Department of Park Operations
Division of Natural Resources

Carbon Accounting for Cleveland Metroparks' Forest Communities

Cleveland Metroparks Technical Report 2023/NR-05

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Executive Summary

Cleveland Metroparks is committed to finding innovative solutions to protecting nature and managing forest resilience. The impact of climate change threatens forest health, which is why it is necessary to understand how our forests store and sequester carbon. In 2021, Cleveland Metroparks partnered with The Lubrizol Foundation, which funded targeted projects that include the development of carbon accounting reports. As a result of this partnership, a Preliminary Carbon Accounting Report was produced in early in 2022 with the intentions of understanding carbon storage and sequestration across the park system, evaluating the condition of our forests, and identifying changes over a 10-year window of time. Through the preliminary report, we found that: a) trees increased in size and carbon storage from 2010 to 2021, b) native trees vary in their projected climate change resilience, and c) there was a net loss of trees largely due to reductions in ash abundance from mortality caused by the emerald ash borer (Volk and Hausman, 2022). Changes varied across forest communities, with alluvial, wet-mesic red maple, and beech-mixed hardwood being more vulnerable to climate change than others. Changes in abundance were variable among tree species, with those species impacted by significant ongoing pest infestations such as ash, beech, and hemlock experiencing the most dramatic shifts. Furthermore, tree species differed in their tolerance to future climate change with some species found to be less likely to tolerate climate change. For example, American beech (*Fagus grandifolia*) has poor tolerance to future climate change (Iverson et al. 2019).

For this project, a full carbon accounting analysis was completed to capture both current forested community capacity and future carbon storage and sequestration. We utilized a larger robust empirical dataset and a computer model through USDA Forest Service's Forest Vegetation Simulator (FVS) to forecast future forest conditions. Established in 1917, Cleveland Metroparks now has 18 distinct reservations (7 major and 11 minor) totaling almost 10,000 hectares (24,705 acres). Leveraging data from >50,000 stems across 80 species, we predicted total stem count across the park system to be nearly 7.8 million in 2021, which includes both saplings (5.40 million) and trees (2.37 million).

If properly managed, Cleveland Metroparks has the potential to increase the natural tree population by nearly 1 million trees by 2075.

Although the Cleveland Metroparks system protects critical forest resources, characteristics of tree stands vary across reservations. The tree population with the highest stem count is in Brecksville Reservation with almost half a million trees (470,000). Hinckley Reservation has the densest and youngest forest with the vast majority of its 1.42 million stems being saplings (77%). Bedford Reservation and the collective group of 11 minor reservations have the lowest stem density and the oldest population. These differences in age structure among reservations provide critical context on reservation-specific tree demography needed to determine appropriate forest management options for a given reservation.

Estimates of carbon storage varied depending on the carbon pools examined, reservation, and forest community type. Cleveland Metroparks' current carbon storage capacity is 1,181,788 metric tons of carbon (mt C). As a result of growing forests and high number of stems, storage is projected to increase across all carbon pool types over the next 50 years to 2,023,700 mt C. Carbon storage is highest in aboveground biomass and lowest in standing dead trees. Thus, forests can be simultaneously managed for health condition, regeneration, and carbon pool maintenance. While soil carbon is among the

largest carbon pool in many ecosystems, it represents the second largest carbon pool estimated in our park system. Total carbon storage is highest in Brecksville Reservation (198,805 mt C) which is also our largest reservation by area. Hinckley Reservation has the most total stems with 1.4 million trees and saplings combined.

There were 6 forest types identified for this project, listed here in order from largest to smallest area: sugar maple-mixed hardwood, wet-mesic red maple, beech-mixed hardwood (hemlock), oak-mixed hardwood, alluvial forest, ruderal wet-mesic.

Even though it is one of the smaller forest types by area, oak-mixed hardwood has the greatest carbon storage (238 mt C/ha) and carbon sequestration (2.385 mt C/year) of all forest community types.

At the individual species level, species of interest are categorized into three general groups: 1) species with small average tree size and abundant saplings (sugar maple, American beech, and green ash), 2) trees with intermediate size, longevity, and population size (black cherry, red maple, and hickory species), and 3) large, long-lived trees with few saplings (red and white oak). These species are all important to the composition of Cleveland Metroparks' forests and need continued monitoring and management to maintain species distributions and ecosystem function.

QUICK FACTS

- Current tree population is 2.37 million and is predicted to increase by nearly 1 million trees by 2075
- Carbon storage is estimated at 1,181,788 metric tons of carbon (mt C) from all pools and will continue to increase to 2,023,700 mt C by 2075
- Brecksville Reservation has the largest tree population (470,000) and the most total carbon stored (198,805 mt C)
- Hinckley Reservation has the most total stems with 1.4 million trees and saplings combined
- Oak-mixed Hardwood forests have the greatest carbon storage (238 mt C/ha) and carbon sequestration (2.385 mt C/year) of all forest community types
- Sugar maple (515,000), red maple (399,000), and American beech (134,000) are the three most common trees species excluding saplings[1]
- Sugar maple (2,484,000), American beech (1,039,000), and green ash (649,000) are the three most common tree saplings[1]
- The population of green ash was modeled to expand to over 500,000 by 2045; however, this is likely unrealistic due to vulnerability and mortality caused by the emerald ash borer.

[1] tree = stem >10cm dbh, sapling = stem 0.1-10cm dbh

Introduction

Forests serve many critical roles both for people and the environment. Forests are invaluable for wildlife, human culture, aesthetics, and health benefits. Some ecosystem services provided by forests include reducing air pollution and stormwater runoff, providing food and shelter, producing oxygen, and capturing carbon dioxide (CO_2), a major contributor to climate change (Jenkins and Schaap, 2018). Unfortunately, both forests and their ecosystem services are at risk of degradation due to stressors including invasive species, diseases, habitat loss, and climate change. At a broader scale, climate change is a pervasive and systemic ecosystem issue having profound impact on temperature and precipitation (Weiskopf et al., 2020), which will in turn affect species' habitat suitability and susceptibility to pests and pathogens (Rustad et al., 2014). In addition, multiple climate-related disasters that occur in the same year can lead to even greater ecosystem stress (Jay et al., 2018).

Properly managed forests are more resilient to these changing conditions and can be an important resource for reducing atmospheric CO_2 as a natural climate solution (NCS). Trees sequester CO_2 through photosynthesis and store it in wood, leaves, and soil thus reducing the amount of greenhouse gas (GHG) in the atmosphere. Forests across the United States serve as a sink for 742 million metric tons (MMT) of carbon dioxide equivalent (CO_2e; US EPA, 2021), yet the effectiveness of trees to absorb CO_2 varies based on age, size, species, and condition (Ameray et al., 2021; Birdsey et al., 2006). Healthy, native forests capture more carbon compared to degraded, non-native forests (Pregitzer et al., 2020). In addition, forest pests and diseases may decrease carbon storage by 69% and 28%, respectively, compared to forests without disturbance (Quirion et al., 2021).

