Carbon Accounting for New York City's Natural Area Forests

Natural Areas Conservancy

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Executive Summary

Forests play an important role in mitigating the many negative effects of climate change. One of the ways trees help to mitigate impacts of climate change is by absorbing carbon dioxide and storing carbon in their wood, leaves, and soil. Forest assessments and carbon accounting are common approaches used to quantify the value of trees and their contribution to mitigating these negative effects across different landscapes. In cities, assessments of forests, and the ecological benefits that they can provide have not been rigorously quantified beyond the scale of the entire city, thus making it difficult to understand how different types of urban greenspace contribute to meeting city sustainability goals. The number of trees, their size, and growing conditions can play an important role in the benefits they provide, including how much carbon they store and sequester. Urban forested natural areas often have greater tree density compared to trees planted in designed cityscapes suggesting that natural area forests could be an important carbon sink for cities to understand. To our knowledge the amount of carbon stored and sequestered in urban forested natural areas has never been estimated. This report is the first comprehensive carbon budget created for an urban forested natural area using field-collected data. We found that natural area forests in New York City store 1.89 Teragrams of carbon and sequester 0.044 Teragrams of carbon annually, with the majority being stored in trees and soil. Urban forested natural areas store and sequester carbon at similar rates to rural forests. Native, mature forests store the more carbon than invaded vinelands. Natural area forests in New York City store more than three times more carbon than the street tree population. Our results show that urban forested natural areas play an important role in localized, nature-based climate solutions and should be at the center of urban greening policies looking to mitigate climate change.

Introduction

Forests are a component of urban green space that can greatly contribute to supporting healthy cities. Forests can absorb storm water, cool buildings, clean air and provide opportunities for residents to experience nature within an otherwise built environment. One important way trees and forests improve the environment is by storing and sequestering carbon. Strategies to increase carbon storage and avoid greenhouse gas emissions in natural landscapes includes the conservation, restoration and improved land management actions; which can account for one third of the solution to climate change goals of emission reduction by 2050 (Griscom et al. 2017). However, the contribution of forests in urban settings is not well quantified.

Urban land is expanding, making forests in the urban context more common. As more land is converted to urban uses and as city populations increase, and city temperatures increase, urban forests will become ever more important for supporting healthy and resilient cities. Urban forests, just like rural forests, help mitigate climate change by capturing and storing atmospheric carbon dioxide during photosynthesis, and by influencing energy needs for heating and cooling buildings; trees typically reduce cooling costs, but can increase or decrease winter heating use depending on their location around a building and whether they are evergreen or deciduous. In the contiguous United States alone, urban land accounts for 128 million acres, and urban trees store over 708 teragrams (Tg) of carbon (approximately 12.6% of annual carbon dioxide emissions in the United States) (Safford, USFS). However, the benefits individual trees and forests can provide vary, and their contribution to mitigating climate change, can be largely dependent on species, size, density, and growing conditions.

Forested natural areas are wooded ecosystems within the boundaries of a city. While the term “urban forest” refers to all trees within a city, including street trees, trees in landscaped parks, private property, and traditional natural forests, “Forested natural areas” are distinct from street and park trees in their size, biodiversity, composition, and how they’re managed. They connect us to place with historical native habitats and are the “woods” in cities. Natural area forests can include native dominated mature forest stands that have natural regenerated, and also young growing forests, and degraded non-native dominated forests. In New York City, forested natural areas make up 5.5% of the city land area and contain approximately 70% of the total number of trees (Pregitzer et al. 2019) making them potentially important to understand in the context of climate change/mitigation.

To date, most estimates of urban forests exclude carbon pools that are not trees (Nowak & Crane, 2002). To the best of our knowledge, this is one of the first comprehensive carbon budgets created for an urban forest using field-collected data (similar studies include Jo et al., 2002 and Hutyra et al., 2011).

Goals

The goals of this study are as follows:

1. Estimate the amount of carbon stored and sequestered by natural areas in NYC using field-collected data and methods from the scientific literature.
2. Compare the carbon storage and sequestration of the various forest community types found in NYC, with a focus on native vs. nonnative types.
3. Estimate the contribution of forested natural areas to the entire urban forest, which includes street trees and landscaped or park trees.

Methods Overview

To determine the amount of carbon stored in NYC natural area forests, we calculated the amount of carbon stored in different components, or pools, within the forest. To calculate each pool, we used field-collected forest plot data from NYC forested natural areas (Pregitzer et al., 2019; Forgione et al., 2016) and related those data to published estimates of carbon for each component (i.e. trees, soil, etc.). Our forest plot data was collected during 2013-2014, and each plot was visited once. In order to calculate the changes of carbon in pools over time, we selected sequestration and emission rates from the scientific literature to estimate the annual change in stock pools. We assumed that the pools, except soil, are in steady state (i.e. inputs equal outputs) with regards to transfers between pools. All carbon stock and stock change were calculated on a per-plot basis and all plots were assigned forest and vegetation types using various classification systems (see Appendix). We calculated average carbon per unit area values for types in all classification system. To calculate the overall carbon budget for NYC's urban forests, we used a hybrid of NY Natural Heritage Program (NYNHP) community type and the US National Vegetation Classification (USNVC) system. The NYNHP classified each field-sampled plot to a specific vegetation class based on the species present and dominant in the plot, whereas the Ecological Covertype Map (O'Neil-Dunne et al., 2014) used remote sensing to spatially represent vegetation types across all of NYC. We then extrapolated each estimate for the forest type to a spatially explicit map to generate a complete budget for all of New York Cities natural areas. For full documentation of the methods we used see the Appendix.

Calculating the amount of carbon stored and sequestered in NYC forested natural areas

Trees and forests remove CO_2 from the atmosphere through photosynthesis and store it in their leaves, trunk, roots, and ultimately the soil. Carbon comprises roughly 50% of the organic material in trees, soil, and other forest components. Carbon exits in the tree in various ways: through root exudates into the soil, from the leaves into the litter layer, in branches or twigs that fall onto the ground and take the form of coarse woody material (CWM) or fine woody material (FWM), and through autotrophic respiration, the process of converting sugar to energy, which releases CO_2 into the atmosphere. Throughout this cycle carbon can be stored and sequestered in different parts of the forest system, or pools within the forest. The main pools we accounted for in this report include 1) live trees, or living trees and woody shrubs 2) herbaceous: small shrubs, saplings and other plants 3) standing dead trees 4) Woody Material: dead wood on the ground 5) Litter & Duff: freshly fallen leaves, twigs and other plant material on top of soil 6) Mineral Soil: soil below the layer of duff. Carbon in dead wood or soil organic matter is decomposed by soil organisms, fungi, and microbes. During decomposition, some carbon is respired into the atmosphere as CO_2, while the rest remains in the wood or goes into the soil. Soil organic carbon (SOC) can be readily available to decomposers, or it can be bound to other soil particles for decades or millennia.

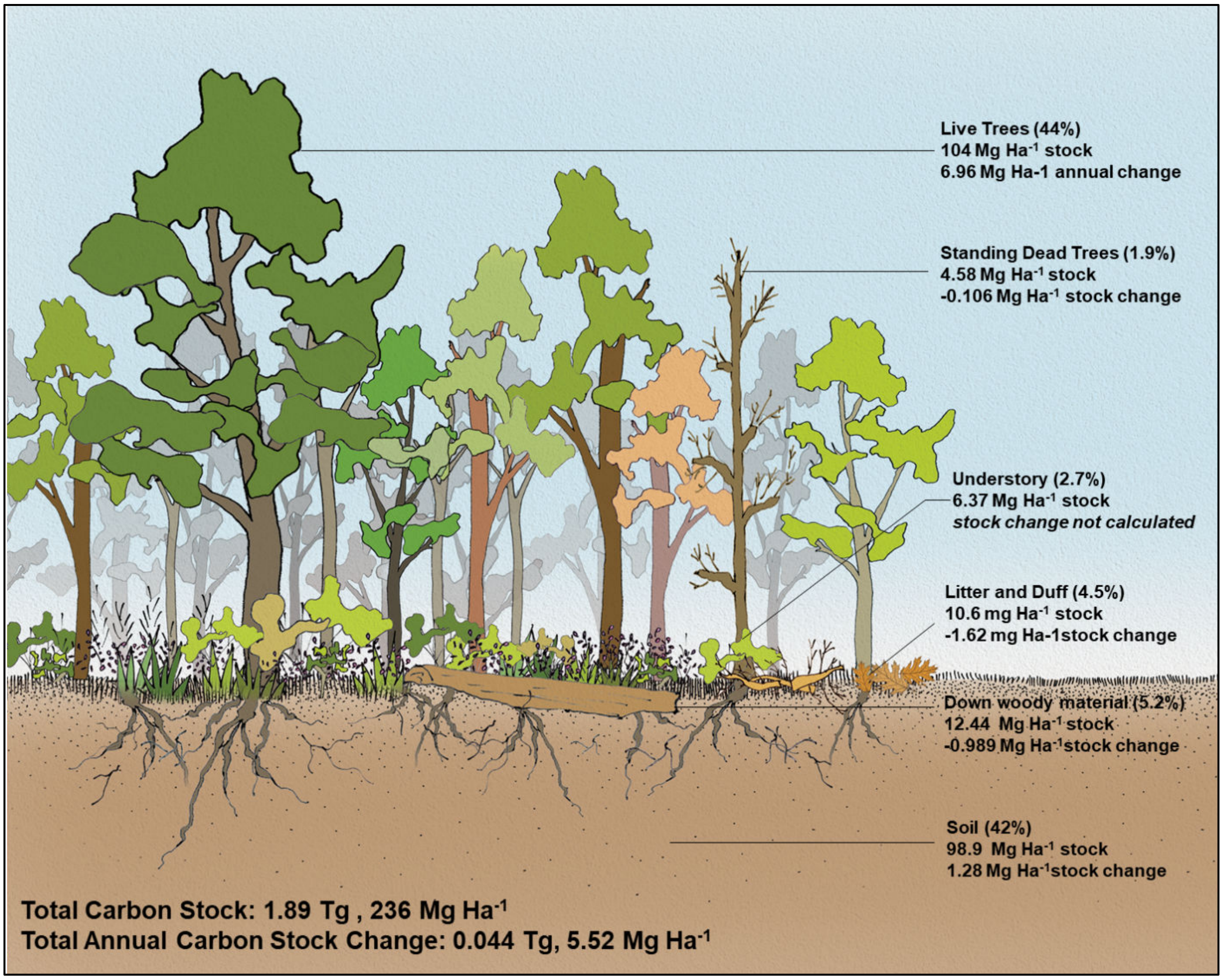


Figure 1. Total carbon stock and stock change in New York City's natural area forests by pool. For each pool we calculated the total stock, and stock change for all natural area upland acres and the percentage of the total is listed next to each pool, and the per hectare estimate is listed below each pool. Live trees include above and below ground totals, and down woody material includes coarse and fine woody material. The majority of carbon stocks are in the trees and soil.

We estimate that natural areas in NYC store 1.89 ± 0.3 teragrams (Tg) carbon, and have an annual net sequestration of 0.044 Tg. Most of this carbon is stored in trees (44%) and soil (42%). NYC natural areas gain between 27,300 and 51,700 Mg carbon per year (mean of 44,200 Mg). Forests gain approximately 87% of this carbon. The soil and trees have a net sequestration of 65,900 Mg carbon per year, while the litter and duff, downed wood, and standing dead tree pools emit 21,800 Mg carbon per year. Trees are responsible for 85% of sequestration, and the litter and duff layers are responsible for 60% of emission.

The amount of carbon stored in different forest types that occur in New York City

The species composition, tree size and stand conditions within forests can influence the amount of carbon stored and sequestered. Urban forests are particularly vulnerable due to at increased risk of fragmentation, exposure to invasive species, and complex land use history which can cause decline and degradation of forest conditions. Invasive species can outcompete native trees and lead to decreases in biodiversity, habitat quality and reduced benefits for city residents. As the stressors from urbanization magnify, understanding the trajectory of forests and the consequences for benefits, including carbon storage and sequestration will become more important.

