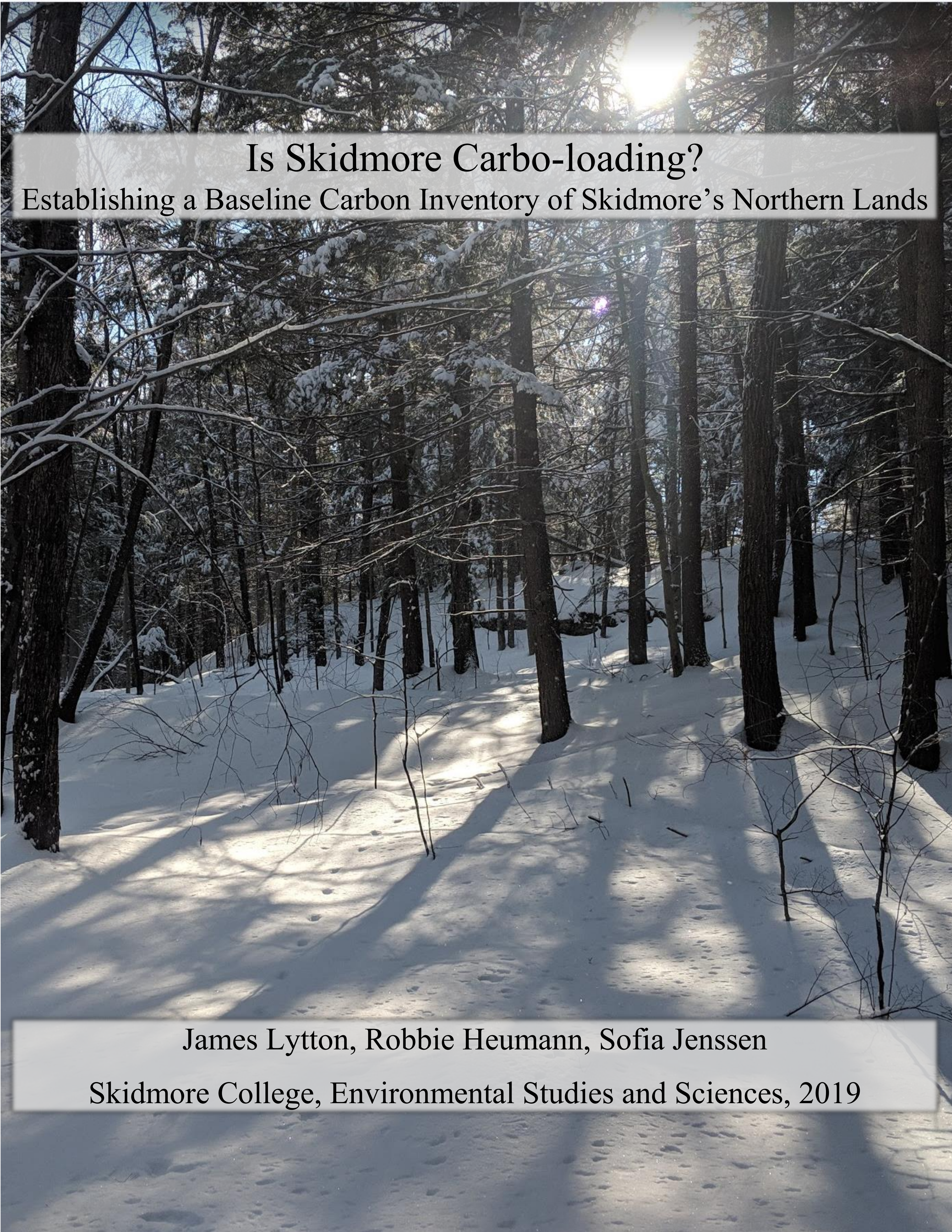
Is Skidmore Carbo-loading?

Establishing a Baseline Carbon Inventory of Skidmore's Northern Lands



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Abshracht shmabstract

Forests store carbon. We have a forest. We measured carbon in the forest. We found some carbon. We suggest the forests be left alone to store more carbon. Other people should do the same. You might find some carbon yourself, ya never know.

Abstract

Approximately half of the world's terrestrially sequestered carbon is held in forests and wetlands. Landowners and institutions can manage forests to maximize their sequestration potential for the purpose of offsetting greenhouse gas emissions. Skidmore College owns 272 hectares of unmanaged forested lands, 60 of which have been subjected to logging and road building. This study aims to establish a baseline carbon inventory of aboveground and belowground carbon stocks in these 5 parcels of land (Kellogg, Disturbed, Compost, Stables, Homestead) and examine the impact of disturbance on carbon. We randomly generated 42 fixed area plots with a 15 m radius throughout our entire study area in which we measured and identified trees above 10 cm DBH and trees with a DBH between 2.5cm and 10cm in a 5 m radius subplot. Within each plot we collected soil samples at depths of 0-10 cm and 10-20cm; we collected leaf litter and wetland peat core samples. We found that when carbon stocks in Skidmore's lands were compared to a common practice baseline of 227.3 mgC/ha, the Stables and Kellogg were above this baseline. This indicates that these parcels may be viable for a carbon sequestration project by reducing greenhouse gas emissions (from the year 2000) by 17237 Mg CO_2eq, or 234% at most. Other parcels have carbon densities below baseline. Moving forward, we should allow the Disturbed parcel regenerate naturally to restore its carbon sequestration potential, as well as monitor carbon storage in all parcels. When variables potentially affecting carbon densities were investigated, few showed statistically significant differences. Future studies should focus on the viability of Kellogg and Stables parcels for sequestration projects, as well as expanding our plot network and quantifying carbon held in wetlands. Management recommendations include focuses on education, recreation, and sequestration. We found that Skidmore is, in fact, carbo-loading.

Introduction

Forests cover about 4.1 billion hectares globally (Dixon & Wisniewski, 1995). Approximately half of the world's terrestrially sequestered carbon is held in forests, with about a third in the soil pool, making forests central to carbon stock and storage research (Nave 2010**,** Roy & Mooney 2001). This is critical given that global climate change is driven by the disruption in the carbon cycle caused by emissions of greenhouse gases such as carbon dioxide (CO_2) into the atmosphere. The atmospheric concentration of CO_2 has increased by anthropogenic activities including burning fossil fuels and deforestation for land development (Schimel, 1995). The resulting elevated carbon dioxide levels in the atmosphere and reduced carbon storage in terrestrial ecosystems leads to global environmental change (Nabuurs et al. 2007). The Intergovernmental Panel on Climate Change 2018 report indicates that without immediate and aggressive action, the average atmospheric temperature will increase by 1.5 degrees Celsius by 2040. The consequences of this include but are not limited to extreme weather & climate events (drought, floods, extreme heat), sea level rise, and loss of biodiversity, leading to climate-related poverty and displacement in many countries (IPCC, 2018). Actions currently undertaken for climate change mitigation are not sufficient, with carbon emissions reaching a record global high of 38.1 billion tons of carbon dioxide in 2018 alone, and expected increases of 2.5% in the United States (Global Carbon Project, 2018). In order to mitigate these effects, more carbon can be sequestered in ecosystems using forests and soils , making the preservation of terrestrial ecosystem services essential (Brown et al., 1996) . In order to harness the potential of carbon sequestration, management plans and strategies focused on carbon offsets are critical in the face of detrimental climate change predictions.

Carbon Sequestration

Temperate forests have contributed about 27-34% to the global carbon sink in the past two decades (Pan et ak, 2011). Within these ecosystems carbon is stored in components such as aboveground biomass (trees, leaf litter, deadwood) and belowground stocks including soil organic and inorganic carbon (Bouwman & Leemans, 1995). Forests absorb carbon dioxide from the atmosphere through photosynthesis and release it through respiration, while much of the carbon is stored in aboveground and belowground biomass in stocks. In the U.S., these terrestrial carbon stocks in temperate forests are sequestering about 10% of American annual carbon dioxide emissions (Birdsey et al., 2006). The U.S. forest carbon sink has increased about 33% since the 1990s due to trends in reforestation, growth of immature forests, and recovering historical agricultural areas resulting in increased forest area and density of biomass (Birdsey et al., 2006; Kauppi et al., 2006).

Forest disturbances constrain carbon dynamics in terrestrial ecosystems as a source of carbon emissions (Wofsy & Harris, 2002). Disturbances, including deforestation and land use change, cause perturbations in terrestrial carbon stocks and fluxes releasing significant portions of carbon dioxide and other greenhouse gases (GHGs) into the atmosphere (Wigley &

Schlesinger, 1985). For instance, land use conversion for agriculture depletes soil organic carbon stocks 20-50% (Post & Mann, 1990). In addition, 18% of carbon dioxide emissions are rooted in deforestation across the globe (Stern 2006). Fire, disease, logging and harvesting, and insect outbreaks also can cause large perturbations in carbon cycling (Goward et al., 2008).

Despite these impacts from landscape degradation and disturbance, disturbed forests have the capability to regrow and recover; temperate forests throughout the U.S. have been undergoing this process for the past 20 years, resulting in US forests ultimately becoming carbon sinks. Regenerated forest carbon stocks can potentially sequester even more carbon than pre-disturbance, but over the duration of tens to hundreds of years (Korner 2003). Active reforestation can also offer a modality of carbon sequestration by rehabilitating a disturbed forest in order to re-establish ecosystem productivity. Disturbed forests could sequester even more carbon when managed for efficient regrowth and sequestration rather than a "business as usual" or baseline condition of regrowth (Ruddell et al, 2007). Proactive forest management can help maximize carbon stored during regeneration after disturbance.

Another major biotic factor in terrestrial carbon storage are wetlands. Wetlands often are situated within forests. wetlands and forests commonly coexist and rely on the function of each other to maintain their respective nutrient and carbon cycles. Although they cover much less land than forests, wetlands account for roughly one-third of the carbon stored in terrestrial ecosystems (Turunen et al, 2001). The slow decomposition rates and acidic soils allow wetlands to accumulate copious organic matter and preserve a much larger carbon pool. As a result, wetlands play a major role in moderating the global carbon budget. However, wetlands are fragile ecosystems whose carbon and nutrient cycling processes can be dramatically altered by small changes in their environment (Holden, 2005). Small scale changes in wetland hydrology as well as large scale changes like the drainage of wetlands can result in significant releases of GHGs (Holden, 2005). The health of a wetland is therefore reliant on the health of its neighboring forest. Disturbances in one can dramatically disturb the other. For such reasons, it is essential to regard both ecosystems and their carbon storing potential as interconnected and mutualistic.

Managing for Carbon Sequestration

Ecosystems, in particular temperate forests, are complex and dynamic systems, which is sometimes a hurdle to overcome in our attempts to understand them. Carbon sinks are often diverse and heterogeneous landscapes. This requires management plans to address all types of micro-habitats located in the carbon sink. Many temperate forests include a range of micro-habitats such as varying tree stands, successional stages, and wetlands. Wetlands in particular are major carbon sinks due to their capacity to preserve and retain organic matter (Bridgham et al, 2006). For this reason wetlands should play a major role in determining how to manage land for carbon sequestration.

The first and most important goal of any carbon storage plan is to set aside the sequestering ecosystems for conservation. Once this is accomplished, plans for what practices are implemented in the conserved land can then be determined (Brown et al, 2005). Practices such as selective logging, controlled burning or fertilizing intend to boost and maintain the ecosystem's productivity. Before designing a management plan for a forest, it is essential to produce a baseline measurement of carbon storage by inventorying all aboveground and belowground carbon stocks in the proposed forest.A forest inventory entails designing a sampling method that includes measurement of target carbon pools (for example: living and dead above and below ground biomass) in stratified plots for a uniform duration of time and frequency throughout the project area.

<u>Institutional Forest Carbon Projects</u>

Some colleges and universities across the U.S. have recently been purchasing and managing forested land for carbon offsetting as this will help with their achieving emissions goals set by the institution. Middlebury College has conserved and managed 2100 acres of forest around their Bread Loaf campus. Middlebury has outsourced assessments of these lands to a third party company with the ultimate goal of gaining carbon credits. Middlebury's management of these forests allows their use as educational tools and recreational areas in addition to carbon sinks (middlebury.edu/sustainability, 2017).