To better protect our urban forests from climate change, maximize their resilience, and increase their ability to capture carbon, we need to understand their current status and future trajectory such that we might alter or correct conditions proactively. For instance, modeling expected forest trajectories can be a useful tool to identify specific areas in need of management (Peng, 2000). We previously described several changes that occurred in Cleveland Metroparks' forests from 2010 to 2021 (Volk and Hausman, 2022). One of the most important changes was the introduction of emerald ash borer (EAB) which caused significant mortality of the ash population (Knight et al., 2013, PCAP report). Other highlights include mature tree growth, increases in carbon storage, and the identification of climate-tolerant species.

To get a more accurate picture of current and future forest conditions, we used a large dataset of trees from across Cleveland Metroparks' natural areas to model future forest growth. Specifically, we compared stem density, carbon storage, and sequestration rates overall, among forest communities, and among individual species, and projected these estimates over the next 50 years. Habitat implications for park-wide habitat management and protection are included.

Goals

1. Estimate current and future carbon storage across Cleveland Metroparks
2. Assess carbon storage, sequestration across forest community types
3. Evaluate individual tree species current and future population demographics

Methods

This study took place in Cleveland Metroparks, a regional park district in Northeast Ohio that includes nearly 80% natural land. Following Carolina Vegetation Survey protocols, a long-term monitoring program was established in 2010 called the Plant Community Assessment Program (PCAP). Through PCAP, 400 geospatially balanced plots 0.1 ha in size were located across natural landscapes (i.e. excluding development, mowed grass, trails, etc.) in the park system (~6820 ha in 2010) (Hausman and Robison, 2010). A five-year cycle allowed one hundred different plots to be visited every year for four years, with the fifth year designated for data analysis. The data utilized from PCAP comprised of woody stems which are defined by height as those at or above 1.37 m. All stems measured were given a species designation. Saplings were defined as any woody stem measuring 0.1 – 10 cm diameter at breast height (dbh) and trees defined as anything >10 cm dbh.

Cleveland Metroparks has 18 total reservations, 7 major (Bedford (BE), Brecksville (BR), Hinckley (HI), Mill Stream Run (MS), North Chagrin (NC), Rocky River (RR), South Chagrin (SC)) and 11 minor (Acacia, Big Creek, Bradley Woods, Brookside, Euclid Creek, Garfield Park, Huntington, Lakefront, Ohio & Erie Canal, Washington, West Creek) reservations. Data analyses included all 7 major reservations, but due to size and habitat limitations, most of the minor reservations were lumped together into a single group (Minor). Fifty plots were distributed throughout each of the eight reservation groups. PCAP plots were assigned one of the following community designations: oak-mixed hardwood, alluvial forest, beech-mixed hardwood (hemlock), wet-mesic red maple, ruderal wet-mesic, or sugar maple-mixed hardwood based on updates to a hierarchical clustering analysis (Reinier et al., 2018). Wetland habitats and mesic meadows are also identified community types, and while important for biodiversity, these plots were excluded from the model since they lack or have limited woody stems. Therefore, we used 364 of 400 total plots from the most recently completed data collection cycle, 2015-2018. Forests were assessed at the stand-level by grouping PCAP plot community types within the same reservation. In this way, six forest community types were analyzed across eight reservation groups, totaling 48 potential unique stands assessed. This also resulted in a total of 5,900 forested hectares used in the model.

Data were formatted for processing through Forest Vegetation Simulator (FVS), a growth and yield model based on individual tree data (Dixon, 2002). FVS has a wide range of utility and can estimate a variety of forest parameters including growth and mortality rates, tree density, carbon storage, and many other metrics. The FVS model requires users to select an existing variant to serve as a comparable system. The Northeast variant was selected as well as the nearest national forest identified as Allegheny National Forest.

To ensure accurate model estimates, we first iteratively tested the FVS model against i-Tree (i-Tree Eco v6.0, 2021) estimates as a benchmark to determine proper model parameters. Because stand density index (SDI) is tightly linked to density-dependent mortality, Radtke et al. (2012) suggested modifying stand density index to higher thresholds to achieve more accurate results in FVS. So, SDI was set at 95% for moderate and 99% for severe density-dependent mortality. Mortality from EAB was increased to a static rate of 11.4% in ash (*Fraxinus* spp.) based on mortality from EAB nine years after initial infestation and to mimic baseline conditions when our first data collection began in 2015 (Morin et al., 2017). This modification of ash mortality was conservative, given that empirical estimates of annual mortality have been estimated at a maximum of 23% (Morin et al., 2017). For benchmarking, we included stems >10 cm dbh to provide a more comparable estimate to our preliminary report (Volk and Hausman 2022). Once the final model was selected, all stems >0.1 cm dbh were incorporated.

To get a better understanding of tree populations and age structure, we estimated sapling and tree population sizes across the entire park system and for each reservation. We then compared the percentage of trees within each reservation to the total amount of stems in each reservation. Total stem density was calculated over time within each reservation to project future changes. These steps were repeated at the community level to understand population structure within each native forest community.

For carbon stock estimates, FVS calculates six carbon pools measured in metric tons of carbon (mt C) in plant tissue: 1) total stand carbon, 2) aboveground live (tree biomass), 3) standing dead, 4) belowground biomass or roots, 5) leaf litter, and 6) down woody debris. Because soil is not directly captured through FVS and typically represents a large component of carbon storage (Domke et al., 2021), soil carbon in the top 30 cm was estimated using SoilGrids (Poggio et al., 2021). SoilGrids uses machine learning to apply global estimates of soil properties across 250 m grids. Because SoilGrids is applied at a broad resolution, a park system wide average was approximated for soil carbon storage rather than estimating at a finer forest community level scale. For additional comparisons among carbon estimation methodologies, see Appendix A.

The last evaluation included individual species performance for nine pre-determined tree species of interest: sugar maple (*Acer saccharum*), red maple (*A. rubrum*), American beech (*Fagus grandifolia*), black cherry (*Prunus serotina*), green ash (*Fraxinus pennsylvanica*), shagbark hickory (*Carya ovata*), other hickories (*Carya* spp.), red oak (*Quercus rubra*), and white oak (*Q. alba*). These species and species groups were identified because of their importance or dominance within Cleveland Metroparks. They also represent a range of life-history strategies, climate tolerance and wildlife importance. Therefore, it is important to track population changes over time for each species of interest to determine future impacts. These species were categorized into three general groups based on current size (average dbh) and stem (tree and sapling) abundance.

1) small average tree size and abundant saplings (sugar maple, American beech, and green ash),
2) intermediate size, and stem abundance (black cherry, red maple, shagbark and hickory species),
3) large, long-lived trees with few saplings (red oak and white oak).

