# Carbon Storage and Potential for Emissions Offset in the Long Lane Forest, Wesleyan University

Thomas Davoren
Rebecca Downer
Terra Ganey
Andrew Hennessy

## ***ABSTRACT***

$CO_2$ emissions stemming from human activity have been steadily increasing since the industrial revolution, posing an enormous risk to global climate. In order to prevent global temperature from rising dramatically, emissions need to be significantly reduced or offset by carbon sinks. The largest terrestrial carbon sinks on Earth are forests, which have the capacity to sequester as much as 0.002 Pg of carbon per year. For this reason, promoting the growth and carbon sequestration of forests is incredibly important. If deforestation continues at its current pace, land that was once a significant sink for carbon may instead become a source of harmful emissions. Wesleyan University may be able to offset its emissions by preserving forested land and documenting annual amounts of sequestered forest carbon. To evaluate this possibility, we established eight permanent carbon monitoring plots within Wesleyan's 12.2-hectare Long Lane Forest (LLF). 168 tree stems were tagged and measured, and soil samples were collected from each plot in an effort to estimate the carbon stored in the aboveground living biomass and soils of LLF. We also described the understory of each plot and catalogued native and exotic species to create a record for future successional stage comparison. Our results indicate that LLF currently harbors $1.98 \times 10^6$ kg carbon, which implies that the forest would need to effectively double its total carbon every year in order to offset annual university travel emissions. Future efforts to reduce Wesleyan's carbon emissions, as well as increasing the area of forested land, may allow for increased emissions offset.

## ***1. INTRODUCTION***

Anthropogenic $CO_2$ emissions have been steadily increasing since the industrial revolution, and humans are now considered responsible for the output of 10.9 petagrams (Pg) of carbon (C) per year (Royal Society 2018). In order to prevent catastrophic increases in global temperature, emissions need to be reduced dramatically. Forests, which store carbon in woody biomass and soils, are the largest terrestrial carbon sink on earth (Canadell and Schulze 2014) and thus have the potential to offset emissions. Northern Hemisphere forests, in particular, have the capacity to sequester carbon in a variety of pools, including aboveground biomass, belowground biomass, dead wood, litter, and soil, resulting in substantial reductions to a region's carbon footprint (Domke et al. 2018; Goodale et al. 2002; Newell and Stavins 2000). Studying forest ecosystems provides an opportunity to identify vital sinks of carbon.

Research forests may be the best tool for monitoring carbon reservoirs in natural systems. Since the early 1900s, research forests have been at the forefront of scientific study of such ecosystems. Establishing a forest enables researchers to conduct long-term studies on biogeochemical cycling, anthropogenic forces, disturbance ecology, and general forest health (Adair et al. 2018; Foster and Aber 2004; Holmes and Likens 2016; Robinson 1997). Since forests (and other fragile natural systems) have suffered macro-scale adverse effects from harmful anthropogenic emissions (Holmes and Likens 2016), the burning of fossil fuels is in the public eye now more than ever. With this in mind, the availability of research forests for long-term study can be applied to a different cause: namely, to investigate ways to offset harmful emissions in order to preserve remaining forest ecosystems. To this end, studies from the past twenty years show that carbon stocks in North American forests have increased to an estimate of 103 Pg of carbon, largely due to increased aboveground biomass in the eastern United States (Köhl et al. 2015; Stinson et al. 2011). The growth of aboveground living biomass—especially woody biomass which consists of roughly 50% carbon by weight—sequesters carbon from the atmosphere through photosynthesis. Forest ecosystems provide a promising opportunity to reduce the impact of anthropogenic carbon emissions.

Soils, which play a key role in the development and carbon storage of all forests, contain three times the mass of carbon stored in the atmosphere (Lajtha et al. 2018). The processes of storing carbon in soils are impacted by a variety of factors, including soil organisms and different land uses (Lajtha et al. 2018). Soils and leaf litter can store additional carbon through both the growth of plants and partial decomposition (Nijnik 2010). The amount of carbon in a soil is directly related to the quantity and decompositional state of organic matter; carbon storage will also change according to the extent of the microbial community and mycorrhizal associations. While complete decomposition of plant matter releases carbon dioxide to the atmosphere, partial decomposition into more stable forms of organic matter will end up storing carbon within the soil. US soils are predicted to be able to sequester large amounts of carbon on a longer timescale ($10^2$ to $10^3$ years) than sequestration through photosynthesis and woody tissue growth (Heath et al. 2003; Kimble et al. 2002). By thinking about both the forest's aboveground biomass and soil as carbon sinks, we can effectively manage a Wesleyan-owned research forest and plan to maximize short term and long term carbon offsets.

Land-use change is one of the primary ways in which humans directly impact forest carbon sequestration, and New England has a long history of large-scale land-use changes (Houghton et al. 1999). Clear cutting forests and converting land into farms or urban development not only releases carbon into the atmosphere but also severely diminishes the capacity of the landscape to sequester carbon. In the reverse, reforestation allows for increased carbon sequestration, albeit at a much slower rate. A complete transformation of New England forest lands has occurred in only three centuries, as the countryside was deforested for settlement and farming and then reforested over time (Foster 1992). It is estimated that at least ninety percent of New England's area (not including lakes, streams, and other land not suitable for stand establishment) was forested when the pilgrims landed in the 1600's. The gradual depletion of this timber by settlers was then followed by low-intensity agriculture which eventually expanded into commercial agriculture and industrialization. Population migrations after the purchase of Western states resulted in farm abandonment leading to the reforestation of many forests in New England from the 1850s to 1970s (Foster 1992).

Though there are significant tracts of forest in present day New England, forest area has been decreasing since the 1980s as pressure for more housing and development has encroached on stands across the region. Since 1985, a total of 386,657 ± 98,137 hectares of forest have been converted to other land uses, and an area of 226,519 ± 66,682 hectares have been harvested for timber (Olofsson et al. 2016). As a result, the forest sink may have decreased ten-fold from as much as 0.002 Pg of carbon per year in 1980 to 0.0002 Pg in 2005 (Olofsson et al. 2016). Protecting New England forests and promoting their growth and carbon sequestration is incredibly important; if deforestation continues on the same trajectory, land that once was a significant sink may be converted to sources of atmospheric carbon emission.

Connecticut has followed this recent pattern of deforestation, and according to recent infographics from UCONN's Center for Land Use Education & Research (CLEAR), Connecticut forests have declined by roughly 46,500 hectares since 1985. In the case of Wesleyan University's forest, our stand behind the Long Lane Farm has a different history of land-use changes relative to the surrounding Connecticut forests. Beginning in 1864 the Long Lane Farm property was part of a school and detention center that changed hands multiple times until finally being shut down and sold to Wesleyan in 2000. Our ~12 hectare forest on this property was cleared for agriculture and abandoned at some point during that history. Aerial photos of Connecticut allow us to estimate when it began reforesting. In the earliest photos from 1934 some large trees are present, but the bulk of the land is cleared (*Figure A-1*). It is not until 1970 that we see expansion from the center stand of older trees, and in 1986 the plot is clearly returning to a forested state. There are many more trees, and understory vegetation can be seen through gaps in the canopy, marking the transition from cleared agricultural land to a more forested environment. Pictures from 1990 and 2020 show the consistent growth of tree stems and canopies, and succession of the understory. Unlike the general trend of New England, our forest has expanded since 1986, and it still has the potential to sequester carbon and to offset some of Wesleyan's emissions.

In October 2020, Wesleyan modified its target date for carbon neutrality to 2035, a shift from its previous date of 2050. This decision was driven by an alarming 2018 United Nations report stating that global emissions must decline by 45% by 2030 to avoid a global surface temperature increase over 1.5°C (Wesleyan Sustainability Office 2020). In Wesleyan's 2019 carbon footprint report, Wesleyan's commuting and travel from faculty and staff contributed 1289 metric tons (Mt) of carbon ($1.289 \times 10^{-6}$ Pg; Wesleyan Sustainability Office 2020). In addition to taking steps to reduce Wesleyan's gross carbon emissions, Wesleyan can preserve and maintain its forest in order to offset some of the University's net emissions that stem from commuting. Therefore, using Long Lane Forest as a research forest is an important tool for balancing Wesleyan's carbon budget. We hope to follow the precedent set by other institutions like Colgate University, who have already established research forests and estimated annual carbon sequestration in their forest as an effort to offset their emissions (Northeast Forest LLC 2018).

Identifying a carbon sink requires (by definition) a multiyear study of carbon storage in a given reservoir. For this reason, a research forest is the optimal tool with which to study carbon sequestration. Not only are forests relatively stable ecosystems in the long-term, but their steady growth presumably provides an increasing capacity for carbon storage (Pan et al. 2011). The Wesleyan research forest has the capacity to both provide useful data on carbon storage for this year and to allow future measurements within the same plots to compare values from time 0 with years to come (Yang et al. 2019). Many of the younger trees can be monitored for carbon sequestration throughout their lifespan and their growth in diameter can be measured as they move through various successional class stages. Studies conducted in the Harvard Forest using permanent sampling plots have produced estimates of $1.42 \times 10^{-7} \pm 4.4 \times 10^{-8}$ Pg of carbon per hectare in the aboveground live biomass of hardwood stands of comparable composition and age to our forest (Finzi et al. 2020).