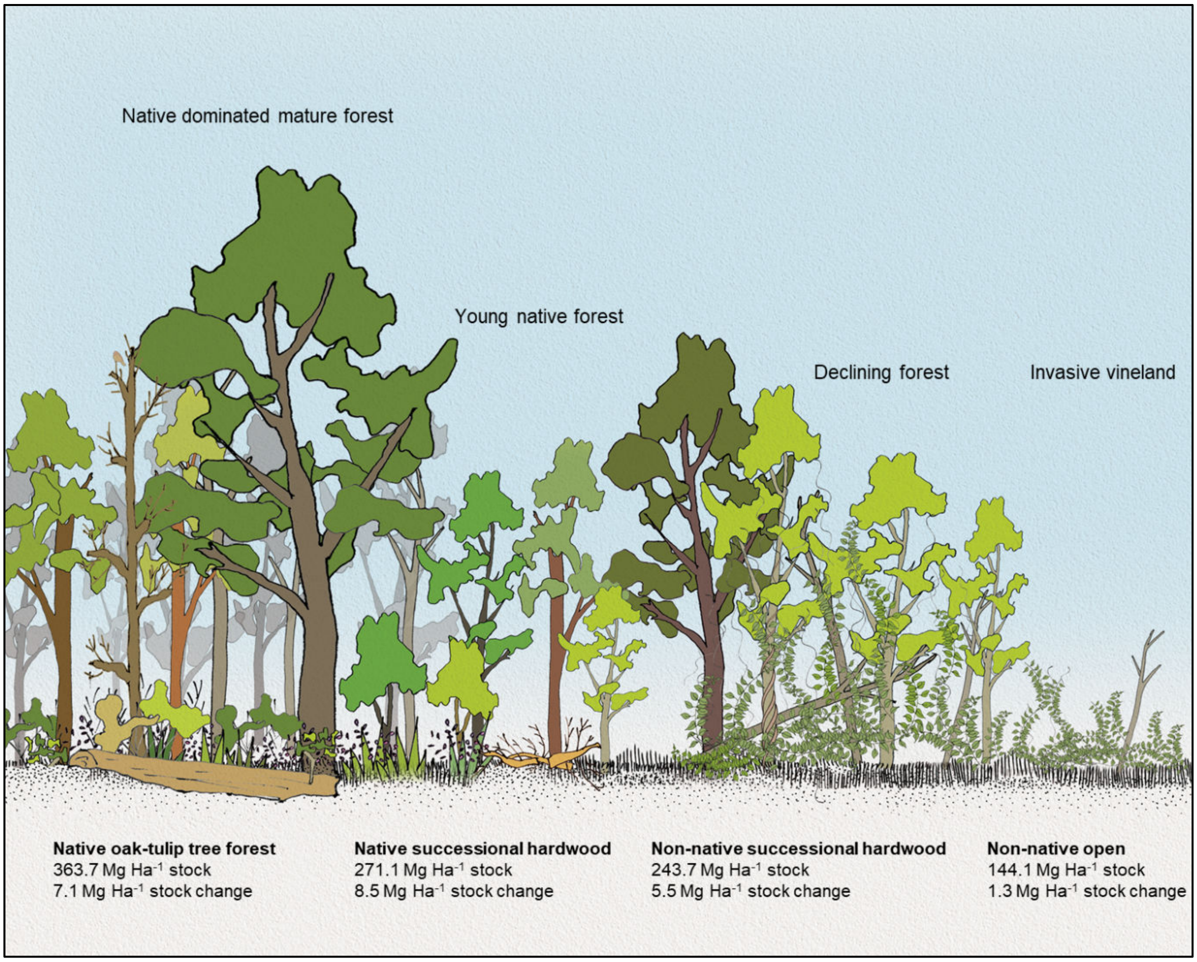


Figure 2. Carbon stock and stock change by different forest types in New York City natural area forests. Native dominated mature forests with large trees store the most carbon per hectare. Native successional hardwood forests have the highest rate of sequestration. Non-native open areas (e.g. grasslands, shrublands, vinelands) store the lowest amount of carbon per hectare and have the lowest rate of sequestration.

Healthy, native forests store and sequester more carbon than invaded, declining and degraded forests. Native community groups account for 75% of NYC natural areas, but 81% of carbon stocks and 85% of carbon gain. For a full list of the carbon stock and stock change rates by type see the appendix.

Comparisons with other trees in New York City and forests outside of NYC

All trees in New York City provide important benefits that contribute to improving the quality of life and mitigating climate change. Understanding the importance and relative contribution different urban forest types in the overall potential for climate mitigation will be important as different solutions are considered. Using existing data from a street tree census (NYC Parks) and assessment of the entire urban forest (Nowak et al. 2018) we compared the stocks of trees only. We also compared natural area forests to rural forests.

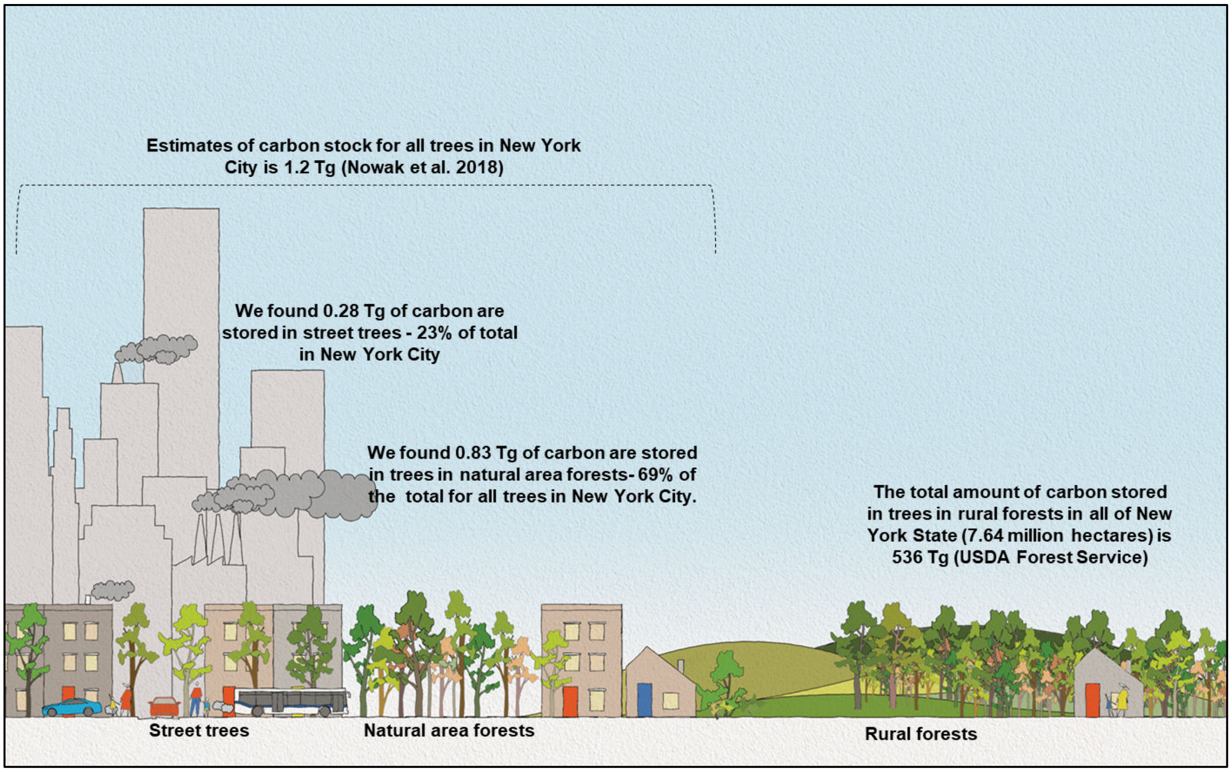


Figure 3. Trees in New York City's natural areas account for 69% of carbon stored in all trees in New York City, three times more carbon storage than street trees. On a per hectare basis natural area forests in New York City store and sequester similar rates to rural forests. Trees in New York City's natural areas account for 0.15% of total state estimate for carbon storage.

Natural area trees (excluding other pools) store 0.83 Tg of carbon. The estimate of the total amount of carbon stored in all trees in NYC is 1.2 Tg of carbon, and we calculated that street trees store 0.23 Tg carbon. Given that natural areas account for ¼ of the tree canopy in New York City (Pregitzer et al. 2019) this shows they are providing a disproportionate high amount of carbon storage per unit tree canopy, and account for 69% of carbon storage for the entire city found in trees, and account for over 3x more carbon that street trees. Compared to rural forests, natural areas store similar, and slightly higher storage and sequestration on a per hectare basis. New York State, is 63% forested and stores 536 Tg of carbon (USFS) across 7.64 million hectares.

Conclusions

As the world looks towards natural landscapes as a solution to climate change, urban forested natural area is a critical land type to consider in cities. Mature, native forested natural areas store and sequester the most carbon. More than street trees, more than degraded or invaded forests and just as much as rural forests. In order to ensure that our local forests reach their carbon storage potential, management of forests is key. Management such as invasive species removal, tree planting and other interventions are important tools for ensuring healthy, mature forests that will offer maximum carbon storage benefits.

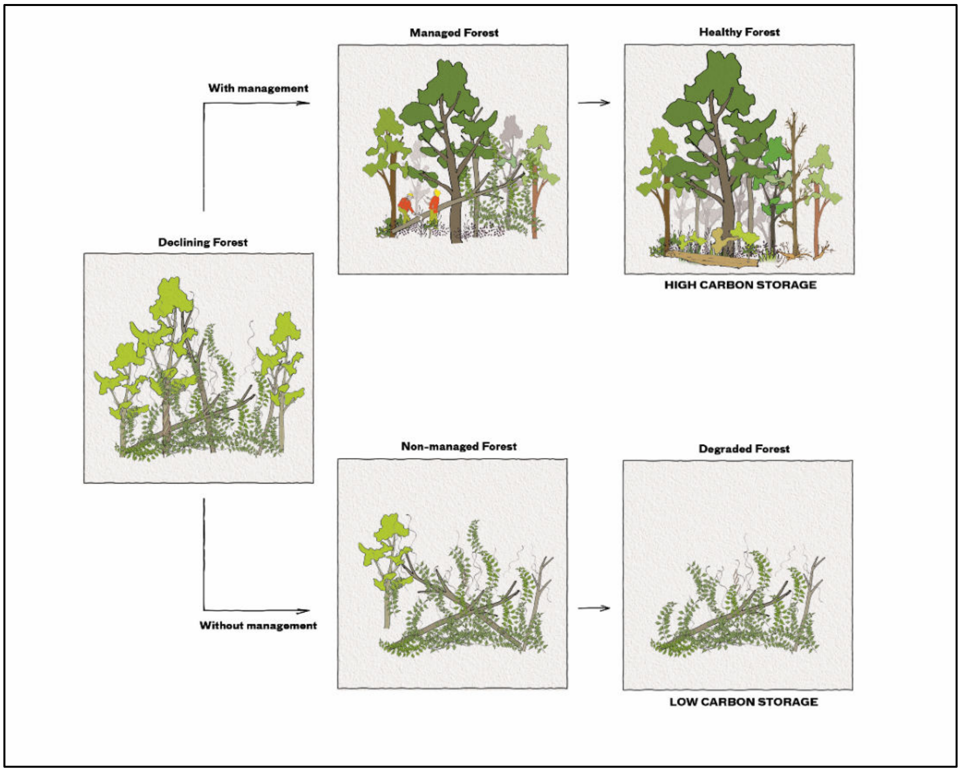


Figure 5. Management of urban forests that are in decline could lead to healthier forests, with higher carbon storage and more co-benefits.

Achieving healthy urban forests and greenspace within cities rests on disentangling the relationship between urbanization and forest ecology across a variety of spatial scales.

- NYC natural areas are net sinks for carbon and gain between 27,300 and 51,700 Mg carbon per year, 87% of which is gained by forests.
- Trees in natural forested areas store and sequester most of the carbon (75% and 83%, respectively) of all trees in NYC.
- Native forest types store and sequester more carbon that nonnative forest types.
- The PRI method for tree growth estimation results in three times more carbon sequestration than i-Tree estimates.

Appendix: Approach Overview

Forest Carbon Cycle

Carbon comprises roughly 50% of the organic material in trees, soil, and other forest components (soil also contains inorganic carbon, which is not accounted for in this budget due as the data would not allow us to estimate this). Atmospheric carbon is most prevalent in the form of carbon dioxide (CO_2) and methane (CH_4). Trees take CO_2 out of the atmosphere and convert it to sugar, 50% of which is stored in the tree trunk, or bole, the portion of the tree between the stump and branches (Birdsey & Heath, 1995). Carbon exits the tree in various ways: 1) through root exudates into the soil, 2) from the leaves into the litter layer, 3) in branches or twigs that fall onto the ground and take the form of coarse woody material (CWM) or fine woody material (FWM), and 4) through autotrophic respiration, i.e. the process of converting sugar to energy, which releases CO_2 into the atmosphere.

Carbon in dead wood or soil organic matter is decomposed by soil organisms, fungi, and microbes. During decomposition, some carbon is respired into the atmosphere as CO_2, while the rest remains in the wood or goes into the soil. Soil organic carbon (SOC) can be readily available to decomposers, or it can be bound to other soil particles for decades or millennia. A small amount of carbon also leaches from soil and dead wood; however, leaching is not included in this budget.