Results

Goal 1: Estimate current and future carbon storage across Cleveland Metroparks

Cleveland Metroparks has approximately 7.8 million total stems (2.37 million trees and 5.40 million saplings) in natural, forested areas as of 2021 (Figure 1; Table 1). FVS predicts that our total tree count over 50 years will rise by about a million trees. Model fluctuations, likely attributed to an influx of growing stems that transition from sapling to trees, project a pulse increase to about 4 million trees by 2045 and then a decline, likely attributed to mortality events, to about 3 million by 2075.

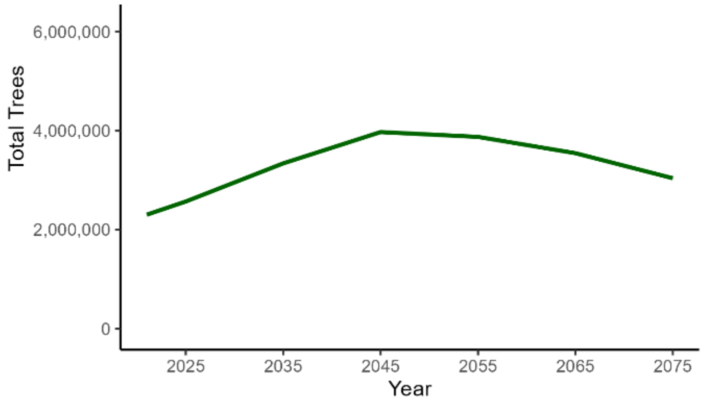


Figure 1. Projected total number of trees (size: >10cm dbh) across Cleveland Metroparks through time.

Of all parks, Brecksville Reservation (BR) has the most forested land (1,072 ha) and the highest number of trees (0.47 million) (Table 1). However, Hinckley Reservation (HI) has the greatest number of total stems (1.42 million saplings and trees combined) and the greatest stem density (1,874 avg stems/ha). Bedford (BE) and South Chagrin Reservations (SC) have the smallest forested area (553 ha, 421 ha respectively), fewest number of total stems (0.52, 0.57 million respectively) and fewest trees (0.21, 0.16 million respectively). However, South Chagrin has the 3rd highest stem density (1,345 avg stems/ha), likely attributed to young dense forests (Table 1).

Table 1. Reservation summary of stem count in 2021. Reservations are listed in descending order by size. Hectares include only forested habitat within these parks. Code: BR = Brecksville; MS = Mill Stream Run; RR = Rocky River; HI = Hinckley; Minor = collective group of minor reservations (see Methods); NC = North Chagrin; BE = Bedford; SC = South Chagrin. Trees are >10 cm dbh and saplings are 0.1-10 cm dbh.

† in millions

		Stem count			
Reservation	**Hectares**	**Total†**	**Trees†**	**Saplings†**	**Avg. # per hectare**
BR	1,072	1.38	0.47	0.91	1,285
MS	999	1.23	0.37	0.87	1,235
RR	779	0.98	0.28	0.70	1,259
HI	758	1.42	0.32	1.10	1,874
Minor	747	0.83	0.33	0.49	1,105
NC	571	0.84	0.23	0.61	1,471
BE	553	0.52	0.21	0.31	939
SC	421	0.57	0.16	0.41	1,345
Total	**5,900**	**7.77**	**2.37**	**5.40**	**1,316**

Over the next 50 years, carbon storage (metric tons per hectare) is expected to linearly increase (Figure 2). Most of the increase is from the aboveground live carbon pool and attributed to growth and increase in tree biomass. All other carbon pools combined (root, litter, downed woody and standing dead) contribute less than 30% of the total carbon storage. Parkwide carbon estimates through FVS total

1,181,788 metric tons of carbon (mt C) as of 2021 (Table 2). This estimate includes carbon from aboveground live trees (832,530 mt C), standing dead trees (43,916 mt C), belowground root biomass (167,742 mt C), leaf litter (81,663 mt C), and down woody debris (51,836 mt C). Per unit area, carbon storage in these five pools averages 200.3 mt C per hectare, of which over 70% is attributed to aboveground live trees (141 mt C/ha).

Of all parks, Brecksville Reservation has the highest total stand carbon storage (198,805 mt C) which is again attributed to the most forested land and highest number of trees as previously mentioned (Table 2). Rocky River Reservation constitutes the second highest total stand carbon storage with 176,567 mt C followed closely by the collective group of Minor Reservations with 175,538 mt C. However, on a per hectare basis, carbon storage is highest in the Minor Reservation group followed by Rocky River Reservation. While all reservations are expected to increase in total carbon storage over the next 50 years, they will do so depending on the proportion of saplings and trees and the forest community type found within.

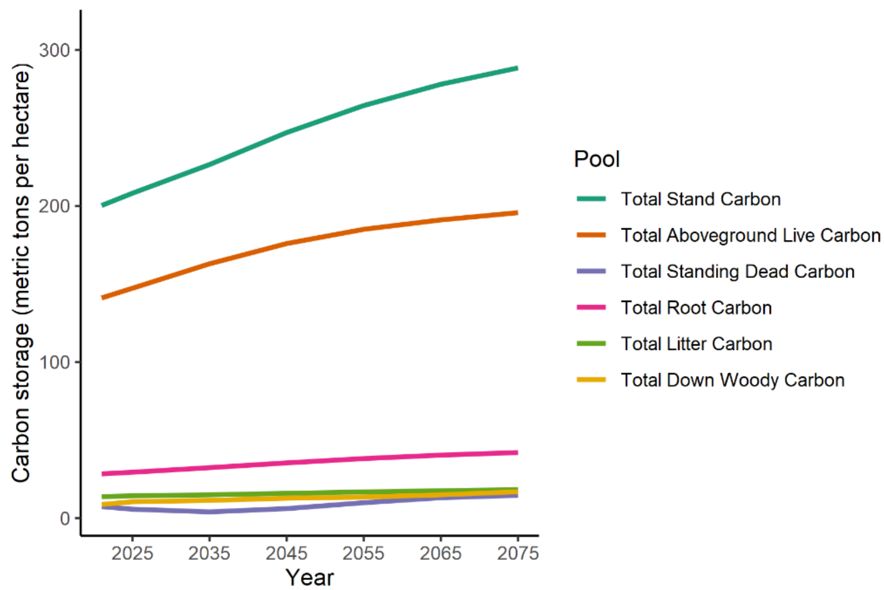


Figure 2. Carbon pool estimates over time. Total stand carbon (teal line) represents the sum of all pools estimated by FVS: aboveground live, standing dead, root, litter, and down woody carbon. Soil carbon is not included.