Colgate University is another institution that has committed to carbon neutrality and is dedicated to using carbon offset projects to achieve this goal. The campus forest encompasses about 1,000 acres and Colgate has conducted its own researches to determine the viability of using carbon offsets on campus. They have analyzed different scenarios of projects including working with Second Nature to adopt a 'Peer-Review' protocol modeled after the American Carbon Registry Improved Forest Management. This, however, would produce less offsets because of a limit on counting carbon offsets to 30% of total emissions of the college. They also will proceed with using third-party verifications to their forest carbon inventory (Bianco et al. 2017). This project has yet to come to fruition, but provides an example of a successful project analysis by an institution with similar esteem and size as Skidmore College, who also has an ambitious reduction goal for greenhouse gases. It should be noted that this is a new, emerging field does not have a standard method of counting carbon stored in forests for all institutions, and there are different approaches and third-party verification processes that are undertaken by these institutions.

<u>Skidmore College: Sustainability & Unmanaged Lands</u>

Skidmore College's sustainability plan for 2025 takes a stepwise approach to achieving a large emissions reduction. Goals included in this plan will be achieved using sustainable energy, food, waste, and lands and grounds management. One goal included in the plan is to create a comprehensive land management plan for Skidmore's over 1,000 acres of developed and undeveloped lands. Many of the undeveloped lands are mixed conifer and hardwood forests with peat forming wetlands. Included in Skidmore's sustainability plan is the goal of offsetting the college's greenhouse gas emissions by establishing a stewardship plan for the school's undeveloped forested land (Campus Sustainability Subcommittee, 2015). The resulting carbon offsets will ultimately help the school achieve a 75% reduction in their greenhouse gas emissions by 2025.

Study Purpose

The purpose of this study was to inventory carbon stocks among four parcels of Skidmore's unmanaged forest lands in order to establish a baseline measurement of carbon storage from which a carbon storage stewardship plan can be developed for the lands. This will indicate the feasibility of managing the lands for carbon sequestration and entering carbon markets for Skidmore to achieve our reduction in greenhouse gas emissions goal and eventually attain carbon neutrality. Our inventory will create a comprehensive dataset of carbon stocks in the unmanaged lands; this will allow future studies to calculate change in carbon pools over time. Our dataset is the foundation of a stewardship plan to conserve and expand the inventoried carbon stocks. This study also aims to examine the relationship between the disturbances that took place on one parcel of Skidmore's unmanaged land and its effects on carbon stocks in the forest ecosystem.

Our inventory builds on the preliminary dataset provided by Kristie Sills, Becca Halter, and Andy frank in their 2017 capstone paper "Putting a Price on it: Measuring Ecological Value of a Diverse Landscape". This paper focused only on the undisturbed portion of the Kellogg forest. The study also roughly estimated wetland carbon storage from peat cores and associated depths and carbon densities. Comparing our results with their data will help quantify the difference in rates of carbon sequestration between relatively old-growth forest and newly regenerating forest.

Methods

Survey Sites

Our largest parcel, Kellogg, was donated to Skidmore in 2010. Following the donation, a subset of the property (Disturbed parcel) was logged in a patchwork fashion, leaving some pockets of intact forest. The land is now unmanaged and designated for educational purposes and land conservation (Freeman et al., 2012). Our second largest parcel (Stables) is a portion of forest behind the Skidmore stables which is maintained by the Saratoga Springs Mountain Bike Association. However there is no formal stewardship plan for the parcel. Our third parcel, Homestead, is an unmanaged forest parcel that was partially developed during the late 1800s in which the forest has since grown back. The final and smallest parcel, Compost, is a portion of forest behind the college's composting facility. Assessing the carbon pools impacted by recent development-related disturbances on this land provides a baseline measurement for future calculations of carbon sequestration.

Kellogg Parcel

Kellogg is the largest parcel we chose for our carbon inventory; it is roughly 145 hectares (ha) of hardwood and conifer forest area. The main forest species on the parcel is second-growth *Acer saccharum*, *Quercus rubra*, *Pinus strobus*, *Betula allegheniensis*, and *Tsuga canadensis*. Peat-forming wetlands make up ~32 ha of the area we studied, and consist of open sedge (Carex spp. dominated) and wooded (Picea spp. dominated) riverine fens with seasonal water, and open-water palustrine wetlands**.** Soils in the New Lands are categorized as rocky with a thin organic layer and an underlying fine sandy loam (Sills et al. 2017). In 2009, a portion of the property was donated by Michael Roohan to Skidmore College, but prior to this, was publicly used with a few trails. In the 1880s, the Abenaki Native American tribe seasonally resided on the land and had built campsites across the area after logging.

Disturbed Parcel

In 2016, a 60.3 hectare section of Kellogg Forest on the northeast edge of the property was selectively logged (66% vegetation loss), resulting in roads, patches of logged forest, exposed bedrock, and debris. We refer to this disturbed area as the Disturbed Parcel when discussing sampling and results.

Homestead Parcel

The Homestead Parcel is just northwest of Skidmore's North Woods and main campus, representing 32.2 hectares of Skidmore's total property; it has belonged to Skidmore since 1961. This parcel was formerly an estate in the late 1800s with foundations remaining: a main house, barn, and well foundations. The surficial geology of the Homestead Parcel is primarily sand, outwash sand and glacial till (Rosen et al., 2014).

Stables Parcel

Stables Parcel is about 84 hectares and is just north of the Homestead Parcel behind Skidmore's stables. It was formerly a part of a park in the 1800s, then an estate that maintained the forest and wetlands, and has been owned by Skidmore since the 1960s. The parcel contains small trails used recreationally; these have been maintained by the Saratoga Mountain Bike Association. The parcel is primarily outwash sand and gravel. It also contains a small swampland and pond (Rosen et al., 2014).

Compost Parcel

The compost parcel is about 15.7 hectares, southwest of the Stables Parcel. A small portion of it is currently used as the school's composting facility.

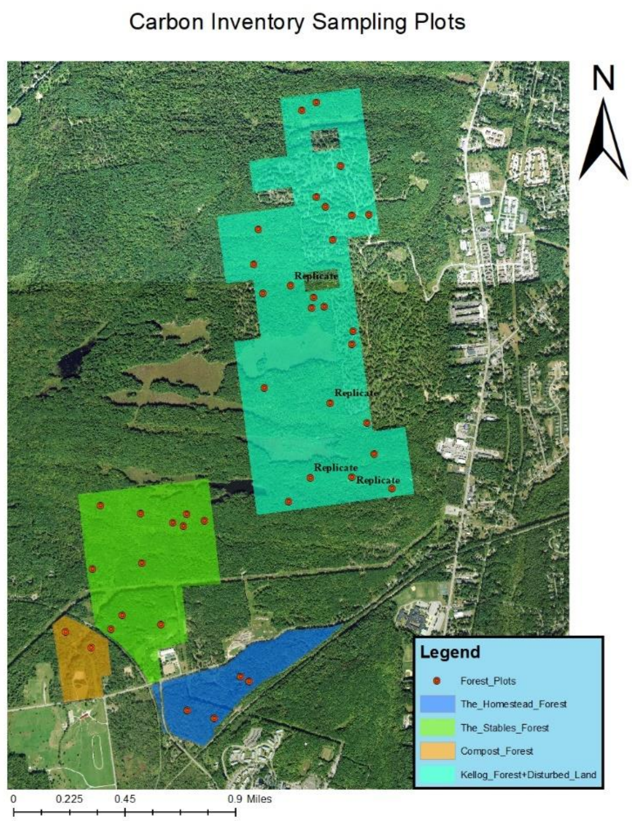

Figure 1. Complete Map of Study Area with Forest and Wetland Plots

<u>**Plot Generation**</u>

We created maps of the study area using ArcMap (Figure 1). Due to the relatively short time frame allotted for this study, we chose a 1% sampling intensity of the study parcels

We calculated the number of plots required to sample 1% of each study parcel, with each plot having an area of 706.85 m². These 42 plots were randomly generated using ArcMap's random point generator tool and dispersed among all of the parcels. On the same program, a buffer zone of 15 m was created to ensure that no plots overlapped with the borders of parcels or wetlands. In the field, we navigated to the GPS location of each plot to begin forest sampling.

Within these plots, all were sampled for the 0-10 cm depth of soil. Since some plots were on hillsides or hilltops where the soil is shallower and less developed, we sampled the 10-20 cm soil depth for 38 plots. The timeframe of the study required us to scale back our sampling for aboveground stocks: tree measurements were conducted in 20 of the stocks, 18 of the plots were sampled for deadwood and 14 for leaf litter.

We used a nested plot design for forest sampling (Figure 2). This plot design allows you to collect data on multiple factors (soil, leaf litter, deadwood, and aboveground biomass) in one plot. These data can then be scaled up to represent totals among each parcel. The plot design makes for a more efficient and replicable data collection strategy. The center point of each plot was designated according to methods above. Each plot was a fixed area 15 meter radius plot with a 5 meter radius subplot in its center.

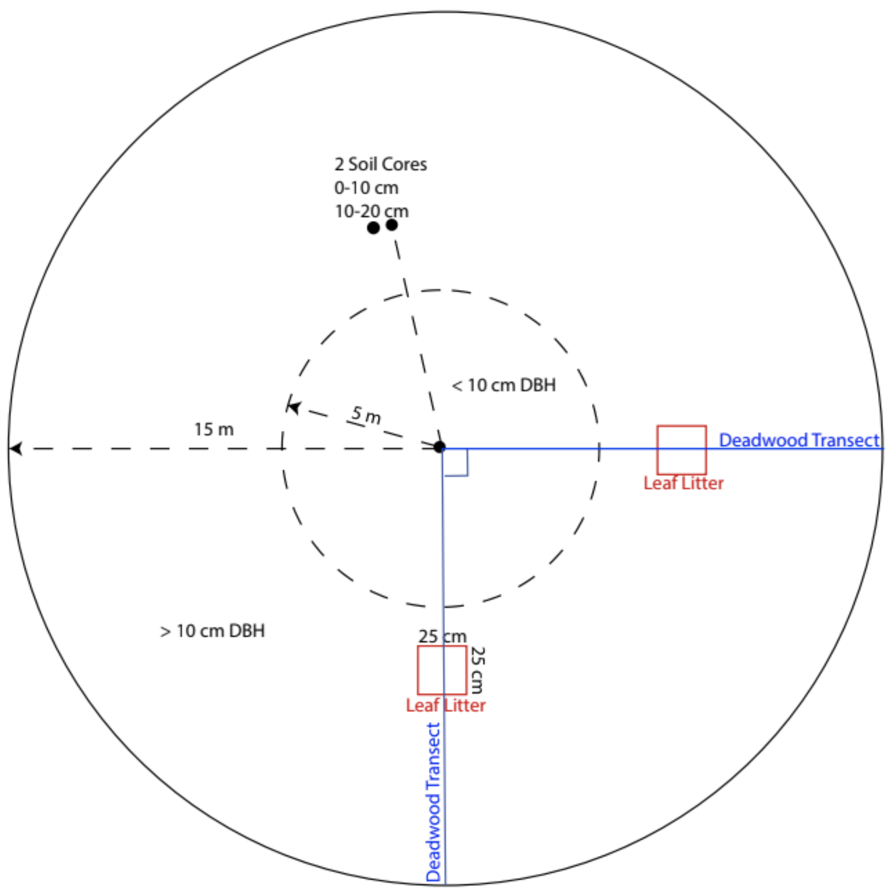

Figure 2. Nested plot design for forest plots.

Aboveground Carbon (AGC)

Tree Data Collection & Analysis

We measured trees with ≥10 cm diameter at breast height (DBH) in the entire 15 m plot. We only measured trees with DBH ≤10 cm within the 5 m radius subplot. Since carbon sequestration potential varies among tree species, we recorded the species of each tree (Lamlom & Savidge, 2003).

To estimate biomass of tree species, we used equations developed by Jenkins et al. (2004):

$$y = \mathrm{Exp}\,(\beta 0 + \beta 1 \;\mathrm{Ln}\; x)$$

Where y = total aboveground biomass (kg) for trees ≥2.5 cm DBH, x = DBH (cm),

$B0$, $\beta 1$ represent species group specific parameters for estimating aboveground biomass (Table 3, Jenkins et al. 2004). The values for aboveground biomass were used to calculate aboveground Carbon using an equation derived from Hughes et al. (1999):

$$AGC = AGB \times 0.47$$

Vegetation Loss Analysis

We used National Agriculture Imagery Program (NAIP) imagery from 2013 prior to disturbed parcel logging and NAIP Imagery from 2017 (post-logging) to calculate vegetation loss in the disturbed parcel in Arcmap. We conducted normalized difference vegetation index (NDVI) analyses on both those images then reclassified the NDVI color values so that all vegetation was represented by one value and everything else in the parcel that absorbed infrared light was a different value (Figures 3, 4). This allowed us to separate vegetation from non vegetation. Using the number of attributes for the vegetation color value, we then calculated the vegetation loss from logging as a percent by dividing the count of attributes from the post disturbance image by the count of attributes of the pre disturbance image. This resulted in about 66 percent loss of vegetation from that parcel of land after the logging event.