Although there is a rich history of quantifying carbon in forested systems (Goodale et al. 2002), the Long Lane Forest has not been studied in this capacity. We aim to quantitatively and qualitatively describe Long Lane Forest through data from our sampled plots on the trees, understory, and soils. We think extrapolation of this sample to the whole Long Lane Forest population, in combination with GIS, historical records, and comparisons to other New England temperate forests will allow us to adequately describe Long Lane Forest and draw conclusions about its succession and carbon storage. We also hope to produce a comprehensive description of the forest that can serve as inspiration and a starting point for many future projects.

Long Lane also belongs to an important enclave of northern hemisphere temperate forests that have been shown to provide significant carbon sinks. Therefore, we hypothesize that Long Lane Forest will store enough carbon to offset emissions at Wesleyan. However, this result cannot be properly evaluated with only a single study. We anticipate that Long Lane Forest will store somewhat less carbon than mature New England forests of about the same size, since it is holistically a younger stand. Compared to the Harvard Forest, this would imply that we expect less than or close to $1.73 \times 10^{-7}$ Pg of carbon per hectare. This estimate of Harvard's forest comes from the aboveground living biomass and first 15 cm of mineral horizon of long-term hardwood plots in the Harvard Forest (Finzi et al. 2020). Future resampling of our permanent carbon plots will be able to build off this study, using it as a baseline measurement in order to determine whether or not Long Lane Forest can be used as a carbon offset for Wesleyan.

In this report, we present our analysis of carbon storage data collected from Long Lane Forest and conclude that the forest has the potential to serve as a carbon sink for Wesleyan following further investigation. In section 2, we outline our methods for data collection and analysis and detail our reports in section 3. Our main finding is that the Long Lane Forest contains $1.67 \times 10^{-7}$ Pg C per hectare. Section 4 provides a discussion of the implications of this result, and section 5 summarizes our study and outlines recommendations for future work.

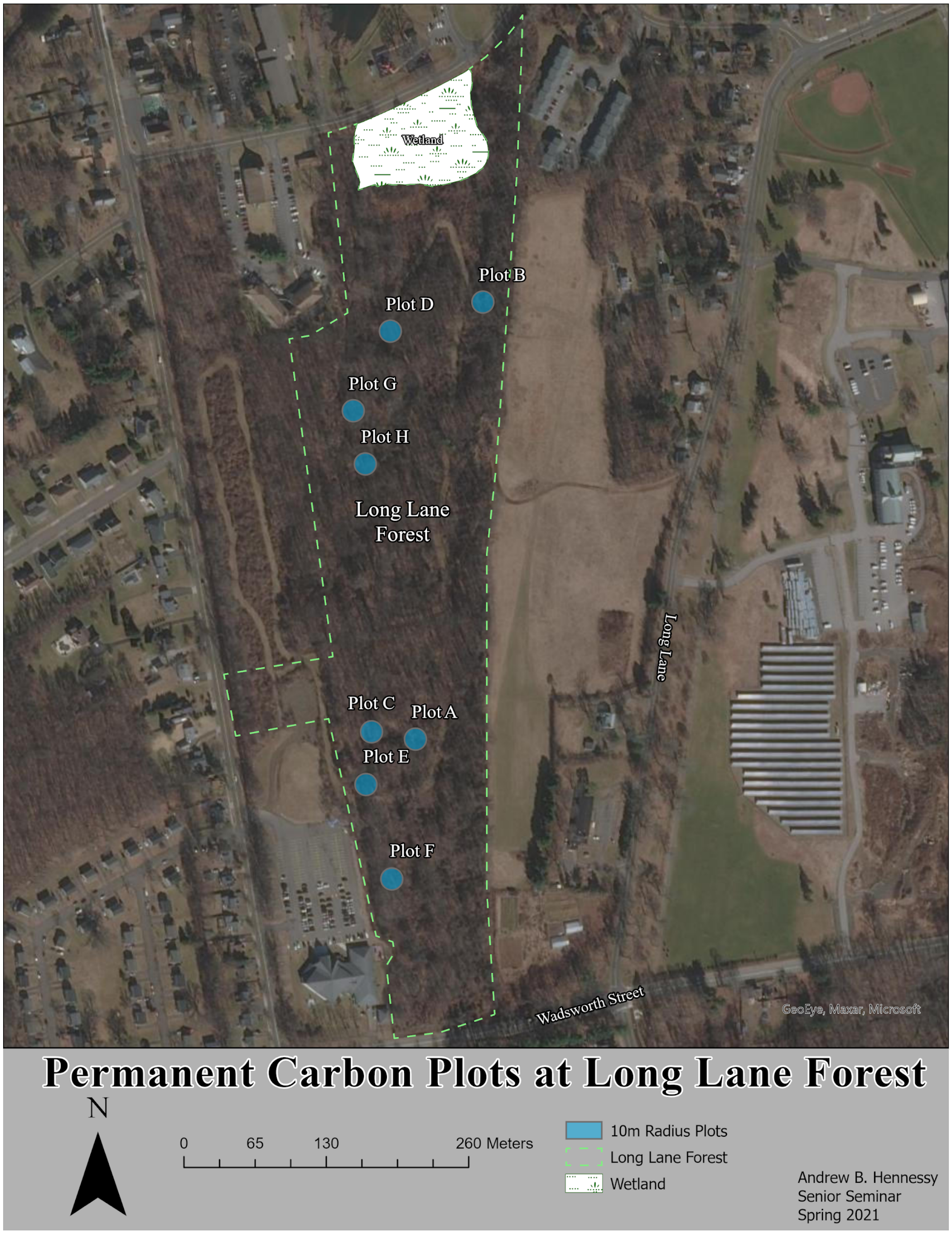
## ***2. METHODS***

### 2.1 FIELD COMPONENT

All of our fieldwork methods were adapted from forestry research standards outlined in the USDA Forest Service's Measurement Guidelines for the Sequestration of Forest Carbon and the USFS Forest Inventory Methods technical guide (Pearson et al. 2007; USDA 2018). We are also very grateful to Dr. Helen Poulos for her expert opinions and guidance on our methodology.

### 2.1.1 Plot Setup

We used ArcMAP (ESRI) to randomly distribute points within the forest boundary polygon and assigned those as center points for our plots. We did this to get the most representative sample of the forest as possible. We repeated this process twice with 20 points each time and moved down the list of potential sites, scouting each until we had eight that met the following criteria: accessible (students had to be able to reach each plot on foot within the time our field days allowed), off the forest walking paths, no closer than roughly 20 meters from the forest edge, and had at least one tree. We then tracked down the plot center with GPS coordinates, took soil measurements from the center of the plot following the soil sampling protocol below, and hammered rebar with an orange visibility cap to officially mark the plot. *Map 1* shows the approximate position of each of the eight plots and their plot ID (A-H). We also used a geodetic-grade GPS that allowed us to take measurements over the course of 15 minutes. The GPS coordinates were processed with NOAA's Online Positioning User Service (OPUS) to get a precise location for the center of each plot. Our eight plots comprised an area equal to roughly 2% of the total area of Long Lane Forest.



***Map 1:*** Map of permanent carbon plots in the Long Lane Forest

### 2.1.2 DBH Sampling and Identification of Trees

We established circular plots with a 10 m radius. We measured 10 meters from the center rebar with a 20-meter open reel tape measure to find the edge of each plot. The field team measured the diameter-at-breast-height (DBH) and identified the species of each tree with a DBH greater than 2.5 cm (Pearson et al. 2007). Tree identification was done visually by students using indicators like leaf shape and bark and verified using *Seek* (iOS and Android mobile app). If a species-level identification could not be made, the finest taxonomic classification the field crew could confidently determine was recorded, sometimes resulting in an "unknown." If a tree was on the edge of a plot, we only included it if more than half of the tree fell within the plot (Pearson et al. 2007). If there were multiple trunks growing out of one stem, we measured and recorded each individual trunk DBH. We systematically sampled the plots by stretching the 10 m tape fully in a cardinal direction and moved in a consistent circle around the plot, tagging (*Figure A-2*) and measuring trees until we returned to the starting direction. All data was recorded in *Sheet 1*.

### 2.1.3 Soil Sampling

While students were sampling the trees, another field team member measured out 5 meters (half the plot radius) from the rebar in a cardinal direction. Using the auger (*Figure A-2*), we collected a soil core. We measured the length of this core in the auger and put the soil in a gallon sized plastic bag. These samples were used to calculate bulk density, along with the sample from the plot center that was taken during plot setup. Then, using the trowel, we collected a sample of the soil A-horizon, being careful to only collect soil and no undecomposed litter. The depth that our auger could probe depended on the soil texture of each plot, but by never digging into the B-horizon we tended to sample soil about 10-30 cm deep. This was placed in a different gallon plastic bag. These soil samples were used to calculate %C. This process was repeated for the other cardinal directions, creating four quadrants. To collect a representative sample of the plot's soil, we combined the samples taken in each of the four quadrants with the samples taken from the plot center during setup.

### 2.1.4 Description of Understory Community

We described the understory plant community with the aid of *Seek* and estimated the percent ground cover and representative height of each species. The dominant understory plants were identified to the finest taxonomic classification possible. The understory data recorded will be compared with future samples to document changes to the Wesleyan forest over time. This will enable us to describe general trends of populations of different species.