Table 2. FVS summary of carbon pools by reservation in 2021. Hectares include only forested habitat. See Table 1 for full reservation names. *does not include soil carbon from SoilGrids

		Carbon Storage (metric tons)						
Reservation	**Hectares**	**Total stand**	**Above-ground live**	**Standing dead**	**Root**	**Litter**	**Down woody**	***Carbon storage per hectare**
BR	1,072	198,805	140,780	6,085	28,039	13,974	9,183	185.5
MS	999	170,639	119,079	7,116	24,252	11,144	8,353	170.8
RR	779	176,567	125,051	7,244	25,295	11,336	7,099	226.6
HI	758	149,956	100,697	8,941	21,083	11,659	7,050	197.8
Minor	747	175,538	127,853	5,773	25,420	9,729	6,243	234.9
NC	571	116,817	83,448	2,750	16,453	8,778	4,991	204.7
BE	553	103,760	72,263	3,180	14,463	8,431	5,040	187.7
SC	421	89,705	63,360	2,827	12,737	6,612	3,877	213.0
Total	**5,900**	**1,181,788**	**832,530**	**43,916**	**167,742**	**81,663**	**51,836**	**200.3**

Soil carbon measurements were estimated using a different program (SoilGrids), which projected an average of 55 mt organic C/ha in the top 30 cm of soil across the park district with a minimum of 43 mt C/ha and a maximum of 80 mt C/ha (Figure 3). Combining soil carbon storage estimates from SoilGrids with estimates from FVS, Cleveland Metroparks stores approximately 255 mt C/ha or 1,504,500 mt C based on 5900 hectares of forest. Assuming no change in soil carbon, the total amount of carbon storage across the park district in 2075 is predicted to be 343 mt C/ha or 2,023,700 mt C.

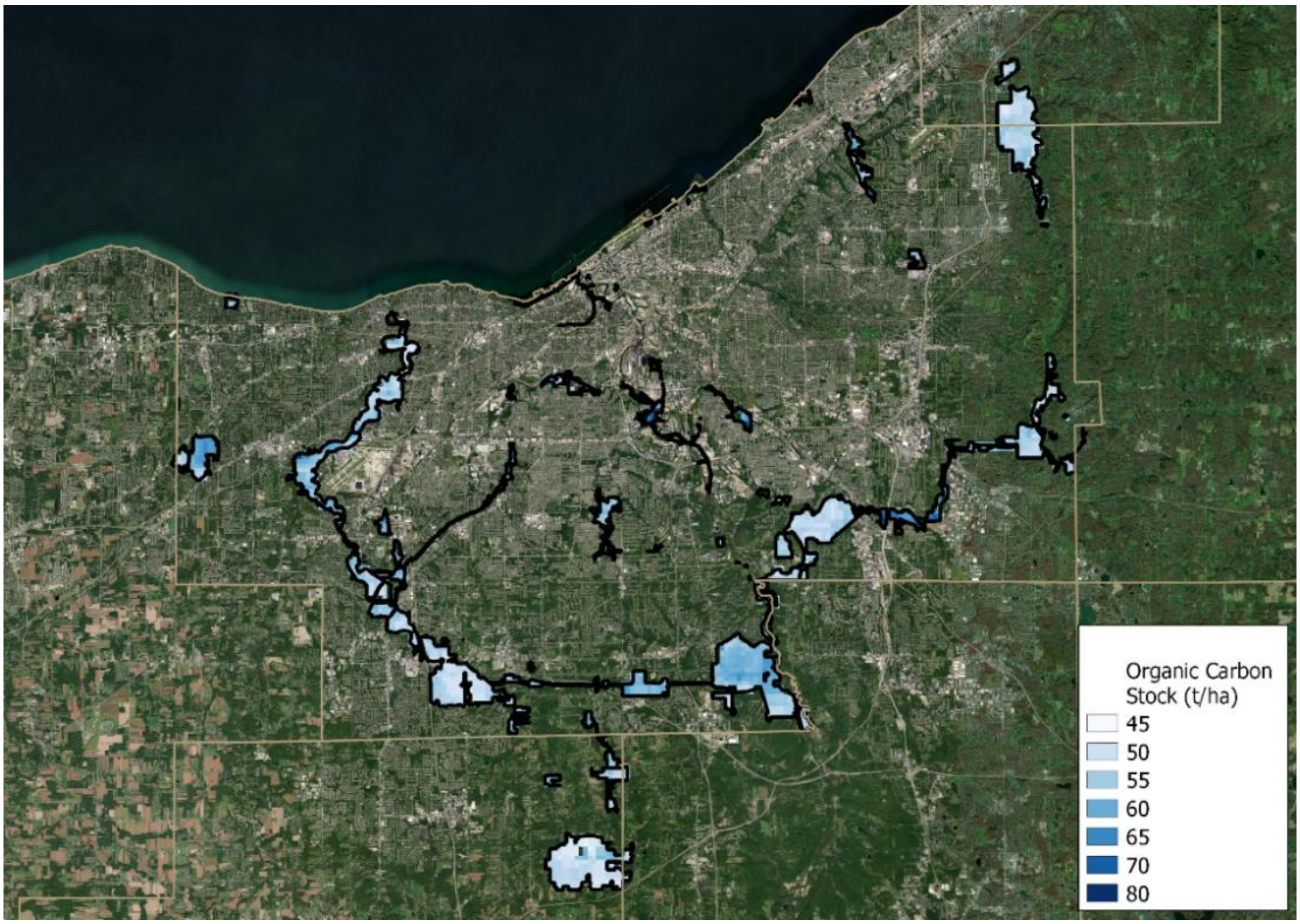


Figure 3. Map of SoilGrids organic carbon stock estimates for Cleveland Metroparks in metric tons per hectare.

Goal 2: Assess carbon storage, sequestration across forest community types

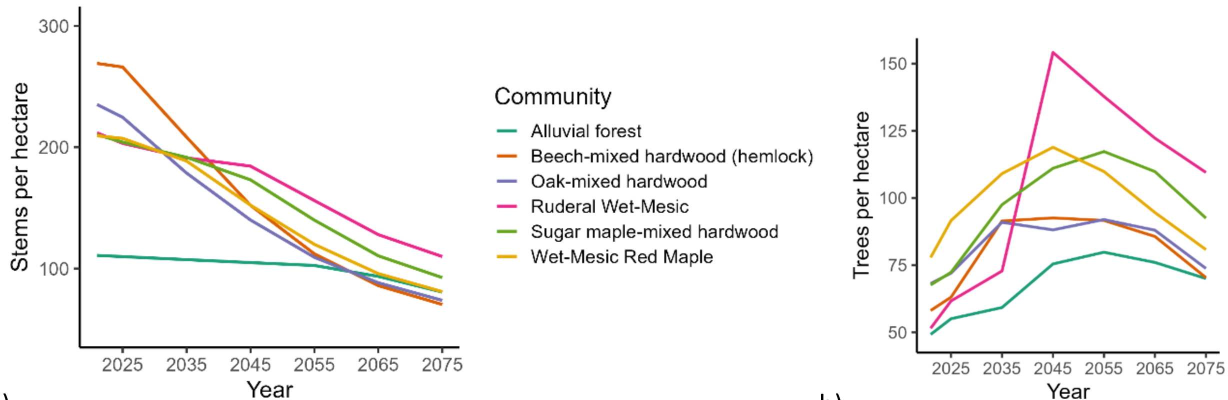
Cleveland Metroparks' forest communities were split into six types: sugar maple-mixed hardwood, wet-mesic red maple, beech-mixed hardwood (hemlock), oak-mixed hardwood, alluvial forest, and ruderal wet-mesic. These 6 types are not equally distributed across the landscape, nor do they have equal proportion of habitat area. Sugar maple-mixed hardwood is the most dominant community by size (1587 ha) and is nearly three times greater than the smallest forest type, ruderal wet-mesic (549 ha)

