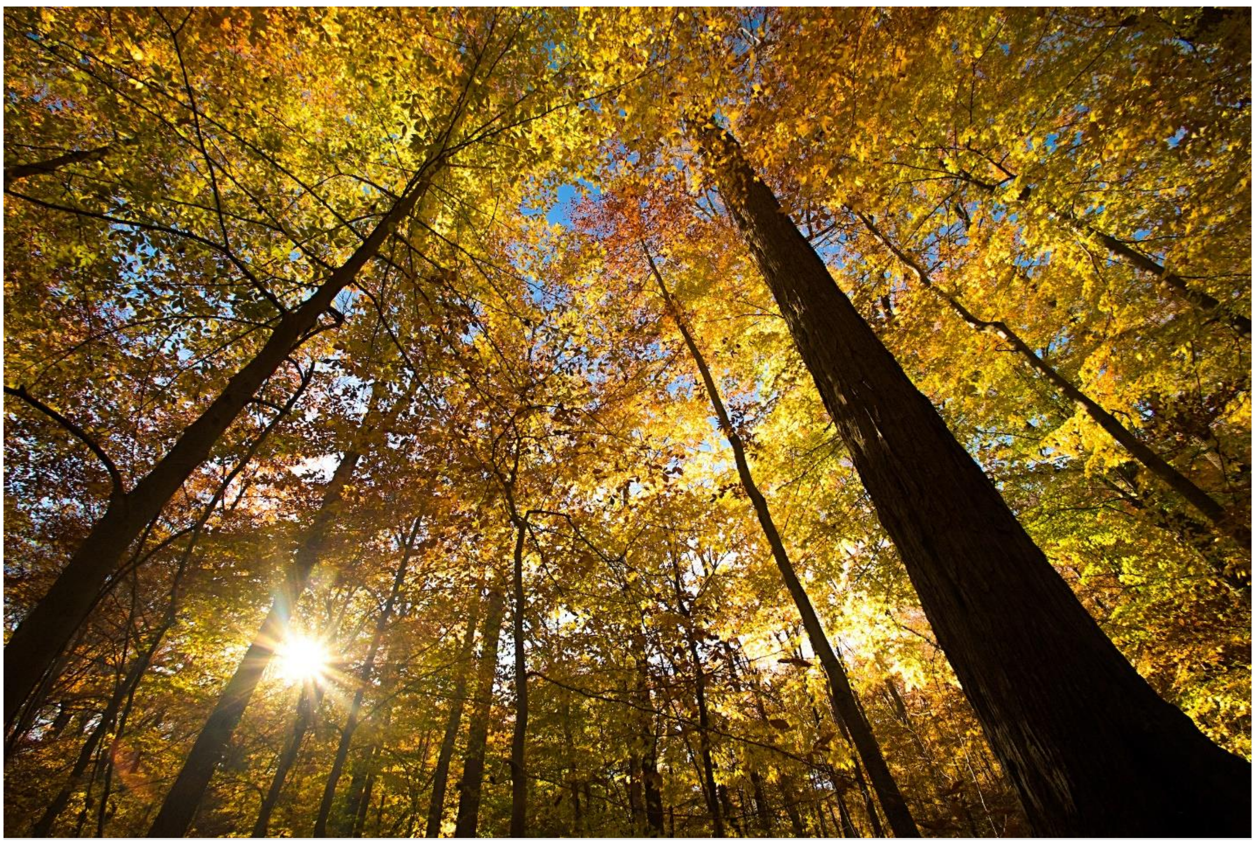
Department of Park Operations
Division of Natural Resources

Preliminary Carbon Accounting Report for Cleveland Metroparks' Plant Communities (2010-2021)

Cleveland Metroparks Technical Report 2022/NR-01



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Executive Summary

Forests are essential for balancing our natural world within urban cities and provide benefits to wildlife, people, and the environment. One essential role of forests is the ability to mitigate climate change by removing carbon dioxide (CO_2) from the atmosphere and storing it as carbon. Carbon can be stored in plant material like trees, saplings, shrubs, leaf litter, and even soil. Through this report, live and standing dead trees were measured in Cleveland Metroparks' long-term Plant Community Assessment Program (PCAP) over three time periods: 2010, 2015, and 2021. Using these measurements, we evaluated carbon storage, sequestration, and the overall condition of our tree population.

We estimate that Cleveland Metroparks' natural areas store 982,500 metric tons of C (3.6 million MTCO2e) and have a gross sequestration rate of 20,410 mt C (74,837 MTCO2e) per year. Annual carbon sequestration is above average compared to other urban forests within Ohio and around the US, but only offsets the equivalent of a small town of 4,067 residents in Cuyahoga County or 8,420,914 gallons of gasoline. Our summarized carbon report highlights are below.

- Increase in carbon storage of +71,300 mt C (or 261,433 MTCO2e) from 2010 to 2021
- Total carbon storage of 982,500 mt C (or 3,602,500 MTCO2e) valued at $185 million in 2021
- Gross carbon sequestration is 20,410 mt C (or 74,837 MTCO2e) per year
- Net sequestration is 11,080 mt C (or 40,627 MTCO2e) per year
- Structural value of natural areas is $1.47 billion in 2021

Table 1. Executive Summary

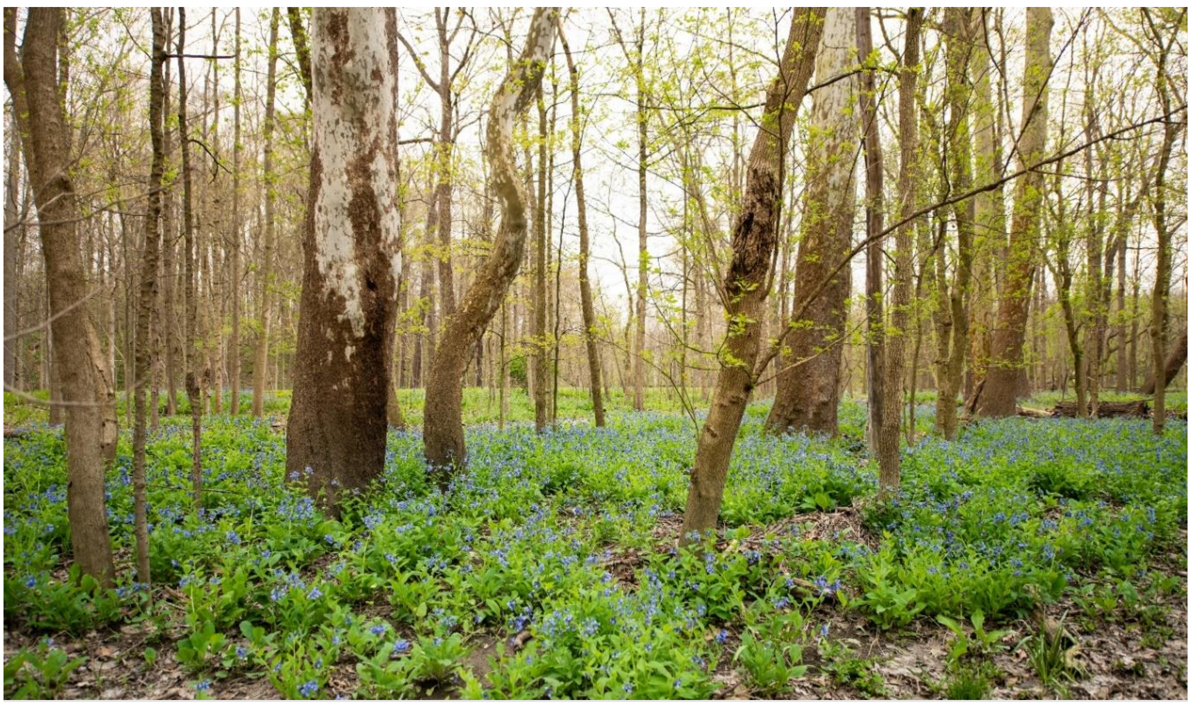
	2010	2015	2021	Change
Number of trees:	2,731,000	2,570,000	2,457,000	-274,000
Most common species of trees (in order):	Red maple, sugar maple, American beech	Sugar maple, red maple, American beech	Sugar maple, red maple, American beech	
Average tree size (cm):	26.5	N/a	27.6	+1.09
Tree Cover:	80.7%	86.80%	87.40%	+7%
Structural value:	$1.51 billion	N/a	$1.47 billion	-$40 million

Despite these immense ecosystem services, forest health is under threat from various pests and pathogens. Since 2010, Cleveland Metroparks has lost approximately 274,000 trees. Emerald ash borer was discovered in Cleveland Metroparks in 2006 and has since decimated our ash population over the last decade, causing mortality of roughly 161,000 trees to date. Beech leaf disease has caused substantial decline in American beech health, our third most abundant tree in the park system. Oak wilt has recently become a large risk for some of our most iconic species. Other forest pests like spotted lanternfly and hemlock woolly adelgid are present in Northeast Ohio but have not yet been found in our park system. These pests individually and collectively pose a serious threat to our forests and their ability to function as a carbon reservoir. In total, nine significant pests or pathogens are present in

Cleveland Metroparks or the immediate vicinity, affecting at least 21 tree species (approximately 49% of tree species in this study).