Methane (CH_4) is both produced and consumed by microbes. Soil and dead wood can be a source or sink for CH_4 depending on conditions (e.g. oxygen availability). A 2017 study by Warner and others found that, depending on the global warming conversion factor, CH_4 capture by soil and CWM offset below-canopy CO_2 emissions by between 1.5 and 4.5% (Warner et al., 2017). The study also concluded that living trees are a net source of atmospheric CH_4 and that they offset CH_4 uptake in soil and CWM by 3.5% (Warner et al., 2017). These findings indicate that CH_4 is not a large component of overall forest-atmosphere carbon exchange. Unlike CO_2, CH_4 pools and fluxes have not been widely studied and modeled in forest systems. For these reasons, CH_4 was excluded from this budget.

Carbon Pools

To determine the amount of carbon stored in NYC natural area forests, we calculated the amount of carbon stored in different components, or pools, within the forest. To calculate each pool, we used field-collected data from NYC forested natural areas (Pregitzer et al., 2019; Forgione et al., 2016) and related those data to published estimates of carbon for each component (i.e. trees, soil, etc.). Table 1 lists each forest carbon pool and provides a description of how the pool was defined/parameterized for this analysis, published benchmark estimates of pool sizes, net atmosphere exchange rates per hectare from the scientific literature, as well as factors to consider during interpretation of these estimates due to the urban context. For comparative stock estimates and exchange rates, we provided local and/or regional estimates as available. For pools without regional data, we selected estimates from studies on temperate, deciduous forests.

The benchmark estimates are intended to provide a point of reference to help contextualize our calculations for carbon pools in NYC's forests. Forest carbon is highly variable and dependent on microclimatic conditions such as moisture, microbial communities, and nutrient availability, all of which can be impacted by human activity in urban or altered environments. Given that most carbon pool estimates are based on rural forests and thus do not account for differences in urban areas, such as the urban heat island effect, we expect to see some differences in these estimates. In addition, some differences in sampling techniques, estimation methods, and/or carbon pool attributes vary between studies that could contribute to some differences between our estimates and others. For example, some studies include fine roots in the soil pool, not the live tree pool (Smith et al., 2013).

Table 1. Forest carbon pools, attributes, estimates, and urban considerations.

Pool	Definition/Attributes	Carbon Stock Estimates	Atmosphere Exchange Estimates	Urban Sequestration/ Emission Considerations
Live Trees	Living trees and shrubs >2 cm DBH (NAC, 2014), including biomass aboveground (stump, bole, branches, twigs, and foliage) and belowground (coarse and fine roots) (Jenkins et al., 2003)	**87.1 Mg/ha**, Northeastern US (Smith et al., 2013) **73.3 Mg/ha**, NYC assuming 100% cover (Nowak et al., 2013)	**1.24 Mg/ha/yr** sequestered, NYC assuming 100% cover (Nowak et al., 2013)	Lower ozone levels, higher CO_2, warmer temperatures, and higher nutrient deposition increase growth/sequestration, while pollutants in soil (e.g. heavy metals) and atmosphere (e.g. NOX and SO_2) decrease sequestration (Gregg et al., 2003)
Herbaceous	Tree/shrub seedlings <2 cm DBH and nonwoody plants, including forbs and graminoids (Johnson et al., 2017)	**1.8 Mg/ha**, Northeastern US (Smith et al., 2013)	Negligible (not included in budget)	Anthropogenic disturbance creates canopy gaps that accelerate herbaceous growth; invasive vines are prevalent in urban forests
Standing Dead Trees (SDT)	Dead trees >10 cm DBH and leaning <45 degrees from the perpendicular axis to the ground (NAC 2014)	**5.1 Mg/ha**, Northeastern US (Smith et al., 2013) **2.59 Mg/ha**, Massachusetts (Liu et al., 2006)	**0.08 Mg/ha/yr** emitted, Massachusetts (Liu et al., 2006) **1.52 Mg/ha/yr** emitted, Japan (Jomura et al., 2007)	Removal may occur
Coarse Woody Material (CWM)	Downed dead wood >10 cm DBH and <1 m above the ground, including detached tree pieces, fence posts, slash piles, etc. (NAC, 2014)	**9.18 Mg/ha**, NY (Woodall et al., 2013) **2.52 Mg/ha**, Massachusetts (Liu et al., 2006)	**0.53 Mg/ha/yr** emitted, Wisconsin (Forrester et al., 2012) **0.21 Mg/ha/yr**, Michigan (Gough et al., 2007) and Massachusetts (Liu et al., 2006)	Removal may occur

Fine Woody Material (FWM)	Downed dead wood >0.2 and <10 cm DBH detached from source and <30 cm above the ground (NAC, 2014)	**6.37 Mg/ha**, NY (Woodall et al., 2013) **3.67 Mg/ha,** Northern hardwood; **0 to 227.94 Mg/ha**, Northern US (Domke et al., 2016)	**0.08 Mg/ha/yr** emitted, Massachusetts (Liu et al., 2006)	Soil warming increases FWM decomposition (Berbecco et al., 2011)
Litter & Duff	Litter consists of freshly fallen plant material such as foliage, twigs <0.025 cm DBH, etc.; Duff contains decomposing plant material between the litter layer and mineral soil (NAC, 2014); litter & duff are also known as the soil O horizon	**12 Mg/ha**, NYC (Pouyat et al., 2002) **9.36 Mg/ha,** Northern hardwood; **0.04 to 86.1 Mg/ha**, Northern US (Domke et al., 2016)	**0.6 to 1.3 Mg/ha/yr** emitted, Massachusetts (Gaudinski et al., 2000) **2.3 to 2.6 Mg/ha/yr** emitted, Rhode Island (Davis et al., 2010)	Decomposition increases with temperature (Hanson et al., 2003); decreased ozone levels facilitate litter decay (Carreiro et al., 2009)
Mineral Soil (Organic)	Soil below the duff layer/O horizon, including all organic carbon to a depth of 30 cm or bedrock, whichever is higher	**104 Mg/ha** to 30 cm depth, NYC (Cambou et al., 2018) **50 Mg/ha** to 10 cm depth, NYC (Pouyat et al., 2002)	**6.83 Mg/ha/yr** emitted (A & Ap layers), Massachusetts (Gaudinski et al., 2000) – *heterotrophic respiration only, excludes root respiration and sequesteration*	Urban heat island effect and pollution alter the litter chemistry, decomposer organisms, conditions, and resources, which all influence respiration rates (Carreiro et al., 2009); earthworms, prevalent in urban areas, accelerate decay, but some carbon is sequestered in passive pools (Pouyat et al., 2002)

Methods

Approach & Limitations

We calculated carbon stocks for this budget using forest inventory data collected by the Natural Areas Conservancy (NAC) in 2013 and 2014. NAC developed its field protocol based on the USFS Forest Inventory Analysis (FIA) Program's methods with some minor differences in transect length, plot size, minimum diameter, etc. (NAC, 2014). Whenever possible, we estimated plot-level carbon using FIA estimation methods with modifications that account for differences in NAC's sampling protocol. All modifications are described in this report. Many FIA equations used in the pool calculations require forest type and/or tree species attributes (e.g. wood density). We obtained this data from FIA manuals and databases when available (see citations in Carbon Estimation section). However, FIA does not have data on many of the non-native tree species present in NYC and other urban areas. We used averages when species-specific information was lacking, which may impact results and hinder comparisons between native and non-native forest types.

NAC's collected data on each plot only once, so we are unable to detect actual changes in pools over time. Instead, we selected sequestration and emission rates from the scientific literature to estimate the annual change in stock pools. We assumed that the pools, except soil, are in steady state (i.e. inputs equal outputs) with regards to transfers between pools. Forests that have higher sequestration than respiration are a carbon sink, while forests with higher respiration than sequestration are a carbon source. To estimate carbon stock change in each pool with a higher degree of certainty, future work could include: 1) remeasurement of existing field plots with the collection of additional data such as tree growth and soil respiration rates, or 2) entering assessment data into ecosystem modeling and/or carbon accounting programs to account for fluxes and transfers between pools.

For sequestration, we predicted annual tree growth using published growth equations. Annual tree growth accounts for carbon that the tree sequesters in the form of live biomass and loses in the form of autotrophic respiration (metabolism of organic matter by plants), but it does not account for carbon that the tree loses from leaf and fine root turnover. Trees allocate up to 75% of annual net primary production to their fine roots and, as fine roots die throughout the year, they lose the equivalent of up to double their amount of fine root biomass to the soil pool (Finér et al., 2011). We accounted for this form of soil sequestration by estimating fine root turnover in the tree and herbaceous pools using published turnover rates. Our estimate of soil sequestration also includes inputs from the litter and duff layers, which are presumably replenished by inputs from other pools (leaf turnover, wood decay, etc.).

For emission, we estimated heterotrophic respiration in pools with dead organic matter (soil, downed and standing wood, litter, and duff) using published rates of carbon respired per carbon stock. Heterotrophic respiration (metabolism of organic matter by animals, bacteria, fungi) rates vary depending on biotic and abiotic factors. Regression equations that account for these factors are available in the scientific literature, however these equations require fine scale input data (e.g. the temperature of a piece of CWM) that was not included in NAC's forest assessment. Therefore, we selected respiration rates based on the closest location, climate, and forest type, and multiplied them by the pool's carbon stock to obtain the amount of carbon emitted into the atmosphere in the form of CO_2.

For all pools except soil, we estimate stock change based on atmosphere exchange alone, which requires the assumption that the pool is in steady state. However, some pools are likely gaining more carbon than they are losing, or vice versa. For example, a disturbance such as a storm can add a large amount of carbon to the CWM pool, which then decays over a long period of time. Another shortcoming of the stock change calculations is that, with one exception (wetland vs upland soils), the rate of emission depends entirely on the amount of carbon in the pool. In reality, emission rates vary due to environmental conditions. For example, saturated soil will respire less carbon than dry soil that contains the same amount of carbon (Gaisson et al., 2013). Also, an increase in emission in one pool may be accompanied by a decrease in emission in another pool, resulting in zero net change (Schmid et al., 2015).

Despite these limitations, the stock change values in this report provide some insight into the sink source relationship of NYC urban forests. Previous studies on carbon sequestration in urban forests assume that net ecosystem exchange is equal to net sequestration in the live tree pool, which excludes heterotrophic respiration in the soil and dead wood pools (Nowak et al., 2013). This assumption may make sense for the portion of the urban canopy occupied by street trees, from which dead wood and litter is removed. However, 25% of the urban canopy is comprised of natural forested areas (Pregitzer et al. 2019), this type of urban forest can contain high volumes of dead organic material. Thus, ignoring heterotrophic respiration overvalues the sequestration potential of urban forests.

Live Tree Pool

Carbon stocks of live trees can be estimated from field measurements of individual trees or remote sensing data. NAC's data is comprised of field measurements; therefore, we did not consider remote sensing methods were for this pool. During the 2013-2014 forest assessment, the NAC field team measured the diameter at breast height (DBH) of all trees per plot that had a DBH of 2 cm or higher. The team also recorded total height for some trees (1684/11469).

The scientific literature contains two prominent methods to estimate carbon in live trees in the US that rely on measurements of individual trees: 1) allometric equations for tree species and species groups developed from a meta-analysis by Jenkins et al., 2003 and 2) FIA's Component Ratio Method (CRM) described in Woodall et al., 2011.

Jenkins' biomass regression equation, derived from national forest inventory data, predicts total aboveground biomass with DBH and species group (Jenkins et al., 2003). A ratio formula with coefficients for each tree component estimates belowground biomass (both coarse and fine roots) and the biomass of aboveground components (branches, foliage, etc.).

CRM builds on the Jenkins method by incorporating tree height and regional differences into the calculations (Woodall et al., 2011). It estimates bole (trunk) biomass using region-specific volume formula and the specific gravity of the tree species. Other components are calculated using the Jenkins ratio formula adjusted for the difference in bole biomass. Studies estimate that CRM results in a 15% reduction in biomass for forests in the Northeast (Heath et al., 2009).

We chose the Jenkins method for this project because NAC's dataset did not include bole height. We obtained equations from Jenkins et al., 2003, however, species group coefficients came from a 2014 paper by Chojnacky, Jenkins, and others, which provided updated coefficients that account for differences in wood density between species of the same group (Chojnacky et al., 2014). Our dataset did not provide the DBH of mid-story trees (between 2 and 10 cm DBH) so we substituted a median value of 6 cm. The impact of this assumption on error and uncertainty is difficult to quantify. Appendix I contains more details on carbon calculations for each pool, including live trees.

