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DECADAL REEVALUATION OF SUGAR MAPLE DIEBACK ETIOLOGY ACROSS THE UPPER GREAT LAKES REGION

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By

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Table of Contents

List of Figures

Appendix – Additional Materials

List of Tables

Appendix – Additional Materials

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Abstract

Sugar maple (*Acer saccharum*) is a foundational tree species in northern hardwood forests of the United States and Canada. Though previous work has documented areas of substantial stress for this species in eastern North America, increasing reports of crown dieback in the Upper Great Lake states through the early 2000's highlighted the relative lack of understanding of regional trends and causes. A 120-plot network of maple forest health monitoring sites was established and annually visited across Upper Michigan, northern Wisconsin, and eastern Minnesota between 2009 and 2012 to catalog and understand the regional phenomenon.

Results from the project's initial years (Phase I) determined a significant correlation between sugar maple dieback and interrelated forest floor conditions (earthworm impact rating, soil carbon, herbaceous cover, and soil manganese) known to be influenced by exotic earthworms.

Ten years later, the network was resurveyed in 2021 and 2022 (Phase II). Sampling methods replicated prior methodology and added additional damaging agent signs and symptoms, including ungulate browse, lecanium species (*Parthenolecanium* spp.) and cottony maple scale (*Pulvinaria innumerabilis*), as well as more detailed sampling of earthworm species abundance, diversity, and impact.

Resurvey data suggest earthworm impact rating is still significantly correlated with sugar maple dieback across the network. Sugar maple dieback is ongoing and is 15.4% per tree averaged at the plot level (compared with 12.4% ten years ago) across the study area, though it is highly variable. Also, average canopy dieback for residual trees in harvest treatments worsened over the intervening years. Scale are not apparently linked to dieback condition. Future uses for the data include amendment of risk maps that land managers can incorporate into treatment plans using key correlates of decreased sugar maple health and vigor.

1 Introduction

Tree decline phenomena are broad disease conceptions that capture many underlying biotic and abiotic stressors as defined variously by different authors (Bal et al., 2015; Manion and Lachance 1992; Neely and Manion 1991). Forest or tree declines are generally defined as episodes where: a) a pattern of measurable and premature loss of health, growth, successful regeneration, and/or vigor outside of senescence within a given forested area and among a particular species or set of species is observed; and b) there is no single, obvious agent of that decline (i.e., major pest outbreak or severe drought) (Houston 1999; Jenkins et al., 1999; Sinclair and Hudler 1988). Rather, these phenomena tend to afflict species that are caught at the nexus of multiple forest health stressors. The concept has been further refined to consider triggers that fall roughly into three categories: predisposing, inciting, and contributing as in decline and death spiral concept proposed by Paul Manion (Manion and Lachance 1992; Neely and Manion 1991).

Canopy dieback (Figure 1), though frequently referred to interchangeably with tree ‘decline,’ is a symptom of a broad variety of tree-stressing events that cause the leaves, fine twigs, and small branches of the canopy to die from the tip downwards and can, in some instances, help diagnose a decline (Neely and Manion 1991). It is used as a tree and stand diagnostic measure, that can be assessed from the ground by trained technicians visually estimating percentages of the live crown where recent dieback of leaves and fine twigs has occurred from the top and outermost portions of the tree downwards. This dieback can be temporary, in response to a specific event, such as drought or defoliation, or can linger and worsen in response to conditions that are not improved (Schomaker et al., 2007).

Sugar maple (*Acer saccharum* Marsh) is a foundational tree species throughout the northern hardwood forests of the United States and Canada, fulfilling vital ecological, economic, and social roles (Ellison 2019; Ellison et al., 2005; Horsley et al., 2002; Houston 1999; Long et al., 2009). In the Upper Great Lakes region, this species was abundant prior to European settlement, frequently exceeding 50% stand basal area (Whitney 1999). Now, fire regime, land use, and forest management changes in the wake of European settlement have, in most cases, only increased sugar maple dominance, homogenizing stands and making them potentially less resilient to climate change and pathogens (Burton et al., 2009; Schulte et al., 2007; Whitney 1999).

Figure 1. Example of canopy dieback on codominant sugar maple in a forest health research plot in 2022 (Houghton County, MI).

Sugar maple declines in the past 60 years have received the most focus in the species' eastern extent, with individual episodes attributed to site- and region-specific variables (Cleavitt et al., 2018; Horsley and Long 1999). Many of the decline studies throughout the Appalachian Mountains found calcium deficiency to be a predisposing factor, which stressed sugar maple, either reducing its vigor and growth directly and/or limiting its ability to fight off infection and recover from wounding (Bailey et al., 2005; Bailey et al., 2004; Bal et al., 2015; Halman et al., 2013; Long et al., 2009; Schaberg et al., 2006). Key inciting factors implicated in other declines include acute and chronic defoliation events (Houston 1999; Wink and Allen 1999); climatic variations, extreme weather, and drought stress (Auclair et al., 1996; Auclair et al., 2010; Payette et al., 1996); and management and site selection (Auclair et al., 2010; Horsley et al., 2002; St Clair and Lynch 2005; Whitney 1999).

Though it may appear that the contributing factors are the agent solely responsible for tree mortality, their contribution to mortality is dependent on the stresses the tree has undergone previously. Healthy sugar maples have robust defenses against fungal pathogens, pests, and wounding (Huggett et al., 2007; Schaberg et al., 2006). Trees under repeated prior stress from climatic events (Bauce and Allen 1991), physical damage from pests (Patton et al., 2021) harvest activities (Hesterberg 1957), and nutrient deficiencies (Long et al., 2009) or toxicities (Schier and McQuattie 2000) have diminished defenses and are more susceptible to attack. It is also the case that multiple factors may exacerbate one another – for example, calcium-deficient sugar maple may have difficulty closing or controlling stomatal openings, leading to greater moisture loss and drought stress during drier periods (Ridolfi et al., 1994).

Sugar maple declines in the midwestern United States have received relatively less attention, with a handful of studies in the prior 50 years suggesting climatic anomalies and harvesting practices as causal agents in specific episodes (Horsley and Long 1999; Millers et al., 1989), but there is a general paucity of decline-like phenomena described for this region's maple-dominated forests. Studying the forests of the Upper Great Lakes, with its unique land use history and broad swaths of contiguous forest can give useful insights the broader management questions facing sugar maple throughout North America.

Phase I: 2009 – 2012

Accounts from regional foresters and state forest health reporting suggested a widespread dieback episode was unfolding in the Upper Great Lakes region during the mid- to late-2000's (Michigan DNR 2009; Michigan DNR 2010; Michigan DNR 2012). These accounts, as well as documented cases of defoliation, and abiotic and biotic impacts (Minnesota DNR 2001; Wisconsin DNR 2006; Wisconsin DNR 2008) led to the establishment of a network of forest health monitoring sites throughout the western Upper Peninsula of Michigan, northeast Wisconsin, and northeast Minnesota to quantify the dieback and identify common mechanisms that might be responsible for the observed symptoms (Bal et al., 2018).

The study identified exotic earthworms and their associated forest floor and nutrient cycle impacts as key common variables throughout regional dieback episodes (Bal et al., 2018). Depending on cover, soil type, and community assemblages, earthworms are capable of rapidly breaking down the thick litter layer of northern deciduous forests (Figure 2) and mixing the organic matter with the upper horizons of mineral soil and increasing soil bulk density (contrary to gardening conventional wisdom) (Gorres et al., 2017; Hale 2007). These relatively rapid changes can lead to resource unavailability and leaching from the system, and greater fine root stress from moisture and temperature extrema less moderated by an insulating litter layer (Frelich et al., 2006).

The results of Phase I of this study of annual surveys from 2009-2012 found a mean plot canopy dieback of 12.5% for all live sugar maple, though this number was variable across plots and study years. Phase I findings also indicated that ownership (plots were stratified public and private), and by extension varied management, was not apparently a factor affecting canopy dieback. In addition to the forest floor impact rating system being linked to dieback, it was also found that other earthworm-related metrics were correlated, including increased soil carbon, decreased herbaceous cover, and elevated soil manganese.

Figure 2. Example of heavy exotic earthworm impacts on the forest floor. Mineral soil is bare, with numerous middens and copious castings present and less-preferred litter of oak trees more abundant ((Côté and Fyles 1994), Houghton County, MI).

Phase II: 2021 – 2022

Ten years after those initial findings, with ongoing reports of dieback from forest managers, Phase II of the study aimed to resurvey the original plots to characterize trends and possible related additional variables.

Phase I quantified forest floor impacts in order to describe surface conditions but, given varied feeding and habitation traits of various invasive earthworm functional groups, Phase II was designed to dig deeper into functional groups present and species abundance (Bohlen et al., 2004; Hale 2007). Three earthworm functional groups are delineated to roughly describe where species live and how they feed. Epigeic worms live at or near the surface and feed on the litter layer; endogeic worms feed and live in the mineral soil, mixing layers there; and anecic worms construct deep, permanent middens, connecting the mineral soil where they live to the surface where they feed (Bouché 1977; Huang et al., 2020). While any exotic worms are an indication of invasion, certain populations may be indicative of greater impacts. For example, the common nightcrawler (*Lumbricus terrestris* L.) has been noted to be a key indicator species of advanced earthworm invasion and disturbance (Loss et al., 2013), and efforts to model its occupation of ideal habitat in the region show that it has not yet reached its full potential (Shartell et al., 2013). While certain species and groups may have more profound effects, it has been found that a diversity of functional groups have the greatest impact on litter loss and forest floor conditions (Huang et al., 2020), so information on community composition was deemed valuable to identifying the extent of site colonization.

Additionally, in the years since Phase I, reports in the region of outbreak levels of lecanium scale (*Parthenolecanium* spp.) (Michigan DNR 2015; Michigan DNR 2016; Michigan DNR 2017; Wisconsin DNR 2015; Wisconsin DNR 2016) led to the inclusion of sampling for this potentially damaging pest to assess its role in regional dieback. Scale insects attach to twigs of trees and suck nutrient-rich sap. In sufficient quantities, scale may harm trees directly (especially those already under stress) by reducing stocks of carbohydrates (Camacho and Chong 2015; Washburn et al., 1985). Additionally, the insects excrete sugar-rich "honeydew," which rains down on leaves below the feeding site (Frank et al., 2013; Fulcher et al., 2013). Leaves covered in this substance can host on their surfaces a variety of sooty mold fungi in the *Capnodiaceae* family, which are not themselves parasitic to trees, but which can reduce photosynthetic efficiency through the blackening of the mold film (Fulcher et al., 2013). Given the potential for injury in stands of sugar maple already stressed by site conditions or exotic earthworm impacts, efforts were undertaken to assess the degree of scale occurrence.

Phase II also investigated ungulate browse impacts to assess what role white-tailed deer (*Odocoileus virginianus* Zimmerman) and moose (*Alces alces* L.) may play. Considering maple decline, a key component is regeneration failure, an aspect deer have been linked with in studies throughout the Lake States (Matonis et al., 2011; Patton et al., 2021). Also, deer have been shown to interact with and potentially facilitate earthworm and non-native plant invasion, further exacerbating site stress (Dávalos et al., 2015; Dávalos et al., 2015; Fisichelli et al., 2013)

With these new areas of investigation considered, Phase II was designed to revisit the established network and: 1) characterize current sugar maple dieback levels 2) compare dieback levels during Phases I and II to assess change and trends over the past decade and 3) investigate potential new factors, including scale insects and ungulate browse. On the basis of local observation (Michigan DNR 2020; Wisconsin DNR 2014) we expected that the dieback continued at similar levels observed before, with high variability across the landscape and that associated earthworm impacts had remained similar or increased as ongoing invasions have intensified at certain sites.

2 Methods

2.1 Study area

In Phase II, the 120-plot forest health monitoring network (Figure 3) was revisited in the summers of 2021 and 2022 to compare results from a decade prior. The network was initially established with 60 plots in 2009, expanded to 120 in 2010, and surveyed annually through 2012. The study area spreads across the western Upper Peninsula of Michigan, northern Wisconsin, and northeastern Minnesota (Bal et al., 2018). The plots were stratified evenly between private and public forested lands (to assess varying management impacts) and selected with assistance from the managing foresters to identify proximate stands that were apparently more and less affected by sugar maple crown dieback at the time. A list of measurements collected or calculated throughout the entire study has been logged for continuity (Supplemental Table 1). Original data sheets are stored in a locked lab at Michigan Technological University, with data and analysis backed up in duplicate and shared via password-protected Google Drive with project team members for ongoing research and future field work.

Surveys in both Phases were conducted after full leaf-out (roughly the middle of June in this region) and complete by the end of August each year. A total of 119 of the original 120 plots were assessed. Specific trees originally tagged in plot 71 were not located during Phase II and the plot was re-established near the original plot's coordinates in the same stand. As such, its data was not included in comparative analysis with Phase I but was used for descriptive purposes.

The study area ranges from 45.72° N at the furthest south in the Chequamegon-Nicolet National Forest, to 89.52° W at the eastern extent in the Hiawatha National Forest, to 48.44° N and 91.04° W at the furthest north and west, respectively, in the Superior National Forest. These latter plots represent some of western and northernmost populations within sugar maple's naturally occurring range (Godman et al., 1990). The humid continental climate at the study sites is highly variable, with distance from Lake Superior playing a major role in annual temperatures and precipitation. A thorough description of established plot physiographic characteristics can be found in the original study (Bal et al., 2018). Plots were, on average, 29 km from Lake Superior and located at 452 m above sea level and were established a minimum of 40 m from the nearest road or trail. Pooling data from 12 weather stations within the study area, the U.S. Climate Normals for the 30-year period ending in 2010 show an average annual rainfall of 78.0 cm and snowfall of 3.42 m, (with snowfall minimum of 1.0 m and maximum of 5.3 m) and an average annual minimum temperature of -0.5°C and maximum of 9.3°C (climate data summarized from nearby NOAA weather stations National Oceanic Atmospheric Administration, National Climatic Data Center, Ashville, NC. http://www.ncdc.noaa.gov/ (accessed October 2022)). Drought effects were considered using district level data from NW Michigan, NE Wisconsin, and NE Minnesota for monthly Palmer Drought Severity Index data going back to 1999 (Supplemental Figure 1).