In addition to pests and pathogens, our forests are showing signs of aging based on the increase in average tree size and canopy cover despite a decrease in tree number. Mature forests provide substantial ecosystem benefits but grow at a slower rate than young forests and can even begin to decrease in the presence of many stressors. The combination of pests and aging forests has caused a decline in forest valuation from $1.51 billion to $1.47 billion, a decrease of $40 million.

Finally, climate change is a significant threat to our forests that will decrease forest function even further; thirteen native tree species in our region are not tolerant to climate change. These poorly adapted species will likely decline over the remainder of the century and may even become lost altogether. Projected range expansion for 8-12 species indicates possible migration into our region, but landscape barriers and habitat fragmentation likely impede that process. Thus, Cleveland Metroparks and our larger Northeast Ohio region may experience a net loss of tree biodiversity. Our results show the importance and need to maintain our forests for the future.



Introduction

Climate change is a well-known, pervasive, and systemic issue throughout natural resource management. Climate change causes increased temperatures and altered precipitation dynamics with increased frequency and severity of storms. As a consequence, habitat availability is reduced and species must adapt, migrate, or die. The ultimate way to combat climate change is to reduce greenhouse gases (GHG). Our forest habitats are a significant resource for reducing GHG by removing atmospheric carbon dioxide (CO2) and storing carbon in woody tissue. In fact, tree planting is one of the most popular global methods for reducing the negative effects of climate change (Popkin, 2019).

To maximize carbon capture efficiency, forests must be healthy and functioning properly which requires an understanding of their current and historical status. As an example, Pregitzer et al. (2020) found that healthy, native forests capture more carbon than degraded, non-native forests. Other threats to carbon sequestration include the introduction of invasive species, exotic pests, and pathogens. Compared to forests with no disturbance, insect and disease may reduce carbon storage by 69% and 28% respectively (Quirion et al., 2021). Emerald ash borer, spotted lanternfly, beech leaf disease, hemlock wooly adelgid, oak wilt, and many other forest health issues have had major negative impacts on forest health for decades. Additional forest stressors can be caused by fragmentation and overall reduction in forest area due to land-use change from forests to agricultural, residential, or commercial land. The combination of these multiple stressors has led to an overall decrease in carbon uptake across the United States since 1990 (Domke et al. 2021).

The first step to understanding forest carbon is to quantify how much is present and then determine how carbon pools have changed over time. Cleveland Metroparks has a long-term vegetation monitoring program (Plant Community Assessment Program; PCAP) which is ideal for documenting forest changes over time. We used the PCAP dataset to calculate carbon storage and sequestration across the park system and to assess forest health by evaluating changes in population size and canopy condition.

Goals

1. Evaluate Cleveland Metroparks' natural landscape to understand carbon storage and sequestration through time
2. Compare condition and carbon pool differences among plant communities through time
3. Assess individual tree species growth, performance, and health through time

Methods Overview

We used field data collected from 2010-21 to estimate carbon storage and sequestration in Cleveland Metroparks. One hundred three PCAP plots were established in 2010 using a standardized data collection protocol, then reassessed in 2015 and 2021 (Hausman and Robison, 2010). Plots are geospatially balanced across 16,850 ac (or 6,819 ha) of natural areas throughout the park system (circa 2010) and were classified into one of six plant communities (see Appendix 1: Expanded Methods). We then compared carbon pool measurements based on plant community type and by individual tree species performance. Carbon pool measurements focused on live and standing dead trees. This report does not attempt to quantify other carbon pools such as understory, litter and duff, down woody material, or soil carbon. Total carbon storage and sequestration across the park district as well as carbon captured across each community was estimated using i-Tree Eco (i-Tree Eco User's Manual v6.0). We also quantified canopy condition, population size, and average tree size for each community and species. For more details on plot establishment, data collection, and community designation, see Appendix 1: Expanded Methods.

This report provides results that are divided into separate highlight sections.

- Highlight 1: provides totals for all of Cleveland Metroparks
- Highlight 2: breaks down results based on plant community types
- Highlight 3: provides individual tree species performance summaries

Highlight 1: Evaluate Cleveland Metroparks' forest health, carbon storage, and sequestration between 2010 – 2021.

Cleveland Metroparks' total tree population in natural areas decreased from 2.73 million trees in 2010 to 2.46 million trees in 2021. Average condition of individual trees also declined by 9% (from 84% to 75%). Despite a decrease in average tree condition, overall forest canopy cover increased by 6.7% (Table 2). The increase in overall canopy cover was also associated with an increase in average tree size from 26.5 cm to 27.6 cm.

We estimate that Cleveland Metroparks has a total of 982,500 metric tons of carbon or 144.1 mt C ha^{-1}, an increase of over 71,000 mt C since 2010 (Table 2). By comparison, live and dead tree biomass in forestland across the US averages 83.4 mt C ha^{-1} (Heath et al., 2011). Urban areas average 76.9 mt C ha^{-1} although this average varies considerably across study areas (31.4 – 141.4 mt C ha^{-1}; Nowak et al., 2013). Live tree carbon storage increased 17,227 mt C from 2010 to 2021, totaling 820,355 mt C in 2021. Dead tree carbon storage increased 54,073 mt C from 2010 to 2021, totaling 162,145 mt C in 2021.

Table 2. Changes in carbon storage and sequestration over time. Several metrics are not shown for 2015 due to differences in data collection methods, see Appendix 1: Expanded Methods for more details.

	2010	2015	2021	Change
Number of trees	2,731,000	2,570,000	2,457,000	-274,000
Average tree size (cm)	26.5	N/a	27.6	+1.09
Canopy Cover	80.7%	86.80%	87.40%	+6.7%
Carbon storage in metric tons	911,200 ($130 million)	N/A	982,500 ($185 million)	+71,300
Carbon dioxide storage in metric tons	3,341,067	N/a	3,602,500	+261,433
Gross carbon sequestration in metric tons/yr	23,550 ($3.37 million/year)	N/a	20,410 ($3.84 million/year)	-3,140 mt/yr
Net carbon sequestration in metric tons/yr	17,310	N/a	11,080	-6,230

Carbon sequestration parkwide decreased from 23,550 mt C yr^{-1} in 2010 to 20,410 mt C yr^{-1} (74,837 MTCO2e yr^{-1}) in 2021 or 0.299 kg C m^{-2} yr^{-1} (Table 2). Yet, our gross carbon sequestration rate is still comparable to other cities around the United States like Milwaukee, Arlington, and Sacramento and higher than the expected rate in Ohio (0.248 kg C m^{-2} yr^{-1}; Nowak et al., 2013). Per capita carbon emission within Cuyahoga County was 18.4 MTCO2e per year in 2019 (Cuyahoga County Planning Commission, 2021). Based on the 2021 gross sequestration rate, Cleveland Metroparks forests sequester the equivalent of 4,067 Cuyahoga County residents every year, or approximately the population of Chagrin Falls, Ohio. An alternative carbon capture comparison is equivalent to 8,420,914 gallons of gasoline every year (Figure 1; US EPA, 2021).

Figure 1. Greenhouse gas equivalencies based on 2021 gross sequestration rate for all of Cleveland Metroparks' natural areas. Figures generated from US EPA (2021).

Net carbon sequestration takes into account decomposition which releases carbon dioxide back into the environment as trees decay. Net sequestration in 2010 was 17,310 mt C yr^{-1} which is 74% of 2010 gross sequestration and is on par with ratios in other cities like Atlanta, Boston, and Chicago (Nowak et al., 2013). In contrast, net sequestration in 2021 was 11,080 mt C yr^{-1} which is 54% of gross sequestration in the same year (Table 2). An identical comparison of net and gross sequestration was made in New York City; the large difference was attributed to the considerable number of both dead and old, large trees (Nowak and Crane, 2002). Other cities like Baltimore, Minneapolis, and Casper, WY had similar ratios of net to gross sequestration and were some of the lowest ratios measured (Nowak et al., 2013).