(Table 3). Between each of these communities, total stem count (trees + saplings) per hectare varied with beech-mixed hardwood having the most stems (1643) and alluvial forests having the fewest stems (677). Differences were also found in the proportion of trees to saplings among forest types. Approximately one in five stems in beech-mixed hardwood forests are trees (22%), whereas (44%) of alluvial forest are trees. So, even though beech-mixed hardwood forests had the greatest number of stems, they have the lowest proportion of trees. The opposite is true for alluvial forests, which had the lowest stem number, but highest proportion of trees compared to all other forest types. However, based on community area, the wet-mesic red maple forest community has the most trees per hectare and alluvial forests have the least. Variability between forest community is driven by size, structure and age differences which is further influenced by differences in species composition.

Table 3. Forest community summary of stem count in 2021. Estimated hectares of each forest community with total stem, and tree and sapling numbers. Communities are listed in descending order by forested hectares across Cleveland Metroparks.

		Stems (per hectare)			
Community	**Hectares**	**Total**	**Trees**	**Saplings**	**% Trees**
Sugar maple-mixed hardwood	1587	1284	413	871	32%
Wet-Mesic Red Maple	1232	1279	476	803	37%
Beech-mixed hardwood (hemlock)	985	1643	355	1288	22%
Oak-mixed hardwood	832	1436	416	1020	29%
Alluvial forest	715	677	301	376	44%
Ruderal Wet-Mesic	549	1294	315	979	24%
Total	**5900**	**1315avg**	**398avg**	**917avg**	**30%avg**

Each of these communities is predicted to change over time as saplings grow into trees and mature trees reach life stage capacity and begin to die. The model did not add new saplings through time, so Figure 4 only illustrates the outcome of the 2021 demographics. As such, total stems per hectare decline through time, however each community type varies dramatically in the rate of decline. The beech-mixed hardwood has the highest number of stems per hectare initially but lowest by 2075 (Fig.4a). The various rates of decline across all communities are likely attributed to species differences between the communities. However, Figure 4b demonstrates the projected increase in the number of trees per hectare through time. Through 2045 all communities increase the number of trees, which likely reflects the size and age transition of saplings to trees. The dramatic increase in trees in the ruderal wet-mesic community is due to the presence of green ash which is a dominant tree species in that community (see Goal 3, Fig 6 below).



a) b)

Figure 4. a) Projected stem density for each forest community through 2075. Stem count includes minimum height of 1.37m or dbh. b) Tree density for each forest community through 2075. Trees defined as >10 cm dbh.

The size and density of stems in communities directly affects carbon storage and sequestration capacity. At present, oak-mixed hardwood has the highest carbon storage (238 mt C/ha) and the greatest carbon sequestration (2.385 mt C/yr) of all forest types (Table 4). Beech-mixed hardwood (hemlock) has the second greatest storage (230.6 mt C/ha), but wet-mesic red maple forests sequester more (2.109 mt C/yr) than beech-mixed hardwood forests per year (2.007 mt C/yr). Ruderal wet-mesic has the lowest amount of carbon storage (115 mt C/ha) and lowest sequestration (1.123mt C/ha) of all communities, likely due to the low number and size of trees. However, ruderal wet-mesic communities are modeled to nearly double their carbon storage to 205 mt C/ha within 50 years (Figure 5). This reflects a 78% increase in storage capacity which is likely attributed to high sapling numbers of rapidly growing tree species (especially green ash). So even though stem numbers decline through time without recruitment, tree numbers, growth and size increase resulting in greater carbon storage. All other forest communities are expected to increase storage over the same timeframe, but at approximately half the rate (range 33-49% increase) (Figure 5).

Table 4. Carbon storage and sequestration in 2021 for six forest communities in Cleveland Metroparks. Total stand carbon includes only estimates from FVS. Communities are listed in descending order by forested hectares across Cleveland Metroparks.

		Carbon (metric tons per hectare)	
Community	**Hectares**	**Storage Total stand**	**Sequestration (per year)**
Sugar maple-mixed hardwood	1587	207.2	1.843
Wet-Mesic Red Maple	1232	194.8	2.109
Beech-mixed hardwood (hemlock)	985	230.6	2.007
Oak-mixed hardwood	832	238.0	2.385
Alluvial forest	715	202.2	1.814
Ruderal Wet-Mesic	549	115.2	1.126
	5900	**200.3**	**1.967**

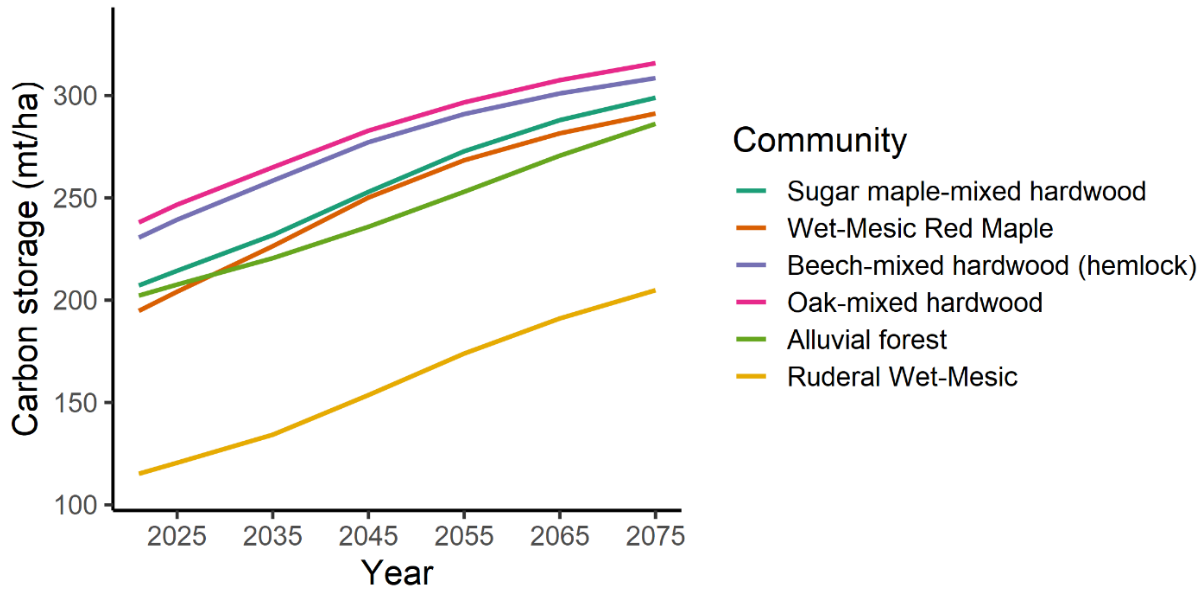


Figure 5. Total stand carbon storage estimated with FVS in each forest community over time. Estimates do not include soil carbon or project impacts due to emerging pests and pathogens.