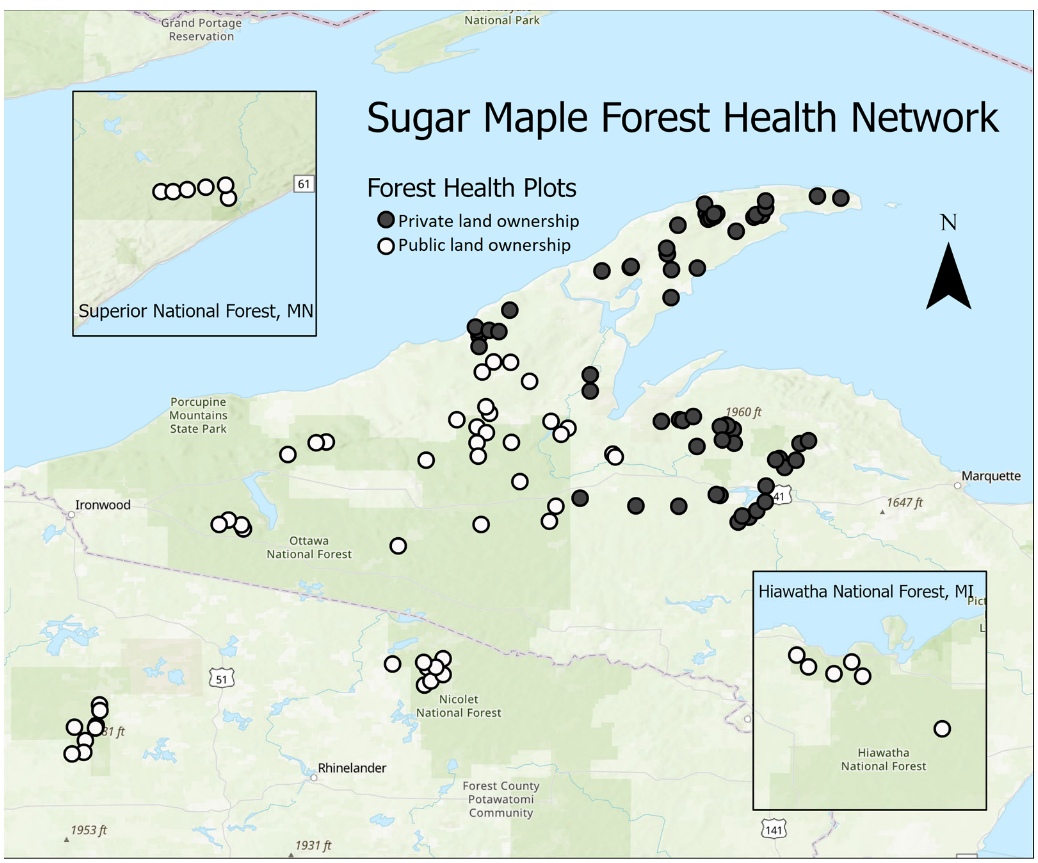

Figure 3. Location of 120 (originally established 2010) and current 119 (revisited 2021-22) maple dieback forest health plots across northwest Michigan, northeast Wisconsin, and northeast Minnesota.

2.2 Overstory measurements

The survey design included 0.04 ha circular plots (11.3 m radius) to assess overstory vegetation (Supplemental Figure 2). Plots were initially established to include at least ten sugar maple stems greater than 10 cm diameter at breast height (DBH). Plot descriptive data were recorded at first entry, including: slope, aspect, and landscape position. Detailed Phase I (not referred to by 'Phase' name until this study) methods are reported in Bal et al., (2018).

As in prior surveys, standard forest health monitoring measurements were collected according to protocol (U.S. Department of Agriculture Forest Service 1999) that included, for each tree >10 cm DBH,: species, diameter, height, canopy assessments (including canopy position, dieback, density, transparency, light exposure and uncompacted live crown ratio), and bole evaluation. Dieback was quantified for each tree, with a percentage of that tree's whole canopy determined to be recently dead. For indications of individual tree health, rates of dieback on that tree can be referenced between survey years by identifying the tree's unique tag. For study-wide analysis, each tree's dieback is averaged to give a plot-wide dieback percentage that indicates how much of each tree's canopy, on average, has died back within a given plot. Items of note were wounds and scarring (cause noted if possible, e.g. harvest damage), cankers (*Nectria and Eutypella* spp.), sugar maple borer (*Glycobius speciosus* Say), and any other visible signs of damage or reduced vigor. Given the potentially subjective nature of crown assessments, all field technicians were trained (for two weeks at minimum) and later measurements were validated for quality control to assure accuracy and consistency in ratings of dieback levels.

To accurately capture changing average rates of canopy dieback, tree vigor and death were also captured. Mortality was noted and included in plot data, however, trees that were dead at plot establishment were tallied but excluded from average figures tabulated in following years to avoid inflating mortality rates. Trees that were harvested or otherwise missing between evaluations were also not included in average figures of mortality or dieback. Ten percent average plot sugar maple canopy dieback was used as a threshold, above which plots were considered to be unhealthy (Bal et al., 2015; Ouimet et al., 1995)

To test the effects of the moderate severity harvesting, individual tagged SM tree dieback was compared between 2012 (the last year of Phase I) and the Phase II values for that same tree. Only trees that were alive in 2012 were included and, where tags could not be matched no comparison was made. The resulting individual tree dieback changes were averaged at the plot level to determine if residual trees benefitted from release as a result of the harvest treatment.

2.3 Understory and subplot measurements

Within the overstory plot, three nested subplots were established 5 m from plot center to the north, southeast, and southwest. At each subplot, a 1 m^2 quadrat was placed at the center to measure percent of herbaceous cover by species. The next larger subplot was 0.0004 ha (1.1 m radius) in which seedlings were measured (trees smaller than 1.27 cm diameter and below 1.37 m height). Finally, the largest of the subplots, 0.004 ha (3.6 m radius), was used to measure saplings between 1.27 and 9.9 cm DBH.

Also, in this largest subplot, browse damage was assessed on all woody plants using a 5-point scale where: 1 signifies no browse damage observed; 2 is lightly browsed, with fewer than half of the stems exhibiting browse; 3 is moderately browsed where greater than half of the stems show browse; 4 is heavily browsed with noticeable hedging but stems still exceed 15 cm in height and; 5 severely browsed with substantial hedging and stems cropped to less than 15 cm in height from deCelesta, et al (2015). At each subplot, a 20 cm soil core was extracted to qualitatively assess soil texture and describe horizons present in the field (detailed soil analysis was conducted at each plot during initial survey but not in Phase II). For efficiency, the number of subplots was changed from 4 to 3 between Phases I and II, which meant that a direct statistical comparison was not done on certain herbaceous metrics. Descriptive analyses were conducted to provide context to other findings.

At the plot level, the forest floor was assessed for overall earthworm impact using a 5-point scale from most (1) to least severe (5) (Supplemental Table 2). This type of rapid and efficient evaluation has been shown to reliably gauge actual earthworm colonization, as well as species and genera of greater concern (Loss et al., 2013). This assessment was conducted around each subplot, ranging outwards roughly 4 meters in all directions to capture the variation of microtopography, forest floor cover, and disturbance, as well as recognizing earthworm's capacity to move within the plot. This yielded an averaged plot-wide assessment based on roughly 1/3 of the area in both Phases I and II.

In Phase II only, at the edges of the plot to the north, southeast, and southwest, 0.09 m^2 subplots were established for timed (10 minutes for each subplot) earthworm extraction. The surface was prepared by removing any litter, humus, or other organic debris until bare soil was exposed. The whole area was then treated with a mixed mustard solution (3.79 l of water and 79 ml of mustard powder), which is irritating to earthworms and causes them to surface as the solution percolates down through the soil (Hale 2007). The mixture was distributed in halves, first at the beginning of observation and collection, and again after 5 minutes once the initial application has soaked into the soil. Sloped surfaces were avoided as much as possible to prevent runoff of the solution. Throughout the 10 minutes, surfacing earthworms were observed and collected for identification and measurement (Figure 4). Earthworms were transported in vials of ethanol from the field and identified promptly in the lab (before samples could begin breaking down) using a dissecting scope and professional field guides (Hale 2007; NatureWatch 2014). In some cases, juvenile samples, such as *Lumbricus,* could only realistically be identified to genus without the mature sex organs that facilitate identification to species. These were grouped in a separate category as *Lumbricus* juvenile species when analyzing functional groups because this genus includes species in multiple groups (Hale 2007). Extractive sampling was not conducted during Phase I but was added to determine community composition of different introduced species and their impacts to ecological niches.

Figure 4. *Lumbricus* spp. juvenile after exiting the soil during application of mustard solution, 2022 (Houghton County, MI).

Additionally, each plot was measured for presence and abundance of scale insects, chiefly lecanium species (*Parthenolecanium* spp.) and cottony maple scale (*Pulvinaria innumerabilis*) (Figure 5). Outbreaks of the former were observed to reach potentially damaging levels in Wisconsin during the 2010's (Wisconsin DNR 2015). Technicians used an extendable pole saw to cut down a midstory branch (5-8 cm in diameter and at least 2 m in length) from two different dominant or codominant sugar maples assessed in the overstory plot. The saw was cleaned with a bleach solution between each use. Scale presence or absence, apparent species, and quantity were captured from visually assessing the entire sampled branch, and specimens were retained for verification. Other signs of pests, pathogens, or damage were also noted on these branches for qualitative assessment.

Figure 5. Cottony maple scale (*Pulvinaria innumerabilis*) at left, (shown parasitized with fungal structures emergent) and lecanium scale (*Parthenolecanium* spp.) at right on sugar maple twigs collected in August 2022 (Houghton County, MI).

2.4 Data analysis

Overstory data were summarized to provide average plot sugar maple dieback percentages (excluding initially dead stems in Phase I) as a comparative value through the course of the study. Changes in stand composition, basal area, and species composition were all analyzed to capture the shifting regional community.

Except for overstory measures explicitly focused on harvest dynamics (network wide sugar maple basal area, for example), sugar maple canopy measurements were analyzed excluding plots lacking overstory sugar maple due to harvests between Phases. Trees > 10 cm DBH but categorized as canopy class 'understory' were also excluded due to naturally varying dieback and mortality dynamics among potentially suppressed individuals (Allen et al., 1999). For dieback, trees that died completely between survey years were counted as 100% dieback for the first survey year in which they were tallied as dead (excluding all harvested trees).

Phase I represents 4 years (2009-2012), with data collection occurring on 60, 120, 119, and 119 plots, chronologically. Phase II represents one full survey of the network split between the 2021 and 2022 summer seasons. In the case of the principle response variable, sugar maple canopy dieback, specific events will remain evident and distinguishable for around 3 years (Manion and Lachance 1992). Likewise, the temporal scale of earthworm impacts, while dramatic in terms of soil processes, spreads over years and decades (Resner et al., 2015). As such, while potential interannual changes may be anticipated, it was determined the benefits of more intensive study methods outweighed these shifts.

Because sugar maple was the species of principle interest in the study and because it constituted the vast majority of stems and basal area, harvest categorization was carried out on the basis of this species alone. The data were categorized by percentage of 2012 sugar maple basal area removed between Phase I and II, with the categories classed as "none" (0%), "moderate" (<50%), and "severe" (>50%). Four plots with apparent management entry but no sugar maples removed were excluded from this analysis to avoid the potential effects of residual operational impacts (bole or root damage, soil disturbance). Plot centers were not permanently monumented, however individual trees from Phase I were identified by tag number and stem map, with cut stumps receiving a harvest dead tree code to disambiguate them from the other codes (1-8) for mortality. Complete data is not available for past management of the units that contain the research plots and, even where available, the prescriptions that were carried out over stands may not be clearly represented in the size of the .04 ha plots. As such, the plots were segregated by the apparent severity of harvest disturbance to sugar maples. Though the silvicultural systems in use are likely some versions of single and group tree selection methods on one end of severity, and clear cuts and shelterwoods on the other, this method does not identify or suggest which systems were deployed. A histogram of sugar maple basal area removed by plot showed that harvests were roughly evenly distributed through 50% removal of 2012 sugar maple basal area, after which the data became sparser and contained more variation (Supplemental Figure 3). Using this visual categorization of the data led to the three, more homogenous groups of relativized harvest severity throughout the study area.

For analysis of regeneration a definition of sugar maple stocking is adapted from the Silviculture of Allegheny Hardwoods (SILVAH) decision-support guide (Brose et al., 2008) conveniently developed in a North American mixed hardwood system to help systematize management on the basis of stocking. To determine if each of the 3 subplots is considered stocked, sugar maple regeneration counts are separated into 3 categories: seedlings (as already described above); saplings > 1.27 cm and < 5.08 cm at breast height; and saplings <9.9 cm at breast height. Then, each category is relativized by area to the 1/1000 ha plot used in the SILVAH system. Stocking threshold numbers are derived from SILVAH's 'other desirable' species category, which explicitly includes maple species. Each size category's stocking threshold is further adjusted on the basis of the plots' rounded average browse rating (Supplemental Table 3). SILVAH uses a slightly differently worded browse impact rating, but it scales in severity identically with this study's scale and was treated analogously. Through this process, plots are determined to be 0%, 33%, 66%, or 100% stocked. Given the study's focus on sugar maple and the preponderance of that species across all plots, other component species were not considered for stocking. Regeneration failure is defined as plots that have 0% stocking of sugar maple regeneration. And, for the purposes of investigating potential decline the study uses two criteria. Plots must both exceed 10% average sugar maple canopy dieback and exhibit apparent regeneration failure, indicated by 0% sugar maple stocking.

