24 < x < 49	Starting basal area (m²/ha),
Quadratic Mean Diameter	T	N	1.8 = x = 4.5	Starting QMD
Structure Class	T	O	0 - 6	0 (bare ground), 1 (stand initiation), 2 (stem exclusion), 3 (understory reinitiating), 4 (young forest, multi-strata), 5 (old forest, single stratum), 6 (old forest, multi-strata) (Crookston and Stage 1999)
Number of strata	T	O	0 - 3	Strata differentiated by 30% differentiation in tree height, with minimum threshold of 5% cover to qualify as a strata (Crookston and Stage 1999)
Slope	E	N	0 - 30	Slope of individual stands, measured as a percentage
Stand age	T	N	80 = x = 100	Starting stand age

Table 7. Comparison of three different calculated mean C uptake rates by management scenario.

Prescription	Mean Forest C uptake rate per harvesting cycle (metric tons C/ha/year)	Mean forest C uptake rate for 160 year simulation period (metric tons C/ha/year)	Mean forest and harvested wood products C uptake rate for 160 year simulation period (metric tons C/ha/year)
Clearcut_High	0.55	0.23	0.23
Clearcut_Low	0.44	0.02	0.08
Shelterwood_High	0.18	0.13	0.13
Shelterwood_Low	0.17	-0.02	0.02
ITS_LowHigh	-0.02	-0.04	0.07
ITS_LowLow	-0.01	-0.04	0.08
ITS_HighHigh	0.04	0.02	0.14
ITS_HighLow	0.05	0.02	0.14
No Management	0.36	0.36	NA

FIGURE LEDGEND

Figure 1. Map of eco-subregions in the Northeast used to stratify the selection of FIA plots.

Figure 2. Simulation output time series of the 9 different management scenarios (values represent 10 year mean C of 32 stands). CH = clearcut with 80 year harvesting frequency, CL = clearcut with 120 year harvesting frequency, SH = shelterwood with 80 year harvesting frequency, SL = shelterwood with 120 year harvesting frequency, ITS_LH= Individual tree selection system with low retention and 15 year harvesting frequency, ITS_LL = Individual tree selection system with low retention and 30 year harvesting frequency, ITS_HH = Individual tree selection system with high retention and 15 year harvesting frequency, ITS_HL = Individual tree selection system with high retention and 30 year harvesting frequency, NM = no management.

Figure 3. Comparison of mean C stocks in nine different management scenarios. CH = clearcut with 80 year harvesting frequency, CL = clearcut with 120 year harvesting frequency, SH = shelterwood with 80 year harvesting frequency, SL = shelterwood with 120 year harvesting frequency, ITS_LH= Individual tree selection system with low retention and 15 year harvesting frequency, ITS_LL = Individual tree selection system with low retention and 30 year harvesting frequency, ITS_HH = Individual tree selection system with high retention and 15 year harvesting frequency, ITS_HL = Individual tree selection system with high retention and 30 year harvesting frequency, NM = no management.

Figure 4. Classification and regression tree (CART) showing independent variables selected, split values, and portioned mean values (bottom) of the dependent variable (mean C

sequestration). The figure ranks independent variables by predictive strength (top to bottom); the length of each vertical line is proportional to the amount of deviance explained by each variable. Independent variables were selected from an initial set of 11 variables. Minimum observations required for each split = 5; minimum deviance = 0.05; N = 288.

