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Regeneration responses in black ash (*Fraxinus nigra*) wetlands: implications for forest diversification to address emerald ash borer (*Agrilus planipennis)*

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Abstract
Emerald ash borer (EAB) (*Agrilus planipennis*) has had an extensive impact across North America. It is currently present in Minnesota, USA but has not been observed in northern portions of the state where the vast majority of black ash (*Fraxinus nigra*) trees are located. Unlike other ash forest communities, the black ash forest type occurs in wetlands and is dominated by black ash with few associate species. Because of this, the loss of black ash can result in changes to the hydrological regime and species composition. The goal of this study was to quantify the structure and composition of regeneration 5 to 11 years post-harvest in three silvicultural systems (group selection, clearcut, and diameter-limit harvesting) to evaluate the potential for establishment of other tree species. Overall, regeneration post-harvest was high but variable across all systems. Across silvicultural systems, there was no significant relationships between residual overstory trees (> 10 cm dbh) basal area and non-ash regeneration TPH, indicating flexibility in designing treatments for diversification. *Populus* sapling (2.54–10 cm) density was significantly negatively correlated to the depth of the soil muck layer. In contrast, a positive relationship was observed between depth of the soil muck and black ash saplings. These findings indicate that specific silvicultural systems in combination with site quality (e.g., clearcuts on high-quality sites with shallow muck layers) may help to promote non-ash species in black ash forests that are threatened with EAB.

Keywords Silviculture · Diameter-limit harvest · Clearcut · Group selection · Wetlands

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Introduction

The economic costs of invasive insects amount to US$70 billion per year globally (Bradshaw et al. 2016). Across the United States, forests are predicted to experience a large loss of host trees through 2027 as a result of non-native forest insects and pathogens (Krist Jr et al. 2014; Lovett et al. 2016). Notably, the emerald ash borer (EAB; *Agrilus planipennis* Fairmaire), an invasive phloem-feeding beetle, was estimated to cost managers US$10.7 billion between 2002 and 2019 to treat, remove, and replace more than 17 million ash trees within a geographic range surrounding Detroit, Michigan, its initial establishment location in the US (Kovacs et al. 2010). Given this, there is urgent need to understand how silvicultural practices can be used to promote stand diversity and increase the proportion of stand volume in non-host tree species to guide the development of strategic forest planning (Muzika 2017).

The expansion of EAB to the US Lake States (Michigan, Minnesota, and Wisconsin) and Canadian Provinces of Ontario and Manitoba has led managers to seek information on alternative forest management scenarios to maintain the health and productivity of ash (*Fraxinus* spp.) forests across the region (McKenney et al. 2012; D'Amato et al. 2018). In 2017, Minnesota natural resource managers cited EAB as the single biggest forest health concern in the management of their forests (Windmuller-Campione et al. 2019). There is particular interest related to black ash (*Fraxinus nigra* Marsh.) wetlands, which are highly susceptible to EAB because stand composition is dominated by black ash with few co-occurring species present (Youngquist et al. 2017; Kolka et al. 2018). Harvesting or simulated EAB mortality in black ash wetland forests has been shown to cause water table rise and a shift in hydrological functions at the site level (Slesak et al. 2014) which may cause a shift to a non-forested wetland ecosystem (Diamond et al. 2018). Planting non-ash trees and conducting regeneration harvests in black ash forests may increase non-ash species diversity and abundance to sustain many of these forested wetland functions (D'Amato et al. 2018). However, despite recent work on potential replacement species in these ecosystems and experiments which have monitored tree survival following planting (e.g., Looney et al. 2015, 2016; Bolton et al. 2018), limited information is available on presence and abundance of non-ash species with natural regeneration after operational treatments (Kolka et al. 2018).

Hydrology has been observed as an important influence on regeneration dynamics; very wet inundated sites with low productivity were susceptible to water table rise and regeneration failure, but that higher productivity sites could be successfully regenerated with clearcutting (Erdmann et al. 1987). Work by Slesak et al. (2014) and Looney et al. (2017) in Minnesota USA supports this, as a group selection harvest with 20% removal of stand area was successful at maintaining water table dynamics and promoting the establishment of species other than black ash. However, the overall diversity of alternative species is generally low and encompasses less than 20% of relative stand density across a range of stand conditions (D'Amato et al. 2018). Similarly, D'Amato et al. (2018) reported on a series of silviculture trials (clearcutting, shelterwood, diameter-limit, single tree selection) established in Wisconsin starting in 1977. General conclusions from that assessment indicated that some level of canopy cover was required for the establishment of non-black ash tree species, which included red maple (*Acer rubrum* L.), yellow birch (*Betula alleghaniensis* Britton), and American elm (*Ulmus americana* L.). However, American elm is unlikely to reach large diameters due to the invasive Dutch elm disease (*Ophiostoma novo-ulmi*). It seems likely that the relative success of a given silvicultural approach will vary depending on differences in hydrology and site quality (e.g., nutrient availability), creating a need for evaluations of silvicultural outcomes across a wide range of sites to inform development of recommendations (see Wisconsin Department of Natural Resources 2018).