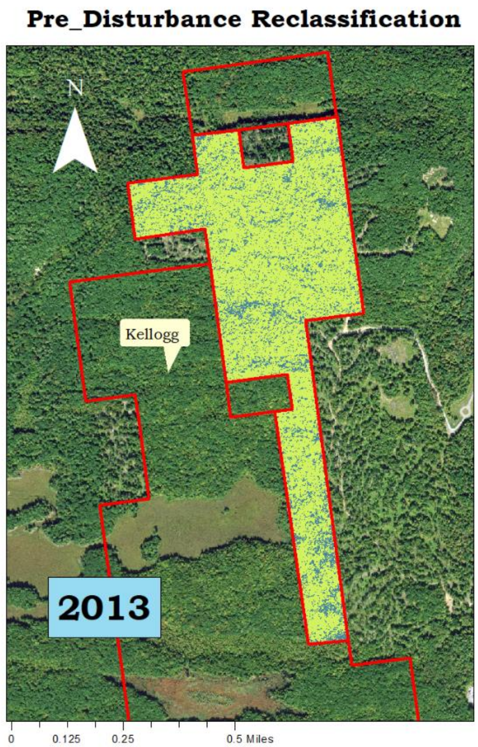

Figure 3. NDVI analysis prior to logging

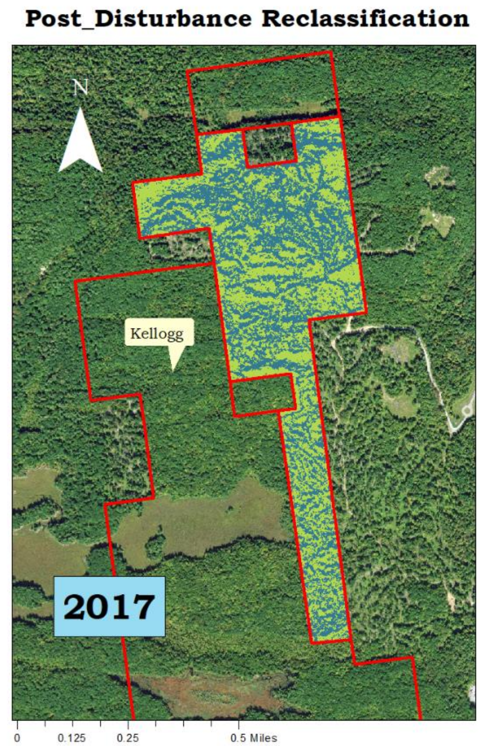

Figure 4. NDVI analysis post logging

Leaf Litter Sampling & Analysis

We took two leaf litter samples from each plot. The first sample was taken 7.5 m from the plot center, following a randomly generated azimuth radiating from the plot center. The second was taken on an azimuth 90 degrees clockwise from the first following the same protocol. We placed a 25x25 cm PVC square on the ground at each sample location. Within each square, we collected leaf litter down to the topmost soil organic layer by hand. Leaf litter samples were manually separated and placed into their respective Ziploc bags for transportation to the lab for analysis.

Once in the lab, we air dried samples then weighed leaf litter biomass. We assumed that the weight of dried leaf litter was 47% carbon (Wind, 2013).

Deadwood data collection & Analysis

We used two 15 m transects to quantify deadwood. The first transect aligned with a randomized azimuth, as with leaf litter sampling. The second was at a bearing 90 degrees clockwise from the first. We walked along each transect measuring DBH of the wider end of each piece of deadwood intersecting the transect line. Only downed deadwood above 2 cm in DBH were recorded. We noted if the deadwood was fallen or standing dead and assumed all deadwood was rotten (40% of original biomass). We used a preexisting density for deadwood at this stage of decomposition: 0.19 tonnes/m^3 (Pearson et al, 2007). The volume of the rotten wood was calculated with the formula: π^2 x [(d1^2 + d2^2.....dn^2/(8*transect length]; D1 to Dn are the DBH measurements of deadwood pieces, and the transect length is 30 m or two 15 m transects.

Belowground Carbon (BGC)

Soil Sampling & Analysis

To calculate carbon content of belowground biomass in our study area, we needed a bulk density measurement for soil types. We decided to use bulk density measurements at 1/3 bar from the USDA's soil web survey for both depths. In order to do this, all the soil types within our study area were identified and mapped in ArcMap. The bulk density at 1/3 bar for each soil type was then used to create a complete map of the different soil bulk densities in our parcel. We compiled this data into a map which can be seen below:

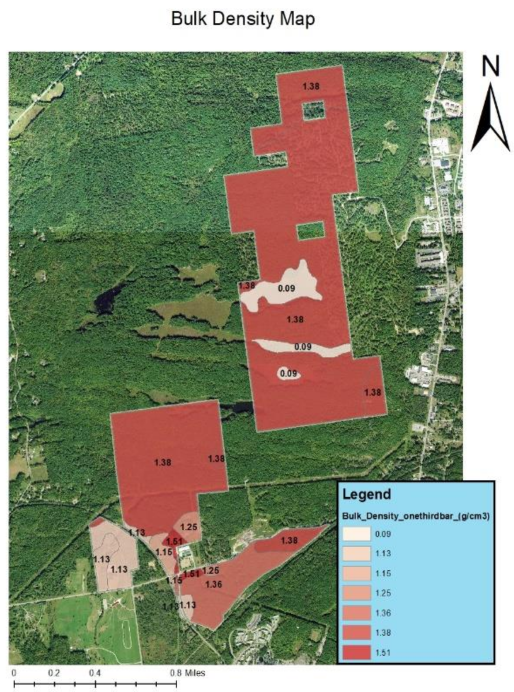

Figure 5. Bulk Density Map of Study Area

We then collected one sample from each soil type at 0-10 cm and 10-20 cm depths using a quick-carbon drill rig; these samples were sent to be analyzed for carbon content at Ward labs. The resulting carbon content was used to calculate soil carbon storage for all the parcels using the bulk densities for each soil type and the estimated volume of each soil type in the parcels.

We calculated belowground carbon (living and dead) by applying a regression model specific to temperate forests as a function of above-ground biomass (BGB; Cairns et al. 1997):

$$BGB = \exp(-1.0587 + 0.8836 \times \ln AGB + 0.2840)$$

Where BGB = below-ground biomass density in tons/hectare (t/ha), AGB = t/ha

Wetland Carbon

To measure carbon percentages in the wetlands of our study area we first sampled the biggest wetland using a standard russian peat borer. We took two samples at 110-120 cm and 190-200 cm. We then sent the two samples along with soil samples to Ward Labs to be analyzed for their carbon percentage. Using the carbon percentages, we calculated a rough estimate of the amount of carbon stored in all the wetlands in the Kellogg parcel (32 ha of wetland). We assumed the entire wetland area was 2 meters deep for the sake of our volume calculations. We then used a bulk density of 0.13 obtained from the 2017 capstone's measurement of the same wetlands.

Aspect

Aspect was calculated in Arcmap using a 3 m digital elevation model (USDA Geospatial Data Gateway). Using the add function command in image analysis tools, a raster was created with symbology depicting the aspect of the study area. Since we were only interested in whether plots were south-facing or not, the data were reclassified to represent south-facing and non-south-facing plots using the reclassify (spatial analyst) tool in Arcmap. Azimuths 320 to 40 were categorized as North-facing, and 140-220 as South-facing. North-facing were assigned a value of 1 and south-facing a value of 2. All others were registered as no data. Once the data were appropriately classified, the "extract values to points" spatial analyst tool in the Arcmap toolbox was used. This tool assigned the raster values to the attribute table of the points feature.

Results

Aboveground

Due to time limitations, we reduced the number of plots from which we sampled aboveground carbon. We sampled all 8 plots in the Disturbed parcel, 2 from Compost, 2 from Homestead, 4 from Kellogg, and 4 from Stables.

We found The Stables parcel to have the highest amount of carbon stored per hectare in aboveground biomass (M = 116.42 Mg/ha, SE = 6.22) followed by aboveground carbon stored in Kellogg (M = 118.46 Mg/ha, SE = 24.90), then Homestead (M = 94.55 Mg/ha, SE = 20.83), then Compost (M = 99.98 Mg/ha, SE = 25.81), and Disturbed (M = 68.43 Mg/ha, SE = 8.99). Figure 6 shows the amount of carbon stored per hectare in each parcel.

We ran a one-way ANOVA investigating differences between mean aboveground carbon held across parcels. This revealed that Kellogg held significantly more carbon (M = 118.45 Mg/ha, SE = 24.90) than the Disturbed parcel (M = 68.43 Mg/ha, SE = 8.99;F (1,10) = 5.57, *p* = 0.04).

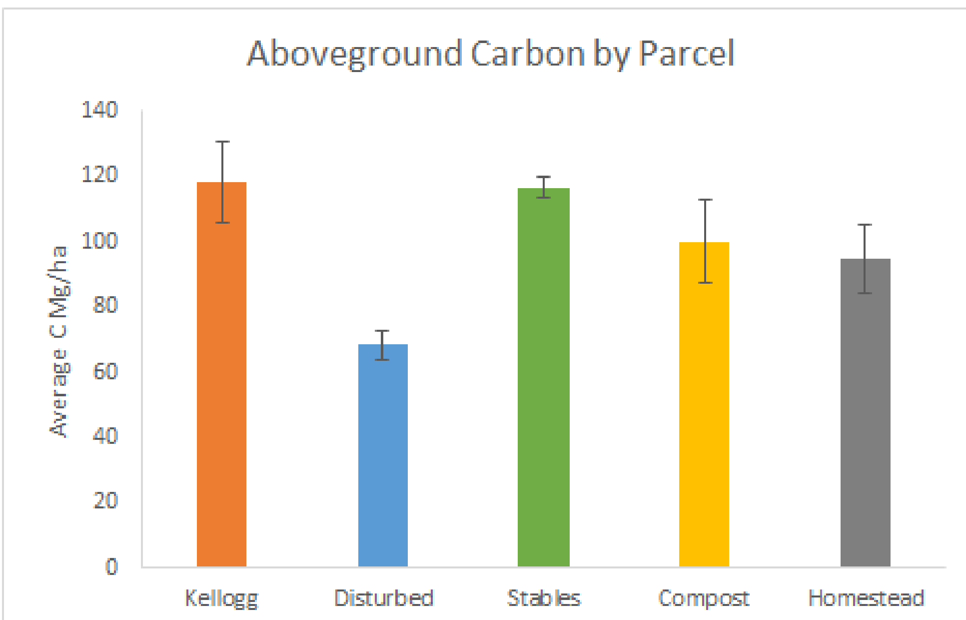

Figure 6. Aboveground carbon across parcels.

Aboveground Across Forest Stand Types

We classified our tree data for each plot into forest stand types based on the two most abundant tree species found in each plot (e.g. Hemlock/Oak). We ended up with 6 stand classification types. The Beech/Oak and Hemlock/Oak stands were by far the most common representing 15 out of the 20 plots we inventoried (7 and 8 plots for Beech/oak and Hemlock/Oak respectively; Figure 7). Out of all the plots, the Beech/Oak stands average the highest amount of carbon in aboveground biomass (M = 109.67, SE = 3.41). Hemlock/Beech stands averaged the lowest carbon in aboveground biomass (M = 45.47, SE = 0). In terms of carbon stored between Beech/Oak Stands and Hemlock/Oak stands, we found no significant difference ($F(1,13) = 0.79$, $p = 0.39$). The other stand types were not considered for analysis since the other stand types only had one sample each.