Goal 3: Evaluate individual tree species current and future population demographics

Several species of interest were selected to highlight current demographics and projections of future population change through time: red maple (*Acer rubrum*), sugar maple (*A. saccharum*), shagbark hickory (*Carya ovata*), other hickories (*Carya* spp.), American beech (*Fagus grandifolia*), green ash (*Fraxinus pennsylvanica*), black cherry (*Prunus serotina*), white oak (*Quercus alba*), and red oak (*Q. rubra*). Species were categorized into 3 groups based on current 2021 size and sapling abundance.

The first group comprised of 3 species: sugar maple, American beech and green ash, are the smallest in average dbh with the most abundant saplings. Sugar maple (12.1 cm dbh) is the most common species across Cleveland Metroparks with over 500,000 trees and nearly 2 million saplings (Table 5). As these saplings grow for the next several decades, most are projected to survive and become trees (Figure 6). American beech (11.1 cm dbh) has the second most saplings with just under 1 million, followed by green ash (7.4 cm dbh) with over 600,000 saplings. Both beech and ash show significant increases in tree population numbers through 2045 due to the large number of maturing saplings (Figure 6). However, both species are experiencing population declines due to pests and diseases. Beech leaf disease, a relatively new affliction, will likely cause population declines that are not included in the modeled outcome for American beech. Likewise, the emerald ash borer causes significant mortality in green ash. While additive ash mortality was included within the FVS model, the rate may not reflect true impact since the initial tree population of 27,801 is still projected to increase to over 200,000 by 2075.

Table 5. Tree species demographic information in 2021. Species are listed based on 3 groups established by 2021 average dbh size, and sapling abundance. 1) small average size and abundant saplings (sugar maple, American beech, and green ash), 2) intermediate size, and stem abundance (black cherry, red maple, shagbark and hickory species), 3) large, long-lived trees with few saplings (red oak and white oak).

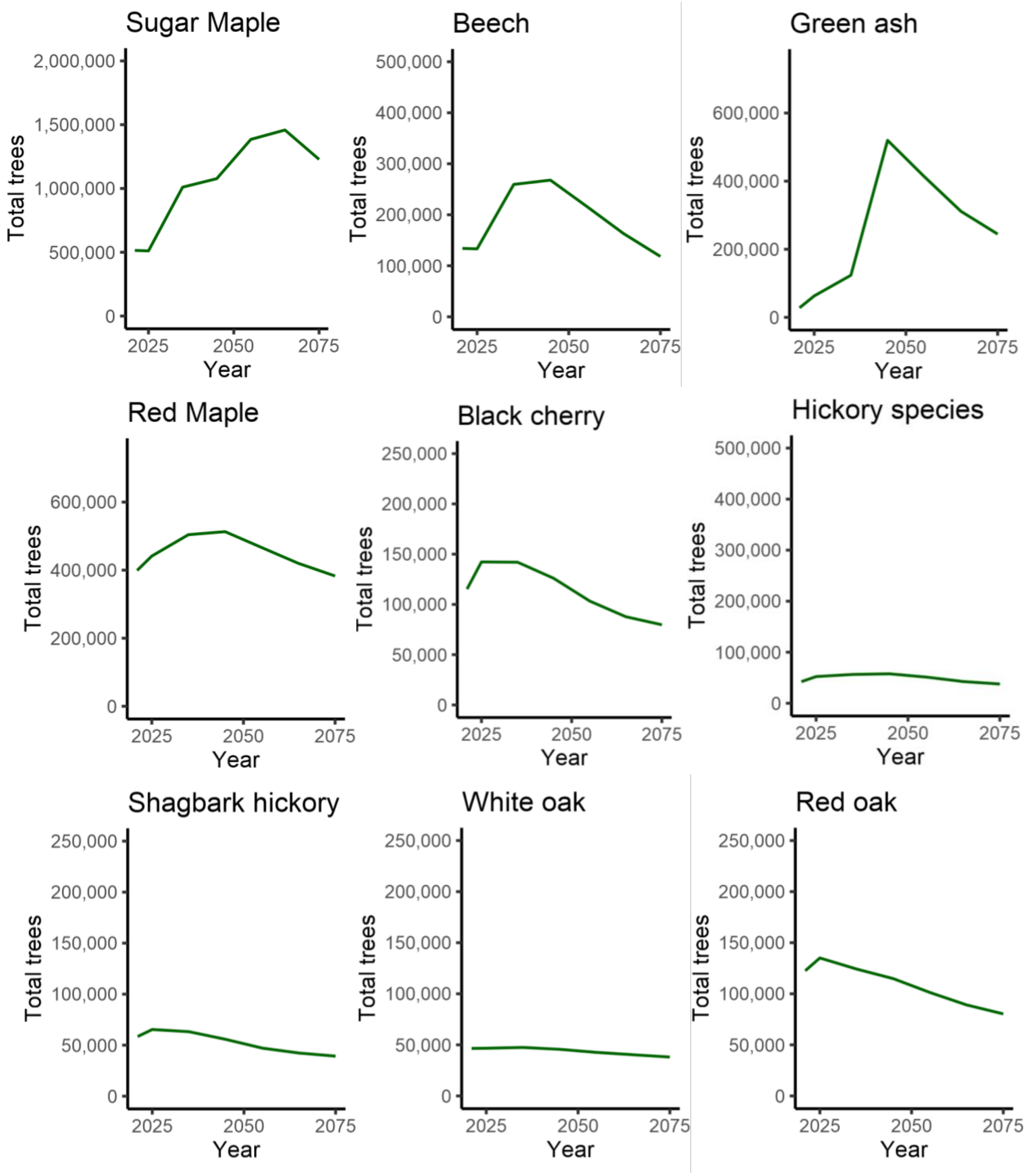
Species	Common name	# trees	# saplings	Average size (dbh cm)
Acer saccharum	Sugar maple	514,695	1,969,387	12.1
Fagus grandifolia	American beech	134,108	905,311	11.1
Fraxinus pennsylvanica	Green ash	27,801	620,997	7.4
Acer rubrum	Red maple	399,043	196,362	22.4
Prunus serotina	Black cherry	115,255	119,607	19.7
***Carya* spp.**	Hickory species	42,225	38,657	19.6
Carya ovata	Shagbark hickory	58,404	20,646	22.6
Quercus alba	White oak	46,547	5,046	44.2
Quercus rubra	Red oak	122,542	33,147	40.1

The second group of species includes medium-sized trees with moderate sapling population; red maple, black cherry, shagbark hickory and other hickory species. Red maple (22.4 cm dbh) shows a large initial increase in tree population of ~100,000 by 2045 and then declines back to 2021 population numbers (Figure 6). While black cherry (19.7 cm dbh) has an initial bump of ~25,000 in 2025, that increase diminishes and the species has fewer trees by 2075 than 2025. While shagbark hickory (22.6 cm dbh) and other hickory species combined (19.6 cm dbh), have medium sized trees, their smaller initial population size do not result in population bumps and ultimately end with comparable numbers by 2075.