## 2.2 LABORATORY COMPONENT

### 2.2.1 Canopy Trees and Woody Understory Vegetation

To calculate biomass for each individual tree in our eight plots, we used the allometric equation provided by Jenkins et al. (2004):

$$\textit{Aboveground Biomass (kg)} = e^{(\beta\_0 + \beta\_1(\ln(DBH))}$$

The coefficients β_0 and β_1 are given in their Table 1 for each grouping of tree species. Soft maples are grouped by themselves, whereas hickories, hard maples (in our study, only sugar maples), and oaks are grouped together. Other species identified include black cherry, ash, common buckthorn, and dogwood, which will all be grouped using the classifications from Jenkins et al. (2004; their Table 4). We imported the data table with DBH measurements into R and programmatically assigned species groups with the corresponding beta coefficients from Jenkins et al. (2004) and calculated kilograms of aboveground biomass per tree. The carbon component of biomass is roughly 50%, so we approximated the kilograms of carbon per tree as half of the calculated biomass (Pearson et al. 2007; Smith et al. 2013).

Two of our measured species, common buckthorn and mountain laurel, were not in the Jenkins et al. (2004) species groups. To calculate their biomass we used similar allometric equations from Mascaro and Schnitzer (2011) for buckthorn, and Brantley et al. (2016) for laurel. Since we cannot know which species groups our unidentified trees belong to, we decided to calculate their biomass in three different ways. Methods 1 and 2 assign all trees we could not identify to the "mixed hardwood" and "hard maples and oaks" groups, respectively. We chose these species groups because the 48% of the sampled trees fall in mixed hardwood and 26% fall in the hard maples and oaks group. These species groups contain the majority of species found in the forest, but since it is very unlikely all of these trees would fall in one species group, we attempted to distribute the unknowns to both species groups in Method 3. This last method assigns all unknown trees in plot D to the hard maple and hickory group, as it is suspected that those trees are a group of hickories. The rest of the unknowns are assigned to the mixed hardwood species group under the assumption that they are less identifiable understory trees that fall in that species group.

After carbon for every sampled tree had been calculated we adapted extrapolation methods from the Colgate report of the carbon stocks in their research forest (Northeast Forest LLC 2018). We summed the carbon from all of our trees and then multiplied by the inverse of the sampling intensity to estimate the total aboveground tree carbon in the forest.

*Sampling Intensity* = (# of plots * plot area / total forest area)

### 2.2.2 Soil

The five combined soil samples taken with augers from each plot were air-dried over the course of ~3 months (December 2020–February 2021). The volume of each sample is the sum of the volumes of each individual sample: the depth of the auger into the soil multiplied by $\pi(1.5 \text{ cm})^2$, where 1.5 cm is the radius of our soil auger. The bulk density of a sample is the dry weight of the soil divided by this cumulative volume. We calculated bulk density for each of our eight plots in order to convert the %C value of a soil sample to the total carbon stored per hectare of land.

Soil elemental composition was measured using the element analyzer in the Wesleyan University Limnology Lab. The five %C soil samples had already been combined into one bag per plot and homogenized before air-drying. A small portion (7-10 mg) of each of the eight samples was weighed and spooned into a miniature aluminum cup to be placed in the element analyzer. This instrument measures the %C by mass of each of the samples. To normalize these concentrations, the weight of the analyzed sample was compared to the bulk density of the soil (calculated earlier, as above). %C is converted to total carbon per hectare by multiplying %C by the soil bulk density. The C/ha measurement was then multiplied by the number of hectares Long Lane Forest covers (12.2 ha) to yield a total carbon measurement down to the A-horizon of the soil (~10-30 cm). We performed this procedure twelve times (once per plot, plus two additional samples from both plots A and D to approximate variance in composition), producing eight estimates of total carbon. These numbers were averaged, and error was included in order to represent the forest as a whole.

## *3. RESULTS*

Within our eight plots we measured 168 total trees of about 20 different tree species with an average DBH of 18.1 cm. The understory composition of these plots was mainly invasive species like multiflora rose and privets (*Figure 1*).

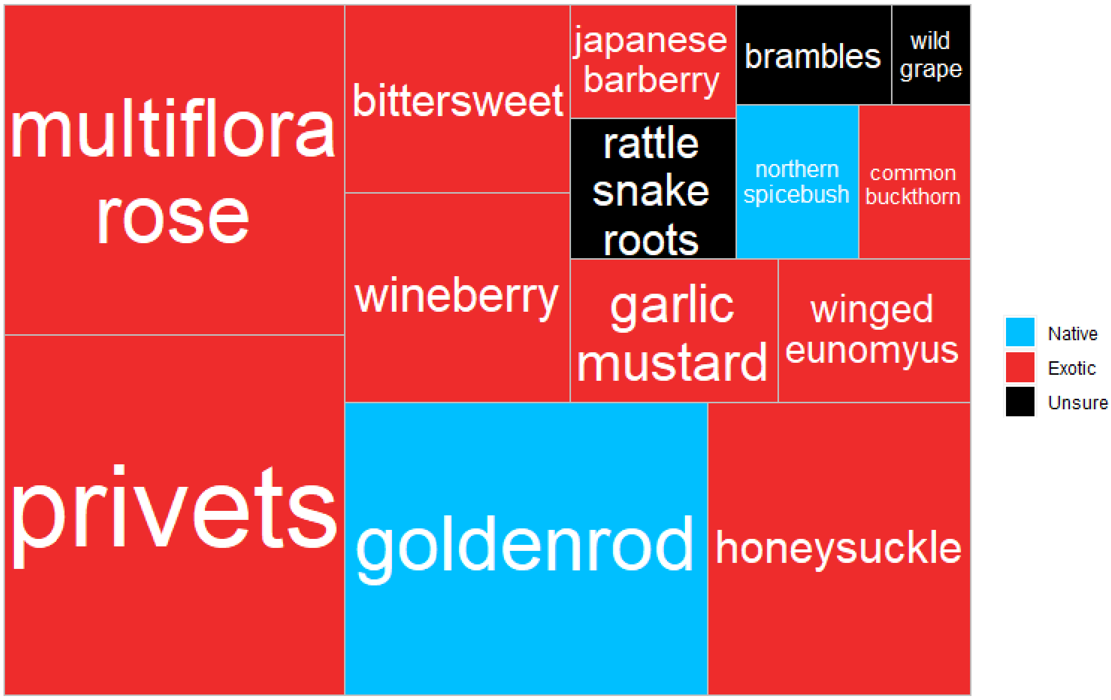


***Figure 1:*** Treemap comparing the relative proportions of understory plant species found in the plots based on estimated ground cover. The boxes are colored by the species origin, and only species that comprised more than 2% of estimated ground cover across the eight plots were included.

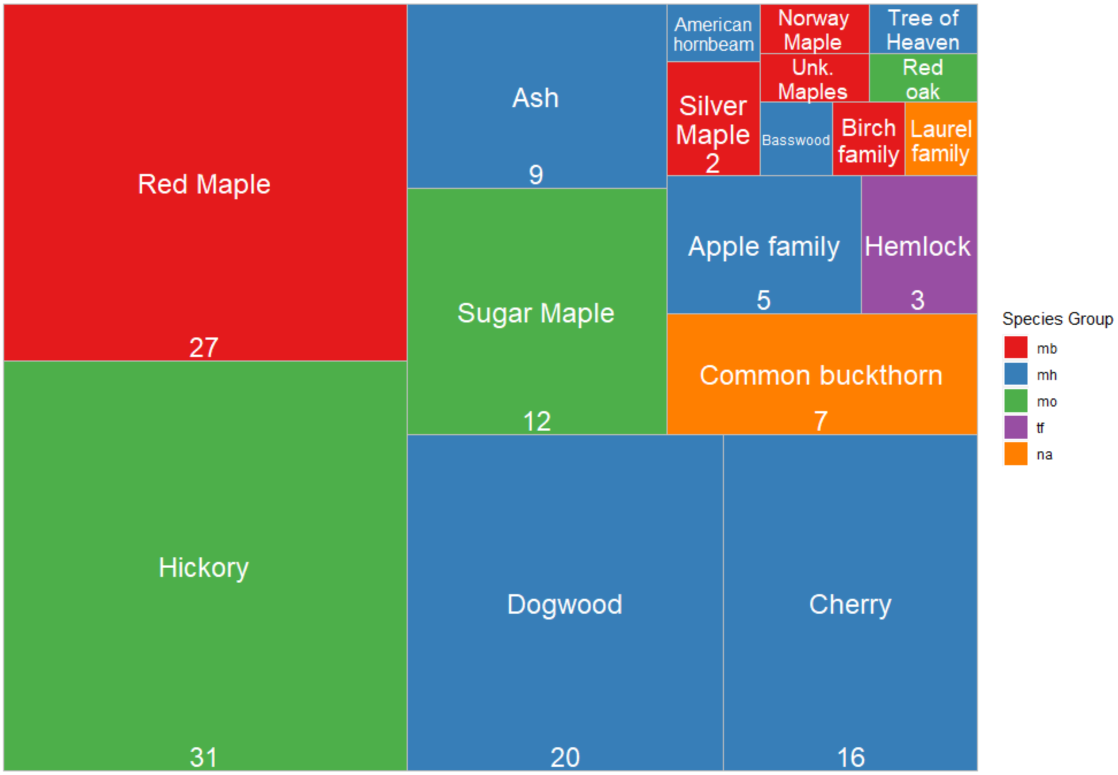


***Figure 2:*** Treemap showing the relative proportions of 140 identified trees. The groups follow the categories of Jenkins et al. (2004). This figure excludes the 28 unidentified trees in our sample. mb = soft maple / birch, mh = mixed hardwood, mo = hard maple / oak / hickory / beech, tf = true fir / hemlock, na = species not listed in Jenkins et al. (2004).