Figure 1: **THIS FIGURE WILL BE RE-DONE IN GIS!**

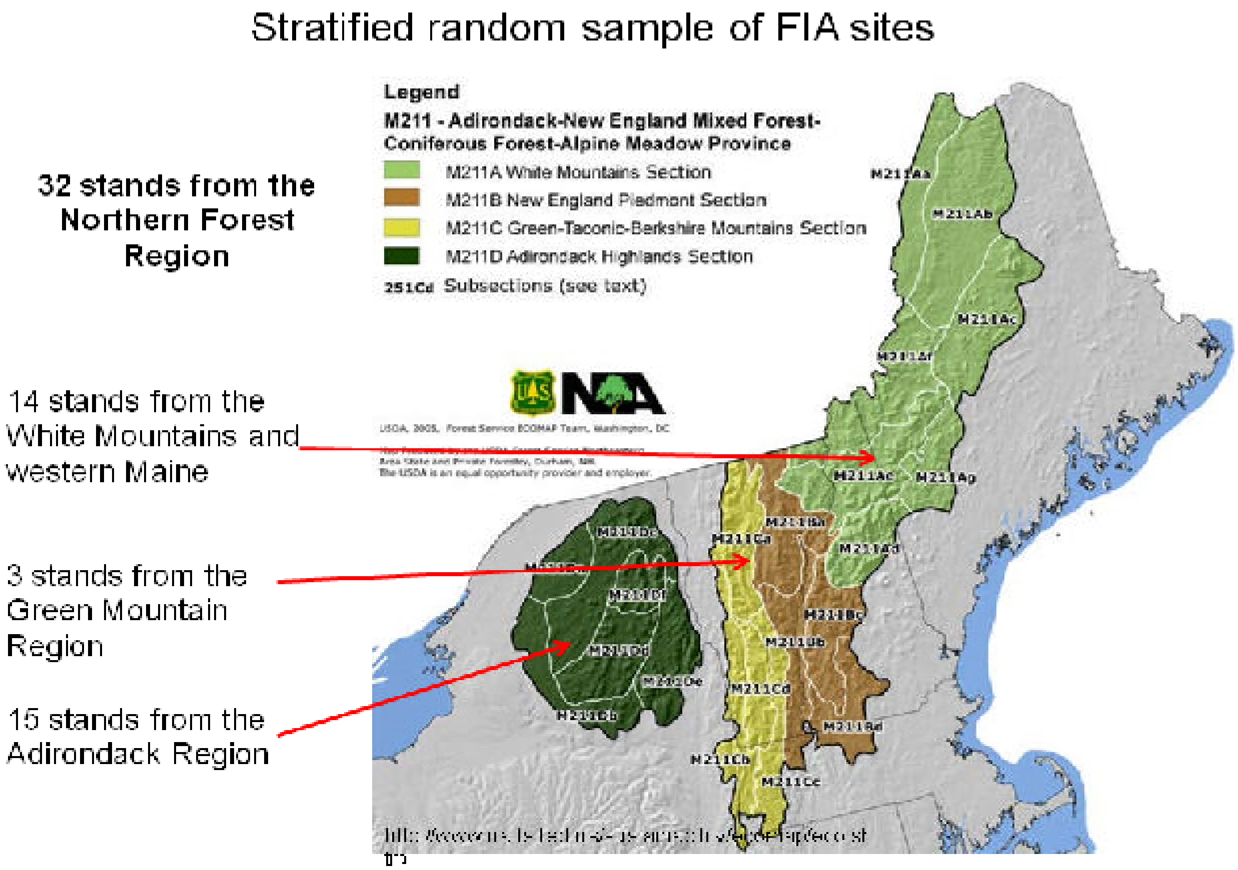
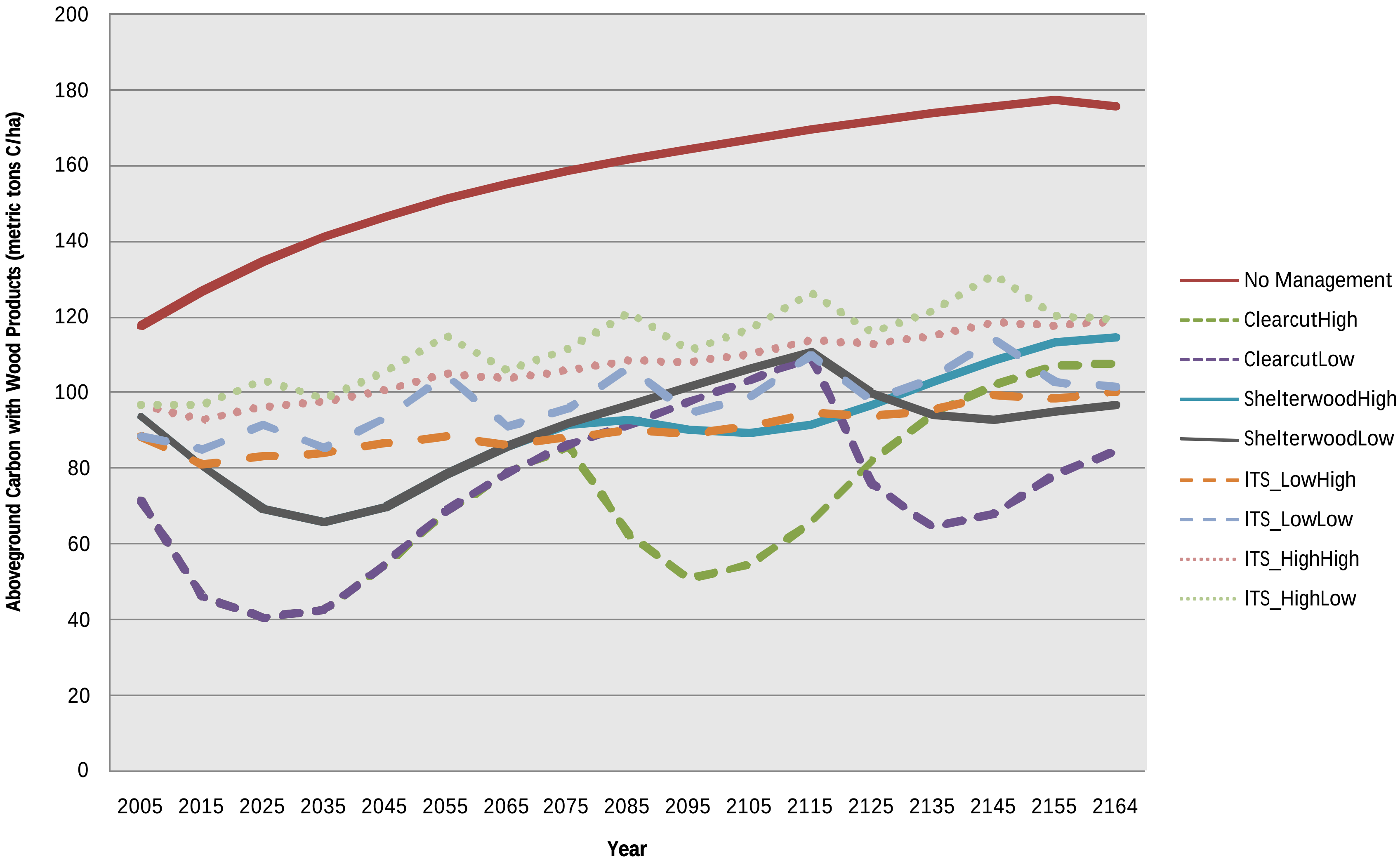