The third group of species include red and white oak and are the largest in size (>40 cm dbh), with the fewest saplings (Table 5). White oak has the largest trees (44.2 cm dbh) and the fewest number of saplings out of all species of interest. This tree has significant wildlife benefits and while our model projects stable population numbers through time, management would seek to increase this species' regeneration and composition on the landscape. Red oak has a similar size (40.1 cm dbh) but shows a population loss over 50 years which raises concerns over population stability (Figure 6). Additionally, red oak are more vulnerable than white oak to the spread and mortality caused by oak wilt. This disease is spreading into our reservations from surrounding areas and management would seek to keep this disease out of our forest interiors.

Individual species projections of carbon storage and sequestration were not a product result from the FVS model run for this project. However, carbon estimates for 42 species, including the 9 highlighted here were provided in the Preliminary Carbon Accounting Report for Cleveland Metroparks' Plant Communities (2010-2021) using the iTREE model (Volk and Hausman 2022).

Figure 6. Tree (>10 cm) population changes over time for select species of interest. Note – the model does not include new recruitment (regeneration) through time.



Overall Summary

The primary goal of this study was to determine the current carbon status (storage and sequestration) across the various forest types of Cleveland Metroparks. In addition to accomplishing this goal, the FVS model provides a mechanism to estimate future change for these forests and approximate carbon potential in the next 50 years. While we acknowledge that there were variables not included in the model due to the complexities of modeling natural seedling regeneration, deer browse, pests and pathogens, and climate change, we believe these results provide a baseline scenario that we may use for future management planning.

The results here provide a baseline of current forest conditions while also projecting future changes under a scenario where minimal stressors are present. The current tree population across the whole park system may increase from 2.37 million to nearly 4 million by 2045, and then decline to about 3 million by 2075. The modeled decline in the last 30 years may be attributed to a variety of factors such as density dependent mortality or age dependent mortality. Total stem count (trees and saplings combined) in 2021 was estimated to be 7.76 million, with 69.5% being saplings smaller than 10 cm dbh. Some reservations, like Hinckley, are well positioned to increase the number of trees based on the high density of stems and proportion of saplings relative to total stems (77%). On the other hand, minor reservations have few stems overall and a lower proportion of saplings (59%). Within a reservation, both size and dominant forest community type shape current population size and age structure. Because forest management strategies can have profound impacts on future forest conditions (Munteanu et al., 2016), forests will need to be properly managed based on their current age structure and condition. In particular, reservations, like Brecksville, with fewer and older stems will need specific forest management prescriptions that maintain tree vigor or species health and to encourage regeneration of younger desirable species. Overall, since there is an increase in tree numbers over 50 years, this results in a potential increase in carbon storage from 1,181,788 mt C (200 mt C/ha) from all pools to 2,023,700 mt C by 2075.

Carbon storage was highest in the aboveground live pool (55%), followed by soil carbon (22%). Soil carbon in other studies often represents nearly half of all carbon (Domke et al., 2021; Pregitzer et al., 2020) but is a much smaller amount here and is likely due to estimation methods used. Since we did not have empirical data on soil carbon, SoilGrids provided our best approximation and implements machine learning to broadly apply global estimates of soil parameters across 250 m grids. As a result, the soil carbon data is a coarse estimation compared to the empirical tree data. The FVS model for aboveground live biomass was estimated at 141 mt C/ha which was similar to the estimate found with the smaller dataset from the preliminary carbon report using the i-Tree Eco model (144.1 mt C/ha; Volk and Hausman, 2022). In a study of 34 other urban areas across the United States, Nowak et al. 2013 found an average carbon storage of (76.9 mt C/ha) with a range of (31.4-141.4 mt C/ha). Other estimates of average carbon storage across USDA Forest Service lands are similar to Nowak et al. (2013) at 83.4 mt C/ha (Heath et al., 2011). While many factors may influence carbon measurement differences, our carbon storage results are at the highest end of the national dataset and likely reflect the protection of large mature forests throughout the 106-year history of Cleveland Metroparks. Carbon storage and sequestration estimations can also be calculated from several easily accessible GIS-based tools, such as The Nature Conservancy's Resilient Land Mapping Tool and ICLEI's LEARN Tool. In Appendix A table S3, we compare these GIS-based tools at similar spatial scales to our FVS models and found their estimates to be much lower than empirical data presented here. The consistently high estimates of carbon storage in Cleveland Metroparks' natural areas are likely attributed to the robust empirical dataset which validates carbon storage as a mechanism to manage overall carbon stocks to combat climate change. However, consideration of differences in carbon stocks between forest community types is important to determine where and what management strategies are necessary to maintain those carbon stocks or to encourage regeneration of climate tolerant tree species and enhance carbon sequestration. Additionally, forest management strategies need to consider species composition differences between forest types to determine patterns of past, impacts of current and possible future changes attributed to tree specific pests and pathogens.

Age structure in forest communities was often associated with historic species-specific stressors. The American chestnut was a dominant species with about 25% cover across the Eastern Deciduous Forest. Since the chestnut blight, this species has been functionally extirpated across its range and was replaced across our landscape by other native trees in our oak-mixed, beech-mixed and sugar maple-mixed hardwood forests. Alluvial forests have few stems and a low proportion of saplings compared to other forest communities. In addition to regular disturbance events caused by flooding, large populations of green ash, which is a dominant species for this forest, have died due to emerald ash borer (EAB; *Agrilus planipennis*) which has decimated ash populations across the eastern United States (Morin et al., 2017). Beech-mixed hardwood (hemlock) stands are also dense with a large proportion of beech saplings, possibly due to beech bark disease (BBD) that appeared at low levels in the 1990's (Flinn et al., 2022). BBD tends to cause overstory beech mortality followed by prolific root sprouts and understory thickets. In fact, the model predicts high beech sapling density followed by a large decline which may be attributed to density-dependent mortality. Several other species-specific pests and pathogens threaten to affect our future forest including spotted lanternfly, Asian long-horned beetle, and oak wilt. These stressors along with climate change have the potential to dramatically shift the outcome of our modeled carbon stock and the resilience of our forests. As such, future management goals must include careful consideration of each species' vulnerability to pests and pathogens, their age structure and their tolerance to climate change.