***Figure 3:*** Treemap showing the relative proportions of 140 identified trees. This figure excludes the 28 unidentified trees in our sample.

Our sample of the forest was largely red maple and hickory (*Figures 2 and 3*), with a variety of other tree species and 28 (16.67%) unidentified individuals. The majority of the trees in the plots were small with large trees being relatively rare.

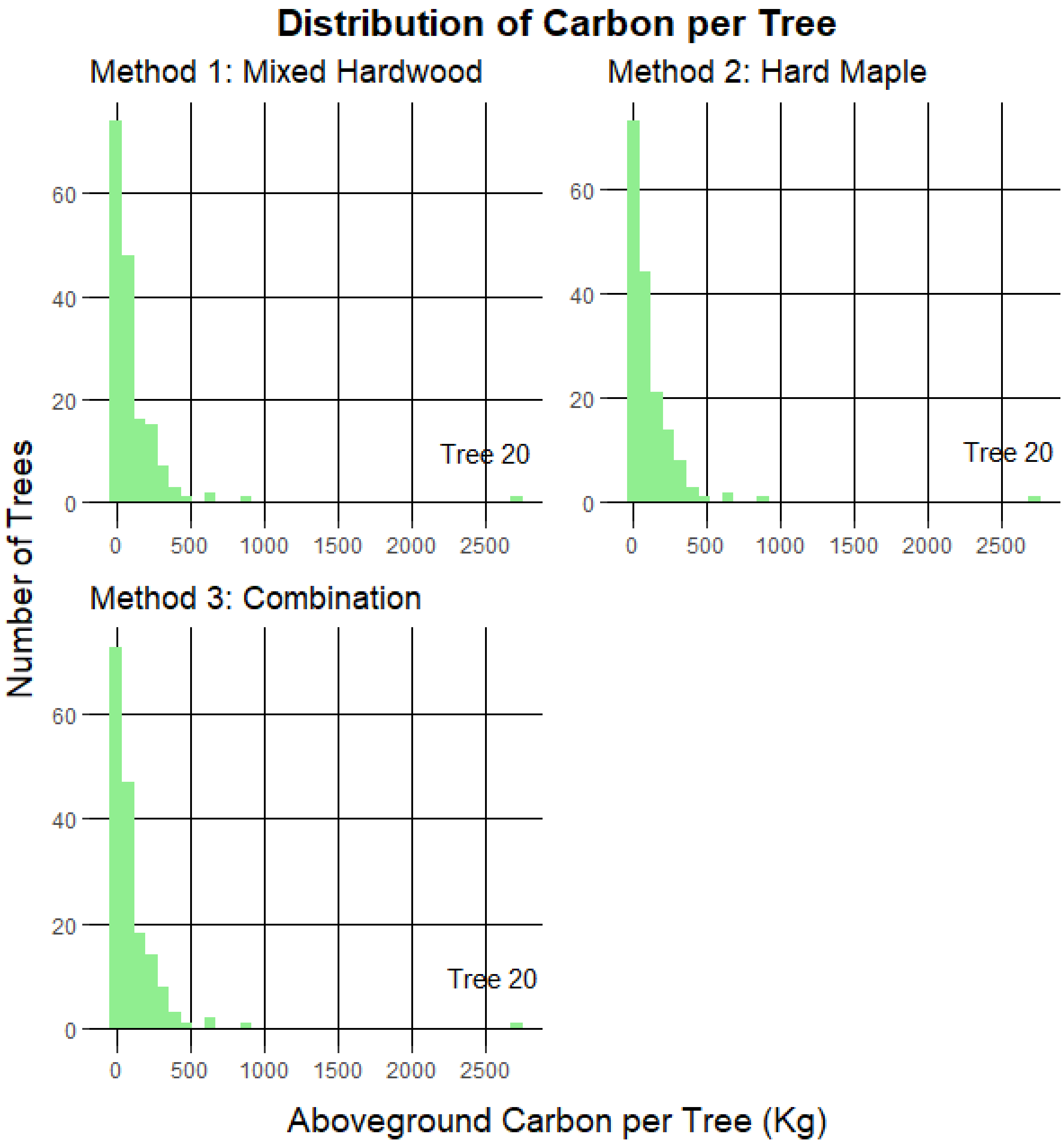


***Figure 4:*** Distribution of carbon found in the aboveground biomass of our sample of trees. Each bin is 80 kg. The three panes represent the different methods of species group assignment for unidentified trees (see *Methods*) discussed above.

*Figure 4* shows that most trees contain between 0 and 160 kg of carbon, but a few larger trees give the distribution a long right tail. Notice tree 20, the largest tree we measured (a red maple with a DBH of 85.6 cm), contained over 2,500 kg of carbon.

The eight plots had a large range of total aboveground carbon and aboveground carbon per tree (*Figures 5 & 6*). In general, total aboveground carbon in our plots increased with the number of trees in the plot and the average DBH. Most of our plots had fairly small ranges of aboveground carbon per tree. Plots A and D have much lower average carbon per tree (*Figure 6)*, lower range in carbon per tree (*Figure 5*), and much lower average DBH than other plots with similar total aboveground carbon numbers, such as C and G. They have similar carbon because plots A and D have about double the amount of trees as plots C and G, making up for the differences in carbon per tree. Plots G and H both have about 20 trees with an average DBH of ~22 cm, but plot H has significantly more carbon and a higher average carbon because of the outlier tree 20 (*Figure 6*). Our plots seem to loosely cluster into groups based on tree carbon and location. The 4 northern plots, B, D, G, and H all have carbon estimates above 2500 kg, while plots A, C, and E in the south have between 750 and 1200 kg of carbon (*Map 1 and Figure 6*).

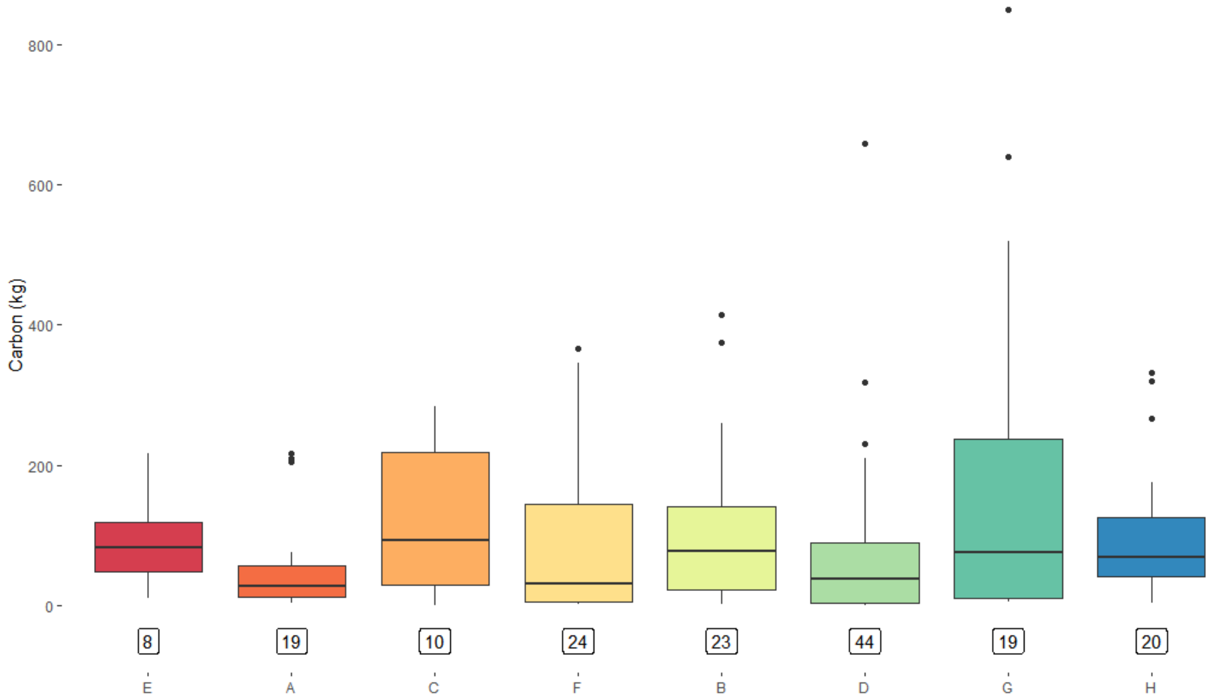


***Figure 5***: Distribution of carbon per tree in the plots. To make the distributions easier to compare only Unknown Method 1 is shown and tree 20 is excluded to reduce the scale needed for the y-axis. The box edges represent the 25th and 75th percentiles and the middle line is the median. Whiskers extend to the min and max values, and outliers are points above the whiskers. The numbers above the plot labels are the number of trees sampled in the plot.