The overall goal of this study is to assess natural regeneration dynamics in black ash forests across three silvicultural systems. We focus on the establishment phase to assess early dynamics in the period 5 to 11 years following harvest. Our specific objective was to quantify the structure and composition of regeneration across three silvicultural systems (clearcut, group selection and diameter-limit). We expect that this information will be utilized by land managers to assess the effectiveness of different silvicultural regeneration harvests in maintaining forest communities prior to widespread infestation of EAB across Minnesota forests.

Methods

Study area

There are approximately 6.9 million hectares of forests in Minnesota, USA managed by multiple organizations including state, federal, county, private industrial, private non-industrial, and tribal governments. As of 2017, Minnesota contains 218 million ash trees larger than 12.7 cm DBH, some 8.4% of all forestland trees in the state (Hillard 2018). Ash is at least 50% of the total live tree volume on 444,000 hectares of forest land across the state and black ash alone ranks fifth as the most common tree across the state, representing 28 million cubic meters of timber volume (Hillard 2018). The vast majority of the black ash forest type is located across the central and northern parts of the state (Host et al. 2020). Currently in Minnesota, the majority of mortality from EAB has been restricted mostly to the southeastern portion of the state in and around major metropolitan areas. However, in 2016 a satellite EAB population was discovered in the urban area of Duluth, MN, which is the "gateway" to the state's northern forests that contain large expanses of black ash wetlands (Engelstad et al. 2019; Host et al. 2020). The relatively slow spread of EAB in Minnesota has likely been influenced by the state's low winter temperatures which can affect the insect's population dynamics (Christianson and Venette 2018) coupled with extensive public awareness efforts to limit EAB spread.

The climate of northern Minnesota is characterized by long, cold, snowy winters and short, cool summers. Average high temperatures in January and July are − 15.1 ± 8.2 °C and 18.9° ± 3.3 °C, respectively. However, low air temperatures can reach − 45 °C in the winter and be as high as 38 °C in the summer. Annual precipitation averages 78 cm with approximately one third falling as snow during the months of November through April (Sebestyen et al. 2011).

Much of Minnesota has been influenced by the most recent glacial activity and soil parent materials encompass a broad array of depositional features. These features influence the primary hydrogeomorphic settings where black ash typically occurs including large expansive complexes with perched water tables, floodplains, topographic low depressional areas, and transition zones between peatlands and uplands (Wright et al. 1969; Diamond et al. 2020). Soils range from deep organic peats (especially in depressional wetlands) to mineral soils derived from a range of parent materials overlain by shallow layers of muck, but all are poorly to very-poorly drained. Black ash forests are variable in size and range from small inclusions (< 0.1 ha) to large expansive stands

(> 100 ha). Sixteen black ash stands that were harvested between 2007 and 2013 were selected for this study (Table 1). Sampled stands were classified as black ash being the dominant overstory species and included a variety of different ownerships (Table 1). All harvesting of stands were completed as part of an organization's regular forest management activities. Harvesting of black ash stands can be difficult due to low market value, harvesting logistics (frozen ground harvesting, proximity to roads and mills), and limited information on silvicultural options to regenerate non-ash species. Due to these limitations, few black ash stands are harvested in a given year, limiting the candidate pool of stands we used to select our sites from. Given these constraints, it is likely the stands within the candidate pool and those selected in this study are more accessible than all black ash stands in Minnesota and the region. However, accessibility will be a major constraint in treating black ash and thus sites selected in our study represent stands that will likely be able to be treated for increasing resilience for EAB. Finally, many of the stands that were harvested were inventoried during the winter resulting in no information on the ecological classification system which is in part determined by the understory plant community.

Stands were separated into three silvicultural systems for evaluation: clearcut with reserves, diameter-limit harvests, and group selection. Forest Management Guidelines within the state of Minnesota recommend retention of 15–30 live trees per hectare following harvesting which results in a clearcut with reserves regeneration harvest (MFRC 2012). Hereafter, we will refer to clearcut with reserves as a clearcut. Diameter-limit harvests are the removal of all trees above a certain threshold (i.e., all trees greater than 18 cm will be harvested) (Nyland 2016), which ranged from 17.8 to 25.4 cm among our stands. Group selection is an uneven-aged silvicultural system that involves the creation of groups of gaps of variable sizes (Nyland 2016). Since stands treated with the group selection system were implemented as part of an organization's forest management activities the size of the groups varied; group opening ranged from 0.08 to 0.2 ha (Table 2). On average group opening composed approximately 1/3rd of the stand; we do not know if the remaining matrix was thinned (Table 2). When the gap size was larger than the plot size, plots were placed in the center of the gap. The diameter-limit harvest and the group selection sites selected for this study have received only one entry.