Because earthworm impact rating is averaged for each plot between the three subplots, non-integer values are possible. So, to conduct factorial analysis earthworm ratings were grouped as 4 categories between the 5 points on the scale, with "severe" corresponding to values between 1 and 2, "substantial" between 2 and 3, "moderate" between 3 and 4, and "minimal" between 4 and 5.

To evaluate hypothesized relationships, Pearson's correlation coefficients were calculated on previously correlated factors (earthworm-related impacts) or those suspected of being related from the literature (management, browse, geography, pest incidence) and data exploration (all tests of significance were performed to $\alpha = 0.05$). To test for differences within variables by grouping, one-way ANOVA tests were used. These tests were run using the statistical software package Minitab (Minitab, LLC, version 21.2). ArcGIS Pro (Esri, Inc., version 2.6.4) was used to explore and visualize the data spatially.

3 Results

3.1 Canopy changes over time

In Phase II, a total of 2,173 live trees were surveyed, 1,586 (73%) of which were sugar maple, compared with 2,827 and 2,120 (75%) in Phase I. Other substantial component species assessed include, in descending abundance: 8% red maple (*Acer rubrum* L.); 3% balsam fir (*Abies balsamea* (L.) Mill.); 3% ironwood (*Ostrya virginiana* Koch); 2% yellow birch (*Betula alleghaniensis* Britton); 2% American basswood (*Tilia Americana* L.); 2% northern red oak (*Quercus rubra* L.); as well as other minor hardwood and conifer components such as American basswood (*Tilia americana* L.), eastern white pine (*Pinus stobus* L.) aspen species (*Populus* spp.) and spruce species (*Picea* spp.). Results of the overstory analysis focus on sugar maple unless otherwise indicated. Suppressed sugar maple trees were excluded (on the basis of crown classification numbers used in FIA protocol referenced in methods) from canopy summarization and analysis, as were plots where no sugar maple remained in the overstory (due to harvest activity, n = 7).

Descriptive summaries of plot average characteristics were prepared for both Phases (Table 1). A notable disturbance occurring between Phases I and II was active management, which occured on 42 (35%) plots. Plots established in Phase I were not set up in clear cuts or within stands harvested within the prior two years. Harvest details are broken out in section 3.2, focusing on the 38 plots in which sugar maple were harvested at varying severity and the remaining 76 on which no apparent management took place within the last decade. The effect of this disturbance is reflected in a reduction of overall basal area, trees per hectare, and canopy cover.

Elevated sugar maple canopy dieback levels persist, though they remain highly variable on the landscape (for the purposes of this study, plot averages of individual sugar maple canopy dieback exceeding 10% were considered unhealthy). Compared with the Phase I average dieback of 12.4% (SE = 0.5), Phase II averages 15.4% (SE 1.3), though the median value is only 11.5% with 44 (40%) of plots averaging less than 10% dieback.

Network-wide averages for sugar and red maple canopy dieback trend upwards and downwards together (Figure 6; Supplemental Figure 4 shows mean dieback % values with 95% confidence intervals and median values). Average % sugar maple dieback values for each survey year were correlated with each other year across the whole study ($P<0.001$ for each of the pairwise relationships; Supplemental Figure 5). No other component species were present in the network in stem numbers greater than 5% to be included in the graph, however when pooling all non-maple broadleaf species, average dieback was 18.1% (SE=2.7 n=71 plots).

Table 1. Plot characteristics for Phases I and II of a network of 118 plots (120 originally) established in 2009, assessed annually 2010-12, and resurveyed in 2021-2 to monitor sugar maple (SM) health and assess dieback and potential decline. Plot number represented is lower where no overstory sugar maple remained after harvest. All Phase I results are from the 2011 survey year except for % herbaceous cover recorded in 2010.

	Phase I[a]		**Phase II[b]**	
	Mean	**Median**	**Mean**	**Median**
Plot mean values for live overstory trees				
total basal area m^2 ha^{-1}	26.2 (0.8)	26.9	23 (1.1)	24.0
sugar maple basal area m^2 ha^{-1}	18.8 (0.7)	19.1	16.8 (0.9)	16.9
total trees per hectare (x10)	52.5 (1.7)	49.4	44.3 (2.0)	42.0
SM trees per hectare (x10)	39.4 (1.4)	37.1	33 (1.6)	33.4
SM DBH (cm)	23.3 (0.4)	22.8	23.7 (0.4)	23.2
SM saplings per hectare (x100)	4.1 (0.5)	3.1	11.5 (1.8)	4.5
SM seedlings per hectare (x10,000)	4.3 (0.4)	3.2	15.5 (2.1)	6.0
SM with borer (%)	28.4 (1.7)	25.7	15.2 (1.7)	7.7
SM with canker (%)	10.3 (0.9)	8.0	4.9 (0.9)	0.0
Plot mean values for sugar maple canopy				
crown dieback (%)	16.4 (0.9)	14.1	15.4 (1.3)	11.5
crown transparency (%)	52.2 (0.5)	53.0	42.2 (0.7)	40.0
crown density (%)	45.4 (0.6)	45.4	53.6 (0.9)	55.7
uncompacted live crown ratio (%)	46.4 (0.6)	45.3	46.3 (0.8)	45.6
crown light exposure (0 - 5 sides)	1.5 (0.1)	1.3	2.3 (0.1)	2.1
Plot mean values				
total canopy cover (%)	85.8 (1.8)	91.7	73.9 (2.2)	83.3
earthworm impact rating (1-5, 1=severe)	3.1 (0.1)	3.0	3.1 (0.1)	3.0
ungulate browse rating (1-5, 5=severe)	-	-	2.8 (0.1)	2.7
herbaceous cover (%)	22.1 (1.8)	15.7	48.5 (3)	44.5

[a]For all of Phase I metrics, n=119 plots, except for canopy measurements, DBH, and sugar maple borer, where n=118, and earthworm impact rating, where n=111
[b]For all of Phase II metrics, n=118 plots, except for canopy measurements, DBH, and sugar maple borer where n=111

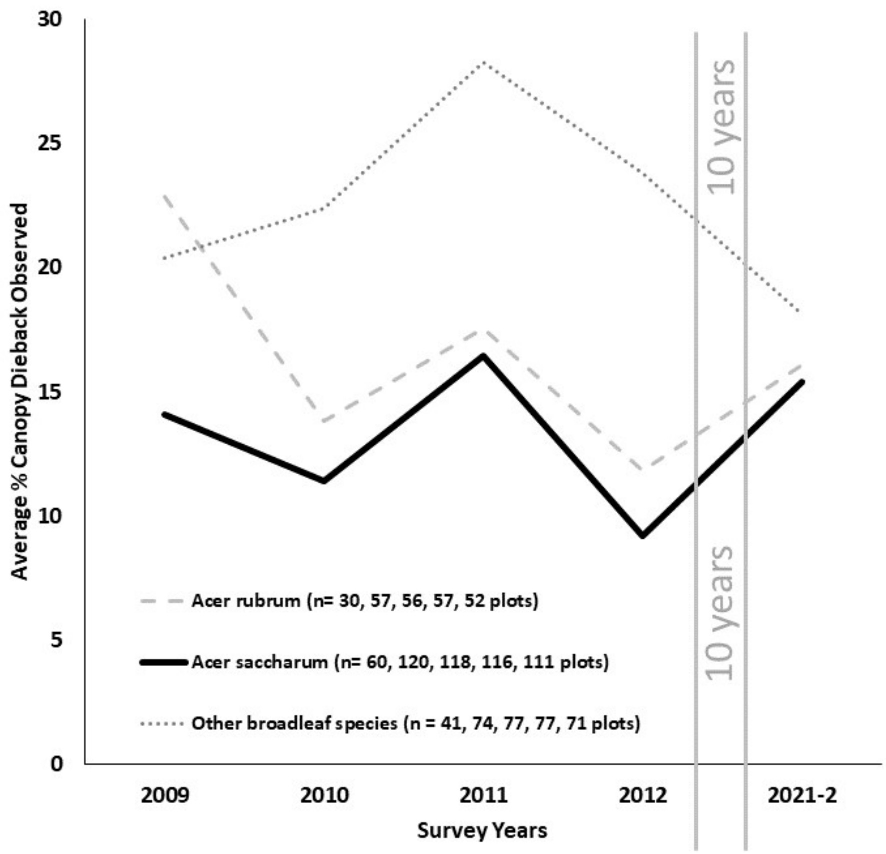

Figure 6. Sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), and other broadleaf species average % canopy dieback by survey year across a maple dieback forest health network in the Upper Great Lakes region. Plot numbers are given per year, with 2021 and 2022 presented as one year.

Comparisons of averages of salient Phase I (all 4 survey years) and Phase II (one full survey of network 2021 and 2022) measures indicate that trees per hectare have significantly decreased ($t(530)= 3.97$, $P < 0.001$) but basal area has not ($t(530) = 1.60$, $P = 0.110$; Table 2). Sugar maple dieback percent ($t(496) = -2.65$, $P = 0.008$) and crown density have both increased ($t(385) = -6.51$, $P < 0.001$), with a decrease in crown transparency (t(385) = 5.29, P < 0.001). Earthworm impacts on the forest floor have significantly intensified (t(459) = 2.99, P = 0.003).

Table 2. Averages, changes, and tests of significance between key sugar maple measures in Phase I versus Phase II in a maple dieback forest health network in the Upper Great Lakes region. Decrease in earthworm impact rating indicates impacts have intensified (on a 1 to 5 scale, with 1 signifying greatest impacts).

	Phase I		**Phase II**		**Difference**	**t-test result**	
	Mean	**SE**	**Mean**	**SE**	**Δ (%)**	**df**	**p-value**
Sugar maple quantities[a]							
trees per hectare (x10)	**39.4**	**0.7**	**33.0**	**1.6**	**-16.2**	**530**	**<0.001**
basal area (m^2 $hectare^{-1}$)	18.2	0.4	16.9	0.9	-7.3	530	0.110
Sugar maple canopy averages							
% canopy dieback[b]	**12.4**	**0.5**	**15.4**	**1.3**	**24.2**	**496**	**0.008**
% canopy transparency[c]	**48.4**	**0.7**	**42.3**	**0.7**	**-12.7**	**385**	**<0.001**
% canopy density[c]	**47.6**	**0.5**	**53.6**	**0.9**	**12.6**	**385**	**<0.001**
Subplot averages[d]							
earthworm impact rating	**3.5**	**0.1**	**3.0**	**0.1**	**-13.0**	**459**	**0.003**

[a] Calculated using all plots except two, which were not resurveyed in Phase II, uses 3 years of data on all plots and 1 year of data on 60 initial plots for Phase I; [b] Calculated on all plots from a, except 7 plots which no longer have sugar maple in the overstory; [c] Calculated on all plots from b except excluding 2012 survey year data from Phase I average due to inconsistency in survey method; [d] calculated on all plots from a, except no values were recorded in 2009 survey year.

To visualize the change in plot average dieback between Phases, each plot was symbolized by a categorical status to represent a trend in dieback within the plot (Figure 7; Supplemental Table 5 details quantities of plots by category and National Forest; Supplemental Figure 6 visualizes the dieback status of plots as they change between Phases). Average plot dieback values were categorized as greater than or equal to 10% and less than 10%. Plots that were above or below 10% in Phase I and remained there in Phase II were categorized as 'stayed unhealthy' (n=40) and 'stayed healthy,' (n=24) respectively. Meanwhile, plots that were below 10% before, and over 10% now and vice versa, were categorized as 'worsened' (n=27) or 'recovered,' (n=20), respectively. A total of 64 plots (58%) remained either consistently above or below the 10% healthy threshold (though their absolute values may have changed). Of the 47 plots that "crossed over," however, 27 (68%) had increased canopy dieback, compared with the remaining 20 (32%) in which dieback decreased.

Three visual clusters of apparent resident and/or heightening dieback can be seen in Superior, Nicolet, and Ottawa National Forests, with the remaining network plots appearing more heterogeneously distributed among the four statuses. A chi-squared test reveals that these proportions are significantly different from an equal distribution, with the majority of the chi-square statistic's value coming from the contribution of more than predicted plots that stayed unhealthy, and fewer than predicted plots that recovered ($\chi 2$=8.10, df=3, p=0.044).