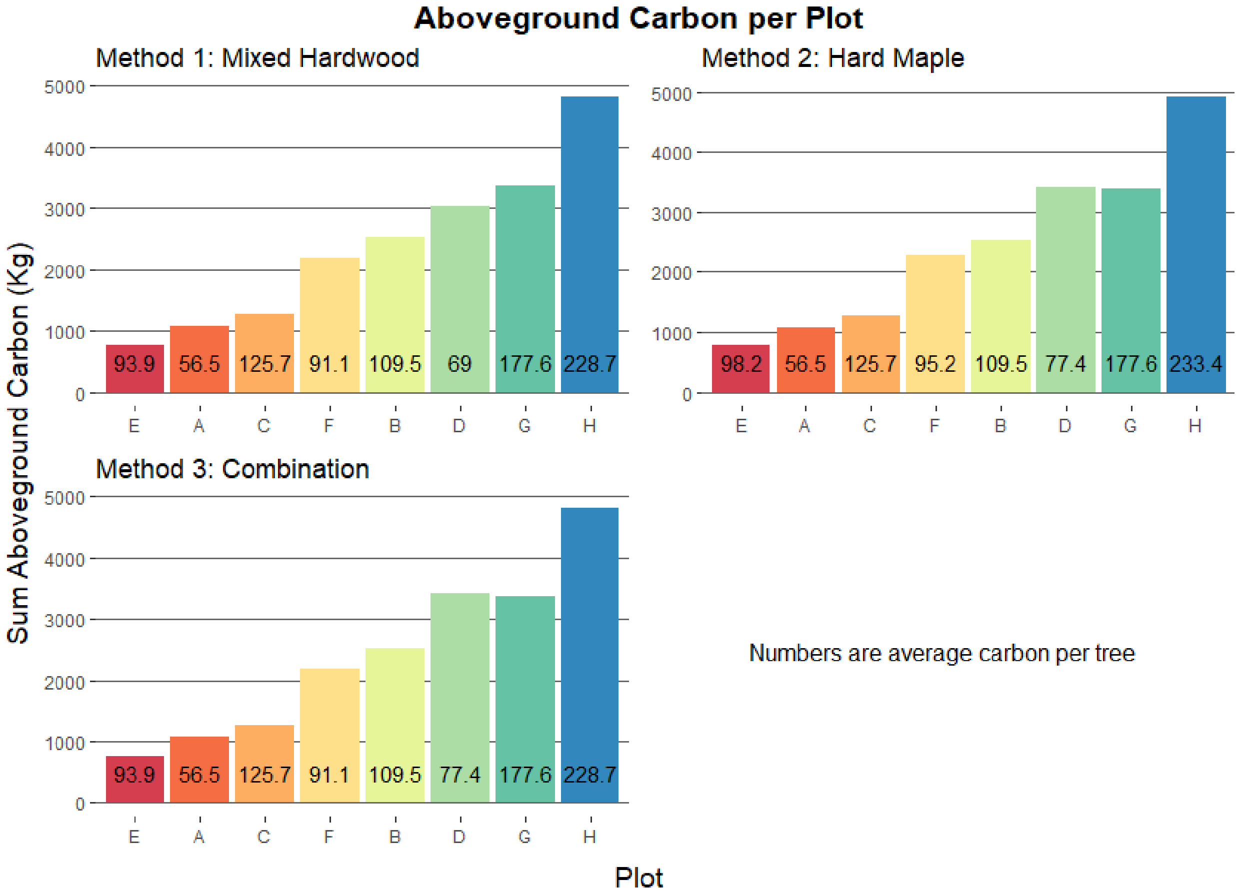


***Figure 6:*** Total carbon from aboveground biomass in each plot.

Red maple contained by far the most carbon of any species, even with outlier tree 20 excluded. The most surprising result from *Figure 7* was that cherry trees have the third highest carbon per species, even though there were only 16 individuals found.

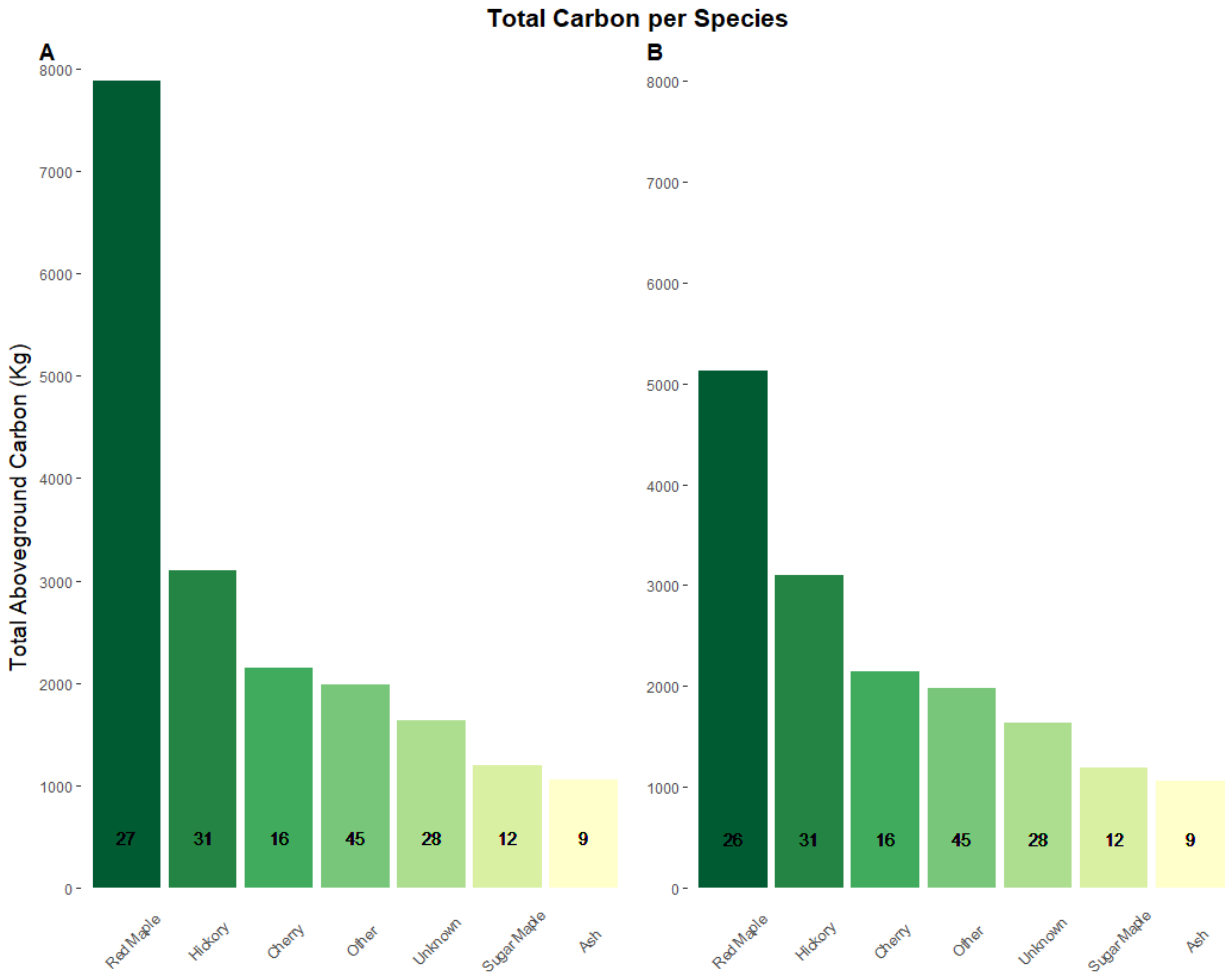


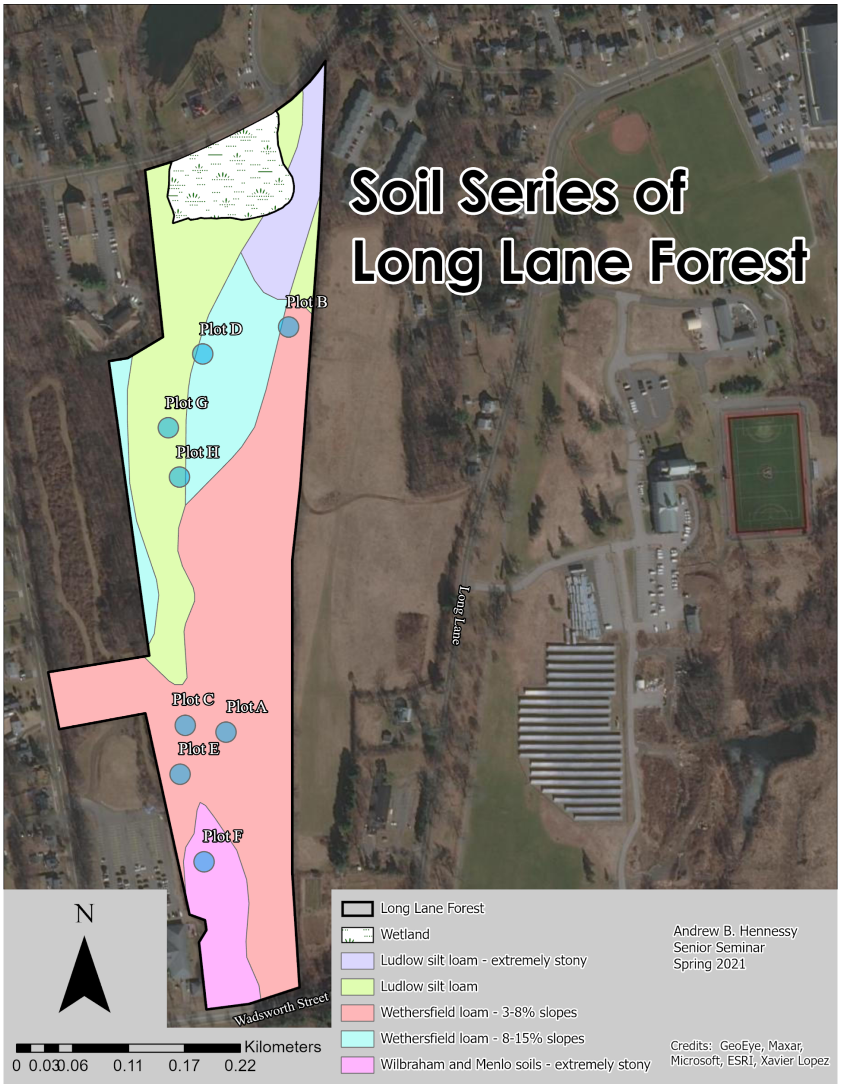
***Figure 7:*** Total carbon by tree species. A is our entire sample and B is without tree 20. Numbers in the bars are the count of that tree species in the sample. Note: the "Unknown" column here sows the carbon calculated by the most conservative assignment method, Method 1.