Highlight 1 Impact Summary: Cleveland Metroparks' natural areas saw an increase in tree size, canopy coverage, and overall carbon storage. Along with these increases, the overall decrease in carbon sequestration indicates our forests are aging. Increased forest age tends to be associated with high carbon storage and decreased carbon sequestration that comes with older, slower growing trees (Pregitzer and Euskirchen, 2004). The large decrease in total tree population and condition is primarily due to the arrival of emerald ash borer (EAB; *Agrilis planipennis*), an invasive insect which has decimated ash trees across the country. Beech leaf disease (BLD) also caused a large decrease in the condition of our third most abundant tree from 2010 to 2021, American beech (*Fagus grandifolia*).

Cleveland Metroparks carbon storage is nearly twice that reported for other forested land and urban areas. However, this project specifically focused on natural areas which tend to have more tree cover and may have led to inflated estimates compared to other urban sites from Nowak et al. (2013). Our estimates do not include understory (seedlings, saplings, and herbaceous plants), down woody material, litter and duff, or soil which may collectively contain 50-70% of total carbon storage (Domke et al. 2021; Pregitzer et al., 2020; Smith et al., 2013).

An item to note is that net sequestration can continue to decrease or even become negative as decomposition and carbon emission becomes higher than growth (Baccini et al., 2017). Large decreases in carbon storage can often be attributed to major disturbances on the landscape (Quirion et al., 2021). Estimates in both Ohio and the United States show a decline in net carbon uptake over the last 30 years (Domke et al., 2021).

Highlight 2: Condition and carbon report by plant communities

Cleveland Metroparks' natural areas have six plant communities, predominantly composed of forests which make up over 15,000 acres across the top five community types (Table 2). For detailed description of community composition including dominant tree species and size structure, see Appendix 1: Expanded Methods.

Oak-mixed hardwood is the dominant plant community in Cleveland Metroparks, encompassing 28% of plots with an estimated area of 4,676 acres (1,892 ha) of park land (Table 3). Alluvial forest is the second most dominant plant community with 26% of plots and an estimated area of 4,423 acres (1,790 ha). The four remaining communities are similar sizes with beech-mixed hardwood (hemlock) comprising 13% (2,233 acres or 904 ha), wet-mesic red maple and sugar maple-mixed hardwood comprising 11% each (1,854 acres or 750 ha), and mesic meadow (ruderal) comprising 11% (1,811 acres or 733 ha).

Table 3. Distribution of plant community types across Cleveland Metroparks' natural areas

Plant Community Type	Percent of Plots	Estimated Area (acres)
Oak-mixed hardwood	28%	4,676
Alluvial forest	26%	4,423
Beech-mixed hardwood (hemlock)	13%	2,233
Wet-mesic red maple	11%	1,854
Sugar maple-mixed hardwood	11%	1,854
Mesic meadow (ruderal)	11%	1,811
Total	**100%**	**16,850**

In 2010, alluvial forest had the highest tree density (504.4 trees/ha). Due largely to impacts and tree mortality caused by the emerald ash borer, tree density in alluvial forest decreased to 402.6 trees/ha in 2021 which ranks third highest for tree density (Figure 2). Wet-mesic red maple also saw a drastic decline in tree density from 469.4 trees/ha in 2010 to 350 trees/ha in 2021. Beech-mixed hardwood and sugar maple-mixed hardwood both had a slight increase in tree density of 13 and 21 trees per hectare respectively. Oak-mixed hardwood had the highest tree density in 2021 with 431.3 trees/ha.

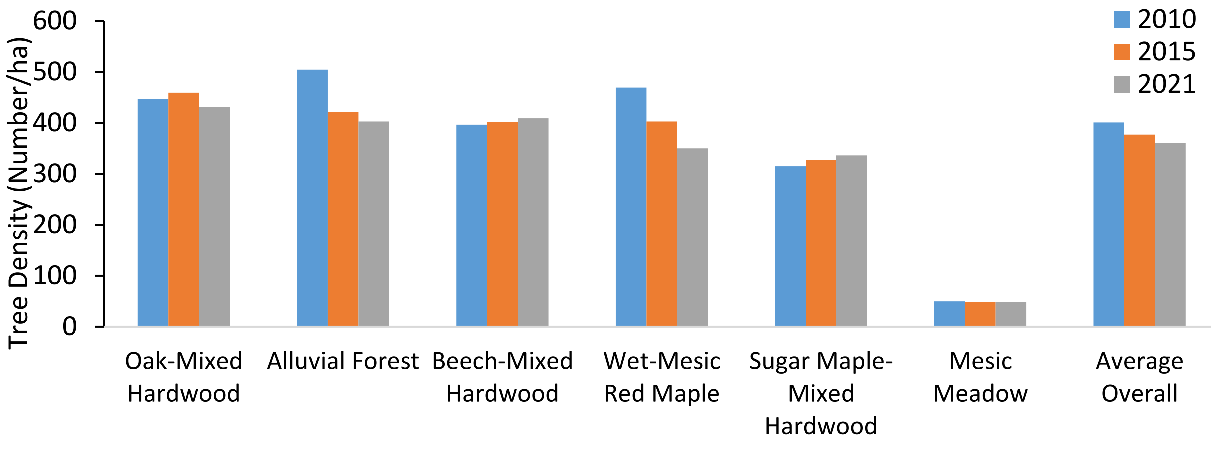


Figure 2. Average number of trees per hectare in each forest type.

Average tree canopy conditions declined overall from 2010 to 2021 (Figure 3). Beech-mixed hardwood had the highest canopy condition in 2010 with an average of 90% canopy cover (10% dieback). Sugar maple-mixed hardwood was the second highest condition in 2010 and the highest condition in 2021 with an average of 86% canopy condition. Alluvial forest and beech-mixed hardwood saw the largest decline in condition from 2010 to 2021 with a decline of 17% and 13% in average canopy condition respectively. In 2021, only two species within beech-mixed hardwood had >20% of trees in bad condition (>25% dieback), American beech and black cherry. In alluvial forest, the decline in forest condition can be attributed to 11 species which had >20% of trees in bad condition including black cherry, hawthorn, green ash, Ohio buckeye, slippery elm, black locust, and boxelder. While mesic meadow (ruderal) consistently had the lowest numbers of any community type for most metrics (carbon storage, carbon sequestration, tree density, tree diversity), it was the only community type where the average tree condition increased from 2010 to 2021.

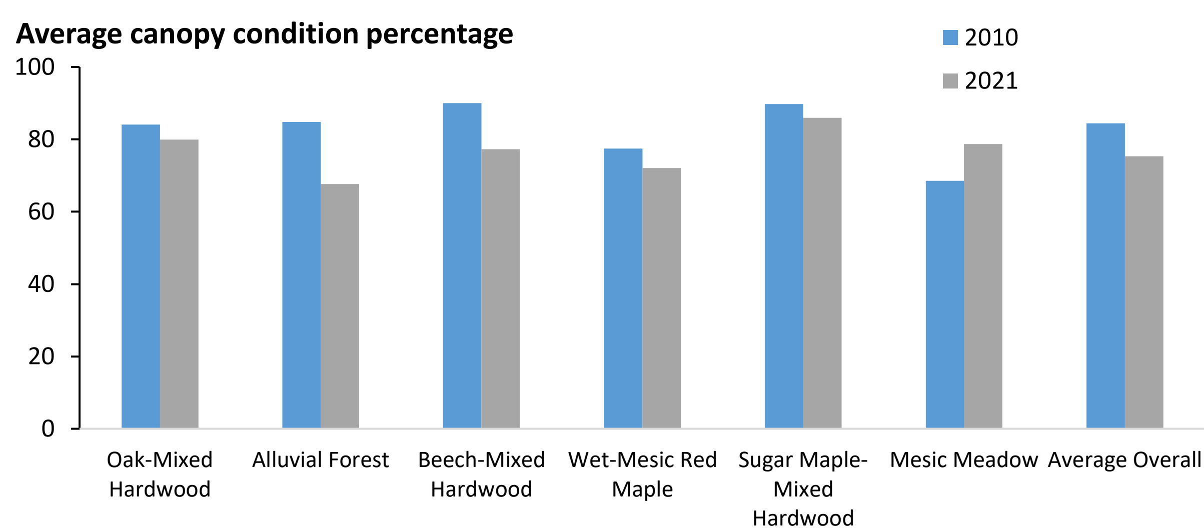


Figure 3. Average tree canopy condition for all community types. No canopy assessments were done in 2015.