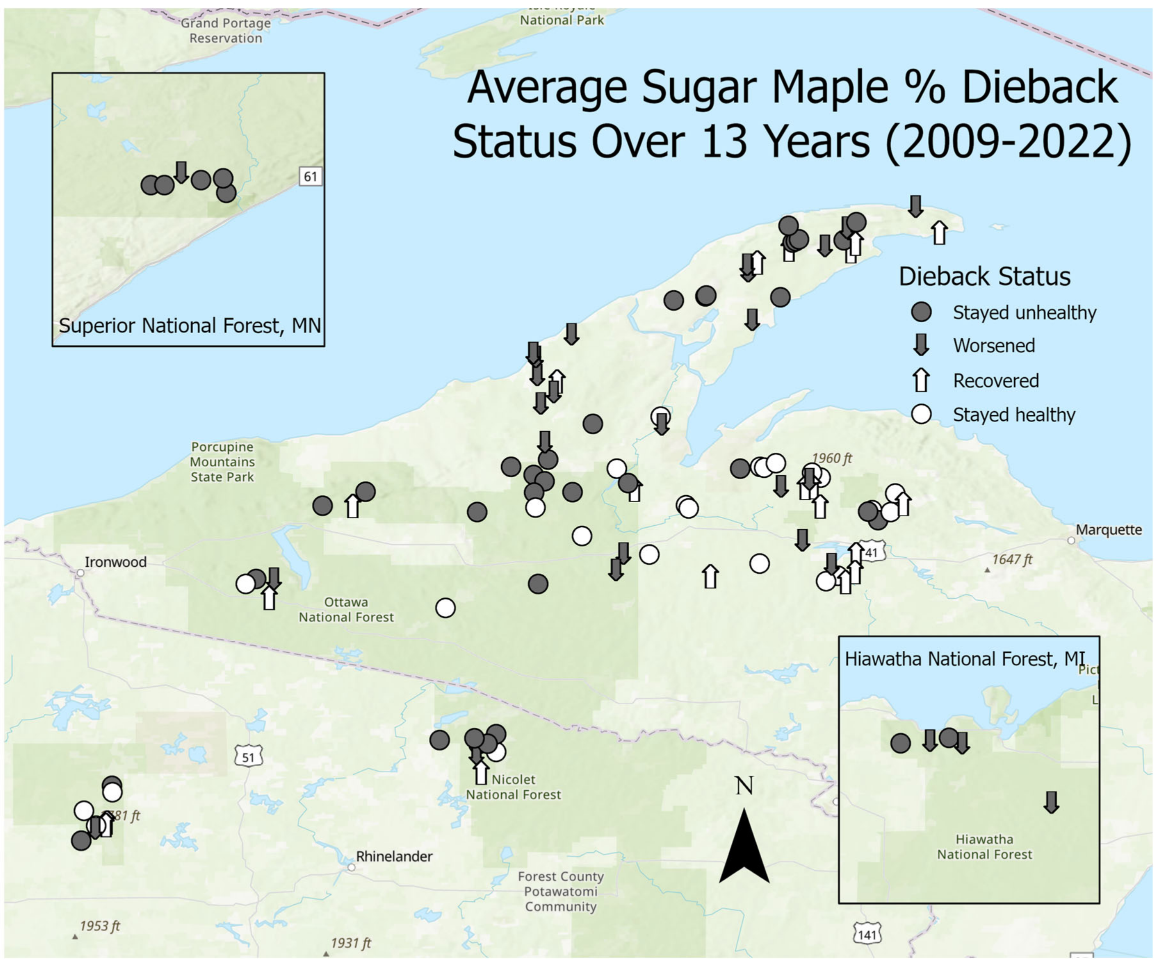

Figure 7. Map of dieback change category between Phases I and II on n=111 plots. Plots were divided into 4 categories based on the possible pairings of Phase I and II average

plot % sugar maple dieback values exceeding 10%. Plots that exceeded 10% in both Phases are categorized, “Stayed unhealthy;” those that exceeded 10% in neither Phase, “Stayed healthy;” those that exceeded 10% in Phase I but not II, “Recovered;” and those that exceeded 10% in II but not I, “Worsened.”

Within dieback status categories, some trends emerge (Table 3). Among both plots that stayed unhealthy and healthy, earthworm impact rating (EIR) increased. The largest increase in EIR however was among those plots that worsened, with plots that recovered being the only category in which EIR did not increase over the past decade. Despite the increase in EIR, plots that stayed healthy had even lower rates of canopy dieback in Phase II than Phase I, but plots that stayed unhealthy show increased rates of dieback. The only noticeable trend among share of plots is that a greater percentage of public plots stayed unhealthy (48% of all public plots), and a smaller percentage recovered (11% of all public plots), whereas private plots are nearly evenly divided among the four statuses.

Table 3. Dieback status categorization of forest health plots (excluding plots without sugar maple in overstory in Phase II, n=111) in Upper Great Lakes region. Plots are categorized 'Stayed unhealthy' if average sugar maple (SM) dieback exceeded 10% in both Phases; ‘Stayed healthy if plots exceeded 10% in neither phase; ‘Recovered’ if plots exceeded 10% in Phase I but not II; and ‘Worsened’ if plots exceeded 10% in Phase II but not I. Average dieback and earthworm impact rating (EIR) are displayed for each of the statuses in Phase I and II.

	Total	Stayed unhealthy	Worsened	Recovered	Stayed healthy
Counts and %					
all plots	111 (100%)	40 (36%)	27 (24%)	20 (18%)	24 (22%)
public	56 (50%)	27 (48%)	12 (21%)	6 (11%)	11 (20%)
private	55 (50%)	13 (24%)	15 (27%)	14 (25%)	13 (24%)
Mean and SE					
Phase I % SM dieback	12.4 (0.5)	18.0 (1.5)	7.7 (0.3)	14.9 (0.9)	6.0 (0.3)
Phase II % SM dieback	15.4 (1.3)	24.9 (2.4)	18.5 (1.8)	6.0 (0.6)	3.9 (0.6)
Phase I EIR	3.5 (0.1)	3.2 (0.2)	4.0 (0.2)	3.3 (0.2)	3.6 (0.1)
Phase II EIR	3.1 (0.1)	2.8 (0.2)	3.2 (0.3)	3.3 (0.4)	3.0 (0.3)

Finally, using the stocking method adapted from the SILVAH methodology, a categorization of plot sugar maple subplot stocking percentage was obtained. Out of 116 plots considered, 45 (38.8%) were considered fully stocked, 24 (20.7%) were 2/3 stocked, 19 (16.4%) were 1/3 stocked, and 28 (24.1%) were unstocked – considered a regeneration failure in this study. 21 (75%) of the 28 unstocked plots also had elevated sugar maple dieback (greater than 10%), making them of greater concern for decline. 10 (48%) of these 21 plots were in private ownership and 11 (52%) were in public ownership. Phase II average % dieback was negatively correlated with plot stocking % ($r(109) = -0.22$, $P = 0.025$).

3.2 Harvest activities

Forest management was an expected disturbance within the study. Trees were identified at the base with aluminum tags, but there was no exclusion or interdiction of regular management activities. As was concluded in Phase I, plot ownership type (public vs. private) and any implied differences in management associated with each, is still not significantly correlated with ongoing dieback measured in Phase II ($F(1,109) = 1.86$, $P = 0.176$). Given the focus on sugar maple and its predominance by stem count and basal area within the study area, categorization of harvest severity between Phases I and II (Table 4) was based on the percentage of sugar maple basal area removed from 2012 levels, to describe three broad categories of harvest severity. These describe rough magnitudes of disturbance, but do not indicate silvicultural method employed or the status of the surrounding vegetation.

Table 4. Mean and SE for Phase II (except where noted) plot values, separated by relative severity of harvesting activity since Phase I in a maple dieback forest health network in the Upper Great Lakes region (no harvest = 0% sugar maple (SM) basal area removed; moderate < 50%; high > 50%; n=114).

	No harvest	**Moderate severity**	**High severity**
Overstory basal area and dieback			
all species residual basal area (m^2 $hectare^{-1}$)	27.0 (1.3)	19.9 (1.3)	5.8 (2.1)
SM residual basal area (m^2 $hectare^{-1}$)	19.9 (1.0)	15.7 (1.3)	3.1 (1.2)
SM canopy dieback (%)	15.7 (1.6)	11.9 (1.5)	16.9 (7.8)
2012 SM canopy mean dieback (%)	9.8 (1.0)	7.7 (1.1)	8.5 (1.9)

SM basal area non-harvest mortality (m^2 $hectare^{-1}$)	1.2 (0.2)	0.4 (0.2)	0.0 (0.0)
SM non-harvest mortality (% of 2012 stems)	7.1 (0.9)	2.3 (0.8)	0.0 (0.0)
Plot characteristics			
plots in public ownership	44 (58%)	11 (44%)	1 (8%)
plots in private ownership	32 (42%)	14 (56%)	12 (92%)
total	76	25	13
herbaceous cover (%)	45.9 (3.7)	53.6 (7.0)	55.6 (8.6)
SM seedlings per hectare (x10,000)	17.8 (3.0)	14.8 (3.3)	5.7 (1.3)
SM saplings per hectare (x100)	9.5 (1.4)	8.4 (2.7)	29.4 (12.5)
SM subplot stocking (%)	59.1 (4.6)	54.2 (8.7)	59.0 (10.1)
ungulate browse rating (1-5, 5=severe)	2.9 (0.1)	2.9 (0.2)	2.2 (0.2)
earthworm impact rating (1-5, 1=severe)	2.9 (0.2)	3.3 (0.3)	3.6 (0.4)

The majority of plots (66%) were in stands where no entry was apparent during this ten-year period. A majority of those that were harvested (66%) fell into the moderate severity category, which captures cutting ranging from just above 0% of 2012 sugar maple basal area to just below 50%. Of those that were harvested, a slight majority of moderate severity harvests (56%) and strong majority of high severity harvests (92%) were conducted on privately owned plots. Unharvested plots lost the largest amount of basal area to mortality between the Phases. Sugar maple canopy dieback was high for those plots with no harvesting and high severity harvesting. Moderate severity harvest plots showed lower dieback levels than either, as well as the network-wide average. Given the limited number of plots, and limited number of trees within each of those plots, it is difficult to draw conclusions from the high severity harvest values. There was no significant difference in dieback levels between the three harvest severity categories ($F(2, 108) = 1.05$, $P = 0.354$) and no difference in pre-harvest 2012 mean plot dieback % ($F(2,113) = 0.66$, $P = 0.521$). Canopy dieback % was correlated with non-harvest % tree mortality ($r(110) = 0.63$, $P < 0.001$; Supplemental Table 4). There is no obvious trend in sugar maple regeneration stocking along the harvest severity gradient.

Out of the 25 plots classed as moderate severity harvests, only 8 (32%) saw any improvement in the average dieback condition of SM trees within the plot. Across all 25 plots, the average of plot-level average dieback of paired SM trees was 5.9% (SE = 0.9) in 2012 and 12.3% (SE = 1.6) in Phase II. A paired one-tail t-test of the two samples found the Phase II dieback plot average for residual SM trees was significantly higher ($t(24) = -5.39$, $P < 0.001$). This analysis was not carried out on unharvested and high severity harvest plots, as dieback averages increased in these categories over Phase I, meaning that residual trees did not improve in the intervening years.

3.3 Earthworm impacts

From the subset of plots sampled for earthworms for which samples were identified in the laboratory (n = 22 plots, 250 earthworms) the following species were identified: *Dendrodrilus rubidus* (94 individuals, 38% of all earthworms sampled, epigeic functional group); *Lumbricus* juveniles (69, 28%, anecic and epi-endogeic); *Eudrilus eugeniae* (35, 14%, epigeic); *Aporrectodea* juveniles (30, 12%, endogeic); *Dendrobaena octaedra* (9, 4%, epigeic); *Lumbricus rubellus* (8, 3%, epi-endogeic); *Lumbricus terrestris* (4, 2%, anecic); *Eiseniella tetaedra* (1, <1%, epigeic).

Overall, since the final year of Phase I (2012), earthworm impact ratings on the forest floor increased from an average rating across the study area of 3.6 to 3.1 (across all original survey years; 1 to 5 scale with 1 being the most severe impacts; Supplemental Table 2) in Phase II (Table 1). As before, earthworm impact rating (EIR) is still correlated with sugar maple dieback ($r(111) = -0.19$, $P = 0.046$), however the strength and significance of this relationship has decreased somewhat, relative to that found in Phase I (Bal et al., 2018). Other significant subplot relationships investigated showed that, as ungulate browse rating increased, sapling density decreased ($r(118) = -0.24$, $P = 0.009$) and EIR intensity increased ($r(118) = -0.18$, $P = 0.046$). Also, the negative relationship between ungulate browse rating and seedling density approached significance ($r(118) = 0.16$, $P = 0.083$; Supplemental Table 4).

Breaking the results out by ownership, EIR increased on private plots from 3.7 (SE = 0.2, n=59) in 2012 to 3.6 (SE = 0.2, n = 61) in 2022. The bulk of the study-wide increase, however, was driven by public plots, on which EIR increased from 3.5 (SE = 0.2, n=57) in 2012 to 2.5 (SE = 0.2, n = 57) in 2022. National Forest plots in Wisconsin and Minnesota demonstrate some of the starkest increases (Figure 8; Supplemental Table 6 breaks out impacts by National Forest). A total of 23 plots are categorized as having improved (by an average amount of 43%) in apparent EIR since 2012. Apparent clustering of values was visible in all National Forests except for the Hiawatha to the east, while spatial trends elsewhere in the network are more mixed.