***Table 1:*** Soil carbon measurements from forest plots

| Plot ID | Volume of soil ($cm^3$) | Mass of soil (g) | Soil Bulk Density ($g/cm^3$) | Soil Carbon wt. % | Soil Carbon (kg) |
|---|---|---|---|---|---|
| A | 646.99 | 548.70 | 0.83513213 | 4.629 | 2729.145 |
| B | 618.36 | 551.92 | 0.87900297 | 5.33 | 3307.276 |

| | | | | | |
|---|---|---|---|---|---|
| C | 562.82 | 362.74 | 0.62961311 | 6.089 | 2706.280 |
| D | 687.067 | 685.68 | 0.98578549 | 4.073 | 2834.326 |
| E | 572.56 | 451.36 | 0.77368951 | 5.406 | 2952.539 |
| F | 649.85 | 676.63 | 1.02831388 | 4.497 | 3264.386 |
| G | 655.58 | 543.84 | 0.8167782 | 3.271 | 1885.982 |
| H | 701.38 | 705.19 | 0.993484 | 2.697 | 1891.450 |

Note: Soil volumes were calculated based on the auger radius and length, but may have been an underestimation of total soil volume.



***Map 2:*** Map of Long Lane Forest with soil series indicated by colored shading.

Forest soils tend to have a bulk density of around 1.0-1.1 g/cm$^3$ (Page‐Dumroese et al. 1999). With higher soil carbon values, bulk density values tend to be lower (Hossain et al. 2015). Plot F's soil had the highest bulk density, and it was the only plot that had a value above 1 g/cm$^3$ (~1.02). Plot C had the lowest bulk density at ~0.63 g/cm$^3$. Plot B had the highest carbon in soil, and plot F was a close second. Plot G had the lowest, with Plot H having less than 100 kg C more than plot G. Soil carbon did not end up aligning with tree carbon within our plots.

Our results indicated that soil bulk density values were lower than expected, with the average bulk density among all plots being 0.868 g/cm$^3$ (*Table 1*). This may have been due to soil being lost when collected with the auger, leading to an overall underestimation of the total soil volume. In total, we estimated about 21,000 kilograms of soil carbon in our eight plots (*Table 1)*. Our soil estimates are consistent between plots in the same soil series (*Map 2*). Plots G and H are both in the ludlow silt loam series and have low carbon estimates of just under 1900 kilograms. In addition, plots A, C, and E are all clustered in the Wethersfield loam and have estimates ranging from 2,700-3,000.

***Table 2:*** Total tree and soil carbon by plot. Number density and average DBH of trees included for comparison.

| Plot ID | # of trees | Avg. tree DBH (cm) | Tree carbon (mean of all 3 methods) (kg) | Soil carbon (kg) | Total Carbon in the Plots (kg) |
|---|---|---|---|---|---|
| A | 19 | 15.2 | 1073.6565 | 2729.1449 | 3802.801 |
| B | 23 | 20.4 | 2518.5520 | 3307.2765 | 5825.829 |
| C | 10 | 20.6 | 1256.7204 | 2706.2797 | 3963 |
| D | 44 | 14.4 | 3283.5244 | 2834.3258 | 6117.85 |
| E | 8 | 20.0 | 762.7802 | 2952.5394 | 3715.32 |
| F | 24 | 16.8 | 2218.4157 | 3264.3862 | 5482.802 |
| G | 19 | 21.5 | 3374.8313 | 1885.9824 | 5260.814 |
| H | 21 | 22.3 | 4835.5806 | 1891.4496 | 6727.03 |
| Total | 168 | 18.1 | 19,324.06 | 21,571.38 | 40,895.44 |

In total, our plots had slightly more soil carbon than tree carbon (*Table 2, Figure 8*). However, the highest and lowest tree carbon values do not necessarily correspond with the highest and lowest soil carbon levels. For example, while Plot E has the lowest tree carbon compared to the rest of the plots, its soil carbon is the third highest compared to the rest of the plots.

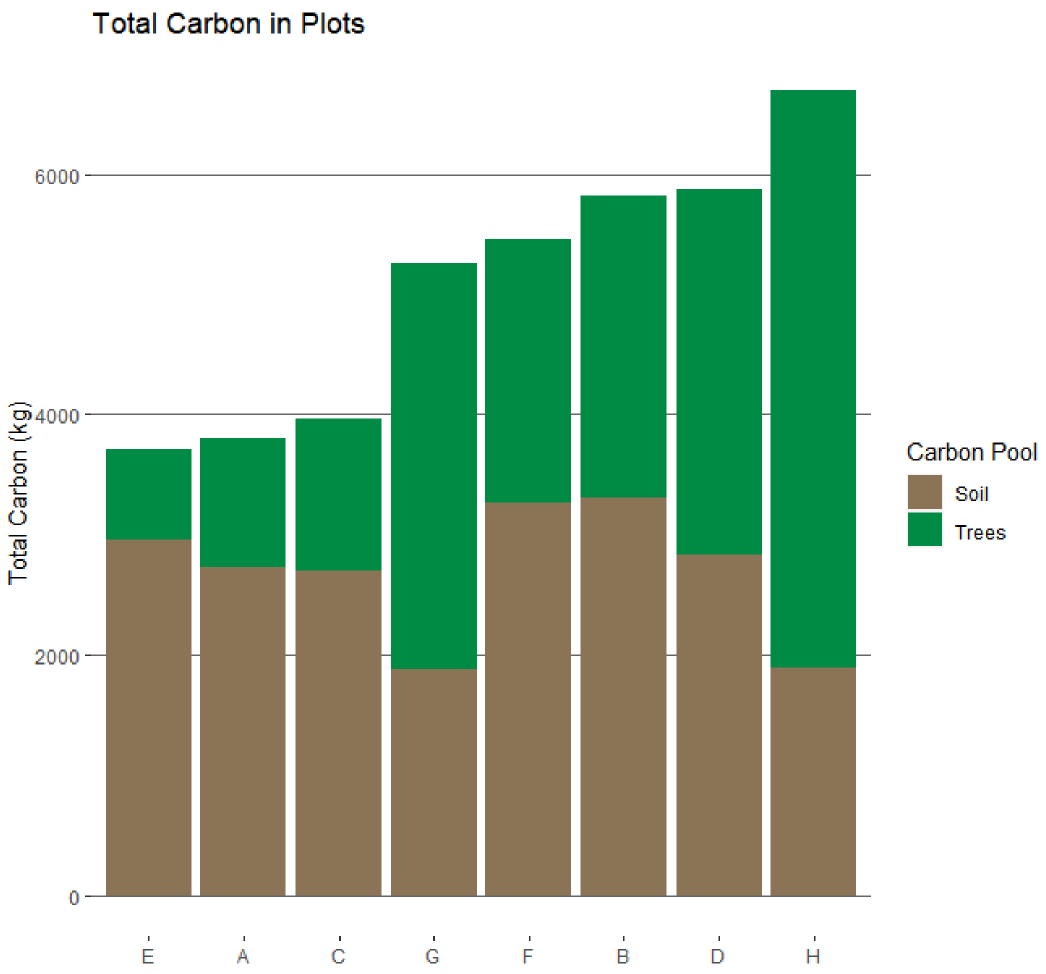


***Figure 8:*** Total aboveground tree carbon and soil carbon in each plot.

The different species groups assigned to the unidentified trees only yielded small differences in our estimate of carbon (*Table 3*). Method 1 (mixed hardwood) resulted in the lowest estimate of carbon (19000 kg), while Method 2 (hard maple/hickory) gave a 3% higher estimate (19602 kg), and Method 3 (combination) yielded an intermediate estimate (19369 kg). The total aboveground living carbon sampled in the plots ranged from 19,000 kg to 19,602 kg (1.9–1.96 × $10^{-8}$ Pg) between the three methods. Our estimates of the total aboveground living carbon in the entire 12.2 hectare forest range from 923,562 kg to 952,809 kg (9.2–9.5 × $10^{-7}$ Pg). We estimated the aboveground carbon per hectare in the Long Lane Forest to be between 7.56 × $10^{-8}$ Pg/ha and 7.79 × $10^{-8}$ Pg/ha.