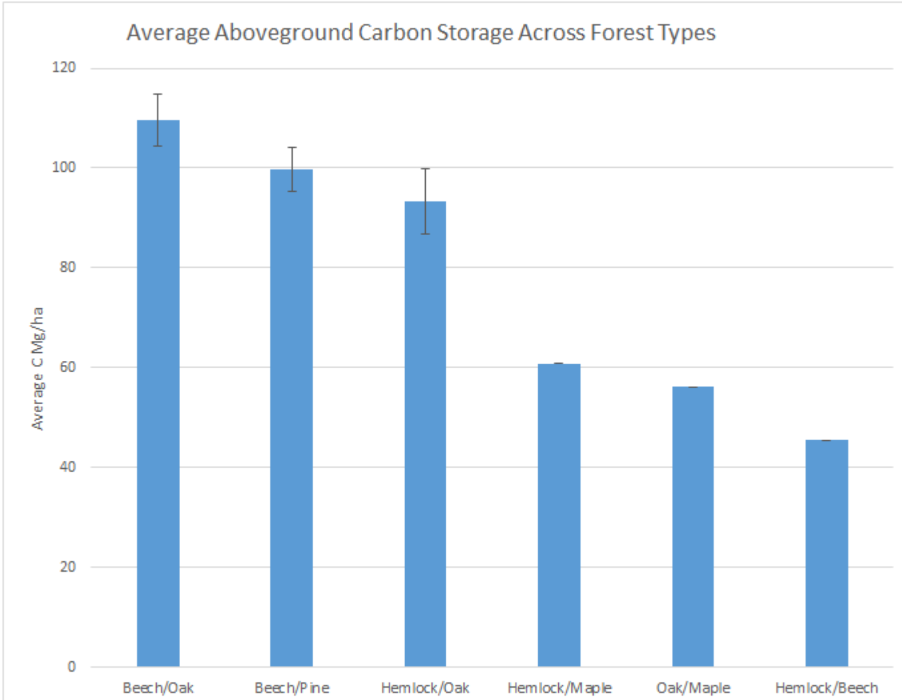

Figure 7. Carbon storage in aboveground across different forest types dominant for plots.

Aboveground and Aspect

To evaluate the influence that aspect had on aboveground carbon storage we ran a one-way ANOVA analysis between north and south facing plots within the disturbed parcel. All other parcels had too few plots with the same aspects making us unable to accurately account for any differences in those parcels. Within the disturbed parcel, we sampled three north facing plots and five south facing plots. We found no significant difference in aboveground carbon storage between the two aspects ($F(1,6) = 2.54$, $p = 0.16$). Across all parcels we sampled 9 North facing plots and 11 south facing plots. On average, north facing plots stored 88.5 Mg/ha of carbon and Southern facing plots stored 98.2 Mg/ha of carbon (North SE = 11.6, South SE = 11.3) Between them we found no significant difference in Aboveground carbon storage ($F(1,18) = 0.35$, $p = 0.56$).

Belowground

Soil proved to be the largest reservoir of carbon among all our plots. It ranked highest in Mg of carbon stored per hectare in all of our parcels (Figure 8). The Stables parcel stored the most carbon per hectare in soil in combined 0-10 cm and 10-20 depths (M = 168.77 Mg/ha, SE = 21.51); followed by Kellogg (M = 147.57 Mg/ha, SE = 18.13), Disturbed (M = 135.01 Mg/ha, SE = 17.91), and Homestead (M = 98.32 Mg/ha, SE = 14.40). Compost (M = 89.13 Mg/ha, SE =

2.40) was excluded due to its limited sample size. A one-way ANOVA revealed that there was no statistically significant difference in combined soil across parcels ($F(4) = 1.50$, $p = 0.22$).

We conducted a one-way ANOVA of 0-10 cm depth soil carbon density across the Stables parcel (M = 199.0 Mg/ha, SE = 19.57), Kellogg (M = 92.15 Mg/ha, SE = 11.02), and Disturbed (M = 83.71 Mg/ha, SE = 14.09), but excluded Compost (M = 55.17 Mg/ha, SE = 14.58). There were no significant differences across these parcels ($F(3) = 2.00$, $p = 0.13$). Neither were there significant differences between 10-20 cm depth soil carbon across parcels ($F(4, 33) = 0.20$, $p = 0.94$). Across parcels, there was considerable variability in the 0-10 cm depth range of soil carbon; this pattern manifested among plots within parcels as well.

Focusing on the soil profile in each parcel, we ran an ANOVA investigating the differences between 0-10 cm and 10-20 cm depth soil carbon densities for Kellogg, Disturbed, and Stables parcels. Compost and Homestead parcels were excluded from this analysis due to low statistical power. Within the Kellogg parcel, there was a significant difference between 0-10 cm and 10-20 cm soil carbon, with 0-10 cm holding more carbon (M = 92.15 Mg/ha, SE =11.02) than 10-20 cm (M = 55.42 Mg/ha, SE = 7.94 ; $F(1) = 7.30$, $p = 0.01$.). There was no significant difference in carbon held between soil depths in the Disturbed parcel ($F(1) = 2.79$, $p = 0.12$). Within the Stables parcel, 0-10 cm soil held more carbon (M = 119.0 Mg/ha, SE = 19.57) than in 10-20 cm depth soil (M = 49.77 Mg/ha, SE = 8.18; $F(1) = 9.90$, $p < 0.01$). Figure 9 displays the average soil carbon (Mg/ha) of each depth in each parcel.

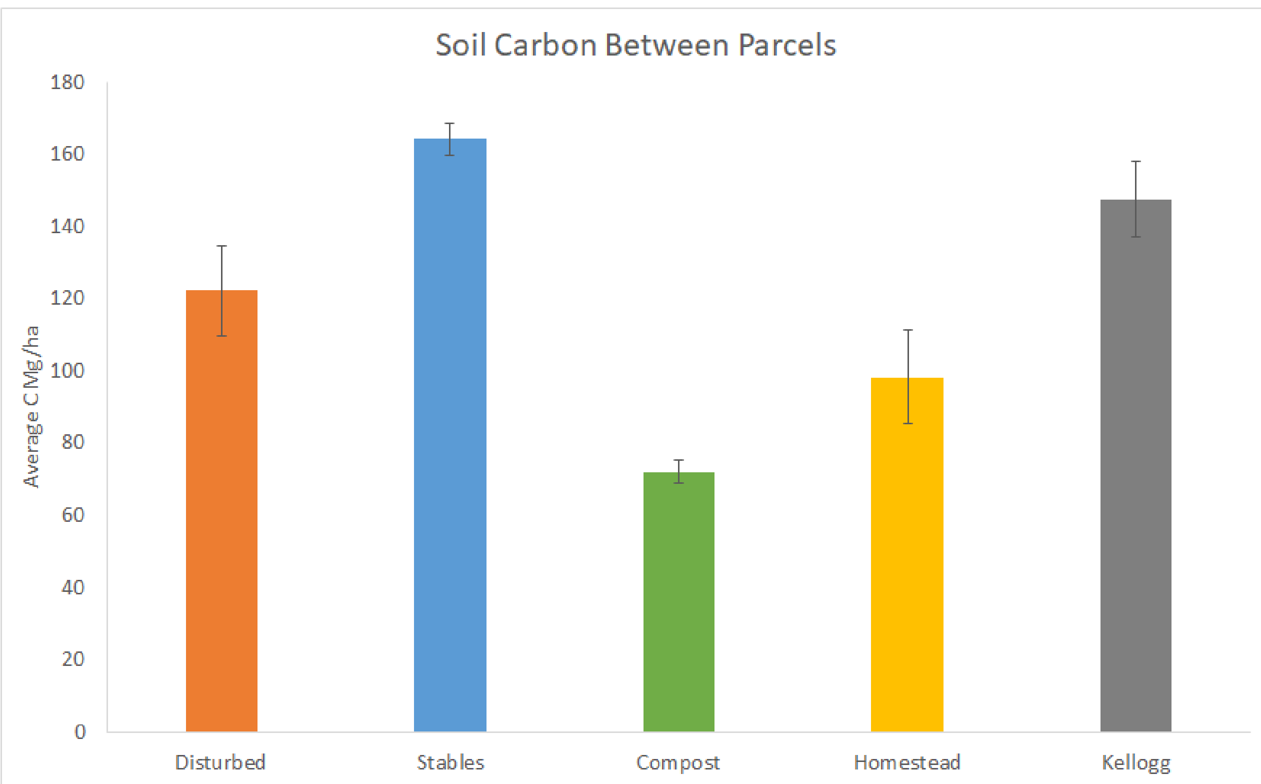

Figure 8. Carbon storage rates in Mg/ha for each parcel. Storage calculations were done only using the combined 0-10cm and 10-20cm depth measurements for each plot.

Kellogg Forest was found to have the most carbon stored in soil, holding a total of 166,754 Mg of carbon. Following Kellogg, the Stables Forest stored 133,364 Mg of carbon in its soil. As expected, our smallest parcels, Homestead and Compost forests, stored far less carbon in soils than either the Kellogg Forest or the Stables Forest (32,347 Mg and 6,506 Mg, respectively). The Disturbed parcel stored 83,684 Mg of Carbon in its soil.

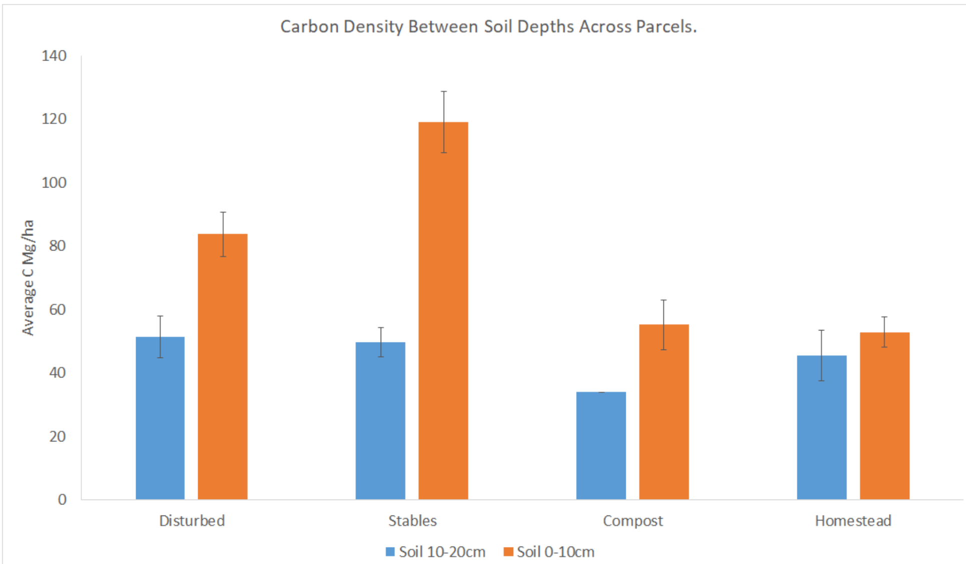

Figure 9. Carbon density found in both soil 0-10 cm and soil 10-20

Soil Carbon and Aspect

To explain the variation in soil carbon data, we compared soil carbon in south-facing plots to soil in non-south-facing plots (Figure 10). Despite 0-10 cm depth soil carbon exhibiting more carbon Mg/ha on south-facing slopes (M = 103.48 Mg/ha, SE = 9.4053) than on other slopes (M = 76.84 Mg/ha, SE = 12.64), there was no significant difference ($F(1,40) = 2.99$, $p = 0.09$). There was also no difference between 10-20 cm depth soil carbon in south-facing plots compared to the rest of the plot samples ($F(1,36) = 3.33$, $p = 0.07$; Figure 11).

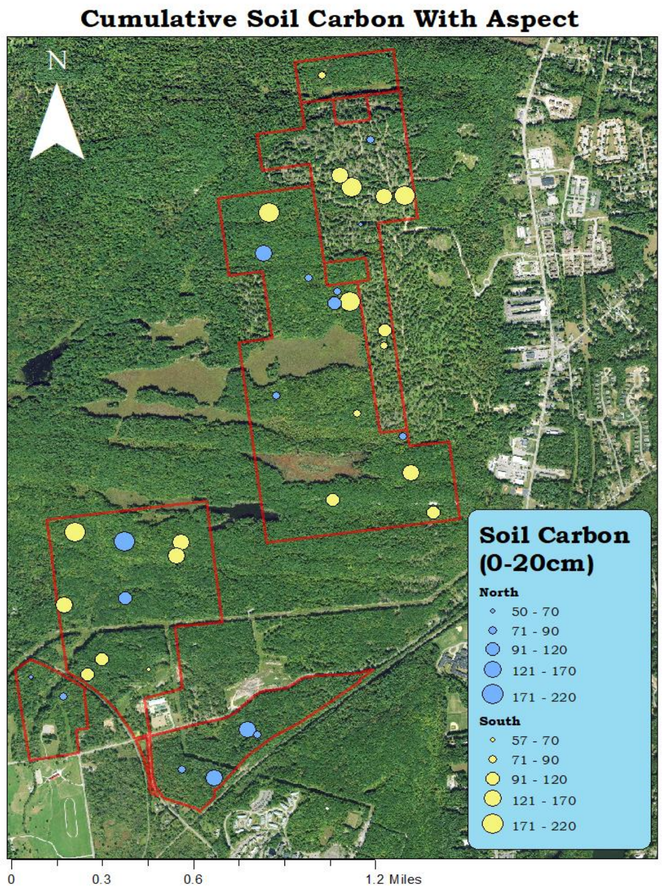

Figure 10. Combined depths soil C within each parcel. Aspect indicated by yellow (south) or blue (north) circles and circle size indicating carbon density found in plot.