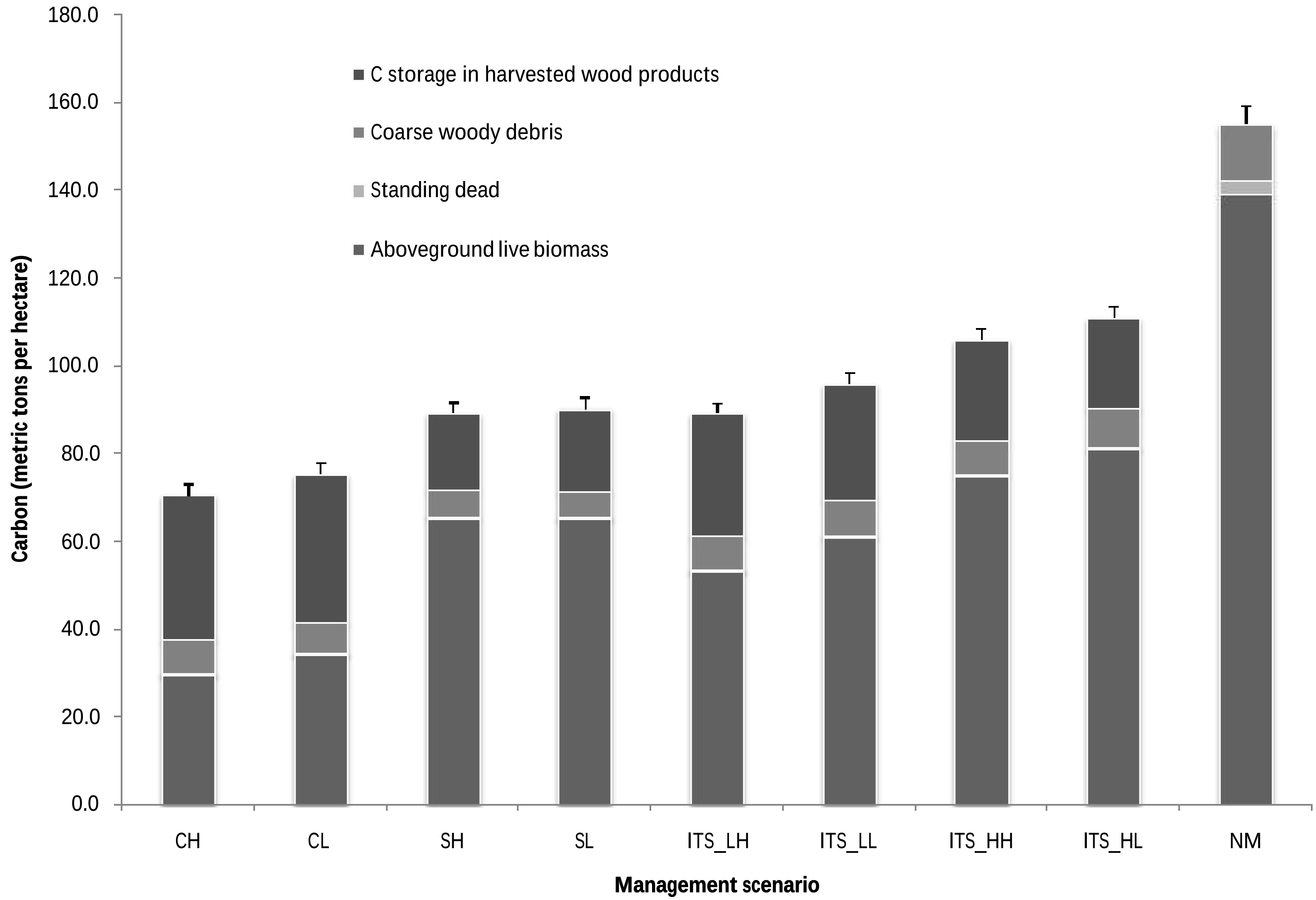