When using the species assignment assumptions from Method 1, the total carbon (including soil and aboveground living biomass) sampled in the plots was 40,895 kg. When extrapolated to the entire forest area, the total carbon was estimated to be 1,987,826 kg (1.987 × $10^{-6}$ Pg). Based on our methods, we estimate that Long Lane Forest contains ~1.67 × $10^{-7}$ Pg C/ha.

***Table 3:*** Tree carbon sums using three different species groups for unidentified trees.

| Method | Sum of Unknown Tree Species Carbon (kg) | Total Sampled Tree Carbon (kg) | Total Forest Aboveground Live Carbon (kg) | Carbon (Pg) per Hectare |
|---|---|---|---|---|
| Unknowns as Mixed Hardwood | 1634.35 | 19000.44 | 923563.9 | 7.560033e-08 |
| Unknowns as Hard Maple / Hickory | 2236.01 | 19602.09 | 952809 | 7.799425e-08 |
| Unknowns as a Combination | 2003.57 | 19369.65 | 941510.7 | 7.70694e-08 |

### *3.1 ERROR ESTIMATION*

There are a lot of areas of uncertainty in our tree carbon calculations, so properly addressing and reporting these potential sources of error requires careful planning and forethought. There is unavoidable uncertainty in both the species-specific regression models and the grouped regressions from Jenkins et al. (2004), and additional uncertainty in our unidentified trees and the methods used to assign them a species-group. We are able to address these two areas of uncertainty, but there are more potential sources of error that we cannot address directly.

In order to more accurately calculate the error in our biomass estimations, we used Monte Carlo simulations to quantify the range of possible estimates that were able to be produced by the Jenkins et al. (2004) allometric equations. Using the root mean square error of each species group equation as standard deviations and the calculated biomass as the mean, a random normal sample of 10,000 observations for each tree was created. To also account for the three methods used to assign species groups to unidentified trees, we repeated this resampling process three times, once for each method. These resampled biomass estimates were summed to give 30,000 forest biomass estimates that are normally distributed around our calculated estimate. The eight buckthorn and laurel trees whose biomass was calculated separately were added as a constant to these total forest biomass resamples, and an uncertainty range was created from the fifth and ninety-fifth percentiles.

The median biomass estimate of the Monte Carlo resampling is roughly 41,300 kg, and the 90% (fifth to ninety-fifth percentiles) confidence range for biomass stretches from about 36,000 to 49,000 kg, which puts our estimate of 38,000 kg (~19,000 kg C) on the low end of the uncertainty range.

Measurement error in our diameters and extrapolation are two large areas of uncertainty that we cannot address. Extrapolating from our plots to the forest population requires the assumption that our sampling intensity of 2% creates a representative sample. The same extrapolation issue occurs at the local, plot-level carbon calculations, for we only took five samples within the 10 m radius. Different auger depths depending on soil texture might have also influenced our soil carbon calculations. We are confident that our aboveground carbon sampling intensity was high enough because it was similar to the intensity of Colgate's 2018 study (1.6%), but this is still a potential source of error (Northeast Forest LLC 2018).

## ***4. DISCUSSION***

Long Lane Forest is in an early successional stage and its successional pattern seems to be typical of New England hardwood forests. Red maple, cherry, hemlock, dogwood, and white ash are all early successional tree species, and the low abundance of very large stems in our sample is indicative of this forest's age. As the forest continues to age, some of these species (maples, ashes, oaks, and hickories) may remain but as resources become slim and stem exclusion begins, many of the shade intolerant pioneer species like dogwood, cherry, apple, and other small mixed hardwood species will be overtopped and outcompeted (Hibbs 1983).

*Figures 2 and 3* show that hickory and red maple were the most numerous species in our plots, omitting the 28 unidentified trees. Looking at *Figure 4*, the majority of trees have between 0 and 160 kg of carbon, with the exception of a few abnormally large trees. This is most likely due to the land clearing and subsequent regrowth of this previously farmed land, and is a distribution of aboveground living carbon that would be expected from a forest of this age.

There seem to be at least three obvious factors that influence plot carbon storage: 1) the influence of a tree with a particularly high DBH, 2) the quantity of trees identified in each plot, and 3) the average DBH of trees in each plot. Plot H had the most aboveground carbon, and this is where our largest tree, a red maple (tree 20) resided. Tree 20 had a DBH of 85.6 cm. This tree was most likely planted by a farmer or naturally sprouted and saved from being cut down in the forest's recent clearing history. As seen in *Table 2*, Plot D had the most trees (n = 44) and the third highest aboveground carbon. Plot G had similar tree carbon to plot D and high average DBH (21.5 cm). While the DBH for plot G was the second highest average DBH, the highest average DBH was in plot H, where tree 20 drastically changed the average. Overall, both plots D and G are on the high end of average DBH (18.1), which is likely the reason for their increased carbon storage. Similarly, plot E had the least carbon storage and the fewest trees (n = 8).

Unfortunately, due to how late in the year we sampled, a large proportion of our trees were labelled "unknown." However, these trees did not have anomalously high DBH and likely did not account for significant carbon. Red maple—though 3rd in quantity overall—stored the most carbon. Hickory seems to be a middle ground, being the second most numerous species and harboring the second highest amount of carbon through its large quantity of low DBH trees (*Figure 7*). Without the influence of exceptionally large trees like tree 20, the same results prevail: red maples store the most carbon, despite the fact that they are not the most numerous.

The only change is in the total aboveground carbon, which dropped from just under 8,000 kg to just over 5,000 kg. Our main conclusion surrounding the various tree species and their respective carbon storage is that the red maples in our plots have the highest carbon storage capacity. Considering that red maple abundance has increased in New England (Abrams 1998), this result bodes well for the future of carbon storage in northern hardwood forests like Long Lane. While plot H is home to tree 20, removing this tree from our calculations still had red maple at the top of the carbon-storing species identified in our plots.

There are some geographic patterns in the aboveground living carbon found in our plots which the land use history of LLF may help explain. The permanent carbon plots are roughly clustered in two groups: the four plots in the northern part of the forest (B, D, G, H) have the most carbon, while plots A, C, and E in the south have the least carbon. Plots G and H have the highest aboveground live carbon and are close together near the middle of the forest, while plots B and D sit further north and have slightly lower carbon levels. When this land was allowed to reforest, trees that were already established on the edges of farm plots had a head start, and created the lines of first growth seen in historical aerial photographs (*Figure A-1*). These early growing trees and their expansion north are a potential reason we see relatively high average DBH (*Table 2*) and carbon (*Figure 6)* in these northern plots. Plots A, C, and E are further from these original areas of reforestation, and consequently have smaller pools of aboveground living carbon. Plot F is separate from these two groups; it has relatively low aboveground living carbon and is in the Wilbraham and Menlo soil series (*Map 2*). This mollisol is typically high in carbon, giving plot F a total carbon estimate in the middle of our plots. (National Cooperative Soil Survey 2005; 2016). Due to the nature of our random plot assignment, there is a large gap in our sample between plots C and G (*Map 1*). This unsampled space has great potential for future work and projects to better estimate the carbon in Long Lane Forest.

We observed three main patterns to aboveground living carbon sequestration between our eight plots that may relate to the age of trees in the plots. Firstly, Plots A and D sequester carbon through what seems to be a single-age cohort of trees. Both plots are seemingly uniform, containing large amounts of small trees with very small ranges in their carbon per tree (*Figure 5*). Secondly, Plots C, G, and H have relatively low numbers of trees but very large ranges in the amount of carbon sequestered in each tree, resulting from their more heterogeneous tree community and multiple cohorts of trees. Finally, B and F seem to form a third group falling between the previous two groups in their number of trees and the range of carbon per tree. This variety between plots exemplifies some of the geographic effects of Long Lane's historical agriculture and clearing.

Our understory data (*Figure* 1) are helpful for identifying the types of species that occur in our forest, but we cannot make assumptions about how much of the overall forest contains these species since we visually estimated ground cover for our individual plots. However, of the top six most common species found in the understories of our plots, goldenrod is the only species native to Connecticut (Connecticut Invasive Plants Council 2010). The understory species composition of Long Lane Forest is very similar to the compositions found in nearby New England forests. In 1999, Duguid et al. (2013) harvested the understory at two sites in northern Connecticut and two sites in central Massachusetts and observed their regrowth by sampling every two summers until 2010. The regrowth they document is much shorter than the 30+ years our site has experienced, but some general trends can be found between their sites and ours. Their Connecticut sites in the Yale-Myers Research Forest both had multiflora rose and many goldenrod species present either in the first sample (2002) or second sample (2004) after clearing the understory. Towards the end of their sampling efforts species like barberry, bittersweet, and buckthorn start to appear. The largest difference between Long Lane and their sites is the lack of privet in the Yale-Myers sites (Duguid et al. 2013). Otherwise, it seems the growth and succession of this understory has been relatively typical for mixed-hardwood forests in southern New England. This primarily exotic understory can be detrimental to overall ecosystem health and potentially carbon sequestration. Many invasive understory plants can crowd and overtop saplings, choke living canopy trees, and have unforeseen negative consequences on forest biota (Fagan and Peart 2004; Webster et al. 2006).