We estimated annual net carbon sequestration in the live tree pool with diameter growth predictions. The scientific literature contains various methods for predicting diameter growth. Some diameter growth models include variables that were not measured as part of the NAC forest assessment, such as crown ratio, and thus were not considered for this project (Lessard et al., 2000). Urban forest carbon sequestration models (e.g. the UFORE model, i-Tree) use average diameter growth from a 1984 study conducted on trees in Indiana and Illinois (Nowak & Crane, 2000; Smith & Shifley, 1984). This method does not account for differences in growth rates between species or regions.

We selected the potential relative increment (PRI) method to predict annual diameter growth. PRI estimates a tree's optimal growth increment using its DBH and species-specific coefficients (Bragg, 2000). We obtained coefficients from a study on trees in the Northeastern US (Bragg, 2005). To account for variation in tree growth, we theorized that trees with low vigor scores (an evaluation of tree health) would have less than optimal growth, and thus applied a reduction factor (see Appendix I). We did not include mortality rates in the sequestration calculations because this would introduce a transfer of carbon between pools and complicate the budget's steady state assumption.

Herbaceous Pool

Compared with other pools, the scientific literature includes few studies on estimating carbon in the herbaceous layer. One model predicts herbaceous biomass using forest type and biomass in the live tree pool (Russell et al., 2014). Another uses only live tree density (Smith et al., 2013). These methods rely on generalized observations of forests, not site-specific field measurements. Other methods, such as FIA's BIOPACK software, predict biomass with percent cover (Chojnacky & Milton, 2008).

NAC's dataset includes, for each subplot, percent cover for herbaceous vegetation to a height of 1 meter, and the number of tree/shrub seedlings. We estimated Herbaceous layer carbon for this project using a method from a 2017 study by Johnson and others, which includes regression equations for shrub biomass, nonwoody biomass, and seedling biomass (Johnson et al., 2017). We excluded shrub biomass because the equation requires height data and because shrubs 2 cm and larger are accounted for in the live tree pool. Nonwoody biomass was predicted using percent cover, and seedling biomass was predicted using seedling density.

We did not estimate net sequestration in the herbaceous layer. The amount of carbon sequestered by the herbaceous layer, if any, is likely to have a very minor impact on the overall stock change budget. Much of the biomass in this layer is in foliage, which has annual turnover. Also, herbaceous carbon comprises only 2% of overall stocks. Lastly, we could not identify methods for calculating herbaceous layer carbon sequestration.

Standing Dead Tree Pool

FIA collects data on standing dead tree (SDT) stocks using the line-intersect sampling (LIS) method and LIS estimation equations. NAC collected SDT data in two ways: 1) using the LIS sampling method, and 2) by recording, for each plot, DBH of every SDT 10 cm or larger and the number of SDTs with a DBH between 2 and 10 cm. The latter method offers more comprehensive data, so we calculated SDT carbon stocks using the same methods as the live tree pool (see Live Trees) with modifications for carbon loss through decay (see Appendix I).

We calculated the rate of heterotrophic respiration used to estimate SDT pool carbon emission from a study conducted in the Harvard Forest in Massachusetts (Liu et al., 2006). The average annual rate (0.0291) reflects SDT carbon respired (Mg/ha/yr) per unit of SDT carbon stock (Mg/ha). We used only control site data (Harvard Forest in MA) in this calculation. This rate is close to that of another study (0.0303) conducted in Japan (Jomura et al., 2007).

We calculated SDT respiration using aboveground carbon stocks only, which may slightly underestimate total respiration. We excluded belowground stocks because the rate from Liu 2006 was derived using only aboveground stocks. The exclusion of SDT root respiration is likely made up for with soil respiration, since SDT root volume was not subtracted from the soil pool because of its negligible impact on soil stocks.

Coarse Woody Material Pool

The NAC assessment team collected coarse woody material (CWM) data using FIA's LIS sampling method. Therefore, we used the LIS CWM estimation formula to estimate carbon stocks (Woodall & Monleon, 2008). This formula requires the volume and density of each CWM piece. We selected the conic-paraboloid volume formula for downed log pieces of CWM because it is the most accurate and least biased formula that is compatible with NAC's diameter measurements, which were taken on both ends of the CWM piece (Fraver et al., 2007). Volume formulae for other CWM pieces (a small proportion of the dataset) were selected from Woodall 2008 based on data constraints (see Appendix I). As CWM pieces decay, volume and density are both reduced. Volume loss through decay was accounted for with structural reduction factors from Fraver 2013. Density loss is incorporated into the absolute density values used to calculate biomass.

We estimated annual stock change in the CWM pool using the same method as the SDT pool but with a different heterotrophic respiration rate. We calculated the CWM rate (0.0814) using the Liu 2006 results for CWM instead of SDT.

Fine Woody Material Pool

NAC staff collected fine woody material (FWM) data using the LIS sampling method. We calculated carbon stocks with the LIS formula for FWM volume, a decay reduction factor from Harmon 2008, and

FWM bulk density estimates for the various forest types (see Appendix I). Annual stock change in the FWM pool was calculated in the same way as the CWM pool, with a rate of 0.0769 (Liu et al., 2006).

Litter & Duff Pool

During the field assessment, staff measured the depth of both the litter and duff layers at several points along the transect line in each plot. We used the LIS litter/duff formula to calculate average depth for each layer. To estimate dry-weight biomass, we multiplied the average layer depth by the bulk density for the layer and plot forest type. We assumed that 50% of biomass is carbon (Woodall et al., 2011).

We multiplied litter and duff carbon stocks by heterotrophic respiration rates to estimate carbon emission. We calculated rates for each layer from a study conducted in the Harvard Forest in Massachusetts (Gaudinski et al., 2000). To obtain an annual litter respiration rate, we divided respiration of carbon from the litter layer/Oi horizon (Mg/ha/yr) by total litter carbon stock (Mg/ha). We also performed this calculation for the duff/Oe and Oa horizon.

Soil Organic Carbon Pool

Three variables are needed to estimate the soil organic carbon (SOC) stock in each plot: volume, bulk density, and percent organic carbon. The NAC field team took a composite soil sample in each plot to a depth of 10 cm. Samples were analyzed for several properties, including percent organic carbon and loss on ignition (LOI). For plots without percent carbon data, we estimated percent carbon by multiplying LOI by a factor of 0.58 (Pribyl, 2010). We tested other methods, including a linear regression model, on observations with both percent carbon and LOI data; the conversion factor of 0.58 produced the most accurate results.

Soil samples were not analyzed for bulk density during the NAC forest assessment, so we instead obtained bulk density from Soil Grid, which uses geospatial analysis to estimate various soil properties (ISRIC, n.d.). For plots without Soil Grid data, we calculated bulk density using a regression equation from Al-Shammary 2018. We assumed the volume of mineral soil to be a hectare in area and 10 cm in depth, minus the coarse fragment and root volume. We estimated coarse fragment from NRCS soil series descriptions, and calculated root volume from live tree belowground biomass (see Appendix I).

Most carbon budgets report soil stocks to 30 cm or 1 m. To extrapolate down to 30 cm, we assumed that 74% of soil is in the first 10 cm. This assumption was based on results from a study of soils using NRCS data, which found that NYC woodland soils have 104 Mg C/ha in the top 30 cm of soil (Cambou et al., 2018). Our SOC plot average to 10 cm is 77 Mg C/ha, which is 74% of the 30 cm estimate from Cambou et al., 2018. This percentage is similar to the Gaudinski et al., 2000 results, which show that, to a total depth of 30 cm, 71% of carbon is in the first 10 cm of soil of the Harvard Forest (percentage estimated from charts).

We calculated the heterotrophic respiration rate for the soil pool from a 2005 study of Hubbard Brook in New Hampshire using the mineral soil results (Fahey et al., 2005). Since the study assessed upland soils, we adjusted the respiration rate for wetland soils (i.e. plots with a vegetation type of “forested wetland” or “marsh”). We determined the wetland adjustment factor based on results from a study conducted in Rhode Island on four forest soils with different drainage classifications (Davis et al., 2010). We calculated this adjustment factor by dividing the average respiration rate (respiration/carbon stock) for the three upland soil types by the respiration rate for the wetland soil (a Histosol in a red maple swamp).To obtain the wetland soil respiration rate (0.00174), we divided the upland soil respiration rate (0.0118) by the adjustment factor (6.78).

To account for carbon sequestration in the soil pool, we estimated carbon entering the soil pool through litter and duff decay and fine root turnover. We calculated annual decay in the litter and duff pools using turnover rates—4 years for litter and 40 years for duff—from a study conducted in Massachusetts (Gaudinski et al., 2000).

A 2011 study that compiled global fine root turnover rates found that, in temperate forests, the average annual fine root turnover rate is 1.32 for trees and 1.21 for all plants, including trees and understory vegetation (Finér et al., 2011). The study calculated fine root turnover by dividing annual fine root production by fine root biomass. Therefore, a fine root turnover rate of 1.32 indicates that annual fine root production is 1.32 times the amount of fine root biomass. We theorized that any fine root biomass not accounted for by tree growth must enter the soil pool in the form of root decay. To estimate carbon entering the soil pool in the form of tree fine root production, we multiplied fine root carbon by the appropriate fine root turnover rate and then subtracted the carbon increase to the fine roots in the live tree pool.

Forest Types and Distribution

All plots were assigned forest and vegetation types using various classification systems (see Table 2). We calculated average carbon per unit area values for types in all classification systems (see Excel results files). To calculate the overall carbon budget for NYC's urban forests, we used a hybrid of NY Natural Heritage Program (NYNHP) community type and the US National Vegetation Classification (USNVC) system. The NYNHP classified each field-sampled plot to a specific vegetation class based on the species present and dominant in the plot, whereas the Ecological Covertype Map (O'Neil-Dunne et al., 2014) used remote sensing to spatially represent vegetation types across all of NYC.

Table 2. Classification systems used to compare forest and vegetation types.

Classification System	Number of Types in NYC	Source
NYNHP Community	57	New York Heritage Foundation (CITE report)
FIA Forest	18 (type level); 7 (group level)	USFS (CITE)
US National Vegetation Classification (USNVC) – Level 4	23	USNVC (http://usnvc.org/); plots classified by Spatial Informatics Group, LLC (CITE)
Vegetation Types	6	New York Heritage - Groups
Native Status	2 (native & non-native)	NA

NYNHP matched all plots to a NYNHP community type based on NAC's forest assessment data (O'Neil-Dunne et al., 2014). Plots may contain numerous community types; the type selected is the dominant one. Unfortunately, no information is available regarding the distribution of hectares in NYC based on the NYNHP classification system. The USNVC classification system includes four levels, with increasing specificity. All four USNVC classification levels have been mapped for NYC, however, an accuracy assessment was not performed for levels three and four, and the level two type is essentially the same as the broad "vegetation" classification system which does not provide differences in forest community types but rather forest groups (i.e. upland forest, maritime forest). Furthermore, NAC plots were classified based on the plot center and thus may not reflect the plot's dominant USNVC type.

To maximize the utility of both data sets while understand their limitations, we calculated hectares for NYNHP community types based on their relative proportion of plots in the appropriate USNVC level two category. We matched NYNHP type to USNVC level two type based on its vegetation classification. For example, the NYNHP community type "maritime post oak forest” represented 4.7% of the plots in the USNVC level two type “maritime forest,” of which there are 562 hectares in NYC. Therefore, there are approximately 26 hectares of “maritime post oak forest” in NYC.

Because the NAC assessment included only a few plots for some NY community types, we grouped community types based on similar characteristics. We used these community groups to calculate the total amount of carbon stored and sequestered by NYC forests. Figure 2 shows the distribution of hectares for grouped community types.