Figure 2:



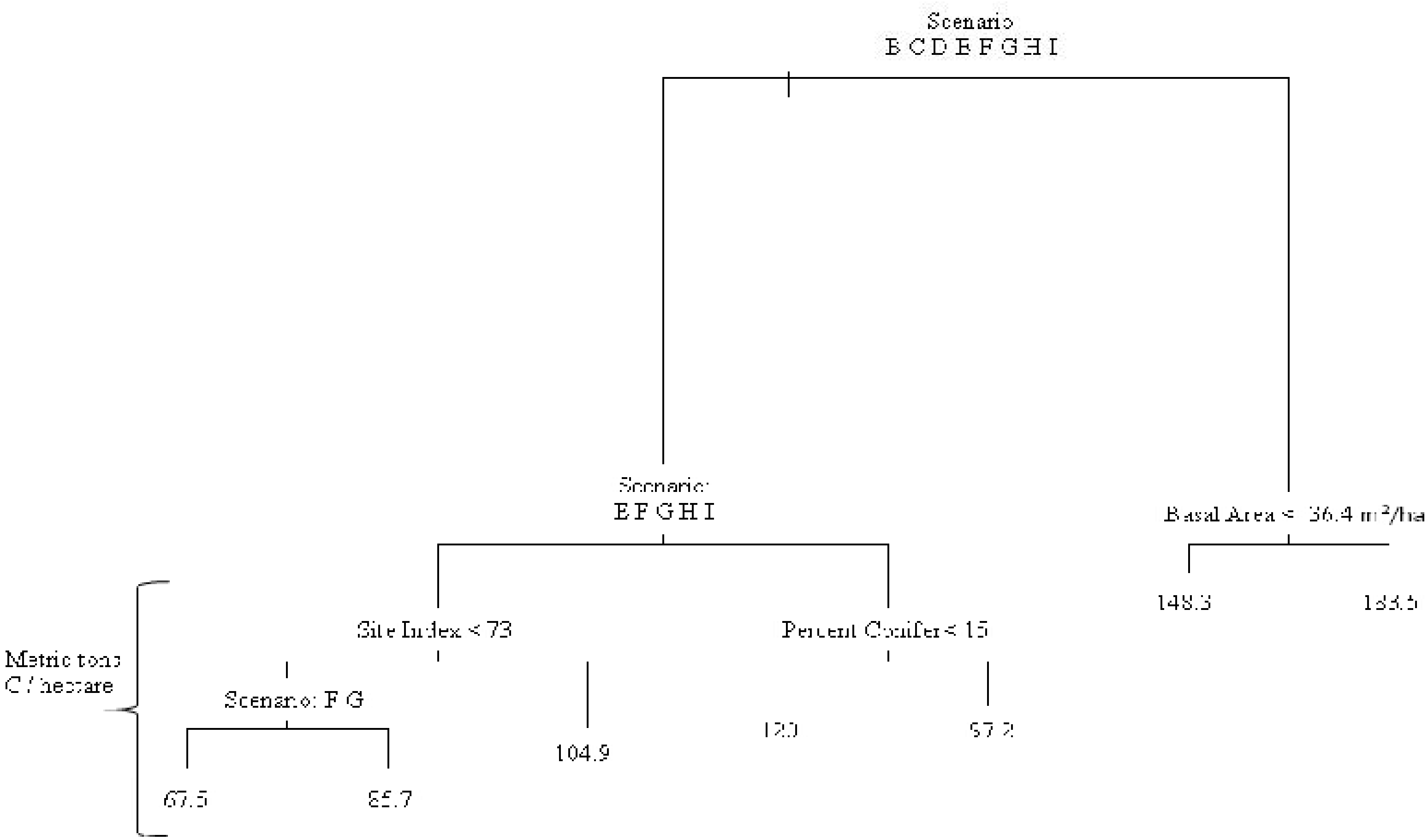
200
180
160
140
120
100
80
60
40
20
0
Aboveground Carbon with Wood Products (metric tons C/ha)
2005
2015
2025
2035
2045
2055
2065
2075
2085
2095
2105
2115
2125
2135
2145
2155
2164
Year
No Management
ClearcutHigh
ClearcutLow
ShelterwoodHigh
ShelterwoodLow
ITS_LowHigh
ITS_LowLow
ITS_HighHigh
ITS_HighLow

Figure 3:



180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
C storage in harvested wood products
Coarse woody debris
Standing dead
Aboveground live biomass
Carbon (metric tons per hectare)
CH
CL
SH
SL
ITS_LH
ITS_LL
ITS_HH
ITS_HL
NM
Management scenario

Figure 4:



Scenario
B C D E F G H I
Scenario:
E F G H I
Basal Area < 36.4 m^2/ha
148.3
Site Index < 73
Percent Conifer < 15
Metric tons
C / hectare
Scenario: F G
104.9
67.5
85.7