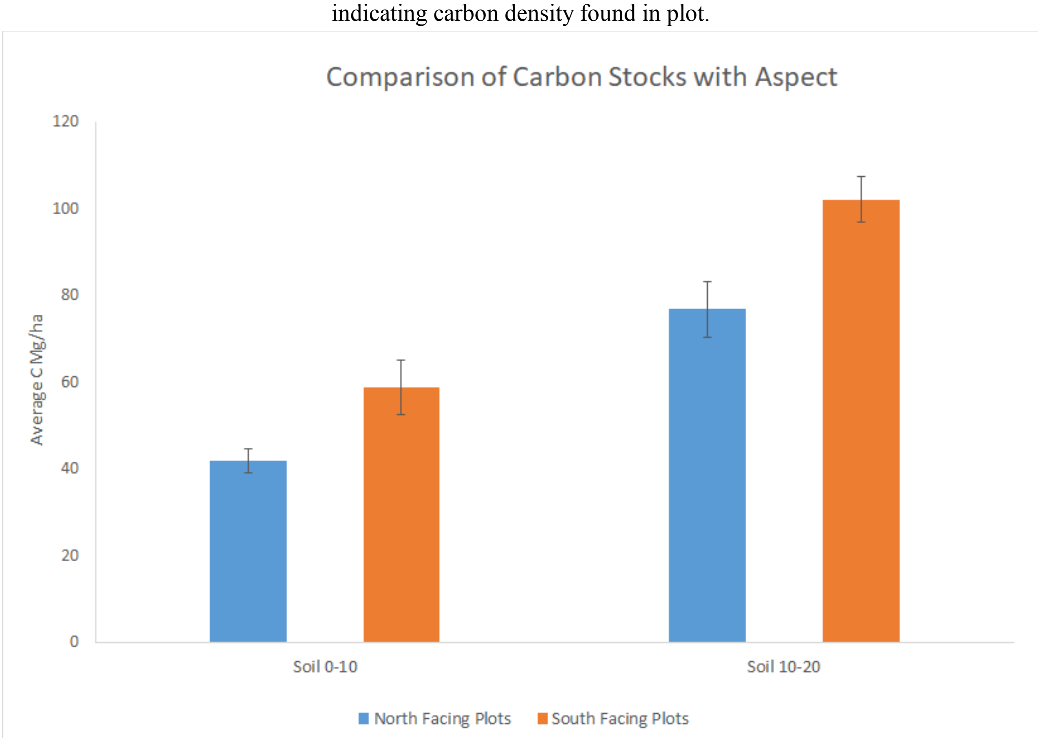

Figure 11. Soil Carbon in 0-10 and 10-20 cm comparing north facing and south facing plots.

Soil by Forest Type Comparisons

When looking at the differences in soil carbon among forest stand type, we analyzed the two most common stand types that we found: Hemlock/Oak and Beech/Oak stands. The four other stand types were not considered for one-way ANOVA analyses since we did not have a big enough sample size. Between the Hemlock/Oak and Beech/Oak stands there was no significant difference in 0-10 cm depth Soil Carbon (F (1, 13) = 1.37, *p* = 0.26). Between the same stands at 10-20 cm soil depths, we found there to be a marginally significant difference in carbon storage (F (1, 11) = 4.56, *p* = 0.056).

Leaf Litter

We discovered Leaf Litter to be the smallest carbon pool of all the pools we looked at. Kellogg parel had the highest amount of leaf litter (3.18 MgC/ha). Homestead was the second highest, with 1.7 MgC/ha. Stables and Compost parcels varied very little with one another, at 0.97 and 1.01 MgC/ha respectively. As expected, the disturbed parcel held the least carbon per hectare (0.58; Figure 12).

Figure 12. Leaf litter carbon (Mg/ha) found in each parcel.

Within parcels, leaf litter showed slight variation, but this variation has little influence when comparing on the scale of other stock's measurements. We did not conduct any statistical analyses between the Compost, Disturbed or Homestead parcels because we only took leaf litter samples from two plots in each of those parcels. Between leaf litter carbon in the Kellogg parcel and the Stables parcel we found no significant difference (F (1, 6) = 2.39, *p* = 0.17). Kellogg forest showed the largest variation (M = 3.14 Mg/ha, SE = 1.4). Other parcels each had standard errors $<$1. This variation can be seen in Figure 13.

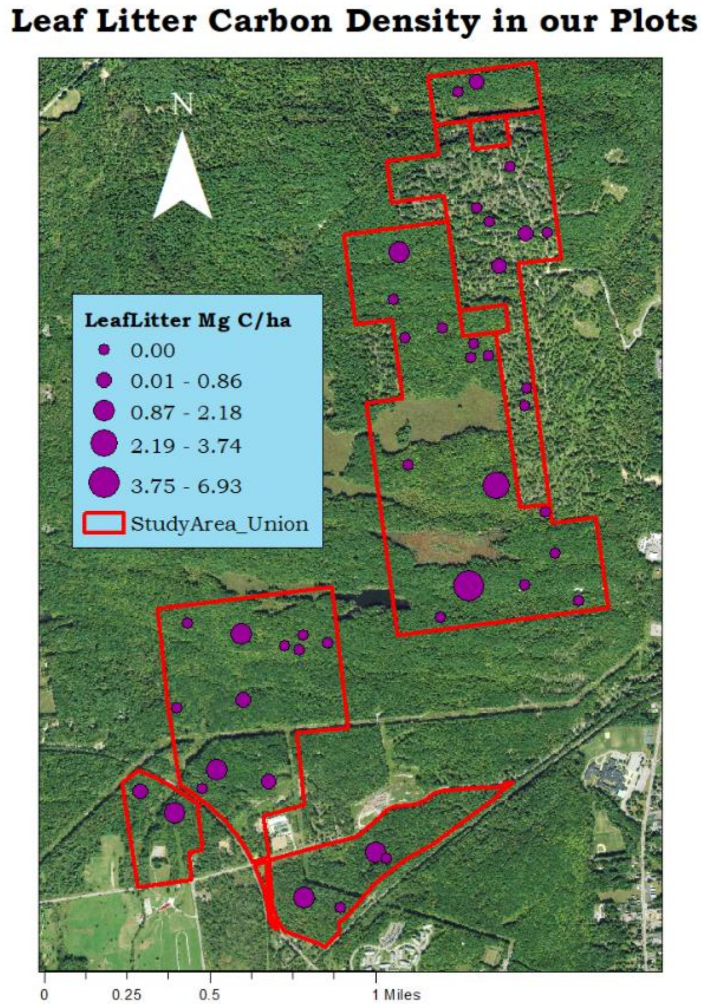

Figure 13. Map of leaf litter carbon densities among study plots. Plots with zero were not sampled for leaf litter.

To investigate the potential impacts forest type may have had on leaf litter carbon pools, we conducted a one-way ANOVA between leaf litter carbon densities from Hemlock/Oak plots and Beech/Oak plots (our two most common forest types). Other forest types were not analyzed for potential impacts on leaf litter carbon pools because we did not have big enough sample sizes. Between Hemlock/Oak plots and Beech/Oak plots, there was no significant difference in leaf litter carbon densities ($F(1, 9) = 1.35$, $p = 0.27$).

<u>Deadwood</u>

Second to leaf litter, deadwood accounted for the smallest portion of carbon stored in our parcels. The Compost parcel, our smallest parcel, was found to have the highest average rate of carbon stored in deadwood (M = 8.55 Mg/ha, SE = 0.87). After running a one-way ANOVA to find differences between parcels, we found there was still no significant difference between any parcels ($F(4,13) = 0.35$, $p = 0.84$). This included the compost parcel which differed the most drastically from others (Figure 14).

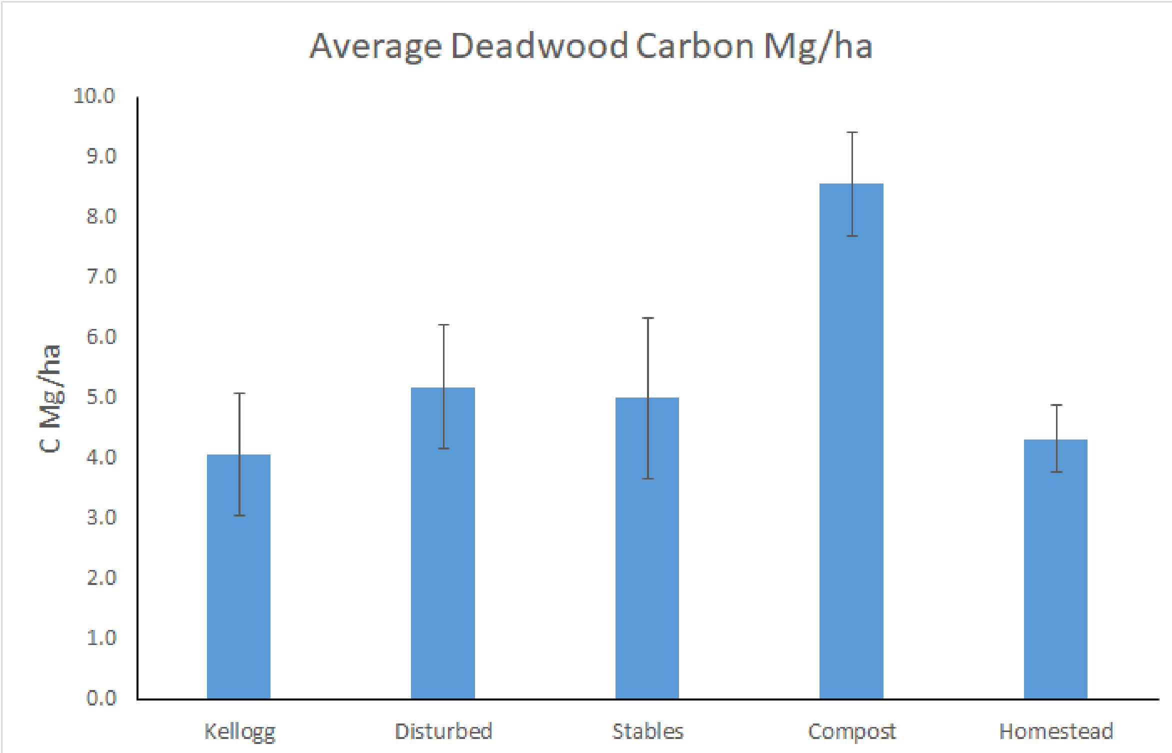

Figure 14. Deadwood carbon (Mg/ha) found in each parcel.

<u>Overall carbon per parcel</u>

When pools were combined to look at the overall carbon storage of each parcel, Stables exhibited the highest Mg/ha carbon density at 291 Mg/ha, followed by Kellogg at 273 Mg/ha, Disturbed at 209 Mg/ha, Compost at 199 Mg/ha, and Homestead at 199 Mg/ha (Figure 15). Because each parcel has mixed aged forests and have all been impacted by disturbance at different points of time (with the exception of the Disturbed Parcel, which has been more recently and extensively logged), we compared Kellogg, Homestead, Compost, and Stables to a forest stand of about 65 years old. The total carbon storage of an 65 year-old stand in the Northeast US is 227.3 Mg/ha for above and belowground (Smith et al. 2005). It is important to note that all the carbon densities reported thus far do not account for wetland carbon data.