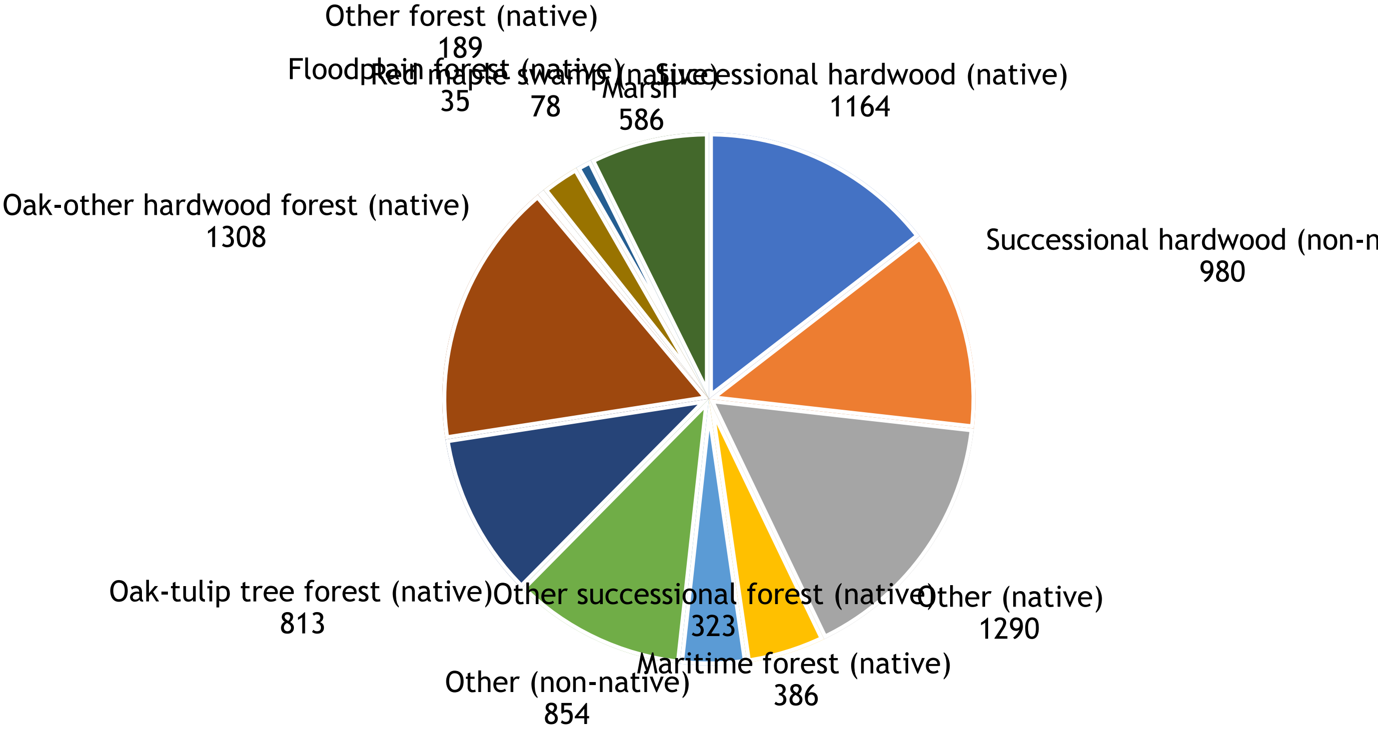


Figure 2. Distribution of NY community groups with the number of hectares for each.

Estimating Uncertainty

All carbon calculations methods used in this budget require data, equations, and assumptions obtained from field assessments, scientific literature, and online databases. Sources of uncertainty vary between pools but in general include:

1. Measurement error from data collected in the field by NAC, FIA, or others (e.g. species identification, DBH, etc.)
2. Allometric equations/model misspecification
3. Published estimates or averages used in equations (e.g. percent carbon in biomass)
4. Assumptions about biotic and abiotic influences

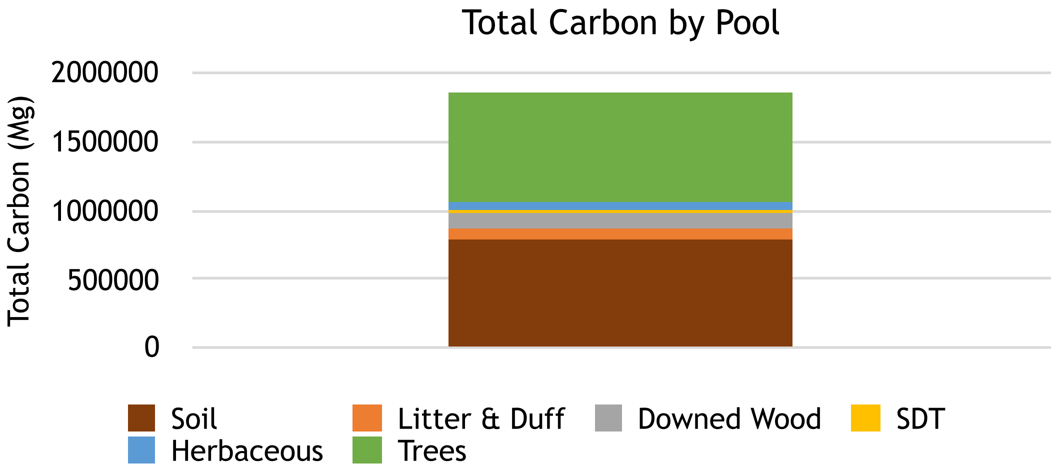
Quantifying individual sources of uncertainty is challenging, with little guidance available in the literature. Modeling error propagation and overall uncertainty is even more complex. First, variables are not always independent (e.g. temperature and moisture). Also, errors may be compounded, as is the case with calculations that entail multiple assumptions based on tree species. Therefore, we estimated uncertainty for each pool using margin of error calculations based on a t-distribution, which we selected because all our data is right-skewed. While beyond the scope of this project, Monte Carlo simulations may provide a better way to estimate uncertainty (Campbell et al., 2019). We did not calculate any uncertainty around assumptions about biotic and abiotic factors related to our estimates.

Expanded Results

NYC Urban Forest Budget

We estimate that natural areas in NYC store between 1.59 and 2.20 Teragrams carbon (mean 1.89 Tg with a 0.3 Tg margin of error). Approximately 80% of total carbon is stored by forests, and 20% by grasslands, marshes, and other non-forest community types. Most carbon is stored in trees (44%) and soil (42%). The other pools contain between 2 and 4% of the total carbon. About half of all carbon (47%) is stored in living pools (trees and herbaceous) and the other half (53%) in dead pools (downed wood, soil, etc.).

Figure 3



The average amount of total carbon per unit area weighted by NY community group is 236 Megagrams/hectare. NY community types range from 31.5 to 561 Mg/ha (see Table 3). Community types also vary in the amount and percentage of carbon stored in each pool. Some types do not have trees or dead wood, while others have more than double the average amount of carbon. One community type, successional southern hardwoods *Acer pseudoplatanus*, has 207 Mg carbon/ha in the CWM pool, while the average of all types is only 7.24 Mg/ha. This variation may be exacerbated by the small sample size for some community types. For example, the community type Successional southern hardwoods *Acer pseudoplatanus* was not widely distributed, hence 11 total plots of this forest type are available.

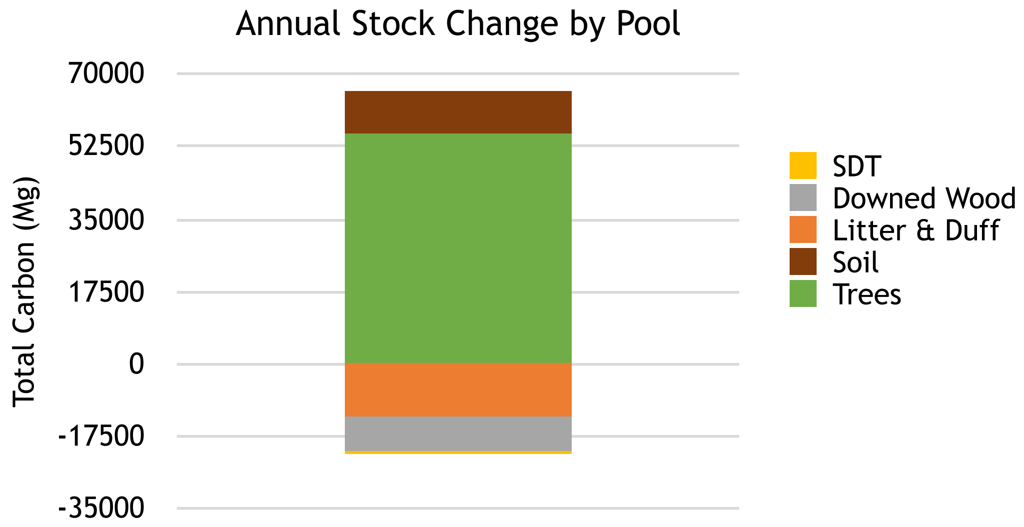
Table 3

Carbon Range for NY Communities (mean values)

	Stock (Mg/ha)		**Stock Change (Mg/ha)**	
Pool	**min**	**max**	**min**	**max**
Trees	0	423	0	19.2
Herbaceous	0.893	12.3	N/A	N/A
Standing Dead Trees	0	61.2	-1.43	0
Coarse Woody Material	0	207	-16.8	0
Fine Woody Material	0	24.0	-1.85	0
Litter & Duff	0	31.3	-3.87	0
Soil	21.5	195	-0.762	3.13
TOTAL	**31.5**	**561**	**-8.11**	**15.0**

NYC natural areas gain between 27,300 and 51,700 Mg carbon per year (mean of 44,200 Mg). Forests gain approximately 87% of this carbon. The soil and trees have a net sequestration of 65,900 Mg carbon per year, while the litter and duff, downed wood, and SDT pools emit 21,800 Mg carbon per year. Trees are responsible for 85% of sequestration, and the litter and duff layers are responsible for 60% of emission.

Figure 4



Tables 4 and 5 contain all total carbon and carbon per unit area values by pool with both the mean values and high and low confidence intervals:

Table 4

Carbon Per Unit Area by Pool (Megagrams/hectare)						
	Stock			Annual Stock Change		
Pool	Min	Mean	Max	Min	Mean	Max
Trees	89.4	104	119	6.06	6.96	7.88
Herbaceous	5.67	6.37	7.07	N/A	N/A	N/A
Standing Dead Trees	2.80	4.58	6.51	-0.152	-0.106	-0.0943
Coarse Woody Material	5.75	7.24	8.83	-1.04	-0.589	-0.554
Fine Woody Material	4.54	5.20	5.89	-0.591	-0.400	-0.337
Litter & Duff	10.0	10.6	11.1	-1.83	-1.62	-1.42
Soil	80.6	98.9	117	0.972	1.28	0.977
TOTAL	**199**	**236**	**275**	**3.41**	**5.52**	**6.45**

Table 5

Total Carbon by Pool (Megagrams)						
	Stock			Annual Stock Change		
Pool	Min	Mean	Max	Min	Mean	Max
Trees	716,000	830,000	949,000	48,500	55,700	63,100
Herbaceous	45,400	51,000	56,600	N/A	N/A	N/A
Standing Dead Trees	22,400	36,700	52,200	-1,210	-850	-755
Coarse Woody Material	46,000	58,000	70,700	-8,350	-4,720	-4,430
Fine Woody Material	36,000	41,600	47,200	-4,730	-3,200	-2,690
Litter & Duff	80,100	84,500	88,900	-14,700	-13,000	-11,300
Soil	645,000	792,000	939,000	7,780	10,200	7,820
TOTAL	**1,590,000**	**1,890,000**	**2,200,000**	**27,300**	**44,200**	**51,700**

Our carbon per unit area stock values for each pool are similar to the estimates from other studies of rural and urban forests that were first presented in Table 1. Table 6 compares the estimates from Table 1 to our results. Our live tree pool result is higher than results from other rural and urban forests, which is likely explained by the different methods used to estimate biomass. The estimate of 87.1 Mg/ha from Smith et al., 2013 is 16% lower than our estimate. This is in line with the assertion from Heath et al., 2009 that CRM results in 15% lower biomass than the allometric equations from Jenkins et al., 2003. The herbaceous pool also has higher than expected carbon per unit area, which may be a result of the methods used, or a reflection of the high levels of disturbance in urban forests that can create conditions for understory growth to flourish.

Table 6

Comparison with Other Studies by Pool (mean Mg carbon/ha)

Pool	Stock - Other Studies*	Stock – Our Estimate	Stock Change - Other Studies*	Stock Change - Our Estimate
Live Trees	73.3 - 87.1	104	1.24 sequestered/ year	6.96 sequestered/ year
Herbaceous	1.8	6.37	N/A	N/A
Standing Dead Trees (SDT)	2.59 - 5.1	4.58	0.08 - 1.52 emitted/ year	0.106 emitted/ year
Coarse Woody Material (CWM)	2.52 - 9.18	7.24	0.21 - 0.53 emitted/ year	0.589 emitted/ year
Fine Woody Material (FWM)	3.67 - 6.37	5.20	0.08 emitted/ year	0.400 emitted/ year
Litter & Duff	9.36 - 12	10.6	0.6 - 1.3 emitted/ year	1.62 emitted/ year
Mineral Soil (Organic)	104	98.9	N/A	1.28 sequestered / year

**See Table 1 for citations of other studies*

Most of our sequestration and emission results are close to those presented in other studies. However, we are less confident in these results because they are not based on observational data. Comparison to the results in Table 6 is further hindered by the fact that some of these studies were used to calculate the respiration rates that we used in our calculations.