Carbon storage on a per hectare basis fluctuated by community type (Figure 4). All communities increased carbon storage from 2010 to 2021 except wet-mesic red maple and mesic meadow. Wet-mesic red maple had the greatest carbon storage in 2010 but beech-mixed hardwood had the greatest carbon storage in 2021. Gross carbon sequestration also varied by year and community type (Figure 5). Wet-mesic red maple had the highest sequestration rate of all community types in either year with 4.7 and 4.3 mt C ha^{-1} yr^{-1} in 2010 and 2021 respectively. Sugar maple-mixed hardwood was the only community to increase in sequestration rate from 2010 to 2021.

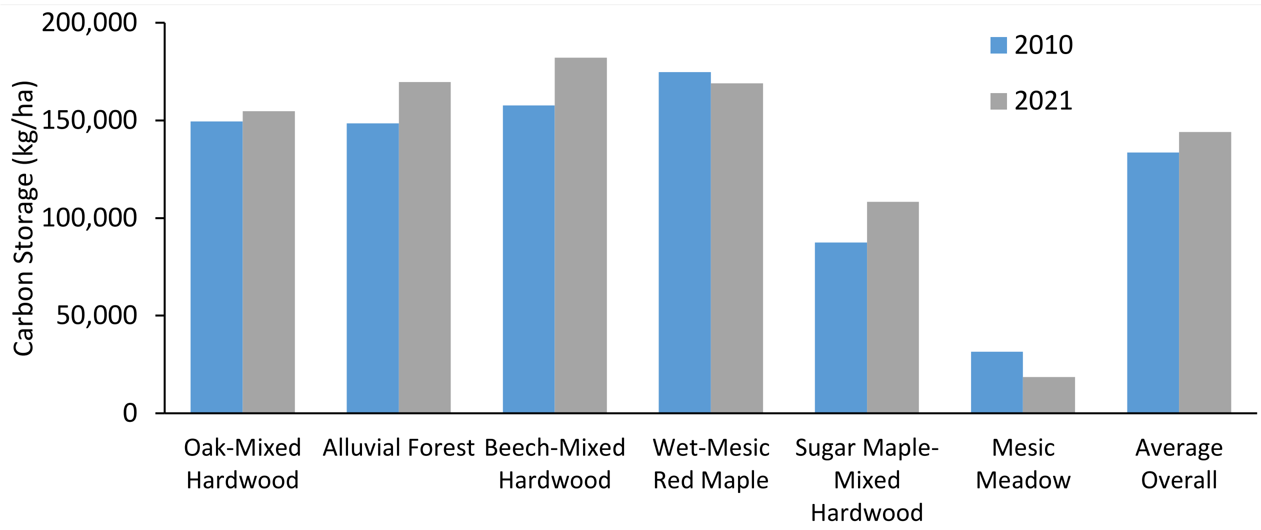


Figure 4. Carbon storage across plant communities in 2010 and 2021.

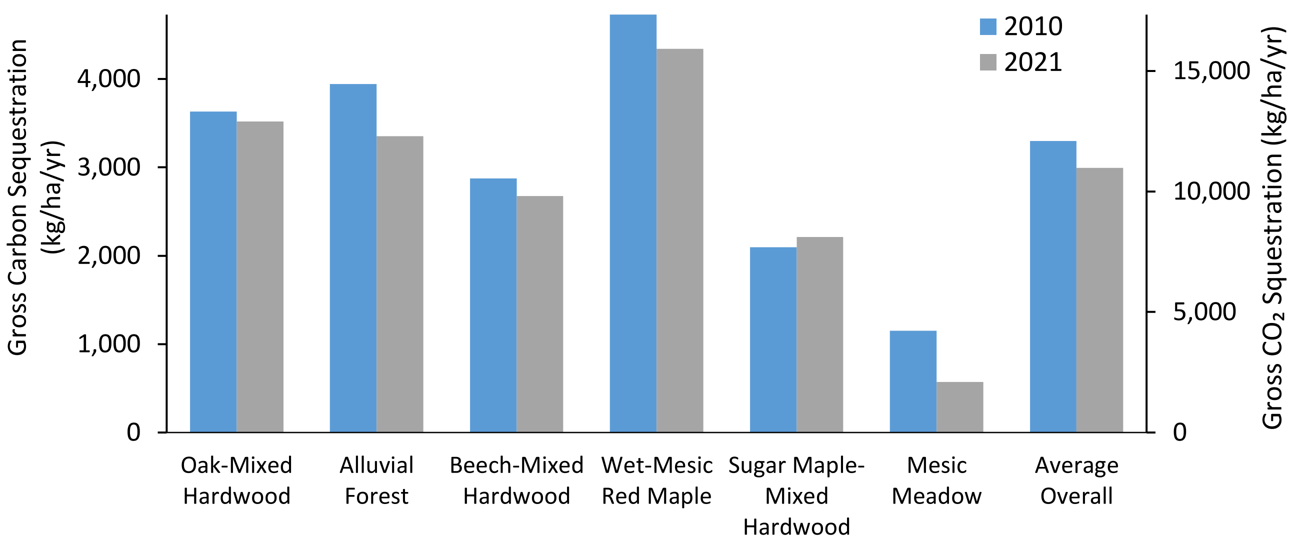


Figure 5. Gross carbon sequestration among plant communities. The left Y-axis shows gross carbon sequestration per hectare per year and the right Y-axis shows gross CO_2 sequestration.

Highlight 2 Impact Summary:

The overall decrease in tree population, condition, and carbon sequestration is likely due to a combination of forest pests and age. Both alluvial forest and wet-mesic red maple communities experienced a large loss of trees over the 11-year timespan. The decline in alluvial forests is due to damage caused by EAB. However, the wet-mesic red maple community is dominated by trees with ruderal life-history strategies. These ruderal species tend to have r-selected traits like early colonization, rapid growth, and are short-lived. We suspect that these ruderal species are turning over from their initial colonization of newly acquired park land 80+ years ago. In turn, the large decrease in tree condition and population is the likely cause for the overall decrease in carbon sequestration in the alluvial and wet-mesic red maple communities.

On the other hand, the older age structure of our beech- and oak-mixed hardwood may explain the decrease in sequestration for these two communities. Sequestration rates tend to peak around 30 years and slowly decline as their growth also slows (Yuhua and Williams, 2013). Both beech- and oak-mixed hardwood are two of our older communities that may not be growing as quickly as a younger forest type, leading to a decrease in sequestration from 2010 to 2021. Beech-mixed hardwood also saw a large decline in canopy condition which may have also contributed to the decrease in sequestration.

Sugar maple-mixed hardwood had minimal change in canopy condition because of fewer disturbances than alluvial or wet-mesic red maple communities. In addition, it is younger than the beech- and oak-mixed hardwood communities. Consequently, it is the only community that had an increase in tree number, carbon storage, and sequestration.

Highlight 3: Assess individual species performance and health

Green and white ash (*Fraxinus pennsylvanica* and *F. americana*) collectively made up approximately 193,500 trees in 2010. By 2015, only 83,000 ash remained and by 2021, no white ash and only 32,000 green ash remained (Figure 6). Red maple (*Acer rubrum*) is one of the most abundant tree species in Cleveland Metroparks with nearly 500,000 stems, encompassing 17% of all trees. However, there has been a steady decrease of 52,000 trees over the last decade. By contrast, sugar maple (*A. saccharum*) increased by 49,000 trees. Other species that increased in population size include American beech (*Fagus grandifolia*), northern red oak (*Quercus rubra*), black maple (*Acer nigrum*), and American hophornbeam (*Ostraya virginiana*).

Canopy condition decreased overall and for most individual species (Figure 7). Positive increases in canopy condition were only noted for a few species and change was minimal. Eastern white pine (*Pinus strobus*) had the largest increase in canopy condition (9.8%), but also had a large decline in overall population size (from 16,400 to 12,600). Other species with a positive change in canopy condition include eastern hemlock (*Tsuga canadensis*; 5.7%), shagbark hickory (*Carya ovata*; 3.7%), American basswood (*Tilia americana*; 1.7%), silver maple (*A. saccharinum*; 1%), northern red oak (<1%), and white oak (*Quercus alba*; <1%). All other species had a decline in canopy condition.