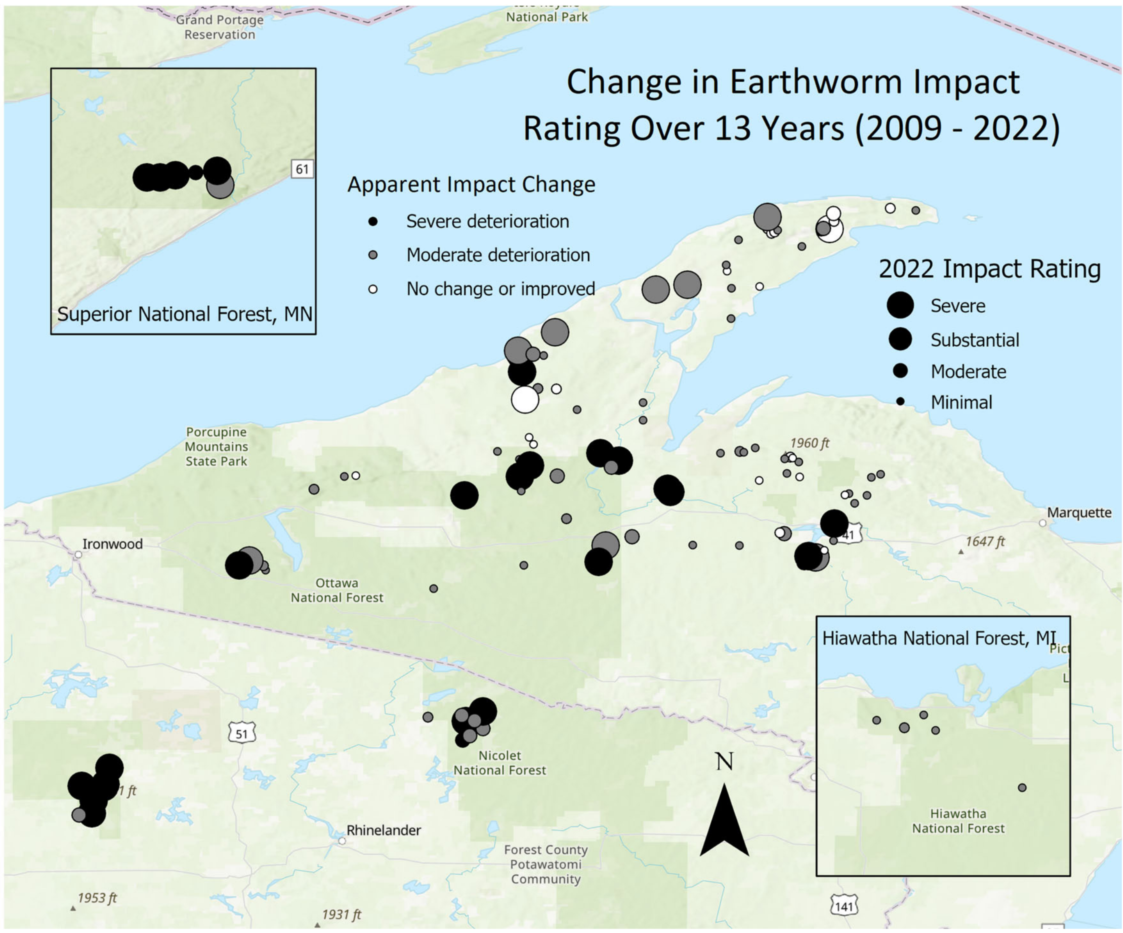

Figure 8. Map of study network in the Upper Great Lakes region showing categorical change in average plot earthworm impact rating between Phases (2012 values compared with Phase II, n = 116). Plots categorized based on the following percentages of change: ≥ 0% = no change or improved (n = 51); 0% to -50% = moderate deterioration (n = 38); < -50% = severe deterioration (n = 27). Plots vary in symbol size by categorized earthworm impact rating in 2022, with 'severe' representing the largest symbols, decreasing in size for lesser forest floor impacts.

The sampling and identification of earthworms allowed for more detailed analysis of community arrangement and insights into which exotic worms were most abundant or having most impact on forest floor conditions. Lab identification to species of collected earthworms was carried out on 35 plots, but field identification to functional group was completed on all 119 sites. Average counts by functional group were divided by EIR categorization. In general, nearly all earthworm species abundance increases along the impact gradient as expected (Table 5), as does dieback and browse. A newer potential finding is that a greater share of the more heavily impacted plots are in public ownership. Ungulate browse rating was correlated with EIR ($r(118) = -0.18$, $P = 0.046$), as more intensely earthworm-impacted plots demonstrated higher levels of herbivory. EIR values appear to be a bimodal distribution, with plots tending either to be largely unimpacted as yet, or on the more heavily impacted side once they have become colonized.

Total worms sampled correlated strongly with the plot's EIR ($r(118) = -0.50$, $P < .001$, scale 1 – 5, with 1 signifying most severe). Likewise, all functional groups were correlated with the impact rating at $\alpha = 0.05$, with anecic and *Lumbricus* spp. groups having correlation values twice as large and p values orders of magnitude smaller than the other groups (respectively, $r(118) = -0.41, -0.53$ with $P < .001$ for both). None of the sugar maple regeneration metrics show clear trends across the gradient.

Table 5. Mean and SE plot characteristics and counts of earthworm functional groups divided by 2021-22 categorized earthworm impact rating (minimal > 4 on 1-5 rating scale with 1 being most severe; moderate > 3; substantial > 2; severe < 1; n=118) on sugar maple (SM) dieback forest health network in Upper Great Lakes region.

	Minimal (5-4)	**Moderate (4-3)**	**Substantial (3-2)**	**Severe (2-1)**
Counts of functional groups				
all earthworms	2.2 (0.8)	5.9 (1.5)	10.0 (1.8)	11.8 (1.7)
epigeic	2.0 (0.7)	3.4 (1.2)	4.5 (1.1)	4.1 (0.7)
epi-endogeic	<0.1 (<0.1)	<0.1 (<0.1)	0.3 (0.2)	0.6 (0.2)
endogeic	2.0 (0.7)	3.4 (1.2)	4.5 (1.1)	4.1 (0.7)
anecic	<0.1 (<0.1)	0.4 (0.2)	0.6 (0.2)	1.2 (0.3)
Lumbricus spp. juveniles	0.1 (0.1)	0.2 (0.1)	2.1 (0.5)	3.2 (0.6)

Plot characteristics				
plots in public ownership (n = 57)	15 (26%)	7 (12%)	10 (18%)	25 (44%)
plots in private ownership (n = 61)	32 (52%)	9 (15%)	8 (13%)	12 (20%)
total (n = 118)	47 (40%)	16 (14%)	18 (15%)	37 (31%)
herbaceous cover average (%)	38.6 (4.5)	55.2 (7.3)	46.2 (8.1)	59.6 (5.7)
SM canopy dieback average (%)	12.6 (1.7)	14.6 (3.2)	15.0 (2.6)	19.3 (2.9)
SM seedlings per hectare (x10,000)	13.3 (2.2)	9.9 (3.3)	26.2 (7.0)	15.5 (4.6)
SM saplings per hectare (x100)	5.8 (1.1)	3.5 (1.0)	5.1 (3.6)	3.4 (0.7)
SM subplot stocking (%)	61.7 (5.7)	50.0 (10.1)	68.8 (9.8)	52.3 (6.9)
ungulate browse rating (1-5)*	2.6 (0.1)	2.9 (0.3)	3.0 (0.2)	3.0 (0.2)

*5 is most severe on browse rating

3.4 Scale insects

Scale insects were found at 65 (62%) of the plots sampled with overstory sugar maple (n = 104) and distributed throughout all regions of the study area. Where found, 6.1 (SE 0.6, Min 1, Max 37) individuals were sampled on average per plot. Scale number was not found to be correlated with sugar maple dieback (r(103) = -0.11, P = 0.253). Dieback grouped by scale presence and absence also do not show significantly different means by one-way ANOVA (F(1,109) = 0.46, P= 0.501).

Of the scale found, about 10% were identified as cottony maple scale on the morphological basis of charismatic cottony egg sac, with the remaining 90% presumed to be lecanium or immature cottony maple scale that have not yet released the waxy tufts that cover their eggs. All scale were sampled only on sugar maple hosts. Of the 65 plots at which scale were found, 20 (31%) had cottony maple scale present and 46 (71%) had lecanium present. Scale number was negatively correlated with % canopy transparency (r(103) = -0.27, P = 0.005), and positively correlated with EIR (meaning scale number increased as EIR impacted decreased; r(103) = 0.24, P = 0.015).

4 Discussion

4.1 Canopy dieback

In answer to one of the main questions of the study, results indicate that sugar maple canopy dieback is still present in a similar (median values) or larger degree (mean values) throughout the region, though it remains highly variable across the study area. Dieback levels continue to exceed reported historic levels, suggesting this interaction of stressors is durable at the decadal scale and not the short-term product of a single event (Allen et al., 1995; Bal et al., 2015; Ouimet and Camiré 1995). Additionally, plot dieback levels in Phase I and Phase II were highly correlated with each other, suggesting that, though dieback is a relatively short-term symptom of stress (Schomaker et al., 2007), the underlying causes of that stress have remained fairly consistent throughout the decade spanning the two Phases.

Red maple was the only other component species within the study plots found in numbers sufficient to provide reliable average dieback values, but both red maple and pooled broadleaf dieback averages were as high as sugar maple (or much higher), suggesting that overall stand health may be impacted and not sugar maple health alone. Despite theories about red maple's relatively recent success throughout the Eastern U.S. due to lower resource requirements and 'super-generalist' traits, this species is faring as poorly or worse than sugar maple on these sites (Abrams 1998). It must also be noted that these plots were selected specifically to study sugar maple and, as such, represent a preponderance of the species and imply long-term management for it as a crop species. This means other co-occurring trees should not be treated as fully representative of the species' health elsewhere on the landscape. Future study investigating whether these symptoms are generalizable to other species across the northern hardwoods matrix within the region would be valuable.

Perhaps counterintuitively, despite dieback mean values being higher in Phase II than I, percent canopy density was higher and percent transparency lower in Phase II. One possible explanation is that relative rates of insect defoliation and other foliar damage may have been higher in Phase I, leading to a less dense canopy or foliage overall, despite lower levels of dieback, which describes twig and whole leaf mortality. Additionally, harvesting between Phases could be expected to increase residual stand growth response, including foliar growth and density (Nyland 2005; Wagner et al., 2011).

Sorting dieback by categories of change between Phase I and Phase II allowed for the observation of some broad trends between statuses, built around the 10% dieback threshold for healthy stands. For those plots that stayed healthy or unhealthy in Phases I and II, the fact that EIR increased for both categories suggests that there may be other underlying variables affecting stand health. In the case of those plots that stayed unhealthy and exhibited greater dieback levels in Phase II, these site characteristics may be conferring greater vulnerability. Conversely, those sites that stayed healthy and had lower dieback in Phase II may have site factors that give greater resilience to earthworm impacts. Many other cases of sugar maple decline have identified underlying nutrient stress as a common feature, which may in turn exacerbate stress from earthworms, defoliators, or drought (Bal et al., 2015; Houle et al., 2007; Ouimet et al., 1995).

4.2 Harvest effects

While predicted and explicitly included in the study design, management activities still represent a complicated variable to disentangle from other signals. According to mean values, harvest severity is not associated with sugar maple dieback, however variance for this category is high as fewer plots are included, and within those plots, many fewer stems remain. Plots with high severity harvests did not have apparently higher average percentage dieback in 2012, however the plots represent a small portion of the area considered for a management unit and may not accurately represent the stands overall for the purposes of larger-scale plans. Moderate severity harvest plots do have lower sugar maple dieback than unharvested plots, but analysis of residual trees shows their condition has deteriorated since Phase I. This indicates that all of the ‘improvement’ in average dieback levels was achieved directly by salvaging those trees exhibiting the worst stress. As a group, those trees that were ultimately selected to remain after harvest had an average dieback below 10% in 2012, suggesting managers may have used dieback as a factor when considering marking guidelines for maple in northern hardwood stands that recommend cuttings remove apparently higher risk trees during entries (Arbogast 1957; Botti 1994). Despite the selection of unhealthier trees for harvest, residual tree condition deteriorated between Phases, suggesting that release from competition intended in management activities was not sufficient to improve the health of remaining individuals. Relatedly, there are progressively lower volumes of sugar maple basal area lost to non-harvest (or 'natural') mortality between Phases as harvest severity increases, suggesting managers likely salvaged stressed trees to prevent economic loss.

The percentage of sugar maple trees lost to natural mortality declined as harvest severity increased, which makes sense if unhealthy trees are removed, and presumably healthier residual stems benefit from reduced competition. The highest average (for no harvest plots) however, is 7.6% mortality which, when annualized down from the ten-year period considered between Phases, is only 0.8%. The results of the North American Maple Project (NAMP), carried out through forests of the Northeast, found that, over the course of ten years (1988-97), the baseline level of annual sugar maple mortality was 1.2%, and ranged from 0.3% to 1.9% (Allen et al., 1995; Allen et al., 1999). Though the time period and region considered are different, the method of tallying mortality is the same as in this study, and the resulting dataset is large (more than 15,000 sugar maples), providing a useful baseline against which to compare this study's results. On average, sugar maple mortality falls within the range reported by NAMP and below the reported overall average, suggesting mortality is not obviously in excess of what would be normally expected. This, in turn, may be evidence that there is not a widespread regional decline, though dieback is still evident, which may also imply slower growth (Manion and Lachance 1992; Neely and Manion 1991).

Another key management consideration after harvest is the status of regeneration (Donovan 2005). Removing trees with substantial dieback and attempting to capture mortality may be a sustainable strategy only so long as the stand continues to regenerate well. Estimates of subplot stocking calculated using the SILVAH method did not show any significant differences between harvest severity and plots were, on average, about 2/3 stocked. This level of stocking indicates room for improvement, but no generalized failure across the study area (Brose et al., 2008). The negative relationship between dieback and plot stocking %, however, raises some concerns for management. If plots exhibiting high levels of dieback are also more prone to lower stocking, salvage methods may not lead to future fully-stocked, healthy stands of sugar maple.

Lower seedlings per hectare in high severity harvests could also be problematic if it limits recruitment to saplings, but lacking information on how recently the harvests occurred or the distribution of seedlings over the harvested area for stocking purposes makes it difficult to project what these densities mean for future regeneration. Further, these counts represent a snapshot of seedling density that is also affected by variable seed crop production, time from harvest (affecting proximity to seed-producing mature sugar maple), and maternal effects, with interannual variation in climate affecting all of the above (Cleavitt et al., 2011; Juice et al., 2006). Overstory density affects both the provision of seed crop as well as conditions favorable to germination and heavier cutting can temporarily increase site water tables, slowing seedling germination (Tubbs 1977). Additionally, sapling density was considerably higher in the high severity harvest plots, suggesting that recruitment may already be underway and could be shading out seedlings below.