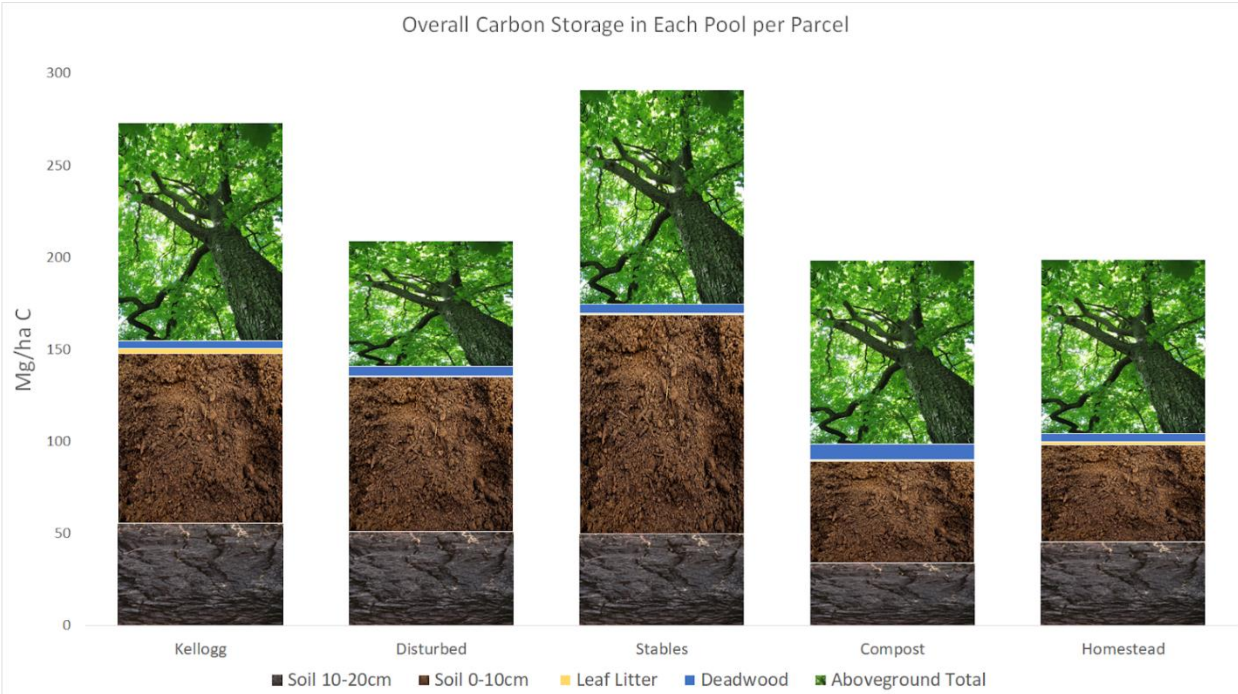

Figure 15. Total average carbon density (aboveground, deadwood, leaf litter, and soil in both depths) in each parcel.

When looking at the impact of North vs. South aspects on carbon storage among all our parcels, we found no significant differences (F (1, 18) = 0.061, p = 0.81). However, we did see a trend where south-facing plots generally had slightly higher overall carbon than their north-facing counterparts (Figure 16).

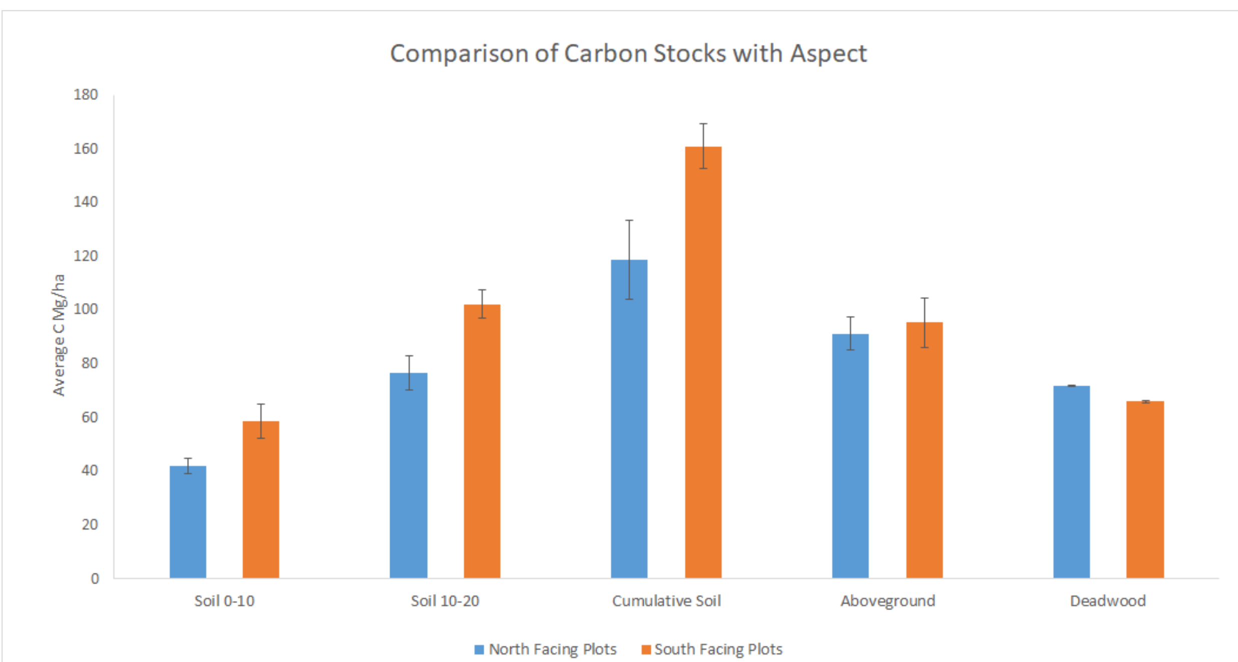

Figure 16. Average carbon (Mg/ha) in each stock separated by north and south facing plots.

Wetlands

Wetland samples for depths 110-120 cm and 190-200 cm were sent to Ward Laboratories for carbon analysis. 110-120 cm samples were 31.366% carbon and 190-200 cm samples were 41.161% carbon. From those numbers we got a total carbon density of 962.5 Mg/ha for our wetlands. After amalgamating the wetland carbon density and the Kellogg parcel's carbon density without wetlands we got a cumulative carbon density of 420 Mg/ha for the Kellogg parcel (Figure 17).

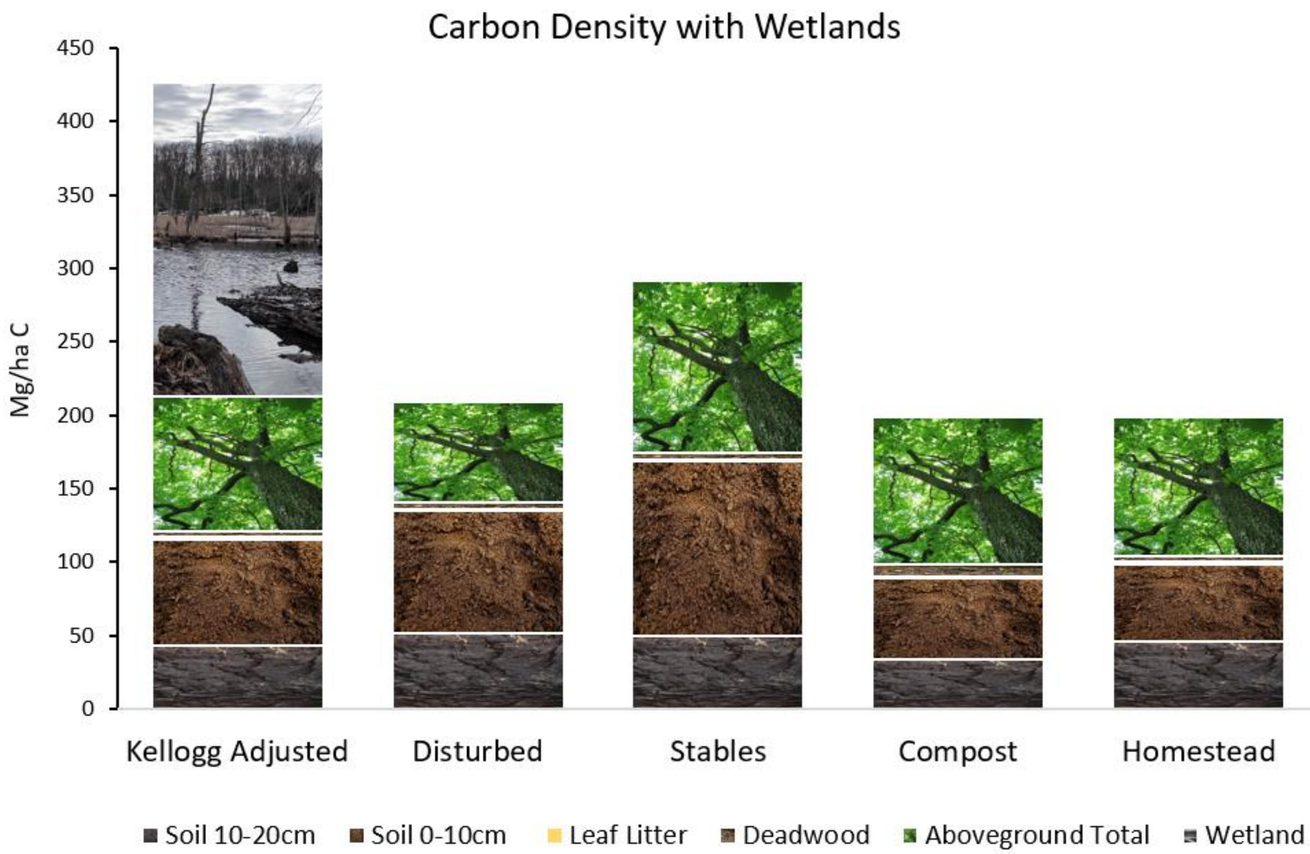

Figure 17. Average carbon density of each stock in each parcel including wetlands in Kellogg.

Discussion

This study established an extensive plot network in Skidmore's unmanaged forested lands to monitor carbon storage. From 42 plots, we gathered a baseline measurement of carbon in soil (0-10 & 10-20 cm), trees, leaf litter, and deadwood pools. The samples we gathered for each of these pools were characterized by variation both between and within parcels. This can be explained by both biotic and abiotic factors. A more robust sampling strategy in all pools is warranted, specifically for aboveground stocks (deadwood, trees, and leaf litter) and wetlands.

Belowground Carbon

The most robust sampling in this study was of soil. 4 samples were taken from each of our 42 plots: 2 from 0-10 cm depths and 2 from 10-20 depths. Our results were incredibly variable, specifically in the Stables parcel. This could be accounted for by examining the slope and aspect of the samples taken, most of which were uniform across a ridge (perhaps a result of random point generation). Future studies may benefit from establishing additional plots in the network that account for other slopes, aspects, and a more proportionate forest type representation. Aspect showed no statistically significant effect on soil carbon, however with more precise estimates of aspect and a higher sampling density, this could be analyzed further.

Soil carbon found in Stables was the highest out of all parcels. Kellogg Forest accounted for the second highest carbon in soil pools, specifically in 10-20 cm depths. Kellogg and Disturbed Parcels were comparable, since Disturbed was previously a section of the Kellogg Parcel. It has since experienced patches of logging and blasting, characterizing it as having undergone intense disturbance. Due to this, one would expect shallow soils (containing more organic matter) to be affected more by disturbance. The disturbance also may have mixed the two soil layers, lowering the difference and blurring the line between our two soil depths. This was shown in a significant difference between Kellogg 10-20 cm depth soil carbon and 0-10 cm depth soil carbon, however this difference was not statistically significant for the Disturbed parcel. Perhaps without this past disturbance, this difference would be more pronounced and soil in 10-20 cm depth in Disturbed would exhibit higher amounts of carbon storage. However, at the same time, there were no differences between parcels in both depths of soil carbon. This attests to the variation within the parcels, since means between parcels were very different (however, not statistically).

Overall, soil remained the biggest pool of carbon with both depths combined, indicating that management for carbon sequestration should emphasize soil's productivity and harness the carbon in this stock to its fullest potential.

Aboveground Carbon

Sampling of aboveground carbon pools was less robust than that of soil; we sampled 0.44% of the Homestead, 1% of Compost, 0.34% of Stables, 0.25% of Kellogg, and 1% of Disturbed. This leaves our findings subject to variation in forest type, aspect, topography, and other variables, as well as underrepresented forest stands. Despite variation, it is clear that the difference in overall carbon density between Kellogg and Disturbed parcels is due to the differences in aboveground carbon, itself a function of the disturbance. Disturbed also held less aboveground carbon than Stables, Compost, and Homestead. However, this stock had the strongest contribution to overall carbon in each parcel after combined soil (0-10 & 10-20), which is comparable to other Northeast temperate forests (Smith et al. 2005).

Deadwood and Leaf Litter

Leaf litter and deadwood accounted for the smallest portions of our parcel totals. As intermediaries between aboveground and belowground carbon however, they are immensely important. We recommend future research to use a higher sampling intensity with these stocks. This would hopefully tease out some of the within plot variation that we saw in each parcel. A higher sampling density would also increase the certainty in our calculations.

The highest amounts of leaf litter were found in the Kellogg parcel. This parcel also had the most aboveground carbon, a correlation that we expected to see.

As can be seen in figure 14**,** deadwood in the Disturbed Parcel holds about one mgC/ha more on average than the Kellogg Parcel. This relationship was not statistically significant but nonetheless we expected to see it considering the degree to which the disturbed parcel was logged (66% vegetation loss).