Species positioned to thrive in the next 50 years have abundant saplings to replace maturing trees and have minimal stressors. Species with the most saplings include sugar maple, red maple, beech, and green ash. However, some species are experiencing significant stress from pests and pathogens. The ash population in Cleveland Metroparks has declined by 160,000 since EAB was introduced (Volk and Hausman, 2022). Within the model, ash mortality was accounted for at a conservative level. Similar to ash, mortality in beech populations may be underrepresented due the presence of both beech leaf disease (BLD) and BBD (Reed et al., 2022). Additive beech mortality due to these pathogens was not explicitly incorporated into this model due to the long-term uncertainty of these impacts. Because of EAB, BBD, and BLD, the projected estimates of beech and ash population change may not reflect biological reality.

Tree species tolerance to climate change is also highly variable. According to USFS Tree Atlas, red oak and white oak have a very good climate tolerance threshold. Red maple, sugar maple and green ash are also good. The various hickory species range from fair to very good climate tolerance. Wild black cherry has fair tolerance to climate change, but is widely distributed across our park system, is an important wildlife species, and is included as a co-dominant tree in all 6 of our forest community types. Beech trees are expected to suffer on two fronts 1) they have poor tolerance to climate change and 2) high vulnerability to beech leaf disease and beech bark disease.

The results of this project provide important information about the condition, carbon storage capacity and climate adaptive potential for the various forest types of Cleveland Metroparks. Based on model predictions, Cleveland Metroparks is positioned to increase both tree numbers and carbon storage over the next 50 years. However, modeled projections do not account for potential impacts due to emerging regional forest pests and pathogens (like beech leaf disease, oak wilt, spotted lanternfly) or climate impacts that disproportionally stress certain trees. Each tree species has climate tolerance thresholds that will need to be considered in future planning. Therefore, more work is needed to incorporate these results into forest management goals that ensure healthy, resilient, and regenerating forests.

Appendix A. Methods Comparison

The goal of the current study is to predict the conditions of our forests in the future. However, we also want to compare methodologies among several leading approaches to gauge the effectiveness of our study. We previously used 100 empirical data plots to estimate carbon storage and sequestration from 2010-21 in i-Tree Eco (Volk and Hausman, 2022). We now focus on the full suite of 400 plots collected from the most recent data collection cycle, 2015-18. We focused our FVS model to include only trees >10 cm dbh for this part of the study and included the full dataset for the main study (Table S1).

Table S1. Preliminary vs Final Report methodology comparison

	Preliminary Report (i-Tree Eco)	**Final Report (Forest Vegetation Simulator)**
# plots	100 (two repeat visits)	400 (single visit)
Plot sample size	0.04 ha (40% of plot)	0.1 ha (100% of plot)
Years	2010, 2015, 2021	2015-18
Total trees (>10cm)	1,718	14,190
Total saplings (<10 cm)	0	36,419*
Future projections	No	Yes

*Saplings were not included for initial model comparison but were included for main text.

As described in the main text (see Methods), we used our preliminary report as a baseline to guide model formulation. We subset trees >10 cm dbh from the FVS dataset to resemble the preliminary report more closely. Once the proper FVS model parameters were identified, we compared high level summary statistics to ensure the FVS model was similar to our preliminary report using i-Tree (Table S2). Both outputs were within a 10% margin of error, so we proceeded with our selected model by incorporating the full dataset.

Table S2. Preliminary vs final report results overview. For comparison purposes only, the final report dataset used stems >10 cm to closely match the preliminary dataset; the results from the main text are based on the full dataset.

	Preliminary Report (i-Tree Eco)			**Final Report (Forest Vegetation Simulator)**		
	2010	2021	**Change**	2015	2021	**Change**
# Trees (millions)	2.73	2.46	**-0.27**	2.42	2.30	**-0.12**
Carbon (mt)	911,200	982,500	**+71,300**	884,000	930,000	**+46,000**
Stem size (cm)	26.5	27.6	**+1.1**	28.9	29.9	**+1.0**

In addition to i-Tree Eco, we also compared FVS model results against The Nature Conservancy's (TNC) Resilient Land Mapping Tool and the LEARN tool from ICLEI – Local Governments for Sustainability. The Resilient Land Mapping Tool combines empirical data from USDA Forest Service Forest Inventory Analysis (FIA) and geospatial data to provide carbon estimates across the United States. The LEARN tool uses National Land Cover Database (NLCD) geospatial data from multi-spectral Landsat imagery which categorizes land cover into one of 16 classes. Changes in carbon emission (or sequestration) are then calculated based on region, forest type, and forest age. We used Indiana as our closest and most similar location within the Central region. For both comparisons, we focused assessments within Cleveland Metroparks' park boundary of 8,620 hectares (21,300 ac) from 2010. The 5,900 hectares used in the FVS model represent only the forested land while the 8,620 hectares reflect total land area.

Estimates of carbon storage were highest using FVS compared to all other methods. The FVS dataset was not only the most robust empirical dataset, but also estimated carbon from all pools except soil carbon. FVS also used 36,000 more saplings than what was used in i-Tree which resulted in a higher estimate of ecosystem carbon storage. Carbon sequestration was estimated as the highest in i-Tree Eco, followed by FVS. TNC's Resilient Land provided the lowest estimate of carbon sequestration at 0.7 mt CO_2 per acre. The LEARN tool does not estimate total carbon storage but estimated sequestration at 2.0 mt CO_2 per acre.

In comparing these tools, it is important to note that the Resilient Land Mapping Tool and LEARN tool both estimated carbon storage and sequestration across all of Cleveland Metroparks and did not distinguish natural areas. As a result of including non-forested land, it is likely that they both underestimate carbon storage and sequestration per acre. If we account for the fact that roughly 75% of Cleveland Metroparks total acreage was forested and weight each estimate accordingly, carbon storage estimated with Resilient Land Mapping Tool is much closer to FVS at 389 mt CO_2 per acre. However, they are both still below the FVS estimate for sequestration rate (Resilient Land Mapping Tool = 0.93 mt CO_2 per acre per year; LEARN = 2.667 mt CO_2 per acre per year).

Table S3. Comparison of other methods across a similar geographic area. Soil is not included for most/all methods. Soil was not included in the FVS estimate.

	Year(s)	Source	Geographic Extent	Carbon Pools	Gross Annual Sequestration (mt CO2/ac)	Total CO2 storage (mt/ac)
FVS (this study)	2021	400 plots	Cleveland Metroparks Natural Areas	Aboveground live & dead, belowground, leaf litter, down wood, herbaceous	3.4	363.6
i-Tree Eco	2021	100 plots[1]	Cleveland Metroparks Natural Areas	Aboveground live & dead (no saplings)	3.9	213.8
TNC Resilient Land	2010	USFS FIA plots[2]	All Cleveland Metroparks	Aboveground live & dead, down wood, and soil/other	0.7	291.9
ICLEI LEARN Tool	2013-19	Landsat satellite imagery[3]	All Cleveland Metroparks	-	2.0	-

Sources:

[1]Estimates from Volk and Hausman, 2022

[2]One FIA plot per 6000 acres; estimates from TNC Resilient Land https://maps.tnc.org/resilientland/

[3]Estimates from https://icleiusa.org/LEARN/

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