Compared to other New England hardwood forests, our estimate of $1.67 \times 10^{-7}$ Pg C per hectare is of the same order of magnitude. The nearby Harvard Forest contains $1.73 \times 10^{-7}$ Pg of carbon per hectare (Finzi et al. 2020). This correlation is probably attributable to similarities between the two forests, including stand type and soil characteristics. In both places, soils are primarily formed from glacial till overlying metamorphic or sedimentary bedrock and tree stands are primarily hardwoods. Long Lane is of a younger successional stage, however, since it was agricultural and/or cleared land until the 1970s, only returning to a full forested state in the late 1980s (see *Introduction*). Considering the fact that Harvard Forest is one of the oldest maintained forests in the region (dating back to the early 1900s), we anticipated that Long Lane would likely contain much less carbon per hectare. Given adequate time to mature, Long Lane may eventually harbor an amount of carbon per hectare closer to Harvard Forest, but it is already surprisingly comparable. Currently, Connecticut forests store a rough approximation of 70 metric tons ($7 \times 10^{-8}$ Pg) of carbon per acre (Urbano 2020). In addition, the capacity of forests to store carbon may change as the New England region experiences warmer climate conditions. Though an increased period of growing time may lead to increased carbon storage, soil decomposition may increase as well, diminishing soil carbon accumulation (Catanzaro & D'Amato 2019).

Our total carbon estimate can also be used to make predictions concerning Wesleyan's goals for carbon neutrality by 2035. In 2019, travel for employee business and student study abroad produced $1.65 \times 10^{-6}$ Pg C (Wesleyan Sustainability Office 2020). Since our estimate for total carbon contained in Long Lane Forest is $1.98 \times 10^{-6}$ Pg C, it is unlikely that forest growth will be able to offset all of the emissions that stem from commuting. Trees and soils would have to accumulate at least $10^{-6}$ Pg C (the same amount of carbon as the entire forest currently contains) in a single year of growth to equal the carbon produced by travel emissions. If Wesleyan reduced travel to a tenth of the current rate (resulting in ~$10^{-7}$ Pg C), Long Lane Forest would have to sequester the equivalent of about a tenth of the total amount of carbon already accounted for in this study every year. This could be possible, but we cannot make any conclusive statements about forest carbon sequestration without subsequent data from future studies.

In the event that the forest's growth rate allows it to accumulate significant (~$10^{-7}$–$10^{-6}$ Pg) carbon on a yearly basis, a reduction of travel combined with forest carbon sequestration could allow Wesleyan to completely offset commuting-based emissions. We recommend that the University encourage as little travel as possible, potentially decreasing commuting to a small fraction (down to a tenth, if possible) of the current rate. We also propose that undeveloped Wesleyan-owned land near Long Lane should be converted to new forests in the coming years. More forested area provides a greater capacity for carbon sequestration and will ultimately help offset emissions, even if only to a small degree.

## ***5. CONCLUSION***

In the fall of 2020 we established eight permanent carbon monitoring plots within Wesleyan's 12.2 hectare Long Lane Forest. We tagged and measured the diameter of 168 total trees in an effort to calculate aboveground living biomass and collected soil samples for bulk density and percent carbon estimations. Lastly, we described the understory of each plot and catalogued native and exotic species to create a record for future successional stage comparisons.

Our main finding is that Long Lane Forest currently contains 1,987,826 kg ($1.987 \times 10^{-6}$ Pg) of carbon, or ~$1.67 \times 10^{-7}$ Pg C/ha. These carbon capacities, while comparable to the amount of carbon stored in nearby New England forests, are not sufficient to offset Wesleyan's annual commuting and study abroad travel emissions. Although we cannot directly evaluate the potential for Long Lane to serve as a carbon sink for Wesleyan with this work alone, future studies of the forest at regular intervals will provide an opportunity to quantify the rate of carbon sequestration in the forest. With this in mind, our preliminary recommendations are twofold. First, we recommend that the University reduce faculty/staff/student travel as much as possible, potentially down to a tenth of the current rate, to increase the fraction of emissions that the forest can offset. Second, we propose reforestation of nearby university-owned land. A reduction of travel combined with increased forest area for carbon sequestration could help Wesleyan completely offset commuting-based emissions and reach its carbon neutrality goals.

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# *APPENDIX*

| | | | | |
|---|---|---|---|---|
| Plot: | **Understory Composition** | Identify with Seek, estimate ground cover and height, describe qualitatively | | |
| Recorder: | Species | % Ground Cover | Height | Description / Notes |
| Description of Site: | | | | |
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| **Tree Tally Sheet** | | | | |
| Tag Number | Tree Species | Crown Class (S,I,C,D) | DBH(cm) | Description/Notes |
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| **Coordinate Data** | GPS Coordinates, center of plot | | | |
| Longitude | Latitude | | | |
| | | | | |

***Sheet 1:*** Blank field data collection sheet for vegetation inventories.

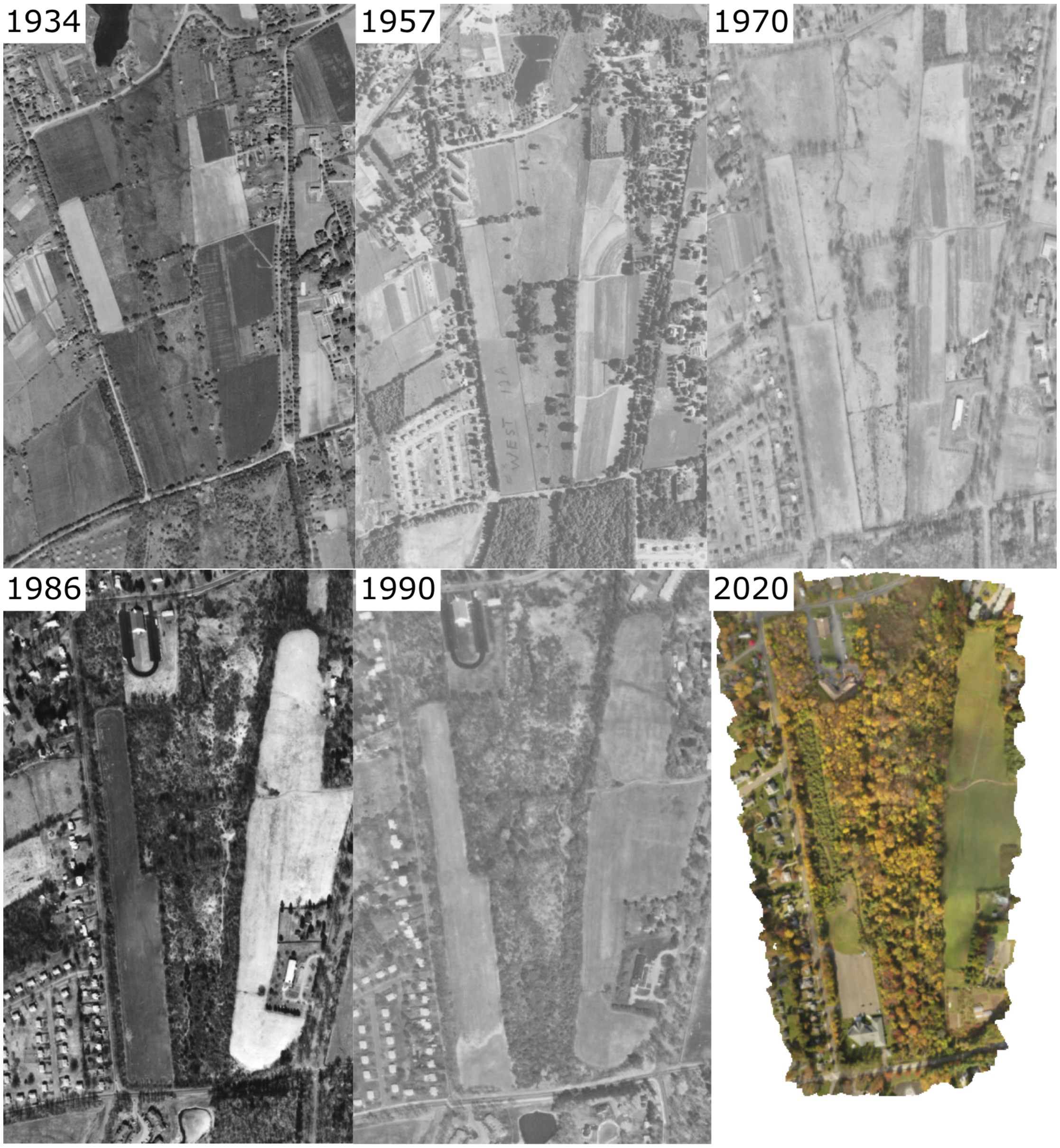

***Figure A-1:*** Aerial photos of the Long Lane Forest area from 1934 to 2020. The 2020 photo was taken with a drone in November.

***Figure A-2:*** (Left) Tree tag at breast height on a red maple in Plot C. (Right) Soil auger partially hammered into the ground before removal, measurement, and bagging of soil for bulk density calculation.