While the status of regeneration in the study area is not completely clear, the data do indicate negative relationships (that are either significant or approaching significance) among dieback, exotic earthworms, and ungulate browse on the one hand, and densities of seedlings and saplings on the other. Earthworms can act as direct seed predators and can modify the forest floor to make it a poorer seedbed for sugar maple germination (Cassin and Kotanen 2016; Frelich et al., 2019; Hale et al., 2008). The negative connection between ungulate browse and the relatively more palatable sugar maple saplings, meanwhile has led to some sounding the alarm about sustainable management of sugar maple in the region going forward (Henry et al., 2021; Matonis et al., 2011).

The linkage of dieback and regeneration could be at least partially related to the balance of carbon allocation. Stressed sugar maples are less able to produce seeds, generate second growths of foliage after late frost, and increase radial increment, meaning dieback as a symptom of stress could indicate such an imbalance, temporary or otherwise for a tree, and the stand at large (Halman et al., 2013).

Another question that arises after harvests is the presence of competing herbaceous cover. In the case of varying management disturbance, where additional light becomes available at the forest floor, certain herbaceous species can outcompete canopy tree regeneration (Wagner et al., 2011). The apparent increase in herbaceous cover between Phase I and II may, in part, be explained by management activities. Indeed, percentage of herbaceous cover increases along the gradient of harvest severity. However, spatial disjunction, interannual variation, and varying climatic events between the two Phases make direct comparison of herbaceous values difficult.

Invasive plant species, such as common buckthorn (*Rhamnus cathartica* L.) and Japanese barberry (*Berberis thunbergii* DC) were found in only three plots, suggesting limited impact from these woody plants. Sedges and other graminoids that are implicated in proximate regeneration failure phenomena (Matonis et al., 2011) are present in plots within the study area, but further analysis would be required to identify species, which is beyond the scope of this manuscript.

Despite relatively lower dieback and mortality in moderate severity harvest plots, managers should exercise caution before inferring these reductions are lasting improvements and not simply the temporary reduction in measurable symptoms created by removing those trees previously most affected. From at least a short-term economic standpoint it seems plausible that some value was captured by management that may otherwise have been lost to mortality in the intervening years, but longer-term study may be needed to understand which management strategies are most appropriate for addressing chronic stand dieback sustainably.

4.3 Earthworms

Study-wide correlations found that earthworm impact was still related to sugar maple dieback, as in Phase I. The decrease in significance and explanatory power may be partly explained by harvest activities, which, according to established marking guidelines for northern hardwoods, could be expected to preferentially remove trees exhibiting defects or stress symptoms (Tubbs 1977), thus lowering those plots' apparent dieback levels regardless of forest floor condition.

Regarding plots for which EIR has apparently improved, it is possible the localized population dynamics may have shifted such that drivers of impact are reduced. However, the processes through which the forest floor and surface soil horizons develop span decades and centuries. This means that exotic earthworm impacts in forested ecosystems are largely considered irreversible in the decadal or even centurial timeframe (Frelich et al., 2006; Vestergård et al., 2015). These changes in rating are more likely related to other finer-scale changes. Litter remaining from the previous season will progressively break down over the course of the summer season, leading to more apparently bare floor conditions later in the season. Field experience also demonstrated that plot slope and aspect can affect the local appearance of the forest floor. Both are impacts that can be accounted for within the rating scale, but which can nonetheless obscure exact impact assessment.

Considering the differences between plots categorized by EIR, the language of the assessment is most strongly tied to anecic and *Lumbricus* spp., which is both a function of the scale's deliberate design to measure lumbricid signs (Supplemental Table 2), and these functional groups' rapid and visual effect on forest floor material (Frelich et al., 2006; Loss et al., 2013). Epigeic and epi-endogeic worms, in particular, are most readily apparent during extractive sampling because they inhabit the forest floor. Their more limited biomass and peregrination, however, make their impacts on surface soil somewhat less pronounced than other functional groups (Hale 2007; Hale et al., 2009). Often, however, they may be the precursors to more substantial invasions, facilitating invasion by endogeic and anecic earthworms through mixing of the upper soil layers and leading to a "cascade" of ecological impacts (Frelich et al., 2019; Frelich et al., 2006; Tiunov et al., 2006). This means that the EIR, which captures markers of advanced invasion best, may be most useful as a rapid, low-cost assessment that land managers can use to evaluate site colonization, whereas metrics that assess earlier invasions more granularly may be helpful for scientific and monitoring efforts.

The apparent inverse nature of the share of public/private ownership along the impact gradient (i.e., a larger portion of the more severely impacted sites are public) may be explained by relative differences in human traffic and use (Shartell et al., 2013), and should be grounded in the spatial context of the study within which public plots tend to be further south and in areas with more human development. The National Forest sites are open to recreational use, including fishing with baitworms, and the operation of vehicles along dirt roads adjacent to forested stands, which can all accelerate the spread of adult earthworms and cocoons to new sites (Gundale et al., 2005). While the private plots are accessible by public dirt roads too and many are open for hunting and fishing per commercial forestry laws (Lind-Riehl et al., 2015), most are not along roads that lead to residential areas, recreational facilities, or further populated points as is often the case for the road network on National Forests. Further study of public usage and traffic patterns would be required to satisfactorily understand the magnitude of these known vectors of exotic earthworm introduction (Shartell et al., 2013).

Herbaceous cover percentage is highest in the most severely earthworm-impacted plots, perhaps underscoring previously found linkages between competition shifts in favor of certain plant functional groups (such as native and nonnative sedges) and increasing earthworm invasion (Craven et al., 2017; Fisichelli et al., 2013). Along similar lines, the more severely earthworm-impacted sites also demonstrated greater levels of ungulate browse. Though, the linkage between exotic earthworms and deer is established by prior studies (Dávalos et al., 2015; Mahon and Crist 2019), the site-level variables responsible for both are variable, and frequently point to mediation of earthworm and deer abundance by climate (e.g., warmer temperatures) and anthropogenic impacts (e.g., introduction and forest fragmentation) on the landscape (Fisichelli et al., 2013).

4.4 Scale

Scale were found to be widely distributed throughout the study network and at apparently non-injurious levels. In many cases, sample branches from the same plots appeared to have the same vigor when one would have scale while the other did not. The visual (shiny coating) and tactile (sticky feeling) signs of honeydew from substantial scale feeding were not noted at any plots, nor was sooty mold growth found blackening the leaves of sampled or other understory branches (Frank et al., 2013). Lastly, no obvious wilting was noted on the sampled branches, a potential symptom of injurious levels of scale sap feeding (Frank et al., 2013).

In the vast majority (73%) of plots where scale were found, three or fewer individuals were collected over two branches. While densities for what constitutes an injurious "outbreak" are not clearly defined in the literature, the Wisconsin Forest Health Highlights (2015; 2016) describe "very heavy populations" of *Parthenolecanium* spp. affecting maple, and show images of infested twigs and branches where dozens of scale are visible clustering around the entire circumference (Wisconsin DNR 2015; Wisconsin DNR 2016).

The data suggest that the levels of scale occurring within the study area currently are not linked to stress: it appears that scale numbers decrease in plots where earthworm impacts are higher, and scale numbers are higher in plots with lower canopy transparency. This may imply that, within the study area, scale found at apparent non-outbreak levels are background pests related to stands of relatively better health. In an urban setting, sub-injury levels of scale infestation have been found to promote and support the natural enemy communities that prey upon them, suggesting that baseline levels of scale presence may be beneficial to maintain balanced predator-prey relationships (Wilson and Frank 2022). In any case, neither qualitative assessments of scale at the sites, nor quantitative analysis indicates that these pests are currently a threat to sugar maple in the region.

4.5 Regional sugar maple decline

While the forgoing analyses have focused on quantifying dieback and investigating some of its potential drivers within the study data, managers would like to know if there is a unified cause or set of causes that are affecting sugar maple across the Upper Great Lake States to an extent that would qualify as a broader decline complex. Answering this question proves more difficult, since it requires establishing that, across the landscape, this species is experiencing increased symptoms of stress (e.g., canopy dieback), potentially heightened mortality, reduced incremental growth, as well as restricted regeneration (Manion and Lachance 1992). There is substantial evidence of regeneration limitation adjacent to the study area in the southern counties of the Upper Peninsula strongly implicating deer browse pressure and related spatial effects (Henry et al., 2021; Matonis et al., 2011). The correlative evidence in this study also suggests that, throughout the network, there are factors interrelating sugar maple dieback and mortality, regeneration density, and earthworm and ungulate impacts

As an initial investigation into where, within the study range, might be considered areas of sugar maple decline, two criteria were considered: 1) plot average sugar maple canopy dieback ≥ 10%; 2) plots with apparent regeneration failure, or 0% sugar maple stocking in the subplots as defined in the methods. A total of 21 (19%) plots met these criteria and are distributed throughout the study area. While these plots indicate areas of greater concern, there do not appear to be obvious regions of decline, but rather localized areas where multiple factors have converged to produce stands of sugar maple that are exhibiting several symptoms of stress. Further investigation into successional stage, time since management, and segregation of types of regeneration would be required to make judgements about the future of these stands from the representative plots (Hett 1971).

Rather than a region-wide, unified decline phenomenon, the study area appears to present a case of shifting and exacerbating stressors. As previously cataloged, many of the cases that further investigation has determined are ‘true’ declines (rather than temporary dieback episodes) share stand composition and/or site condition as predisposing factors – both frequently resulting from silvicultural practices that encourage sugar maple to dominate sites it might not otherwise (Allen et al., 1999). In these instances, additional inciting events (drought, defoliator outbreaks, etc.) can reveal that a potential compositional mismatch to the site and/or anthropogenic impacts (deposition, land use, climate change) may have shifted the site's capacity to support sugar maple (Bal et al., 2015; Horsley et al., 2002). In the context of these other factors, earthworm impacts represent a continually rising tide, reducing a stand's overall resilience to change and varied stressors.

4.6 Other considerations

In the case of declines triggered by distinct pests or pathogens, fronts can be surveyed and tracked through time to mark progress spatially and estimate future impacts (McCullough and Wieferich 2015). In this instance, decline episodes appear to be dependent on the combination of local factors that lead to stresses exceeding sugar maple's ability to cope and recover. While earthworm impacts are clearly a contributing factor throughout the study area, and have intensified in many of the plots, why has dieback remained at similar levels and not increased more?

One mitigating variable may be the degree of drought stress the stands were experiencing at the time of survey. Historical monthly Palmer Drought Severity Index (PDSI) values (starting in 1999, 10 years before the first surveys) from the three NOAA districts (the smallest division to offer monthly PDSI data) encompassing all study plots suggest less drought in more recent years than the decade leading up to Phase I (Supplemental Figure 1). As other studies have established, drought is often a key contributing factor to sugar maple decline phenomena (Bauce and Allen 1991; Houston 1999). Modeled drought can be seen most starkly in chart for Michigan's western Upper Peninsula (though also visible to a lesser degree for the Wisconsin and Minnesota NOAA districts) for the decade prior to Phase I. This period is largely characterized by drought, with many months dipping below -2 (moderate drought) and several periods dropping below -4 (extreme drought). In contrast, the decade between Phase I and Phase II tended to be much wetter, with periods above +2 (unusually moist) and a few peaks exceeding +4 (extremely moist). These trends are similar, though less pronounced for the Wisconsin and Minnesota districts. While these landscape trends would need to be weighed against the hydrological and soil drainage characteristics of a given site, it may be inferred that drought trends are likely present in the relationships at play across the study network. The inclusion of 3- and 5-year prior PDSI averages by district and survey year could be a valuable addition to future models developed from this data.

The Upper Great Lakes region is projected to become warmer and wetter, though precipitation is likely to see most of its increase in the winter (GLISA 2021). Longer, warmer, drier summers could increase the chance for drought (GLISA 2021). More extreme weather events are predicted to represent much of the increase in wetness in short, intense episodes that may lead to more flooding and runoff, instead of longer-term soil moisture recharge (GLISA 2021). Many of these changes, such as drought severity, could be exacerbated by the exotic earthworm impacts on the forest floor already underway (Larson et al., 2010). The litter layer acts as both an insulator against weather variations and a sponge for the mineral soil, and fine roots below (Gosz et al., 1976; Sayer 2006). In its absence, the forest floor may be more susceptible to wintertime freeze/thaw events, erosive soil and nutrient loss in ‘flashier’ precipitation events, and drought stress, all variously demonstrated in other decline events (Manion and Lachance 1992). Additionally, while microclimatic variation will impact these trends variously, it is expected that increased temperatures and moisture are likely to facilitate invasive earthworm spread and populations (Singh et al., 2019). Climate change, earthworms (and their interactions with invasive plants), and native deer and herbaceous plants are likely to combine in varying and novel ways that mean management will have to be fine-tuned to local conditions (Fisichelli et al., 2013; Mahon and Crist 2019; Powers and Nagel 2009).

Finally, while scale do not currently appear to be a driving stressor, there are climate change implications for how both native and non-native pests may behave. In a study on a related lecanium species, density of *Parthenolecanium quercifex* increased dramatically on host trees in warming experiments, reaching injurious levels and taking on invasive-like traits (Frank and Just 2020). Though they were not systematically sampled, the saddled prominent moth (*Heterocampa guttivitta* Walker) was found at several sites where defoliation was visible from below. They did not appear to be at outbreak levels within the study area, but this pest and spongy moth (*Lymantria dispar* L. – active in Michigan's Upper Peninsula (Michigan DNR 2021)) could also experience changes in frequency or intensity as the regional climate changes (Fält-Nardmann et al., 2018).

When considering management steps with an eye to sugar maple-stressed sites and climate change impacts, species diversity and future adaptation may be wise goals in many cases (Duveneck and Scheller 2016; Millar et al., 2007), but the specifics of other component species should be considered and carefully weighed. Pooled other broadleaf species dieback averages equaled or exceeded sugar maple and red maple canopy dieback levels throughout the study, suggesting that the issues affecting sugar maple in these plots are likely not impacting them alone (Figure 6).