None of the potential variables we investigated appeared to effect deadwood density among parcels or plots. This was likely due to our small sample size and resultant low statistical power; we could probably attribute the lack of statistical differences between parcels to this as well.

Overall Carbon

Beyond sampling intensity, consideration of other driving factors for differences in carbon within and across parcels is warranted. Constraints on carbon storage in northeast temperate forests can be a function of species composition, stand age, and climate (Gough et al. 2008). Carbon storage of forests vary based on age, with older forests holding more carbon, particularly aboveground (Pregitzer and Euskirchen 2004). Although sharing the same climatic region, the parcels in this study have varying historical legacies of land use and disturbance that explain carbon storage differences. These factors have shown to be influential in shaping ecosystem function (Foster et al. 2003). Gough et al. (2007b) demonstrated that disturbances from the 19th and 20th centuries have impacts on present day carbon storage due to decreased site productivity and reduced soil fertility and carbon sequestration rates (Latty et al. 2004; Bergeron and Harvey 1997). This is likely true for our study sites as well.

Homestead and Compost held the least carbon per hectare, which likely can be explained by land use and its impact on productivity and age. Homestead in particular shows a rich history of land-use and disturbance. In the southwest corner of the Homestead parcel, an estate was built in the late 1700s with established trails around the property that are mostly overgrown today. The estate included a large house, gates, wells, a barn, and cultivated trees (Skidmore Woodland Atlas, 2012). This likely constrained carbon storage of this parcel's forest.

Compost parcel was home to the most saplings, and a younger forest stand was evident when we sampled aboveground carbon. Roughly half of the compost parcel was a white pine dominant stand with large widely spaced trees and relatively high amounts of deadwood. This and the young stand may have contributed to the lower levels of aboveground carbon found in the Compost parcel.

Stables forest was home to the greatest carbon density found in this study. In comparison to Homestead and Compost, the stands in this parcel were likely older and less affected by land-use and development. This parcel was formerly a part of Woodlawn Park since the 1880s, who built estates on the land and maintained its forests. There are also walking and mountain biking trails that have been maintained (Skidmore Woodland Atlas, 2012).

Kellogg parcel also has a unique history of land use. The Roohan family owned the land (before donating it to Skidmore) since the 1880s and it has remained undeveloped. Its history prior to Roohan ownership is documented by previous seasonal roamers (Skidmore Woodland Atlas, 2012). There are a few trails networking through Kellogg that have not been maintained. This also demonstrates that minimal past disturbance could affect carbon sequestration in these lands, explaining a higher carbon density.

Disturbed parcel, a contiguous forest to Kellogg, demonstrated loss of carbon from logging. Because they are contiguous, we'd expect similar carbon storage if no logging had taken place. The loss was mostly evident from the significant difference in aboveground storage. Logging also has demonstrated impacts on soil carbon storage (Nave et al. 2010), however there was no significant difference in this study, which perhaps warrants more sampling to look at this relationship more closely.

The variables investigated in this study did not adequately explain the evident variation. Both forest composition and aspect showed different trends in carbon storage, but no significant differences were found. Previous studies have shown the carbon stored in forest soils is related to species composition (Gower et al. 1997). No conclusions can be made about how these variables affected carbon storage in this study though due to low statistical power.

We discussed two main growth-limiting factors that could explain what impact aspect may have on carbon storage in plots and why: water and light. Southern facing slopes are exposed to more light and are drier compared to northern facing slopes which retain more moisture and are cooler. In a Northeastern temperate forest, moisture is abundant and therefore sunlight is most likely a larger driver of productivity between the two aspects. For such reasons, southern facing plots would then be more productive and effectively sequester more carbon.When looking at the impacts between our two aspects (north or south), south facing plots appeared to be store slightly more carbon in soil compared to north facing plots. Although this was not a statistically significant result, a larger sampling size of both aspects could potentially reveal a significant difference between soil carbon among aspects and strengthen that result.

Looking at the same trend in aboveground, on average north facing plots stored about 10 Mg of carbon per hectare less than southern facing plots. This result, although not significant, could also be explained by the greater abundance of sunlight in south facing compared to north facing plots driving more aboveground productivity. This trend was not looked at for leaf litter or deadwood since their sample sizes were not large enough.

Carbon content can vary substantially across tree species (Lamlom & Savidge, 2003). This is why we used specific carbon content parameters for specie groups when calculating aboveground carbon. Typically, coniferous trees contain slightly percentages of carbon in their biomass compared to hardwood trees (Lamlom & Savidge, 2003). These differences could therefore explain some of the variability in carbon densities across plots. If a plot was dominated by conifers, it could then contain more carbon in its aboveground stock, and potentially its soil stock since the deadwood from those trees and the leaf litter from those trees contributes to the organic material and therefore carbon building up in the soils stocks. Leaf litter from hemlock stands breaks down much slower than deciduous leaf litter. The needles of conifers have a much higher lignin content than deciduous leaves. We thus expected this humic layer to be represented in our soil carbon measurements. It was not. The 10-20 cm cores of soil, however, tended to have higher carbon values in coniferous stands rather than deciduous. Lack of significant differences could possibly change with a larger sample size and more in depth, multivariate statistical analyses.

Implications for Skidmore's Sustainability Goals

We decided to compare our parcel specific carbon densities to a baseline carbon density of forests in the Northeastern United States. The portion of a parcel's carbon density that was then above the baseline would be used to calculate the total carbon in that parcel. That total carbon was then converted to CO_2eq which Skidmore could theoretically count towards their GHG emission inventory. After several conversations with faculty of Skidmore College, this comparison was determined as a suitable method for our study to calculate theoretical CO_2eq for Skidmore's GHG emissions inventory. However this method is one of many and Skidmore could revise and change this methods for future calculations.

We used 65 years old as the median age of forests in the Northeast United States (US Forest Service, 2014). In Pearson et al. (2014), 65 year old maple-beech-birch stands in the Northeast on average contain about 227.3 Mg/ha of carbon. We used this estimate as a baseline carbon density to compare to the carbon densities of each of our plots. We found that the Kellogg and Stables parcels were both over this baseline (273.3 Mg/ha and 291.2 Mg/ha carbon respectively). Using the 48.27 Mg/ha of carbon above baseline in Kellogg to calculate total carbon for the Kellogg parcel area (118 ha without wetlands), Kellogg contains a total of 5,454.64 Mg of carbon. Doing the same for Stables (66.17 Mg/ha above baseline), Stables contains a total of 5558 Mg of carbon. If this method is used, Kellogg and Stables combined therefore have a total of 40,416 Mg of CO_2eq that Skidmore could count as sequestered carbon in their GHG inventory to help them achieve their goal of reducing their GHG emissions from the year 2000 by 75 percent by the year 2025. If Skidmore were to count all of those emissions they would achieve a 234 percent reduction from their 2000 emissions (17,237 Mg CO_2eq emitted in the year 2000).

After first doing this calculation we debated the rigor and accuracy of the method we used to get 40,416 Mg of “sequestered” CO_2eq. We decided that even though this number was above the baseline we generated, it was still an overestimate of how much CO_2eq is actively being sequestered by the woodlands that we studied. We then decided to examine a more conservative estimate of how much CO_2eq was being sequestered by those lands on a yearly basis. We used carbon data from Smith & USFS (2006) to estimate the yearly growth of carbon of our parcels based on the growth rates of similar forest stands listed in the paper. We used the growth rates for just the Kellogg and Stables parcels because they were the only ones above our baseline. We estimated a average rate of 2.15 Mg/ha of carbon per year for both those parcels then multiplied that rate by the number of hectares in both Kellogg and stables (without wetlands). This resulted in a rate of about 423 Mg of carbon sequestered by those two parcels in just one year. That is equal to 1,552 Mg of CO_2eq sequestered in one year of growth from these parcels. So therefore 9 percent of Skidmore’s GHG emissions from the year 2000 would be sequestered in one year by just the Kellogg and Stables parcels. This percentage we found to be a more conservative but fair projection in terms of GHG sequestration by these parcels. Including the 40% reduction in emissions Skidmore has achieved so far, plus the 9% from these parcels, Skidmore would achieve a 49% reduction in their GHG emissions from 2000.

When an institution like Skidmore decides to count their forest carbon towards their institutional emissions inventory, a verification of how much carbon is actually being sequestered in their forests is necessary. This happens either by hiring a third-party to verify the forest carbon countable towards their emissions or by conducting an internal inventory, like our study, then having the study be reviewed by another institution. Because our study is the first to look at all of Skidmore’s un-managed woodland parcels, and because our sample size was pretty small, another more rigorous and thorough inventory of all the parcels either by a third party or another internal study, such as ES capstone, is necessary for these parcels to legitimately be counted in Skidmore’s GHG inventory. Moving forward, this inventory can expand to a carbon offset project if promising.

However Skidmore decides to count the carbon in our study parcels towards their inventory, Kellogg and Stables should be the only parcels considered for that inventory since they are the only one we found to have carbon densities above our baseline. No densities above baseline should be used in calculating sequestration rates either. A more rigorous baseline should also be generated using more accurate ages of the different parcels.

Management Plan

We discovered that the forests in Kellogg and Stables forests hold more carbon than a standard Northeastern US baseline. This can have different implications for a management plan depending on how one counts this carbon towards reductions in Skidmore's GHG inventory. For the baseline method we used in this study, we counted all carbon above our baseline towards Skidmore's GHG inventory. This is a more conservative estimate than other methods may yield. Since only two of our parcels were above this baseline, Kellogg and Stables, we believe that the carbon held within these parcels should be prioritized above others.

The Stables parcel is currently being managed by Saratoga Mountain Biking Association (SMBA). They have maintained foot and bike paths throughout the Stables parcel. In future practice these trails should remain maintained, but no new trails should be created. According to Nunery & Keeton (2010), the best management plan for carbon sequestration is no active management. No trees should be harvested, and no trails should be established in these parcels. These parcels should be allowed to remain mature forests and continue sequestering carbon at their natural rate. In order to keep track of the carbon sequestered in these parcels, a denser plot network should be established, particularly in the Stables parcel. This would give Skidmore higher resolution and certainty in their carbon calculations.

Wetlands are a large, and presently unaccounted for, stock in our parcels. The Kellogg parcel has the largest, 32 hectares of palustrine emergent wetlands. This and other parcels have forested wetlands scattered throughout; these are much harder to quantify. While we and pre-existing research have established that wetlands are impactful carbon sinks (Chimner et al. 2014; Sills, Halter, Frank, 2017), the decision to include the wetland in a management plan remains unmade. Further measurements of our wetlands are required to make an informed decision on this front.

The Disturbed parcel was a contiguous forest with Kellogg prior to being logged. This leads us to expect that once the Disturbed parcel has progressed through succession to become a mature intact forest once more, it will hold an equal or greater density of carbon than the Kellogg parcel. The Disturbed parcel provides a unique opportunity for education, since it is currently undergoing successive stages following 66% tree cover loss.

The compost and homestead parcels seem less suited for carbon sequestration oriented management due to their relatively low carbon densities. While we think all parcels should be managed for sequestration, education, and recreation in tandem, these smaller parcels should prioritize the latter two objectives in their management.

Moving Forward

Taking pre-discussed variables into account, we believe that future studies must prioritize establishing a more rigorous plot network. This will give statistical power to analyses regarding variables as well as more accurate estimations of carbon density for each stock within each parcel. Regular measurements of plots should also be conducted; this will give us a more accurate rate of sequestration over time. Area of uncertainty can thus be reduced, and more advanced multivariate modeling analyses can be conducted to understand more thoroughly the carbon cycling and forest dynamics in these parcels, as well as the variables that explain these processes. This will also confirm or reject our model generating rates of sequestration.

We also recommend expanding on this study in new ways. An expansion of the plot network should focus on carbon held in wetlands as well as in forested areas. This will give us more accurate numbers to help determine whether wetlands should be included in the GHG inventory in addition to Kellogg and Stables forests. We also recommend taking tree cores to gather an age estimate of these forests, which will also help in examining the rate of carbon sequestration. Additionally, sampling took place in the winter, which complicated sampling strategy because of frozen soil and leaf litter. We recommend that Skidmore continue this project, but during the summer and shoulder seasons to reduce these complications. This would provide more time for the project to achieve a higher sampling intensity and collect more data.

As discussed earlier, Skidmore should count carbon in Kellogg and Stables parcels towards our GHG inventory. As these forests grow, additional carbon can be counted towards this inventory as these parcels hold larger carbon stocks. Management should proceed accounting for this.