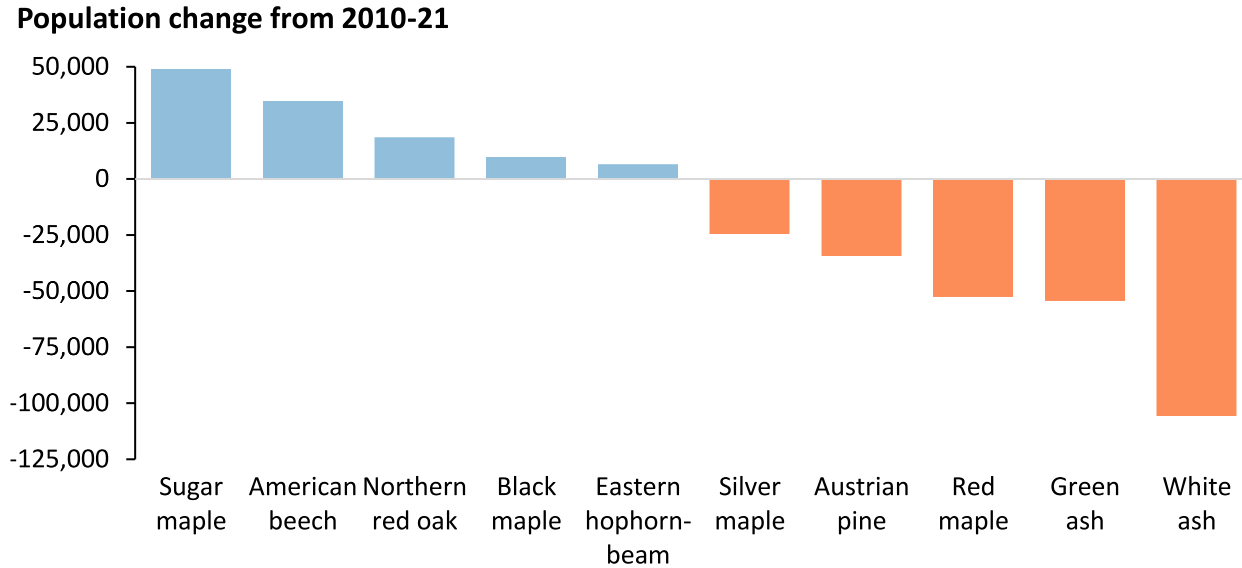


Figure 6. Top five species with the largest increase or decrease in population size from 2010-21.

Average tree size remained the same or increased for most species (Appendix 2: Table 4). Eastern cottonwood (*Populus deltoides*), silver maple, and American sycamore (*Platanus occidentalis*) saw the largest increase in tree size. Other than green ash, three species saw a decrease in average tree size of >1 cm: black walnut (*Juglans nigra*), slippery elm (*Ulmus rubra*), and American beech.

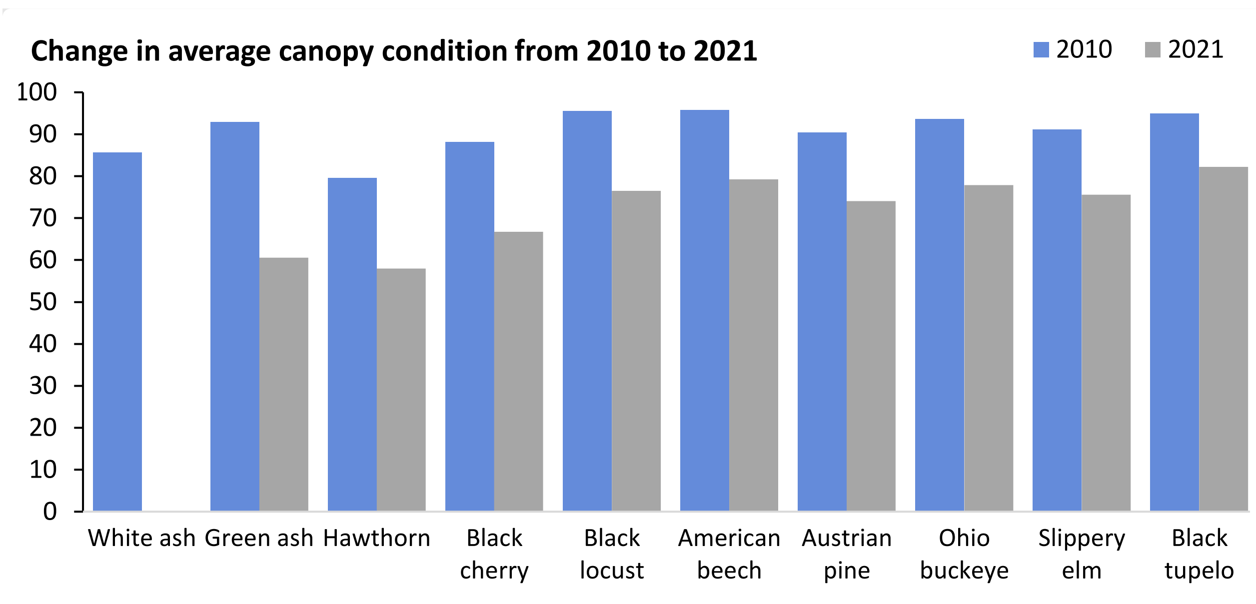


Figure 7. Change in canopy condition for the ten species with the largest decrease. From left to right, species are ordered largest to smallest decrease. Only species with >5 trees assessed were considered.

Highlight 3 Impact Summary: Several major tree pests have appeared in Cleveland Metroparks over the last decade, including one of the most significant pests in recent memory. Emerald ash borer first appeared in Cuyahoga County in 2006 and was first found in Cleveland Metroparks' at Big Creek Reservation two years later. Because there were minimal signs of EAB presence during 2010 sampling (Hausman and Robison, 2010) and EAB can take up to five years for tree mortality (Knight et al., 2013), 2010 population and condition estimates may reflect Cleveland Metroparks' ash population largely unaffected by EAB. Green and white ash collectively lost over 161,000 trees since 2010. Remaining ash in 2021 show substantially reduced canopy condition and average tree size (Figure 7; Appendix 2: Table 4). Although carbon is still present in dead trees until it is decomposed, carbon storage and sequestration estimated from ash in this study has declined to nearly zero due to EAB.

Unlike with ash, there are no obvious health concerns in red maple. Red maple tends to be a pioneer and is one of the earlier species to colonize non-forested land. So, the large decline in population size may be due to their life-history strategy and the fact that forest succession is occurring rather than a decline in health. Other species that decreased in population size also have a similar life-history strategy to red maple and are likely aging out from the initial conversion of agricultural land to newly acquired parkland in the early to mid-1900's.

Despite the increase in American beech population, the emergence of beech leaf disease (BLD) in Cleveland Metroparks in 2014 has caused significant canopy decline in beech across the park system (Figure 7). In addition, the average tree size of beech has decreased over time in contrast with most species' average size which increased or remained stagnant over the study (Appendix 2: Table 4).

Conclusions

Several factors will influence the future of carbon storage and forest health including the age and structure of our forests. Early in Cleveland Metroparks' 105-year history, large portions of agricultural/pasture or other altered lands were converted to park land . These newly acquired lands were colonized by ruderal successional tree species or by planting many fast-growing species like spruce and pines. Over the last 80+ years, these trees and other parts of our forests are now showing signs of aging based on the increase in average tree size, the large amount of carbon stored, and the slowed rate of sequestration. If left unmanaged, carbon sequestration in our forests may continue to slow and could even lead to a net source of carbon through decomposition as opposed to a sink.

Emerging pests and pathogens have and will continue to pose a threat to forest health and can slow sequestration by causing tree mortality or a serious decline in health (Figure 8). In total, there are nine non-native pests or pathogens affecting more than 21 tree species in Cleveland Metroparks or our immediate vicinity. The most impactful pest in recent history, emerald ash borer (EAB), has reduced ash populations by over 161,000 trees and continues to cause decline in forest condition and the ability to sequester carbon.