Native vs. Nonnative Community Groups

Native community groups account for 75% of NYC natural areas, but 81% of carbon stocks and 85% of carbon gain. Figures 5 and 6 show the amount of carbon per hectare for all NY community groups. The one nonnative forest group—successional hardwood (non-native)—has the lowest net carbon gain per hectare, and the second-to-lowest carbon stock per hectare. Tables in Appendix II show the values for each community group by pool.

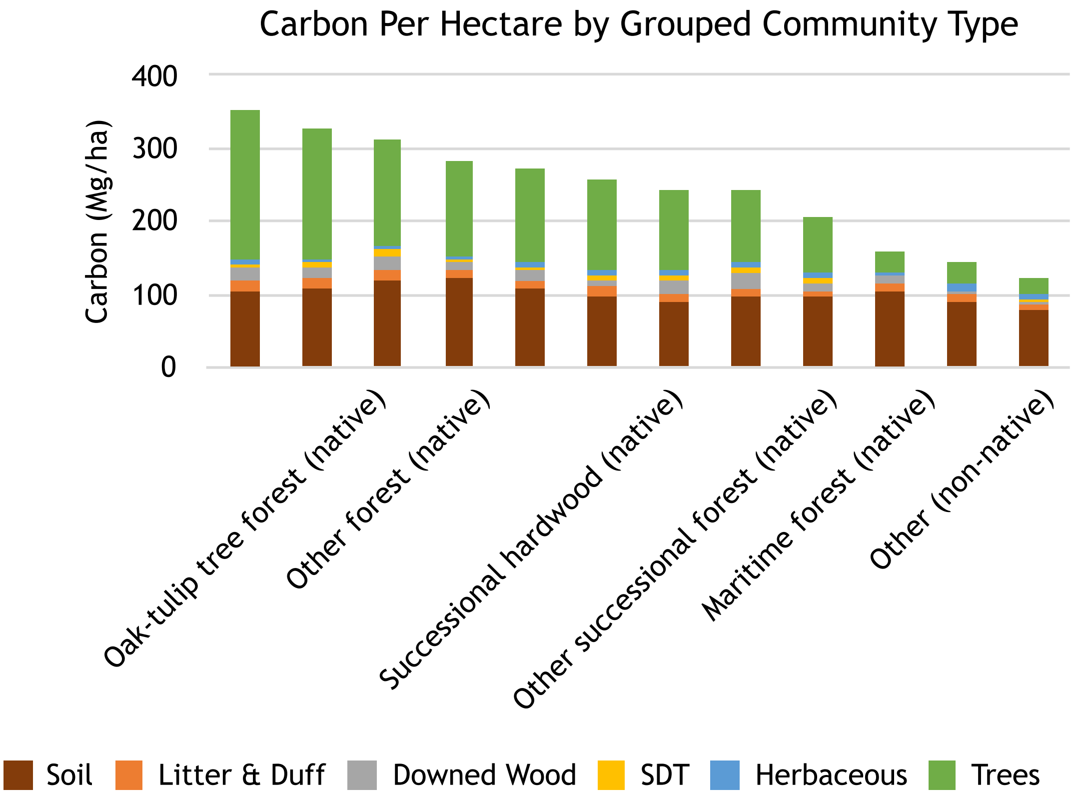
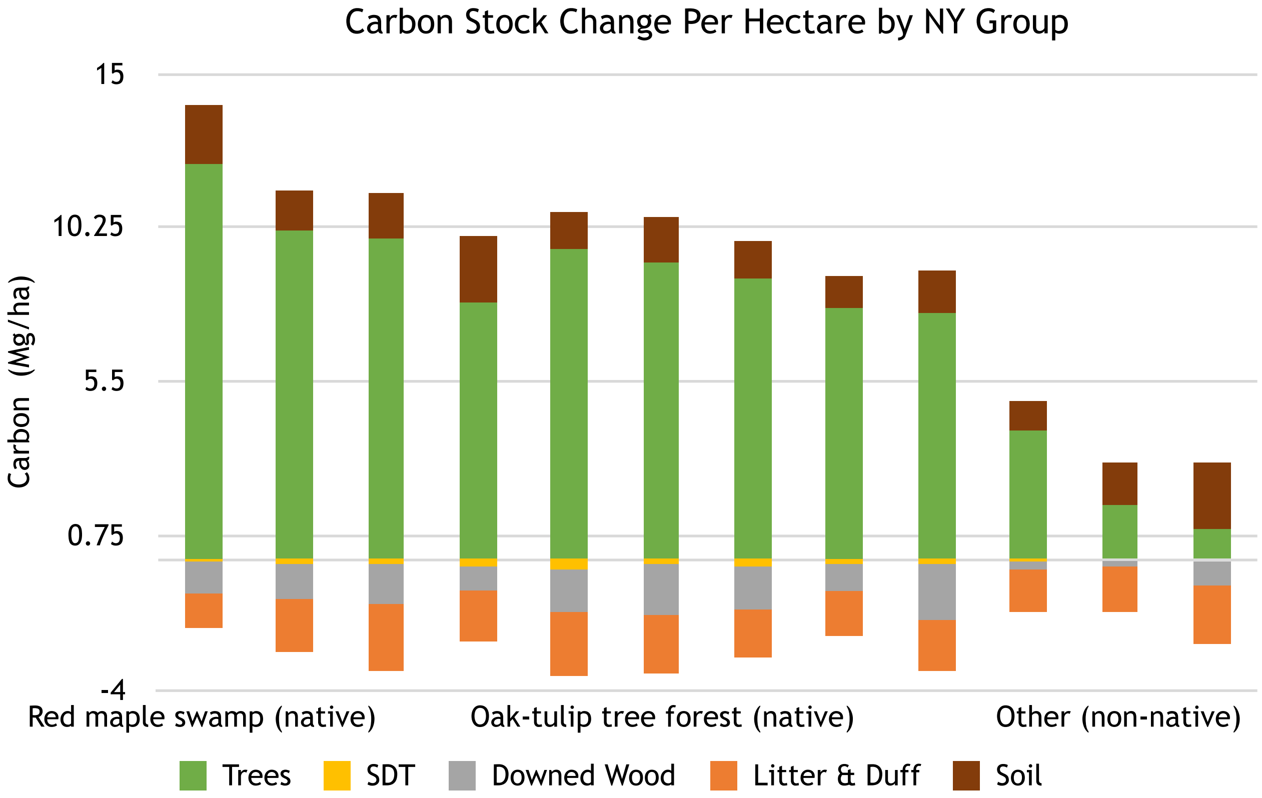


Figure 5

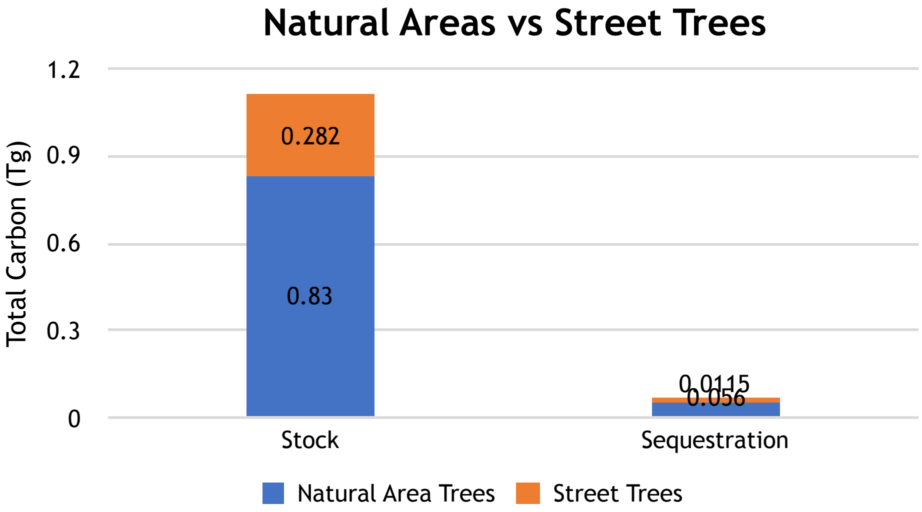
Figure 6



Street Trees vs Natural Forested Areas

We applied the same estimation methods to NYC street trees using street tree census data (NYC Department of Parks, 2018). Excluding all other trees, NYC's natural areas and street trees store 1.11 Tg carbon and sequester 0.0672 Tg carbon in the tree pool only (this estimate excludes soil and all other pools). Of this total the natural areas contain 75% of the urban forest tree carbon stock, and account for 83% of net tree sequestration.

Figure 7



Nowak and Crane report a slightly higher stock of 1.23 Tg carbon for all trees in New York City, (this value includes landscaped/park trees) and a much lower sequestration value of 0.0208 Tg carbon (Nowak & Crane, 2002). The lower sequestration value is likely a result of different estimation method for diameter growth. Our calculations, described in the Live Tree Pool methods section, rely on potential relative increment curves specific to species in the northeastern US. Nowak and Crane applied an average diameter growth rate to all trees regardless of species. This rate, which came from Smith & Shifley, 1984, is not specific to tree species or region.

Conclusions

- Natural areas in NYC store between 1.59 and 2.20 Teragrams carbon, 80% of which is stored in forests.

- NYC natural areas are net sinks for carbon and gain between 27,300 and 51,700 Mg carbon per year, 87% of which is gained by forests.
- Natural areas store and sequester enough carbon to offset 421,000 cars (based on EPA estimates of car emissions).
- Trees in natural forested areas store and sequester most of the carbon (75% and 83%, respectively) of all trees in NYC.
- Native forest types store and sequester more carbon that nonnative forest types.
- The PRI method for tree growth estimation results in three times more carbon sequestration than i-Tree estimates.

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Appendix 2: Calculation Steps

Live Tree Stocks

We performed calculations separately on the overstory (trees DBH ≥ 10 cm) and mid-story (trees between 2 and 9.99 cm DBH) datasets. Dead trees (vigor class of 5) were removed from both datasets and analyzed separately (see standing dead trees pool). Overstory trees with missing DBH (5) were also excluded. Mid-story tree DBH was not measured, so we assumed a median DBH of 6 cm for each observation.

We calculated dry-weight aboveground biomass (i.e. bole, aboveground coarse roots, branches, twigs, and foliage) using the allometric equation from Jenkins et al., 2003:

Equation 1: $\mathbf{ABM_t = \mathit{Exp}(\beta_0 + \beta_1\ \mathit{ln}\ DBH_t)}$, where:

ABM_t = aboveground biomass of tree *t* (kg dry weight)
Exp = exponential function
β_0 and β_1 = species group coefficients
ln = natural log
DBH_t* = diameter at breast height of tree *t* (cm)
*Note that this equation is intended for use with trees ≥ 2.5 cm DBH

We obtained species group coefficients from Chojnacky et al., 2013 and Woodall et al., 2011, and adhered to the following process to match each species in the dataset to the appropriate species group:

1. We matched species to the appropriate combination of taxa (genus or family) and median specific gravity in Chojnacky et al., 2013 (for species with both hardwood and woodland coefficients, hardwood was selected)
2. If the taxa were not included in Chojnacky et al., 2013, we obtained coefficients from the REF_SPECIES spreadsheet in the Woodall et al., 2011 supplemental documents (this spreadsheet uses coefficients from Jenkins et al., 2003)
3. If the species was not listed in REF_SPECIES, we substituted coefficients for mixed hardwoods from Jenkins et al., 2003
4. For trees with missing species information, we substituted a weighted average calculated from the data for each coefficient

We calculated belowground biomass using the Jenkins et al., 2003 ratio equation:

Equation 2: $\mathbf{R_{\mathit{ct}} = \mathit{Exp}(\beta_0 + \beta_1/DBH_t)}$, where:

R_{ct} = ratio of component *c* to aboveground biomass of tree *t*
Exp = exponential function
β_0 and β_1 = component coefficients (e.g. coarse root, foliage, etc.)
DBH_t = diameter at breast height of tree *t* (cm)

To get the biomass of each component, we multiplied the ratio of each belowground biomass component (coarse and fine roots) by the tree's aboveground biomass. Total biomass of the tree was obtained by summing all components:

Equation 3: $\mathbf{TBM_{\mathit{t}} = ABM_t + R_{\mathit{frt}}{*}ABM_t + R_{\mathit{crt}}{*}ABM_t}$, where:

TBM_t = total biomass of tree *t* (kg dry weight)
ABM_t = aboveground biomass of tree *t* (kg dry weight) – *from Equation 1*

R_{frt} = fine root component ratio of tree *t* – *from Equation 2*
R_{crt} = coarse root component ratio of tree *t* – *from Equation 2*

To determine the biomass per unit area in megagrams/hectare, total biomass of the plot (the sum of all trees) was converted from kilograms to megagrams and divided by the plot area (0.0314 hectares). Carbon content was assumed to be 50% (Woodall et al., 2011).