Skidmore is unique in its ownership of 400 hectares of forested land directly north of campus. We should capitalize upon the educational value of this land by taking classes out to the forests and treating their management as a learning opportunity. Future capstones and student employees should carry out the aforementioned research, measurements, and modeling. Regrowth of the disturbed parcel will serve as an opportunity to witness the successional stages of a northeastern forest firsthand. Through the course of this study, we have found that Skidmore's northern forested parcels serve as efficient carbon sinks, educational opportunities, and should be open for recreation.

References

Bellassen, V., and S. Luyssaert. (2014). Carbon sequestration: managing forests in uncertain times. *Nature* 506:153-155.

Bergeron Y, Harvey B. (1997). Basing silviculture on natural ecosystem dynamics: An approach applied to the southern boreal mixedwood forest of Quebec. *Forest Ecology and Management* 92: 235-242.

Bianco, A., Dalsetin, F., Feikens, J. Post, J., Rosenthal, L., Winward, J. (2017). Colgate University Campus Forest Offset Project Analysis.

Bouwman, A.F., Leemans, R., (1995). The role of forest soils in the global carbon cycle. In: McFee, W.W., Kelly, J.M. (Eds.), Carbon Forms and Functions in Forest Soils. *Soil Science Society of America, Madison, WI,* pp. 503–526.

Brown S. (1996). Tropical forests and the global carbon cycle: estimating state and change in biomass density. *Apps M.J., Price D.T. (eds) Forest Ecosystems, Forest Management and the Global Carbon Cycle. NATO ASI Series (Series I: Global Environmental Change), vol 40*. Springer, Berlin, Heidelberg

Brown, S. (2002). Measuring carbon in forests: current status and future challenges. *Environmental Pollution*. 116: 363-372.

Brown, S., J. Sathaye, M. Cannell, P. Kauppi, P. Burschel, A. Grainger, J. Heuveldop, R. Leesman, R. Moura Costa, M. Pinard, S. Nilsson, W. Schopfhauser, R. Sedjo, N. Singh, M. Trexler, J. van Minnen, and S. Weyers. (2005). *Management of Forests for Mitigation of Greenhouse Gas Emissions.* DOE, United States.

Cairns, M.A.; Brown, S.; Helmer, E.H.; Baumgardner, G.A. (1997). Root biomass allocation in the world's upland forests. *Oecologia* 111: 1-11.

Chimner, R., Ott, C., Perry, C., & Kolka, R. (2014). Developing and evaluating rapid field methods to estimate peat carbon. *Peatlands, 34*(6), 1241-1246. doi:10.1007/s13157-014-0574-6

Jenkins, Jennifer C. (Jennifer Caroline), & United States. Forest Service. Northeastern Research Station. (2004). *Comprehensive database of diameter-based biomass regressions for north american tree species* Retrieved from http://hdl.handle.net/2027/umn.31951d029747814

Dixon, R. K., Solomon, A. M., Brown, S., Houghton, R. A., Trexier, M. C., & Wisniewski, J. (1994). Carbon pools and flux of global forest ecosystems. *Science, 263*(5144), 185-190. doi:10.1126/science.263.5144.185

Foster D, Swanson F, Aber J, Burke I, Brokaw N, Tilman D, Knapp A. (2003). The importance of land-use legacies to ecology and conservation. *BioScience 53*(77-88).

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. Liu, G. Nabuurs, S. Nilsson, and A. Z. Shvidenko. (2002). Forest Carbon Sinks in the Northern Hemisphere. *Ecological Applications 12*(891)

Gough CM, Vogel CS, Kazanski C, Nagel L, Flower CE, Curtis PS. (2007b). Coarse woody debris and the carbon balance of a north temperate forest. *Forest Ecology and Management 244*(60-67).

Goward, S. N., Masek, J. G., Cohen, W., Moisen, G., Collatz, G. J., Healey, S., . . . Wulder, M. A. (2008). Forest disturbance and north american carbon flux. *Eos, Transactions American Geophysical Union, 89*(11), 105. doi:10.1029/2008EO110001

Gower ST, Vogel JG, Norman JM, Kucharik CJ, Steele SJ, Stow TK. (1997). Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. *Journal of Geophysical Research - Atmospheres* 102: 2902929041.

Harmon, Mark E. (2001). Carbon sequestration in forests: Addressing the scale question. *Journal of Forestry 99*(24).

Holden, J. (2005). wetland hydrology and carbon release: Why small-scale process matters. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 363*(1837), 2891-2913. doi:10.1098/rsta.2005.1671

Hoover, C. M., and L. S. Heath. (2011). Potential gains in C storage on productive forest lands in the northeastern United States through stocking management. Ecological Applications 21:1154-116IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].1.

Hughes, R. F., Kauffman, J. B., & Jaramillo, V. J. (1999). Biomass, carbon, and nutrient dynamics of secondary forests in a humid tropical region of Mexico. *Ecology*, 80(6).

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., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-scale biomass estimators for United States tree species. *Forest Science*, *49*(1), 12–35.

Keddy Paul A, and Chris G. Drummond. (1996). Ecological Properties for the Evaluation, Management, and Restoration of Temperate Deciduous Forest Ecosystems. *Ecological Applications 6*(748-762).

Körner, C. (2003), Carbon limitation in trees. *Journal of Ecology, 91*(4-17). doi:10.1046/j.1365-2745.2003.00742.x

Körner, C. (2003). Slow in, Rapid out: Carbon Flux Studies and Kyoto Targets. *Science* 300:1242-1243.

Lamlom, S. H., & Savidge, R. A. (2003). *A reassessment of carbon content in wood: Variation within and between 41 north american species* doi://doi.org/10.1016/S0961-9534(03)00033-3.

Latty EF, Canham CD, Marks PL. (2004). The effects of land-use history on soil properties and nutrient dynamics in northern hardwood forests of the Adirondack Mountains. *Ecosystems 7*(193-207).

Madej, M. A. (2001). Erosion and sediment delivery following removal of forest roads. *Earth Surface Processes and Landforms 26*(175-190).

Magnani, F., M. Mencuccini, M. Borghetti, P. Berbigier, F. Berninger, D. Delzon, A. Grelle, P. Hari, P. Jarvis, P. Kolari, A. Kowalski, H. Lankreijer, B. Law, A. Lindroth, D. Loustau, G. Mancal, J. Moncrieff, M. Rayment, V. Tedeschi, R. Valentini, and J. Grace. (2007). The human footprint in the carbon cycle of temperate and boreal forests. *Nature Photonics 447*(848).

Nabuurs, G. J., and R. Sikkema. (2001). International trade in wood products: its role in the land use change and forestry carbon cycle. *Climatic Change 49*(377-395).

Nabuurs, G.J., Masera, O. et al. (2007). Forestry, in Climate Change. (2007). Mitigation. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A., Eds., Contribution of working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, Cambridge University Press, 541-584.

Nave L. E., C. M. Gough, K. D. Maurer, G. Bohrer, B. S. Hardiman, J. Le Moine, A. B. Munoz, K. J. Nadelhoffer, J. P. Sparks, B. D. Strahm, C. S. Vogel, and P. S. Curtis. (2011). Disturbance and the resilience of coupled carbon and nitrogen cycling in a north temperate forest. Journal of Geophysical Research. *Biogeosciences 116*.

Nave, L. E., E. D. Vance, C. W. Swanston, and P. S. Curtis. (2010). Harvest impacts on soil carbon storage in temperate forests. *Forest Ecology and Management 259*(857-866).

Nunery, J. S., & Keeton, W. S. (2010). Forest carbon storage in the northeastern united states: Net effects of harvesting frequency, post-harvest retention, and wood products. *Forest Ecology and Management, 259*(8), 1363-1375. doi:10.1016/j.foreco.2009.12.029

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R. A., Kauppi, P. E., Kurz, W. A., . . . Hayes, D. (2011). A large and persistent carbon sink in the world's forests. Retrieved from http://cfs.nrcan.gc.ca/publications?id=32606

Pearson, T. R. H. (2007). *Measurement guidelines for the sequestration of forest carbon*. United States: Retrieved from http://catalog.hathitrust.org/Record/007425881

Pekka E. Kauppi, Jesse H. Ausubel, Jingyun Fang, Alexander S. Mather, Roger A. Sedjo, & Paul E. Waggoner. (2006). Returning forests analyzed with the forest identity. *Proceedings of the National Academy of Sciences of the United States of America, 103*(46), 17574-17579. doi:10.1073/pnas.0608343103

Post WM, Mann LK. (1990). Changes in soil organic carbon and nitrogen as a result of cultivation. In: Soils and the Greenhouse Effect (ed Bouwman AF), pp. 401-406. John Wiley & Sons, New York.

Robin L. Chazdon. (2008). Beyond Deforestation: Restoring Forests and Ecosystem Services on Degraded Lands. *Science 320*(1458-1460).

Rosen, J., Green, M., Lipshutz, S., Tatkow, M. (2013). Skidmore Woodland Atlas.

Roy, J., Saugier, B. & Mooney, H. A. (2001). Terrestrial global productivity.

Ruddell, S, R. Sampson, Matt Smith, R. Giffen, James Cathcart, John Hagan, Daniel Sosland, John Godbee, John Heissenbuttel, Stephen Lovett, John Helms, William Price, Robert Simpson. (2007). The Role for Sustainably Managed Forests in Climate Change Mitigation, *Journal of Forestry*, *105*, Issue 6, 1 , Pages 314–319, https://doi.org/10.1093/jof/105.6.314

Ruddell, S., M.J. Walsh, M. Kanakasabai. (2006). *Forest carbon trading and marketing in the United States.* A Report to the North Carolina Division of the Society of American Foresters. Available online at www.foreconinc.com/articles.asp?NewsID34.

Schimel, D. S. Terrestrial ecosystems and the carbon cycle. (1995) *Global Change Biol.* 1, 77–91.

Bridgham, Scott D, Megonigal, J. Patrick, Keller, Jason K, . Bliss, Norman B, Carl Trettin. (2006). The carbon balance of north american peatlands. *Peatlands, 26*(4), 889-916. doi:TCBONA]2.0.CO;2.

Smith, J. E., Heath, L. S., Skog, K. E., & Birdsey, R. A. (2006). A Model of Forest Floor Carbon Mass for United States Forest Types. *US Forest Service General Technical Report In Press*, 42.

Retrieved from https://www.fs.fed.us/ne/newtown_square/publications/research_papers/pdfs/2002/rpn722.pdf

Smith, J. E., & United States Forest Service. Northeastern Research Station. (2006). Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Retrieved from http://hdl.handle.net/2027/umn.31951d02881922s

Stechemesser, K., and E. Guenther. (2012). Carbon accounting: a systematic literature review. *Journal of Cleaner Production 36*(17-38).

Stern, N. (2006). The economics of climate change: The stern review. *HM Treasury*. Available on- line at www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm

Tryjanowski, P., A. Imeson, B. Seguin, C. Liu, S. Rawlins, T. L. Root, D. J. Karoly, G. Casassa, C. Rosenzweig, and A. Menzel. (2007). Assessment of observed changes and responses in natural and managed systems.

Turunen, J., Tahvanainen, T., Tolonen, K., & Pitkänen, A. (2001). Carbon accumulation in west siberian mires, russia sphagnum wetland distribution in north america and eurasia during the past 21,000 years. *Global Biogeochemical Cycles, 15*(2), 285-296. doi:10.1029/2000GB001312

UNFCCC, UN Framework Convention on Climate Change. Kyoto Protocol Reference Manual on Accounting of Emissions and Assigned Amount. (2009)

United States, E. (1997). Innovative Uses of Compost: Reforestation, Wetlands Restoration and Revitalization of Habitats.

U.S. Forest Service. (2014). US forest resource facts and historical trends. United States Department of Agriculture.

Vogt, K. (1991). Carbon budgets of temperate forest ecosystems. *Tree physiology 9*(69-86).

Wigley, T. M. L., & Schlesinger, M. E. (1985). Analytical solution for the effect of increasing CO2 on global mean temperature. *Nature, 315*(6021), 649-652. doi:10.1038/315649a0

Wind, L., & Hole, W. (2013). Initial chemistry and decay dynamics of deciduous leaf litter from a long-term soil-warming study in the Northeastern US.

Wofsy, S. C., and R. C. Harris. (2002), The North American Carbon Program (NACP): Report of the NACP. Committee of the U.S. Interagency Carbon Cycle Science Program, U.S. Global Change Res. Program, Washington, D. C.

Yu, Z. C. (2012). Northern wetland carbon stocks and dynamics: A review. *Biogeosciences, 9*(10), 4071-4085. doi:10.5194/bg-9-4071-2012