American beech (*Fagus grandifolia*) is the third most abundant tree in Cleveland Metroparks and has been significantly impacted by two diseases over the last decade. Beech leaf disease (BLD) was first discovered in Lake County, Ohio in 2012 and subsequently found in Cleveland Metroparks' North and South Chagrin Reservations two years later. Although we do not know the full biology of BLD, it has significantly reduced the health of our beech population with canopy reductions and mortality of saplings and small trees (Reed et al., 2022). In addition to BLD, beech bark disease (BBD) was discovered in Cleveland Metroparks in 2021, although it may have been present at low levels before this time. BBD is a disease complex involving a non-native scale insect (*Cryptococcus fagisuga*) and a pathogenic fungus (*Neonectria faginata* or *N. ditissima*). BBD was introduced to the US in the late 1800's and has slowly spread from the Northeast, killing beech as it spreads (Cale et al., 2017). BBD primarily attacks mature trees, shifting population structure toward a high density of smaller trees. BBD may partially explain the increase in tree number over the last decade. However, BLD is generally quicker to kill smaller trees than mature trees. Therefore, we expect the outlook of beech to continue to decline as a result of BLD and BBD.

Other forest pests include elongate hemlock scale (EHS), hemlock woolly adelgid (HWA), oak wilt, and spotted lanternfly (SLF; Figure 8). HWA can cause tree death on its own within 3-10 years, but EHS takes much longer, often 10 years after population densities reach 10 individuals per needle (McClure, 2002). While HWA has not been found in Cleveland Metroparks yet, EHS is present in several locations around the park system and is increasing in population size to harmful levels in North Chagrin Reservation (Volk et al., 2019). Although hemlock is not adequately represented in our PCAP plots due to unsafe sampling conditions along steep slopes, we have approximately 800 acres of hemlock area across our park district. Hemlock stands continue to be monitored for signs of both pests. With an estimated 200,000 oak trees in Cleveland Metroparks, oak wilt poses a significant threat to forest health. Oak wilt is a vascular wilt disease caused by a pathogenic fungus (*Bretziella fagacearum*) that is spread by Nitidulid beetles or from roots of infected trees to surrounding trees. Oak wilt can kill red oaks within a single season and may kill white oaks over several years. Oak wilt has been detected in several locations within Cleveland Metroparks and requires significant, rapid efforts to prevent further spread. Finally, several populations of SLF were found in the City of Cleveland in 2021, though surveys in Cleveland Metroparks have not found any in our park system. SLF is a generalist pest with over 50 potential hosts in North America which it can feed on (Barringer and Ciafré, 2020). While SLF may not directly kill trees, feeding by large numbers of these leaf hoppers can severely stress trees and compromise their ability to manage other stressors effectively.

Figure 8. Various pests and pathogens currently affecting forest health in Cleveland Metroparks. Clockwise from top left: emerald ash borer (photo credit C. Hausman), beech leaf disease (C. Hausman), oak wilt (J. O'Brien), and elongate hemlock scale (D. Volk).

In addition to the various pests and pathogens already present, climate change is likely to have a profound influence on forest structure and function over the remaining century and beyond. To determine the list of climate tolerant tree species, work by USDA Forest Service Landscape Change Research Group consider adaptability, abundance, importance value, and change in habitat suitability. Iverson et al. (2019) indicate that 13 species in this study and several more not included here are projected to do poorly in the face of climate change (Appendix 2: Table 5). Additionally, 20-22 species are projected to decrease in habitat suitability compared to 12-15 species which may increase in habitat suitability. Overall, 21 tree species have fair, good, or very good capability of persisting in our region under future climate projections (https://www.fs.fed.us/nrs/atlas/tree/). To ensure our natural areas are resilient in the face of climate change, adaptability and climate tolerance are being actively considered in restoration projects across Cleveland Metroparks.

Cleveland Metroparks' natural and forested lands have changed over the last decade, from a carbon perspective and in forest health. Despite a significant loss of trees over the last decade, canopy coverage, tree size, and carbon storage have all increased since 2010. Over the last 11 years, both gross and net carbon sequestration have decreased. These results suggest our forests are aging and are experiencing impacts from several major pests. Forest management will need to consider opportunities for enhanced carbon storage and forest health. Some community types have been impacted more than others; alluvial forests have declined as a result of EAB while wet-mesic red maple forests appear to be declining as a result of the life-history strategies of species like red maple. In contrast, young and undisturbed sugar maple-mixed hardwood forests have continued to increase in carbon storage, sequestration, and number of trees. These results are considered through the lens of climate change and are actively being incorporated into management decisions like tree plantings, restoration projects, and mitigation efforts. In addition, Cleveland Metroparks has acquired nearly 3,000 acres of land since 2010 that have not been included in our estimates. These additional acquisitions will significantly benefit our carbon storage ability by ensuring these lands are preserved.

Appendix 1: Expanded Methods

Plot establishment and data collection

In 2010, Cleveland Metroparks developed a long-term vegetation monitoring program called the Plant Community Assessment Program (PCAP; Hausman and Robison, 2010). Plot placement was done using Generalized Random Tesselation Stratified (GRTS) survey method from US EPA's Environmental Monitoring and Assessment Program (EMAP), resulting in 400 spatially balanced plots across the park district (Diaz-Ramos et al. 1996, Herlihy et al. 2000, Olsen et al. 1998, Stevens 1997, Stevens and Olsen 1999, Stevens and Urquhart 1999, Stevens and Olsen 2004). At the start of the program, Cleveland Metroparks had 21,494 acres. However, plots were only placed in natural areas comprising 16,850 acres (6,819 ha). In other words, mowed grass, playgrounds, paved trails, buildings, parking lots, and any other non-natural surface was removed from consideration. PCAP is repeated on a five-year schedule, such that one hundred plots are assessed every year for four years with the fifth year designated for data analysis and reporting (Hausman and Robison, 2010; Eysenbach et al., 2020). This report focuses on one hundred three plots sampled in the first year of the cycle over three sampling periods: 2010, 2015, and 2021 (2020 sampling was missed due to Covid-19; Figure 9).