Equation 4: $\mathbf{C_x = (0.50 * \sum(TBM_x/1000))/0.0314ha}$, where:
C_x = carbon stored in trees for plot x (Mg/ha)
TBM_x = total biomass of all trees in plot x (kg) – *from Equation 3*
0.50 = conversion to carbon (50% of dry-weight biomass is carbon)
1000 = conversion from kg to Mg
0.0314 = hectares in plot (circle with 10 m radius)

Live Tree Net Sequestration

To calculate net carbon sequestration, we first estimated DBH in year 2 using the potential relative increment (PRI) method. The following formula from Bragg 2001 calculates the PRI for an individual tree based on its DBH and species:

Equation 5: $\mathbf{PRI_t = b_1 DBH_{t1}^{b_2}\, b_3^{DBH_{t1}}}$, where:
PRI_t = potential relative increment of tree t (ratio)
DBH_{t1} = year 1 DBH of tree t (cm)
b_1, b_2, b_3 = species-specific coefficients

We assigned trees coefficients based on the species listed in the table in Bragg, 2005. These coefficients are specific to the northeastern U.S. If a tree's species was not included in the table, we substituted an average for its genus. If a genus was not included, we substituted the average for hardwoods or softwoods. This method may underestimate growth of fast-growing non-native trees.

Because PRI is the maximum increment a tree is likely to grow, we adjusted the PRI based on the health of the tree. Specifically, we applied the following reduction factors based on vigor class:

Table 7. PRI reduction factor for each vigor class.

Vigor class	Reduction factor
1	1
2	0.75
3	0.50
4	0.25

We assumed that overstory trees with missing vigor data were class 1. Vigor class was not recorded for the mid-story layer, so we applied an average reduction factor of 0.76 (from the overstory data) to all mid-story trees. The following formula was used to calculate DBH in year 2:

Equation 6: $\mathbf{DBH_{t2} = (PRI * RF * DBH_{t1}) + DBH_{t1}}$, where:
PRI_t = potential relative increment of tree t – *from Equation 5*
RF = reduction factor based on vigor class (ratio) – *from table 7*
DBH_{t1} = year 1 DBH of tree t (cm)

DBH_{t2} = year 2 DBH of tree t (cm)
b_1, b_2, b_3 = species-specific coefficients

We followed the same steps outlined above in Live Tree Stocks to calculate biomass in year 2 using the DBH in year 2 from Equation 6. To get net carbon sequestration for each tree, we subtracted the year 1 biomass from the year 2 biomass and then multiplied this net increase by 50%:

Equation 7: **$NS_t = (TBM_{t2} - TBM_{t1})*0.50$,** where:
NS_t = net sequestration of tree t (kg)
TBM_{t2} = year 2 DBH of tree t (cm)
TBM_{t1} = year 1 DBH of tree t (cm)
0.50 = conversion to carbon (50% of dry-weight biomass is carbon)

Herbaceous Stocks

We calculated nonwoody plant and seedling biomass using the following formulas from Johnson et al., 2017:

Equation 8: **$NWB_x = (b_1 * PC_x)/(b_2 + PC_x)$,** where:
NWB_x = aboveground nonwoody biomass in plot x (Mg/ha)
PC_x = percent cover in plot x (ratio)
b_1 and b_2 = forest type coefficients

Equation 9: **$SB_x = b_1 + b_2 * SD_x$,** where:
SB_x = aboveground seedling biomass in plot x (Mg/ha)
SD_x = seedling density (stems/ha) in plot x – *from Equation 10*
b_1 and b_2 = forest type coefficients

Johnson et al., 2017 only provides one set of nonwoody biomass coefficients for all forest types. For seedling biomass coefficients, there are only two forest types available for the Northeast: maple/beech/birch and spruce/fir. Maple/beech/birch coefficients were used for all plots. We used the following formula to calculate seedling density:

Equation 10: **$SD_x = (ST_x/SP_x) * 10000$,** where:
SD_x = seedling density in plot x (stems/ha)
ST_x = number of stems in plot x (total of all subplots)
SP_x = number of 1 m^2 subplots in plot x (4 or 10)

We calculated aboveground carbon stocks for each plot by adding together the nonwoody and seedling biomass and multiplying the total biomass by 0.50. Belowground carbon stocks were assumed to be 11% of aboveground stocks (Smith et al., 2013).

Equation 11: **$THC_x = (NWB_x + SB_x)*1.11*0.50$,** where:
THB_x = total herbaceous carbon in plot x (Mg/ha)
NWB_x = aboveground nonwoody biomass in plot x (Mg/ha)
SB_x = aboveground seedling biomass in plot x (Mg/ha)
1.11 = adds belowground biomass
0.50 = conversion to carbon (50% of dry-weight biomass is carbon)

Standing Dead Tree Stocks

We calculated standing dead tree (SDT) biomass for each tree component using the Jenkins et al., 2003 method (Equations 1 and 2). To account for volume loss, we reduced component biomass using structural loss adjustment (SLA) factors (see Table 8) from Domke 2011 with the following modifications:

1. We assumed foliage and fine roots to be present only in decay class 1 with 75% reduction from live tree.
2. To account for height loss, we further reduced stem wood and bark SLAs (the Domke 2011 SLAs are for biomass calculated with the Component Ratio Method, which includes height). For decay classes 2 through 4, we reduced stem wood and bark SLAs by 50% of the previous decay class SLA. Using this method, total SLA weighted by decay class is 54%, which is close to the ratio of SDT height to live tree height (0.53) that we calculated using tree observations with height data.

Table 8. Structural loss adjustment factors by decay class and tree component.

Decay class	Stem wood	Stem bark	Foliage	Coarse roots (above)	Coarse roots (below)	Fine roots	Branches
1	1.0	0.92	0.25	1.0	1.0	0.25	1.0
2	0.50	0.33	0.00	0.95	0.95	0.00	0.50
3	0.25	0.10	0.00	0.80	0.8	0.00	0.20
4	0.13	0.03	0.00	0.65	0.65	0.00	0.10

For foliage and fine root components, we applied the SLA factor directly to the component biomass. For all other components (stem wood, stem bark, above and belowground coarse roots, and branches), we applied the SLA factor to the component volume using the following formula:

Equation 12: $\mathbf{ACBM_{ct} = ((ABM_t * R_{ct})/BD) * SLA_c * BD_s}$, where:

$ACBM_{ct}$ = adjusted biomass of component c of SDT t (kg dry weight)
ABM_t = total aboveground biomass of SDT t (kg dry weight) – *from Equation 1*
R_{ct} = ratio of component c to total biomass of SDT t – *from Equation 2*
SLA_c = structural loss adjustment factor for component c (see Table 8)
BD_s = bulk density of species s (ratio) – *from Harmon 2008, see CWM calculations*

To account for density loss, we reduced total biomass further using the following equation:

Equation 13: $\mathbf{TBM_t = DRF * \sum ACBM_{ct}}$, where:

TBM_t = total biomass of SDT t adjusted for structural and decay loss (kg dry weight)
DRF = decay reduction factor (ratio) – *from Harmon 2011*
$\sum$ = sum all components of SDT t
$ACBM_{ct}$ = adjusted biomass of component c of SDT t (kg dry weight) – *from Equation 12*

We obtained decay reduction factors (DRFs) from Harmon et al., 2011 by matching each observation to the appropriate combination of decay class and species classification (hardwood or softwood). Since 99% of SDTs in the dataset were hardwoods, we assumed unknown species to be hardwood. We also assumed SDT carbon to be 50% of biomass (Harmon et al., 2008). To calculate carbon stocks per unit area, we used the same methods as the live tree pool (see Live Tree Stocks).

Coarse Woody Material Stocks

Since we calculated SDT carbon using the tree dataset, we removed SDTs from the coarse woody material (CWM) dataset. The tree dataset provided greater accuracy than the CWM dataset because all SDTs were recorded, as opposed to only SDTs that intercepted the transect line. We calculated the volume of all remaining CWM pieces with different formulas depending on the piece type (downed log, pile, or fence). For downed logs—the vast majority of pieces—we used the conic-paraboloid formula from Fraver et al., 2007:

Equation 14: $\mathbf{VDW_{\mathit{l}} = (L_{\mathit{l}}/12)*(5A_{b\mathit{l}} + 5A_{u\mathit{l}} + 2\sqrt{A_{b\mathit{l}} A_{u\mathit{l}}})}$, where:

VDW_l = volume of downed log *l* (cm^3)
L_l = length of downed log *l* (cm)
A_{bl} = cross-sectional area at the base of downed log *l* (cm^2)
A_{ul} = cross-sectional area at the upper end of downed log *l* (cm^2)

To calculate cross-sectional areas, we used the two diameter measurements recorded for each piece and the area formula for a circle. For the two observations missing a diameter measurement, we calculated volume with Huber's formula (Equation 16) substituting the one recorded diameter measurement for the midpoint diameter. Most class 5 pieces (5/6) did not have diameter measurements and were thus excluded from the calculations.

The CWM dataset noted whether a piece was hollow inside, and if so, provided the diameter of the hollow area. However, only a small number of CWM pieces were hollow (31/1884), and a study on CWM carbon stocks found that hollowness has a minor impact on uncertainty (Campbell et al 2019). Therefore, we did not subtract the hollow area from the piece volume.

For piles (3 total), we calculated volume using the half-elliptical cylinder formula in Woodall et al., 2008:

Equation 15: $\mathbf{V_{\mathit{p}} = P\pi H_{\mathit{p}} W_{\mathit{p}} L_{\mathit{p}}/4}$, where:

V_p = volume of pile *p* (cm^3)
P = packing ratio = 0.15 (Hardy, 1996)
H_p = height of pile *p* (cm)
W_p = width of pile *p* (cm)
L_p = length of pile *p* (cm)

We calculated volume of the one fence in the dataset using Huber's formula (Fraver et al., 2007):

Equation 16: $\mathbf{V_{\mathit{f}} = L_{\mathit{f}} * A_{m\mathit{f}}}$, where:

V_f = volume of fence *f* (cm^3)
L_f = length of fence *f* (cm)
A_{mf} = cross-sectional area at the longitudinal midpoint of fence *f* (cm^2) – *assumed to be DBH*

To account for structural loss in pieces with advanced decay, we multiplied the piece volume by a structural reduction factor (SRF). SRFs were obtained for classes 4 (0.800) and 5 (0.412) from Fraver et al., 2013. Downed logs were the only piece type with decay classes 4 and 5.

To determine the biomass of downed logs and the fence, we multiplied the adjusted piece volume by its absolute density. We obtained absolute density from Harmon et al., 2008 based on the species and decay class. For pieces with unknown decay class, we substituted decay class 3, the average of CWM pieces. We followed this protocol to match species with appropriate density values:

1. If the species value is unavailable, use the genus value
2. If the genus value is unavailable, substitute the value from a species with a similar wood specific gravity (Jenkins et al., 2003)
3. If wood specific gravity is not available (e.g. invasive shrubs), use the Ailanthus value
4. If the species is unknown, use the weighted average for the plot's NY community type (based on relative abundance of live tree species)

For piles, we used the FWM bulk density for the plot's forest type instead of absolute density (Woodall et al., 2008). We multiplied the volume of the pile by the FWM bulk density and a decay reduction factor of 0.8 (see FWM calculations).

To determine the carbon content of each piece, we multiplied the piece biomass by percent carbon (Harmon et al., 2008). Mean CWM percent carbon values are dependent on decay class and range from 0.486 to 0.518. For observations missing decay class, we substituted the average decay class of the dataset (3).

Equation 17: $\mathbf{C_{ix} = V_{ix} * D_{ix} * CP_d}$, where:
C_{ix} = carbon in piece i in plot x (g)
V_{ix} = volume of piece i in plot x (cm^3) – *from Equation 15 or 16*
D_{ix} = density of piece i in plot x (g/cm^3) – *absolute for downed logs and fences (Harmon et al., 2008), FWM bulk multiplied by 0.8 for piles (Woodall et al., 2008)*
CP_d = percent carbon for decay class d – *Harmon et al., 2008*

We calculated carbon stock per unit area for each plot using the plot-level line-intersect sampling (LIS) estimator (adapted from Woodall et al., 2008):

Equation 18: $\mathbf{C_x = 100(\pi/2TL) \sum C_{ix}/L_{ix}}$, where:
100 = convert from g/cm^2 to Mg/ha
C_x = CWM carbon in plot x (Mg/ha)
TL = transect length = 2000 (cm)
$\sum$ = sum all CWM pieces in plot x
C_{ix} = carbon of CWM piece i in plot x (g) – *from Equation 17*
L_{ix} = length of CWM piece i in plot x (cm)

Fine Woody Material Stocks

NAC assessment staff tallied FWM pieces by size class along a portion of the line transect. Table 9 provides the midpoint diameter range and transect length for each size class.