4.7 Management implications

As with all landscape-scale considerations, the management implications of this study will vary. Even within-stand variation in drainage and microrelief can have dramatic implications for sugar maple health and productivity (Roy et al., 2002). Across much of the study area, the predominant silvicultural methods, sites sugar maple occupies, and heightened deer browse impact all raise questions about the sustainability of current sugar maple management (Henry et al., 2021). Even those trends are variable, as the relative climatic buffering present in the northern Upper Peninsula of Michigan, and reduced winter deer pressure (likely due to increased snowpack) mean that sugar maple is regenerating well in that region (Henry et al., 2021). Some operational tools that aim to increase species diversity, such as larger gaps in selection methods, may fail at those goals if deer browse is not considered and managed (Holmes and Webster 2010; VanderMolen and Webster 2021).

Managers will need to consider the network of interacting variables present in their forests and the array of operational tools and constraints (Hupperts et al., 2022) when deciding what sustainability will mean for their landowners (Rogers et al., 2022). When dealing with elevated dieback or other stress symptoms, managers should consider incorporating earthworm monitoring techniques. Relatedly, further development of risk maps for sugar maple that include known variables related to browse pressure and earthworm colonization, would help remove some of the guesswork as managers assess sugar maple's future in their forests. Future efforts will use data from both Phases to examine spatial relationships and use known variables in mapping the likelihood of earthworm colonization. In the context of American beech (*Fagus grandifolia* Ehrh.), Kromroy et al. (2008) outline a helpful process for ground truthing the most salient metrics available in the broad datasets produced by FIA for predicting decline incidence. Such a process for sugar maple would be invaluable in anticipating those stands most likely to show stress and decline. Finally, efforts to understand what management is already occurring on the landscape to combat dieback and assess best practices would be a useful step to help bridge the efforts of researchers and practitioners in the Lake States.

5 Conclusion

The results and analysis provided here show that dieback continues to impact sugar maple throughout the study area and suggest that earthworm impacts continue to be an exacerbating factor interacting with other localized stand variables after a ten-year resurvey in the Upper Great Lakes Region. Given persistent dieback in some stands across the decade between study phases, and the linkage between higher dieback and lower regeneration stocking, traditional single tree marking guidelines or salvage techniques to remove stressed trees may not be sufficient to promote future sustainable management. That scale insects do not appear to be a contributing factor at this time does not preclude the need for monitoring of these and other pests that may, in certain circumstances exceed injurious thresholds. While experience and evidence does not suggest that any reasonable efforts can turn back the clock on exotic earthworm impacts, humans have considerable influence over the rate of their spread. Best management practices surrounding harvesting activities and natural area recreation should be reviewed and maintained to slow the colonization of new sites throughout the region. Finally, given rates of overall stand dieback, monitoring of stand-wide health, linked with earthworm impacts, is warranted to determine which species or communities, and what locations may be more resilient or adaptable to these impacts.

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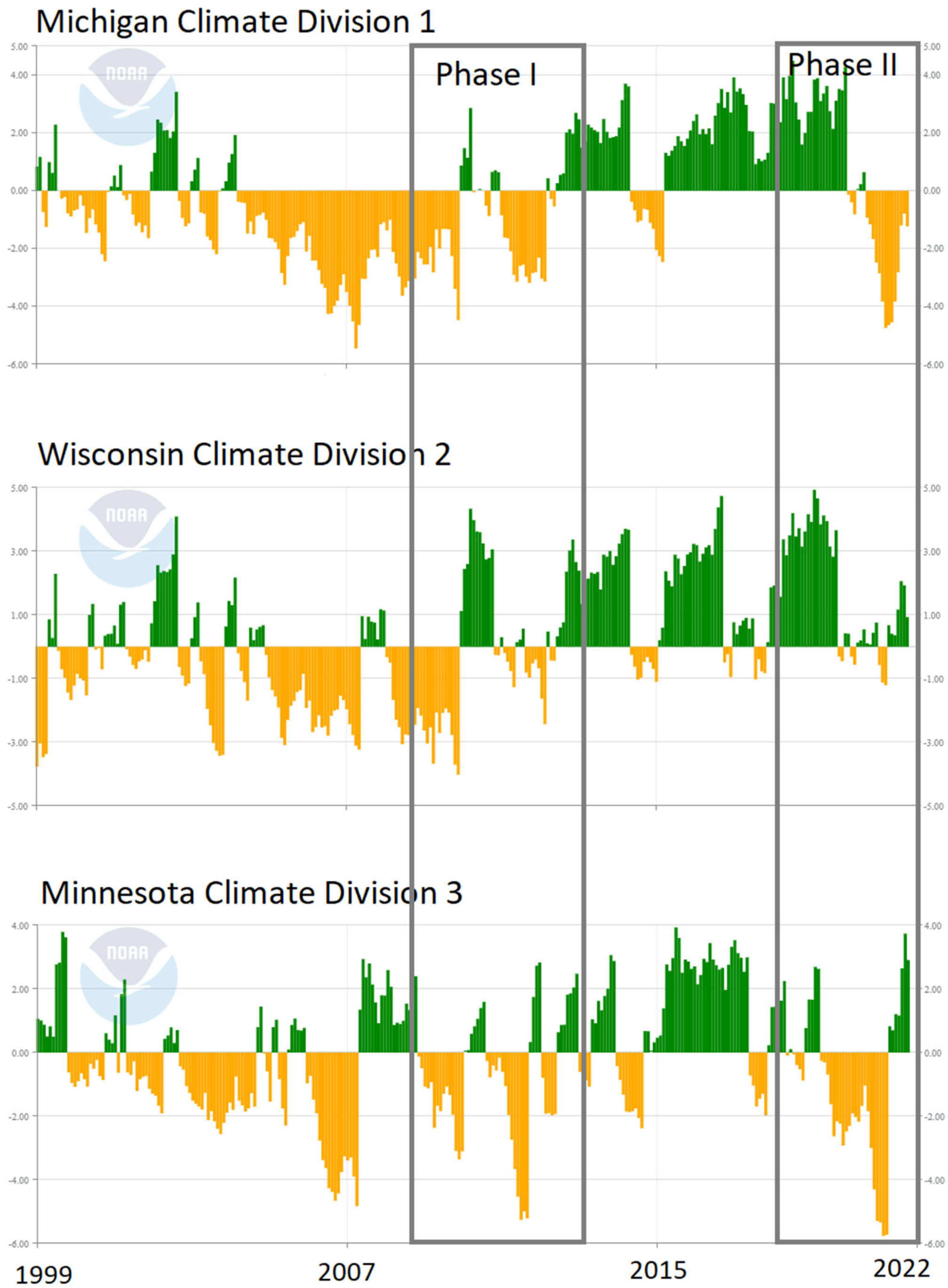
A Appendix – Additional Materials

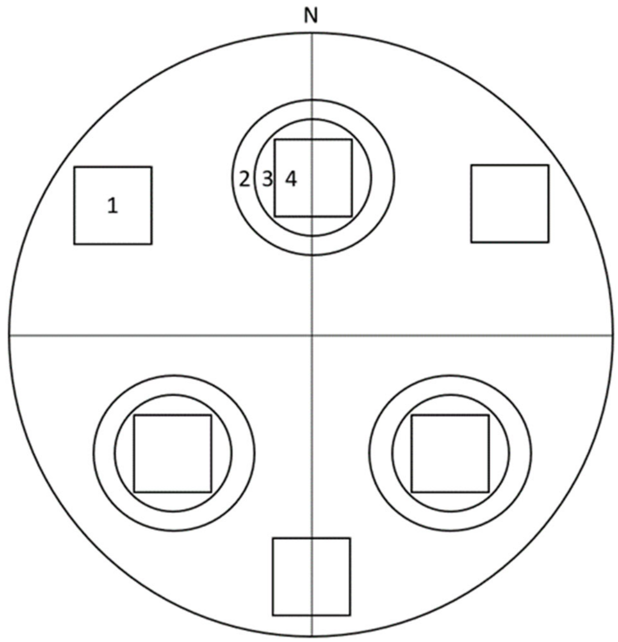
Supplemental Table 1. Data summary and year collected for decadal sugar maple forest health monitoring project in Upper Great Lakes region.

Measurements	Phase I (2009-2012) Years Collected	Phase II (2021-2022) Years Collected
Overstory Forest Health		
DBH, Species, Height, Stem mapping	All years	All years
Tree coring	2009, 2010	-
Recent mean radial increment	2009, 2010	-
Canopy dieback %	All years	All years
Canopy dieback %	All years	All years
Canopy transparency %	All years	All years
Canopy density %	All years	All years
Canopy uncompacted live crown ratio %	All years	All years
Canopy crown light	All years	All years
Crown defoliation/damage %	All years	-
Crown Class	All years	All years
Dead tree decay codes	All years	All years
Calculated harvest codes	-	2022
Calculated mortality	-	2022
Cankers (presence/absence)	All years	All years
Foliage galls and pests (presence/absence)	2010	-
Sugar maple borer (presence/absence)	All years	All years
Wounds (presence/absence)	All years	All years
Wounds (surface area)	All years	All years
Decay obvious (presence/absence)	All years	All years
Missing limbs, forking (presence/absence)	All years	All years
Subplot metrics		
Ungulate browse rating	-	All years
Forest floor condition rating	All years	All years
Earthworm sampling	-	All years
Functional group ID	-	All years
Laboratory species ID and length	-	2022
Biomass calculation	-	2022
Sapling counts (DBH and species)	All years	All years
Seedling counts (species)	All years	All years

Herbaceous species (% cover)	2010	All years
Total herbaceous cover %	2010	All years
Soil density (penetrometer readings)	2011	-
Chemical analysis		
Foliar drip line analysis	2010	-
C and N analysis	2010	-
Soil analysis	2010	-
Particle size	2010	-
pH	2010	-
Organic matter (LoI)	2010	-
Exchangeable cation analysis	2010	-
Plot Characteristics		
Plot center coordinates	All years	All years
Slope	2009, 2010	-
Aspect	2009, 2010	-
Elevation	2009, 2010	-
Landscape position	2009, 2010	-



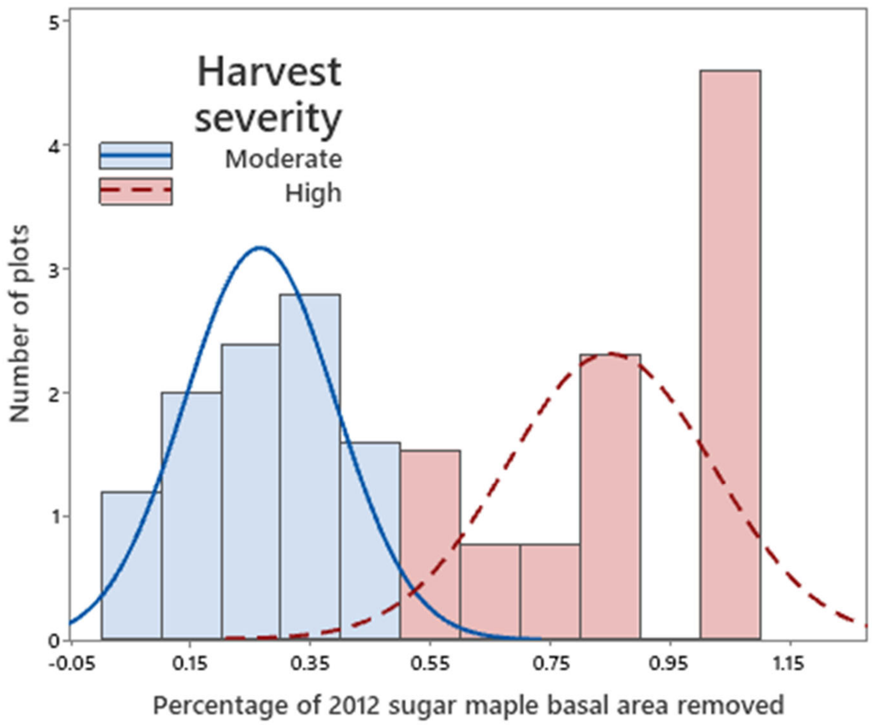
Supplemental Figure 1. NOAA monthly Palmer Drought Severity Index data from three districts encompassing maple dieback forest health study area in the Upper Great Lakes region. Retrieved from https://www.ncei.noaa.gov/cag/divisional/time-series October 27, 2022.



Supplemental Figure 2. Layout of 0.04 ha plots (not to scale), with three each of 0.09 m^2 earthworm assessment (1); 0.004 ha sapling (2); 0.0004 ha seedling (3); and 1 m^2 herbaceous vegetation (4) subplots all nested within the overstory assessment area in a maple dieback forest health network in the Upper Great Lakes region.

Supplemental Table 2. Five-point earthworm impact assessment rating taken at area surrounding each of three subplots, averaged per plot in sugar maple dieback forest health network in Upper Great Lakes region (E. Lilleskov, Northern Research Station, USDA Forest Service, May 19, 2010).