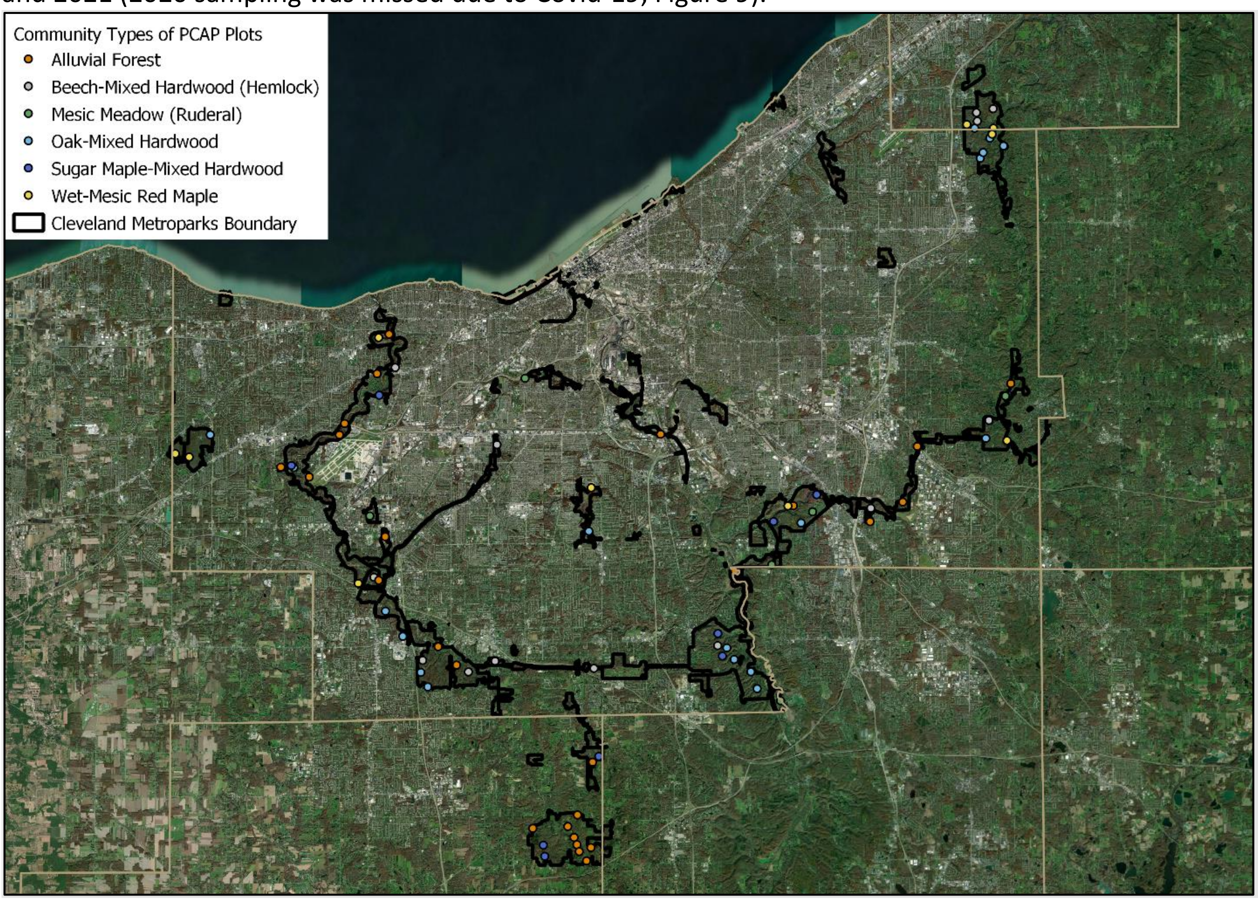


Figure 9. Map of PCAP plots assessed in 2010, 2015, and 2021. Plots are colored by plant community type.

Plot layout follows the North Carolina Vegetation Survey design (Peet et al., 2008; Lee et al., 2008). Plots are 20m x 50m (0.1 ha), with a 20m x 20m (0.04 ha) section being designated as the focal point of data for this study. Plots are surveyed at a similar time every year by a 4- or 5-person crew between June and September.

Data collection within the PCAP program includes woody stem measurements, herbaceous data and vouchers, pest and pathogens, disturbance, invasive species, and deer impact, though many of these metrics were not utilized in the present study (Hausman and Robison, 2010). Woody stem measurements generally include species, DBH, dieback, and overall canopy cover within the plot using densiometers. Enhanced woody stem measurements were taken in 2010 as part of a USDA Forest Service project assessing urban tree cover (UTC). Consequently, total tree height, crown size, crown health, and crown light exposure were also recorded in 2010. Collecting these variables adds significant time to sampling, so this level of effort was not performed every year.

It is important to note that modified data was collected in 2015, which affected the accuracy of individual tree estimates. Rather than exact DBH measurements, trees were classified into size class ranges. Midpoints of the size class were then used as DBH for each tree. For example, a 10.1 cm tree would be placed in the 10-15 cm size class and ultimately recorded as the 12.5 cm midpoint for DBH. In addition, no canopy conditions were assessed in 2015 which led to inaccuracy in growth trends and the inability to determine tree health. If no canopy conditions are recorded, data analysis software (i-Tree) automatically assigns a value of 75% to all trees. By comparison, data collected in 2010 and 2021 included species, exact DBH, canopy dieback, and overall tree cover within the plot.

Plant community characterization

PCAP plots were designated into one of six plant community types based on hierarchical clustering and indicator species analysis: 1) oak-mixed hardwood, 2) alluvial forest, 3) beech-mixed hardwood (hemlock), 4) wet-mesic red maple, 5) sugar maple-mixed hardwood, and 6) mesic meadow (Reinier et al., 2018). The total area of each plant community is based on the proportional number of plots in each community type across the natural park area (16,850 acres).

To better characterize plant community types, an indicator species analysis was performed. Indicator tree species for each community are defined based on constancy and abundance. Species are considered indicators when a significant indicator value (IndVal) is produced for a community type (Dufrene and Legendre 1997). Species with at least 50% constancy but that do not have a significant indicator value are considered "prevalent" in that community type. Prior to analysis, tree taxa were divided into "pseudo-species" based on diameter with small trees (S) defined as <25 cm and large trees (L) >25 cm. This was done to understand the different influences of canopy trees compared to subcanopy and understory trees on the final classification.

Plant Community Descriptions:

Oak-mixed hardwood is characterized by sugar maple (S), red maple (S, L), black cherry (*Prunus serotina*; S), American beech (S), tulip tree (*Liriodendron tulipifera*; S, L), American hornbeam (*Carpinus caroliniana*; S), American hophornbeam (S), red oak (L), shagbark hickory (S, L), and white oak (L) in order of abundance.

Alluvial forest is characterized by American elm (*Ulmus americana*; L), green ash (S), black maple (*Acer nigrum*; S), sycamore (L), white ash (S), slippery elm (S), black walnut (L), and cottonwood (L) in order of abundance.

Beech-mixed hardwood (hemlock) is characterized by American beech (S, L), sugar maple (S, L), red maple (S), and black cherry (S) in order of abundance.

Wet-mesic red maple is characterized by red maple (S, L), black cherry (S), sugar maple (S), American beech (S), slippery elm (S), red oak (S, L), black tupelo (*Nyssa sylvatica*; S), and flowering dogwood (*Cornus florida*; S).

Sugar maple-mixed mesic s characterized by of sugar maple (S, L), American beech (S), bitternut hickory (*Carya cordiformis*; S, L), and American elm (S).

Mesic meadow was not included in the indicator species analysis. The total area of each plant community is based on the proportional number of plots of each community type across the natural park area (16,850 acres).

Land-use mapping

In 2009, Cleveland Metroparks' entire park district (21,494 ac) was mapped using GIS prior to the establishment of the PCAP program. All areas were classified into categories including developed (parking lots, playgrounds, mowed grass), bodies of water, and various natural areas (successional, forest, meadow, wetland). Natural areas comprised 16,850 acres (78%) while developed areas comprised 4,644 acres (22%). The total area of natural lands in 2009 was used as the basis for this study.

Data analysis

All data was recorded in i-Tree for trees >10 cm to estimate carbon storage and sequestration, population size, canopy condition, and ecosystem services. Reports from i-Tree were generated for each year separately, then assembled outside of i-Tree. Standing dead trees are included for carbon storage calculations but are not included for estimates of overall tree population, carbon sequestration, or canopy condition. Species health ratings were classified into one of seven categories based on percent dieback: excellent = 0% dieback, good = 1-10%, fair = 11-25%, poor = 26-50%, critical = 51-75%, dying = 76-99%, and dead = 100% dieback (Nowak et al., 2008). Because there were too few trees in some categories, trees with excellent and good ratings were combined (good) and poor, critical, dying, and dead were combined (bad) when comparing among community types; trees in the fair category were not combined with any other category.

Modeling climate projections

Using a Random Forest DISTRIB model (DISTRIB-II), Iverson et al. (2019) projected future (2070-2099) habitat change of species across the Eastern United States. They projected tree importance values using a suite of environmental variables based on low GHG emissions (RCP 4.5) or high GHG emissions (RCP 8.5). Using habitat change results from this study in addition to species adaptability and abundance, USDA's Forest Service Landscape Change Research Group compiled results into the Climate Change Tree Atlas tool as a full resource guide (https://www.fs.fed.us/nrs/atlas/tree/). Using this tool, we viewed the 1x1 degree grid summary of our study area (41N, 81W) showing which trees are rated as very good, good, fair, poor, very poor, lost, or new habitat.

Appendix 2: Expanded Results

We assessed over 50 tree species in this study and are documenting major changes to many species over the last decade. The change in average tree size is straightforward for most species, but some have seen larger increases than others. Eastern cottonwood was already the largest tree in 2010 and saw the largest increase in tree size (Table 4). Other fast-growing trees include those in wet areas like American sycamore and silver maple. Some species have even decreased in average size, like black walnut, American beech, slippery elm, and green ash. The decrease in average tree size is likely due to age structure of black walnut from trees aging out and pest presence in beech, elm, and ash.

Table 5 represents an overall summary of all species assessed in 2021, including average size, number of trees assessed, average carbon storage, average carbon sequestration, and projected climate tolerance. Of the 42 species assessed in 2021, three species (black maple, flowering dogwood, and eastern hemlock) may be lost by the end of the century. Another ten species are projected to do poorly or very poorly. In comparison, 15 species are projected to perform good or better over the same timeframe although several of those species are facing significant stressors from ongoing pests or pathogens (green ash and oak species).