Table 9. FWM size classes

Size Class	**Diameter**	**Transect Length**
Small	0.02 cm to 0.6 cm	5 m
Medium	0.61 to 2.5 cm	5 m
Large	2.51 to 9.9 cm	8 m

We calculated the volume of pieces in all three size classes at the plot level using the following formula from Woodall et al., 2008:

Equation 19: $\mathbf{V_{sx} = \sum (\pi^2/8)*(S*n_{sx}*QMDI_s^2)/TL_s}$, where:

V_{sx} = volume of pieces of size class s in plot x (m^3/ha)
$\sum$ = sum for all size classes in plot x
S = slope correction factor (1.13 default)
n_{sx} = number of pieces of size class s in plot x
$QMDI_s$ = quadratic mean diameter for size class s (cm)
TL_s = length of transect sampled for size class s (m) – *see Table 9*

We obtained quadratic mean diameter (QMDI) from Woodall et al., 2008 for the appropriate FWM size class and forest type. For plots without an FIA forest type (marshes, uplands, etc.), we used the average QMDI for forest types present in the NAC assessment.

We estimated plot-level carbon with the following formula. We obtained FWM bulk density for the plot's FIA forest type from Woodall et al., 2008. As with QMDI, we used an average if the plot did not have an FIA forest type.

Equation 20: $\mathbf{C_x = V_x*BD_f*DRF*0.50/1E6}$, where:

C_x = FWM carbon in plot x (Mg/ha)
V_x = volume of all pieces in plot x (m^3/ha) – *from Equation 15*
BD_f = FWM bulk density for forest type f (g/m^3) – *from Woodall 2008*
DRF = decay reduction factor; average = 0.8 – *from Harmon 2008*
0.50 = conversion to carbon (50% of dry-weight biomass is carbon)
1E6 = conversion from g to Mg

Litter & Duff Stocks

NAC staff took between 3 and 20 depth measurements of litter and duff layers along the plot transect line. We calculated average depth for both layers in each plot using the LIS estimator for litter/duff (Woodall 2008). This formula is simply the sum of depth measurements divided by the number of depth measurements. We used the following formula to determine carbon per unit area for each plot:

Equation 21: $\mathbf{C_x = (D_{lx}*BD_{lf} + D_{dx}*BD_{df})*100*0.50}$, where:

C_x = litter & duff carbon in plot x (Mg/ha)
D_{lx} = average litter layer depth for plot x (cm)
BD_{lf} = litter bulk density for FIA forest type f (g/cm^3) – *from Woodall 2008*
D_{dx} = average duff layer depth for plot x (cm)
BD_{df} = duff bulk density for FIA forest type f (g/cm^3) – *from Woodall 2008*
100 = conversion from g/cm^2 to Mg/ha
0.50 = conversion to carbon (50% of dry-weight biomass is carbon)

Soil Organic Carbon Stocks

NAC staff collected one composite soil sample in each plot to a depth of 10 cm. The dataset contains loss on ignition (LOI) data for most plots (1017), and percent carbon for some plots (230). For plots missing percent carbon data, we estimated percent carbon to be 0.58 LOI (Pribyl, 2010). We excluded plots without percent carbon and LOI data from the analysis.

We calculated the volume of mineral soil for each plot using the following formula:

Equation 22: $\mathbf{V_{sx} = (V_h\text{-}V_{xr})*(1\text{-}CF_x)}$, where:

V_{sx} = volume of soil in plot *x* to 10 cm depth (cm^3/ha)
V_h = total volume of a hectare to 10 cm depth = *1E9 cm³*
V_{xr} = volume of coarse roots in plot *x* to 10 cm depth (cm^3) = *65% of belowground coarse root biomass (g) ÷ bulk density (g/cm³)*
CF_x = coarse fragment of plot *x* (ratio) – *estimated from NRCS soil series description*

To estimate the coarse root volume in the soil, we used belowground biomass results from the live tree pool calculations. We assumed that 65% of coarse roots are in the top 10 cm of soil (estimated from figures in Yanai et al., 2006). To get volume, we divided 65% of the root biomass by the bulk density of the tree species. We summed the root volume for all trees in the plot and subtracted this from the total soil volume in the plot.

The coarse fragment of soil includes rocks, gravel, debris, etc. NRCS soil series descriptions report coarse fragment for a typical pedon usually with different estimates for each soil horizon. If the first 10 cm of soil included multiple horizons, we used an average of the horizons. We also used an average was for complex soil types. If a range was provided instead of a single value, we used the median of the range. However, for soils designated as “rocky,” “stony,” or any variation of the two, we selected the higher end of the range. We assumed rock outcrop to be 100% coarse fragment. If a soil series description was not located, we used the average of other soil types.

NAC did not analyze soil samples for bulk density, so we obtained bulk density from Soil Grid using the plot center coordinates (ISRIC, n.d.). Soil Grid provides bulk density for depths of 5 and 15 cm, so we averaged the two values to obtain bulk density to 10 cm. If we could not estimate bulk density from Soil Grid, we used an equation from Al-Shammary et al., 2018:

Equation 23: $\mathbf{BD_x = 1.177 + 0.00263*SA_x - 0.0439*\mathit{log}(SI_x) + 0.00208*SI_x}$, where:

BD_x = bulk density of soil in plot *x* (g/cm^3)
SA_x = percent sand for plot *x* (ratio)
log = base 10 log function
SI_x = percent silt for plot *x* (ratio)

We used the following formula to calculate SOC per unit area for each plot to a depth of 10 cm. Then we divided the SOC to 10 cm by 74% to get SOC to a depth of 30 cm (see Soil Organic Carbon Pool section for an explanation of this assumption):

Equation 24: $\mathbf{C_x = (V_{sx}*BD_x*PC_x)/0.74/1E6}$, where:

C_x = SOC in plot *x* to 30 cm (Mg/ha)
V_{sx} = volume of soil in plot *x* to 10 cm (cm^3/ha) – *from Equation 22*
CP_x = percent organic carbon (or 0.58 LOI) for plot *x* (ratio)
BD_x = bulk density for plot *x* (g/cm^3) – *from Soil Grid or Equation 23*
0.74 = ratio of SOC in top 10 cm to SOC in top 30 cm
1E6 = conversion from g to Mg

Soil Sequestration

To get the total amount of carbon transferred from the litter and duff layers to the soil, we divided the carbon in each layer by the layer turnover rate and subtracted respiration. We used turnover rates from Gaudinski et al., 2000—4 years for litter and 40 for duff. The average carbon transfer to the soil was

0.955 Mg/ha from litter, and 0.000115 Mg/ha from duff. The low value for duff is due to the absence of a duff layer in most plots (1069/1124).

We also estimated the fine root turnover of trees and herbaceous vegetation and added this to the soil pool. We obtained annual turnover rates from Finér et al., 2011—1.32 for trees and 1.21 for all plants. Since we could not find a turnover rate for herbaceous plants, we used the rate for all plants. We assumed that 66% of tree fine roots are in the top 30 cm of soil (Joslin et al., 2006). Since we could not find any estimates of fine root distribution in the herbaceous layer, we assumed all herbaceous roots are in the top 30 cm.

Equation 25:

$$\mathbf{CS_x = (C_{lx}/4 - R_{lx}) + (C_{dx}/40 - R_{dx}) + (TRC_x*1.32*0.66 - TRS_x) + (HRC_x*1.21),}$$

where:

CS_x = carbon sequestration of SOC in plot *x* to 30 cm (Mg/ha)
C_{lx} = carbon in the litter layer of plot *x* (Mg/ha)
4 = turnover rate of the litter layer carbon (years)
R_{lx} = respiration from the litter layer in plot *x* (Mg/ha)
C_{dx} = carbon in the duff layer of plot *x* (Mg/ha)
40 = turnover rate of the duff layer carbon (years)
R_{dx} = respiration from the duff layer in plot *x* (Mg/ha)
TRC_x = tree fine root carbon in plot *x* (Mg/ha)
1.32 = fine root turnover rate for trees – *from Finér et al., 2011*
0.66 = percentage of tree fine roots in the top 30 cm of soil – *from Joslin et al., 2006*
TRS_x = tree fine root respiration in plot *x* (Mg/ha)
HRC_x = belowground (root) carbon in the herbaceous layer
1.21 = fine root turnover rate for all plants – *from Finér et al., 2011*

Confidence Intervals

To create confidence intervals for the mean of both carbon and annual carbon change per unit area at the community type level, we created functions in R. First, we calculated variance using the var() function. For pools sampled with the line-intersect sampling method (CWM, FWM, and Litter & Duff), we instead calculated variance using the population-level LIS variance estimator formula:

Equation 26:

$$\mathbf{var(Y_p) = \frac{\sum(y_x - Y_p)^2}{n*(n-1)}},$$

where:

var = variance
Y_p = population-level variable of interest (Mg C/ha)
y_x = variable of interest for plot x (Mg C/ha)
n = number of plots in population

We then created functions to calculate standard error using the variance, and functions to calculate a 95% confidence interval using a t-distribution with n-1 degrees of freedom. The confidence interval function returned values outside of the normal range for some community types that had few observations. For example, the lower end of the interval for FWM carbon stocks in several community types was negative. We could not use negative carbon per unit area values to calculate total carbon. To resolve this problem, we created bootstrapping functions in R using the boot package. The script performs bootstrapping for values outside of the possible range (negative for stocks and sequestration and positive for respiration). While this is not an ideal solution, collecting additional data was not possible.

Appendix 3: NY Community Group Tables

Table 10

Total Stock by NY Group and Pool (Mg Carbon)							
NY Community Group	**Trees**	**Herb-aceous**	**SDT**	**Down Wood**	**Litter & Duff**	**Soil**	**ALL POOLS**
Oak-other hardwood forest (native)	234,000	5,650	8,300	20,000	17,700	143,000	**429,000**
Successional hardwood (native)	149,000	6,390	6,590	15,600	12,400	126,000	**316,000**
Oak-tulip tree forest (native)	169,000	4,030	3,380	16,600	9,140	85,800	**288,000**
Successional hardwood (non-native)	99,200	7,250	6,590	21,000	9,670	95,100	**239,000**
Other (native)	26,000	9,820	2,760	4,510	10,600	102,000	**159,000**
Other (non-native)	25,300	9,610	593	2,160	7,830	77,600	**123,000**
Marsh	15,400	2,800	172	5,900	6,730	61,100	**92,000**
Maritime forest (native)	30,300	2,280	2,530	4,100	3,530	37,100	**79,800**
Other successional forest (native)	36,200	1,850	3,090	5,350	3,110	29,300	**78,900**
Other forest (native)	27,500	820	2,080	3,170	2,690	22,700	**58,900**
Red maple swamp (native)	10,200	327	300	916	696	9,710	**22,100**
Floodplain forest (native)	4,280	195	275	326	404	3,430	**8,910**
ALL GROUPS	**830,000**	**51,000**	**36,700**	**99,600**	**84,500**	**792,000**	**1,890,000**

Table 11

Annual Stock Change by NY Group and Pool (Mg Carbon)						
NY Community Group	**Trees**	**SDT**	**Down Wood**	**Litter & Duff**	**Soil**	**ALL POOLS**
Oak-other hardwood forest (native)	13,000	-194	-1,590	-2,690	1,820	**10,300**
Successional hardwood (native)	11,900	-152	-1,240	-1,930	1,380	**9,920**
Oak-tulip tree forest (native)	7,470	-78.3	-1,320	-1,420	1,110	**5,750**
Successional hardwood (non-native)	7,470	-153	-1,680	-1,500	1,280	**5,420**
Other (native)	5,100	-63.2	-349	-1,640	1,180	**4,230**
Maritime forest (native)	3,000	-58.7	-322	-528	375	**2,470**

Other successional forest (native)	2,790	-71.6	-425	-480	384	**2,200**
Other forest (native)	1,820	-49.4	-253	-375	212	**1,350**
Other (non-native)	1,460	-13.6	-167	-1,230	1,070	**1,120**
Red maple swamp (native)	958	-6.82	-71.4	-88.3	140	**932**
Floodplain forest (native)	277	-6.38	-25.5	-56.7	70.2	**259**
Marsh	551	-3.93	-476	-1,060	1,220	**223**
ALL GROUPS	**55,700**	**-850**	**-7,920**	**-13,000**	**10,200**	**44,200**