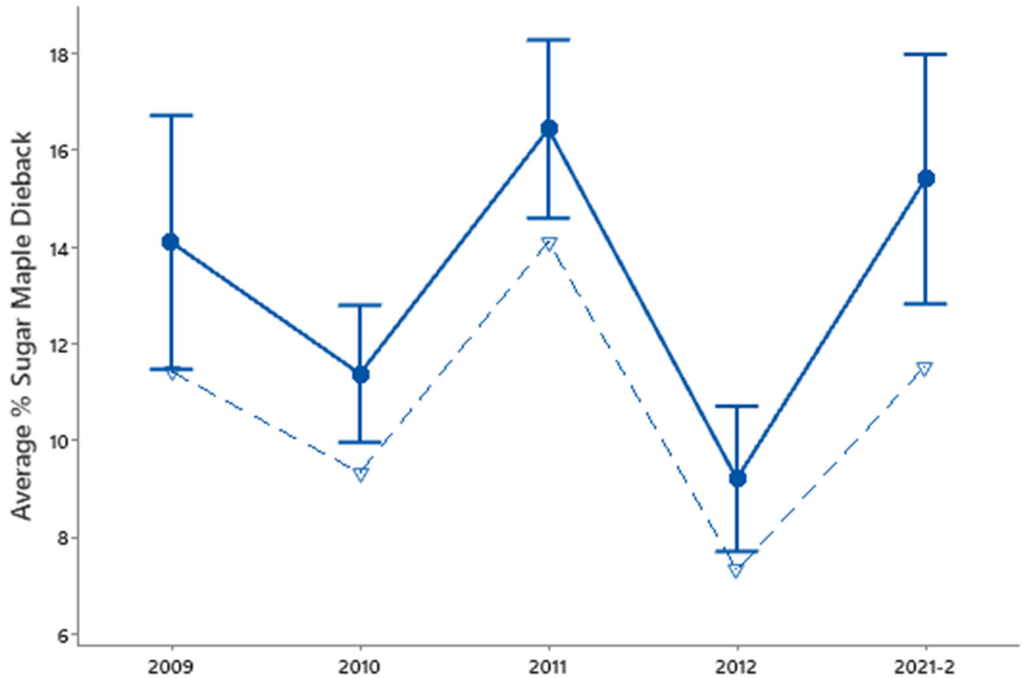
Rating	Description
1	Most severe impact - no forest floor beyond prior year's litterfall; worm sign, including casting and middens, are visible and plentiful
2	Severe - no humus present; large older leaves may persist under last year's litterfall, but smaller fragments are absent; castings present, *Lumbricus* spp. middens may also be apparent; fine roots absent
3	Substantial - no humus present; large older leaves and small leaf fragments may persist under last year's litterfall; few or no fine roots present; castings may be present
4	Light - humus patchy but present and potentially intermixed with mineral soil; forest floor largely intact; fine roots present but may not be abundant; smaller worms present, but larger castings and middens of *Lumbricus* spp. Absent
5	Least severe or no impact - no visible worm sign; roots present and abundant in intact humus; forest floor intact and presenting predictable layers; worm sign absent



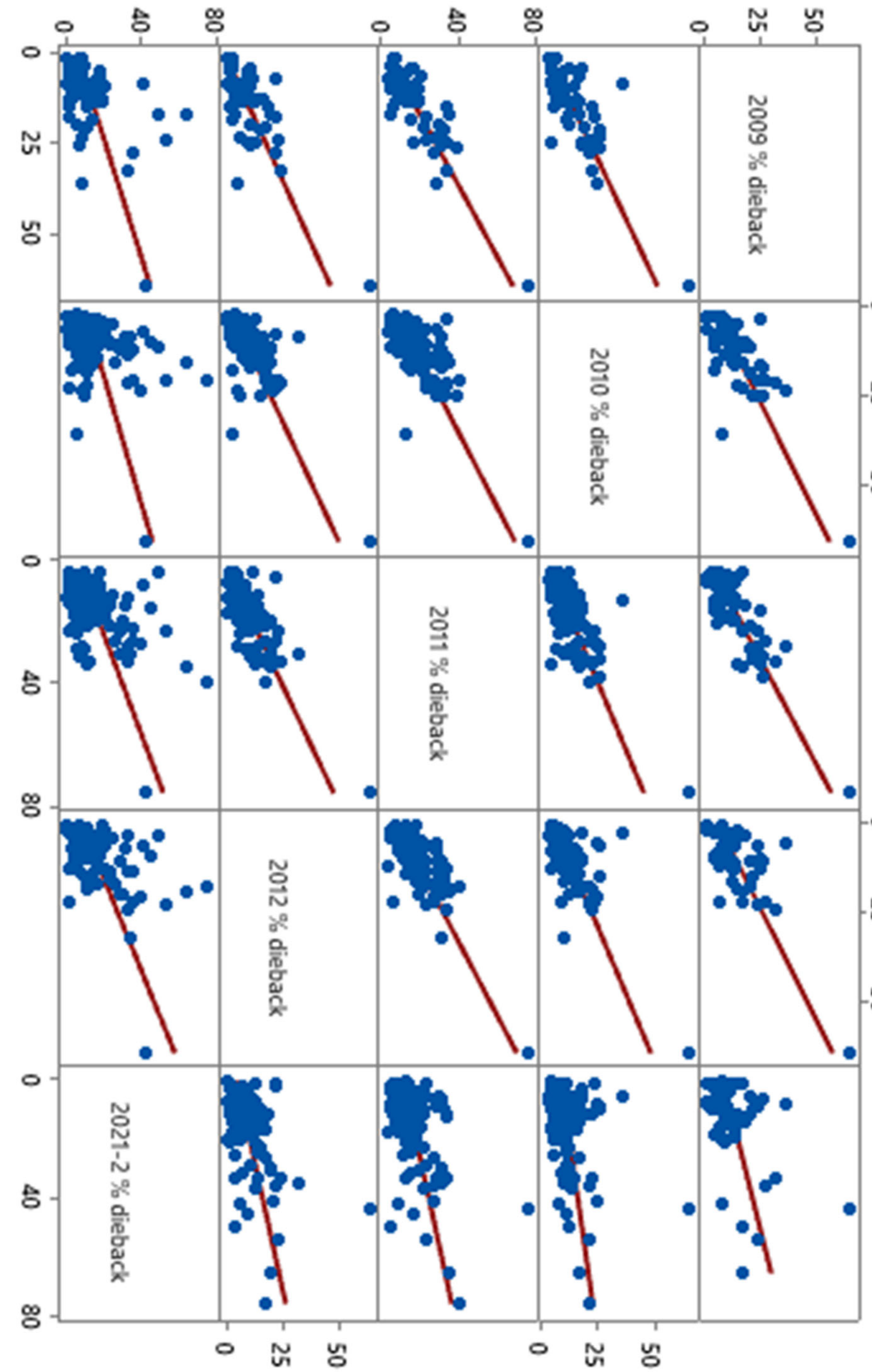
Supplemental Figure 3. Data distribution analysis of plots in which sugar maple were harvested between 2012 and 2021. Plots are grouped by the percentage of sugar maple basal area present in 2012 that was subsequently removed prior to resurvey in a maple dieback forest health network in the Upper Great Lakes region.

Supplemental Table 3. Minimum per hectare subplot stocking numbers for 3 categories of regeneration in sugar maple dieback forest health network in Upper Great Lakes region. Seedling thresholds scale with plot-level ungulate browse rating. Adapted from Brose et al (2008).

	Sugar maple stocking per hectare by browse rating				
	1	**2**	**3**	**4**	**5**
seedlings (< 1.27 m tall)	14,270	28,541	47,568	95,135	190,270
saplings (1.27 - 5.08 cm DBH)	1,903	1,903	1,903	1,903	1,903
saplings (5.08 - 9.99 cm DBH)	951	951	951	951	951



Supplemental Figure 4. Mean % sugar maple dieback by survey year with 95% confidence intervals and median values shown connected with dashed lines for maple dieback forest health network in Upper Great Lakes region.

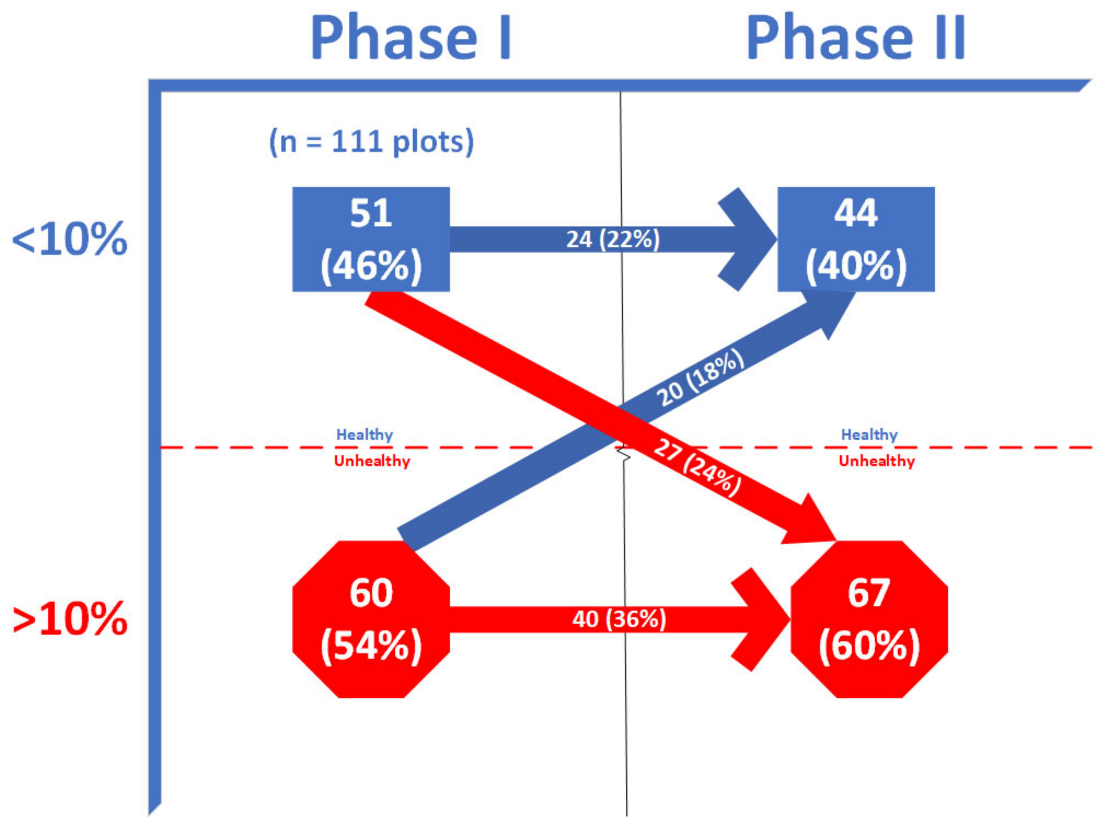


Supplemental Figure 5. Correlation matrix of all pairwise relationships for survey year average % sugar maple canopy dieback in a forest health network in the Upper Great Lakes region. All relationships are significant (P < 0.001).

Supplemental Table 4. Pairwise Pearson correlations on suspected plot-level relationships in maple dieback forest health network in Upper Great Lakes region. All relationships tests were included on the basis of Phase I findings or literature review.

Variable 1	Variable 2	N	Correlation	P-Value
dieback %	**non-harvest mortality %**	**110**	**0.63**	**0.000**
sapling density	**browse rating**	**118**	**-0.24**	**0.009**
browse rating	**earthworm impact rating**	**118**	**-0.18**	**0.046**
dieback %	**earthworm impact rating**	**111**	**-0.19**	**0.046**
seedling density	*browse rating*	*118*	*0.16*	*0.083*
sapling density	*dieback %*	*111*	*-0.16*	*0.090*
sapling density	*non-harvest mortality %*	*115*	*-0.16*	*0.097*
seedling density	dieback %	111	-0.15	0.115
sapling density	earthworm impact rating	118	0.12	0.189
seedling density	earthworm impact rating	118	-0.10	0.280
browse rating	non-harvest mortality %	115	0.09	0.337
non-harvest mortality %	earthworm impact rating	115	-0.04	0.698
dieback %	browse rating	111	-0.03	0.763
seedling density	non-harvest mortality %	115	0.02	0.855
sapling density	seedling density	118	-0.02	0.859

Bold values are significant at α=0.05; italicized values are approaching significance at α=0.10



Supplemental Figure 6. Plots categorized by status of dieback above and below healthy 10% average canopy threshold in Phase I and Phase II in a forest health monitoring network in the Upper Great Lakes Region. Numbers on the arrows show what portion of the plots (n = 111) stayed below 10% across the phases, over 10%, or crossed over from healthy to unhealthy, and unhealthy to healthy.

Supplemental Table 5. Breakdown of sugar maple crown dieback status between Phases I and II in the National Forests surveyed in the Upper Great Lakes region. The 'low' category includes plots that had average sugar maple canopy dieback percentages below 10% in both Phases, with 'high' the inverse. 'Decrease' indicates plots that exceeded 10% in Phase I but fell below 10% in Phase II, with 'increase' the inverse.

		Dieback Status			
National Forest	**# of Plots**	**Low**	**Decrease**	**Increase**	**High**
Chequamegon-Nicolet	16	4	3	2	7
Hiawatha	5	1	0	2	2
Ottawa	23	5	3	3	12
Superior	6	0	0	1	5
		0-10%	**10-20%**	**20-35%**	**35+%**
Chequamegon-Nicolet	16	7	6	3	0
Hiawatha	5	0	4	1	0
Ottawa	23	8	9	6	0
Superior	6	0	0	2	4

Supplemental Table 6. Outline of earthworm impact ratings in the National Forests surveyed in the Upper Great Lakes region. Plots are divided by category (ratings 1-2 = 1; 2-3 = 2; 3-4 = 3; and 4-5= 4, with 1 indicating most severe impacts) of earthworm impact rating in 2022 above, and by % of increase in impact rating between Phase I averages and Phase II below, with <0% representing those plots with apparent improvement or no change.

		Categorized Earthworm Impact Rating			
National Forest	**# of Plots**	**1**	**2**	**3**	**4**
Chequamegon-Nicolet	16	8	7	1	0
Hiawatha	5	0	0	1	4
Ottawa	23	9	2	3	9
Superior	6	5	1	0	0
		% Increase Impact Rating Between Phases			
		50-75%	**0-50%**	**<0%**	
Chequamegon-Nicolet	16	8	7	1	
Hiawatha	5	0	2	3	
Ottawa	23	7	11	5	
Superior	6	6	0	0	