Considering pests and pathogens, there are several current and potential threats to forest health with varying implications for individual tree species and structural value (Figure 10). Emerald ash borer, beech leaf and beech bark disease, oak wilt, hemlock woolly adelgid and elongate hemlock scale, spongy moth (*Lymantria dispar,* formerly gypsy moth), Dutch elm disease, and spotted lanternfly are all current threats or in the immediate vicinity surrounding Cleveland Metroparks. Collectively, these nine pests threaten hundreds of thousands of trees worth hundreds of millions of dollars.

Table 4. Average tree size (in centimeters) over time for any species with ≥10 individuals measured in 2010 and 2021. Measurements in 2015 are not included due to differences in data collection (see Appendix 1: Expanded Methods).

Species	2010	2021	Change
Eastern cottonwood	53.8	66.0	12.1
American sycamore	51.0	57.9	6.8
Black walnut	47.9	43.9	-4.1
Pin oak	39.0	41.9	2.9
Tulip tree	38.0	41.4	3.4
Northern red oak	38.6	39.8	1.2
White oak	32.4	36.5	4.1
Bitternut hickory	27.3	31.7	4.4
Austrian pine	30.3	31.0	0.7
Silver maple	22.5	29.5	7.0
American basswood	25.3	29.3	4.0
Red maple	26.0	27.6	1.6
Shagbark hickory	24.7	27.3	2.6
Black cherry	23.6	25.5	1.9
American beech	26.4	25.1	-1.3
Slippery elm	26.2	23.7	-2.6
Black maple	21.3	21.2	-0.1
Boxelder	19.0	20.5	1.4
Sugar maple	20.4	20.3	-0.1
American elm	18.6	19.6	1.0
Green ash	25.7	15.8	-9.9
Hawthorn species	14.2	14.3	0.1
American hophornbeam	13.4	13.1	-0.3

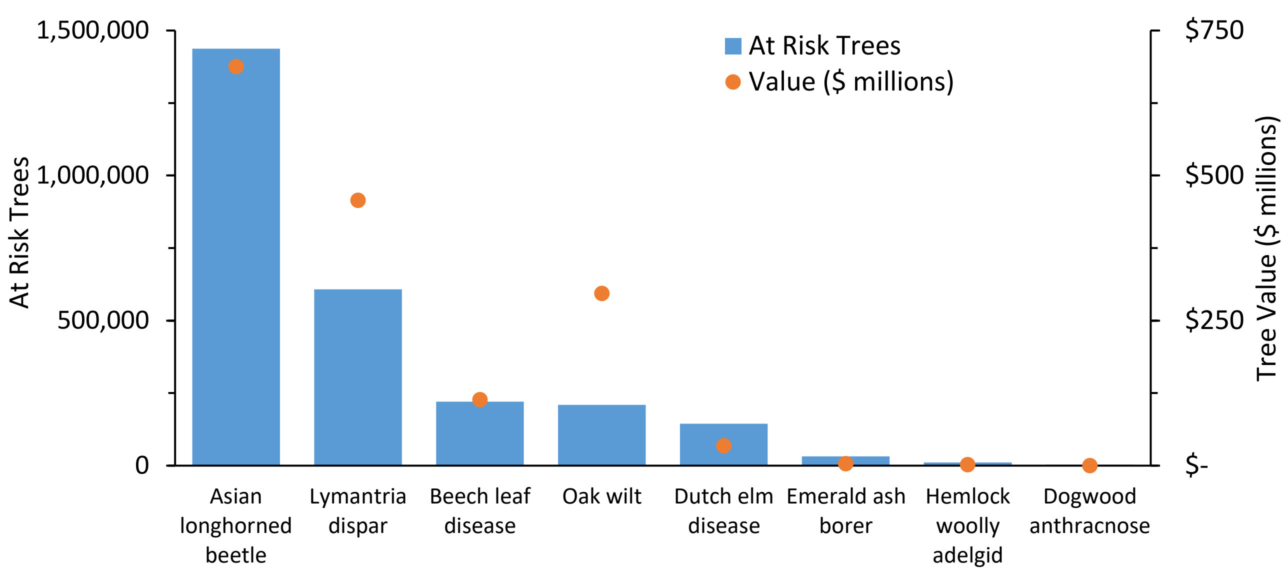


Figure 10. Current and potential forest health pests or pathogens in or near Cleveland Metroparks.

Table 5. Average size, carbon storage, sequestration and predicted climate tolerance for all species measured in 2021. Climate tolerance projections are specific to the 1x1 degree gird summary for 41N, 81W.

Common Name	Scientific Name	Average Size (cm)	Number of trees assessed	Average Carbon Storage (kg)	Average Gross Carbon Sequestration (kg/yr)	Climate tolerance projections
Boxelder	*Acer negundo*	20.5	46	119.8	4.6	Good
Black maple	*Acer nigrum*	21.2	51	168.9	5.2	Lost-Poor
Norway maple	*Acer platanoides*	17.8	8	101.1	5.2	N/a
Red maple	*Acer rubrum*	27.6	271	334.0	10.3	Good
Silver maple	*Acer saccharinum*	29.5	15	280.4	9.4	Very Good
Sugar maple	*Acer saccharum*	20.3	310	182.5	3.9	Good-Very Good
Ohio buckeye	*Aesculus glabra*	21.3	8	287.4	10.5	*Very Poor-Poor
Yellow birch	*Betula alleghaniensis*	17.8	1	77.9	2.5	Very Poor
American hornbeam	*Carpinus caroliniana*	11.7	3	30.9	1.5	Very Poor
Bitternut hickory	*Carya cordiformis*	31.7	27	298.8	5.2	Good
Shagbark hickory	*Carya ovata*	27.3	23	201.0	3.9	Fair
Southern catalpa	*Catalpa bignonioides*	17.6	2	38.0	2.1	N/a
Flowering dogwood	*Cornus florida*	11.5	2	28.7	1.9	Lost
Hawthorn	*Cretagus spp.*	14.3	13	42.7	1.4	N/a
American beech	*Fagus grandifolia*	25.1	135	360.8	4.9	Poor
Green ash	*Fraxinus pennsylvanica*	15.8	20	48.9	1.9	Good
Black walnut	*Juglans nigra*	43.9	24	531.2	14.4	Fair
Sweetgum	*Liquidambar styraciflua*	10.4	1	10.2	0.9	Good
Tulip tree	*Liriodendron tulipifera*	41.4	63	595.1	16.7	Fair-Good
Cucumber magnolia	*Magnolia acuminata*	57.8	2	1443.2	27.3	Very Poor
White mulberry	*Morus alba*	11	1	14.2	0.8	N/a
Black tupelo	*Nyssa sylvatica*	20.4	8	153.9	3.9	Good-Very Good
American hophornbeam	*Ostrya virginiana*	13.1	14	29.0	1.2	Good
Austrian pine	*Pinus nigra*	31.0	49	143.8	4.0	N/a
Eastern white pine	*Pinus strobus*	47.0	8	388.4	13.0	Very Poor
American sycamore	*Platanus occidentalis*	57.9	11	818.7	21.3	Fair
Eastern cottonwood	*Populus deltoides*	66.0	36	1833.5	35.0	Poor
Sweet cherry	*Prunus avium*	15.2	5	61.5	3.2	N/a
Black cherry	*Prunus serotina*	25.5	65	252.6	9.0	Fair

Table 5 (continued)

Pear species	*Pyrus spp.*	14.5	3	49.6	1.7	N/a
White oak	*Quercus alba*	36.5	24	569.4	9.4	Very Good
Chinkapin oak	*Quercus muehlenbergii*	40.4	1	499.7	20.4	Good
Pin oak	*Quercus palustris*	41.9	19	563.7	17.4	Poor
Northern red oak	*Quercus rubra*	39.8	77	720.1	15.0	Very Good
Black oak	*Quercus velutina*	39.0	3	841.7	21.6	Good
Black locust	*Robinia pseudoacacia*	31.7	8	234.7	9.7	Very good
Crack willow	*Salix fragilis*	46.3	9	584.3	17.3	N/a
Sassafras	*Sassafras albidum*	26.8	5	368.2	7.8	Good-Very Good
American basswood	*Tilia americana*	29.3	20	181.0	4.8	Poor
Eastern hemlock	*Tsuga canadensis*	13.8	7	27.4	1.0	Lost-Very Poor
American elm	*Ulmus americana*	19.6	68	90.3	4.7	Fair-Good
Slippery elm	*Ulmus rubra*	23.7	19	224.8	7.2	Very Poor-Poor

*Ohio buckeye climate tolerance projection is based on the Lake Erie Allegheny Plateau region.

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