Given the limitations surrounding the number of available stands and the limited availability of pre-treatment data, we relied on previous research to inform our decisions regarding the grouping or separation of stands in each harvest method category. The clearcut stands were further divided into two site classes: clearcut rich and clearcut poor based on the Minnesota Division of Natural Resources (DNR) Forest Ecological Classification System (ECS) (Aaseng 2003). Within the ECS system, forest communities are delineated based the biotic and abiotic community; black ash is the dominant overstory of the Northern Wet Black Ash Swamp (WFn55) and Northern Very West Ash Swamp (WFn64). While these two systems are very similar, WFn55 is more likely to have mesic hardwood trees including *Populus* species, basswood (*Tilia americana*), and maple (*Acer* spp.) species. However, stands described as clearcut rich specifically noted the inclusion of mesic hardwood species. This was not noted for stands classified as clearcut poor in our study. The separation of the clearcut stands based on the ECS was done for two reasons: (1) this was the most common harvest method during this time period so we could select stands that had ECS data; and (2) previous research observed a change in the water table and impact on regeneration on poor black ash sites (Slesak et al. 2014). Due to the limited number of stands harvested with diameter-limit harvesting or group selection harvesting during this period and the lack of pre-harvest data collected, these systems could not be

Table 1 Site description of sixteen stands used in our study located across norcthern Minnesota, USA

Stand name	Latitude	Longitude	Silviculture systems[a]	Treatment year	Size (ha)	Number of plots	Soils
CCP_1	47.6367	− 93.1744	Clearcut (poor)	2013	4.4	5	Nashuwauk fine sandy loam
CCP_2	46.549295	− 92.848844	Clearcut (poor)	2009	46.5	11	Automba fine sandy loam
CCP_3	46.505159	− 92.534165	Clearcut (poor)	2009	15.0	9	Nemadji fine sand
CCP_4	46.57065	− 92.78637	Clearcut (poor)	2007	64.6	9	Automba fine sandy loam
CCR_1	47.208898	− 93.830295	Clearcut (rich)	2011	13.3	11	Nashwauk fine sandy loam
CCR_2	47.280128	− 94.437125	Clearcut (rich)	2010	8.5	4	Zimmerman loamy fine sand
CCR_3	47.785456	− 94.558448	Clearcut (rich)	2010	10.9	12	Shooker loam
CCR_4	47.341147	− 94.999932	Clearcut (rich)	2012	2.4	5	Mooselake and Lupton soil
DLH_1	47.121021	− 93.112664	Diameter limit	2007	6.5	8	Greenwood – Greenwood, ponded, complex
DLH_2	46.859499	− 95.269711	Diameter limit	2012	4.0	5	Epoufette sandy loam
DLH_3	46.96858	− 91.828129	Diameter limit	2013	4.3	5	Cuttre complex
DLH_4	47.075199	− 91.982515	Diameter limit	2012	4.4	5	Rifle soils
Group_1[b]	47.202768	− 91.546507	Group selection	2008	7.7	8	Wahbegon, depressional-Eldes complex,
Group_2[b]	46.541981	− 92.336478	Group selection	2012	21.4	8	Ontonagon silty clay
Group_3[b]	46.505982	− 93.090025	Group selection	2008	18.2	10	Mora fine sandy loam Ahmeek–Normanna–Cathro, depressionsonal
Group_4[b]	47.151294	− 91.75993	Group selection	2011	6.5	6	Complex

[a]Clearcut followed MN Forest Management Guidelines and includes the retention of 15–30 live trees per hectare following cutting which results in a clearcut with reserves regeneration harvest (MFRC 2012). The clearcut system was divided into rich and poor sites based on the MN Ecological Classification System. Diameter-limit harvests are the removal of all trees above a certain threshold (i.e., all trees greater than 18 cm will be harvested) (Nyland 2016). Group selection is an uneven-aged silvicultural system that involves the creation of groups of gaps of variable sizes

[b]Additional details on group selection treatments can be found in Table 2

Table 2 Additional details regarding stands treated with first entry of a group selection silvicultural system

Silvicultural system	Average group opening (ha)	Range of group opening sizes (ha)	Approximate percent of stand treated (%)
Group_1	0.10 (0.02)	0.08–0.12	35
Group_2	0.13 (0.1)	0.10–0.18	30
Group_3	0.20 (0.2)	0.10–0.25	30
Group_4	0.10 (0.02)	0.08–0.12	30

Location, stand size, soils, site index, and other variables can be found in Table 1

grouped based on ECS alone. Additionally, previous research noted smaller change in the hydrological regime after a group selection harvest (Slesak et al. 2014).

Sampling methods

All sixteen stands were sampled during the summer of 2018. This represents 5 to 11 years post harvest. No pretreatment data was collected prior to harvesting. With the exception of the group selection stands, a systematic sampling design was used. In the group selection systems, plots were located with a priori knowledge to fall within both the gap or group openings and within the forest matrix to capture the variability in species present. There were a minimum of five plots at each site with the exception of CCR_2 which only had four plots due to access issues from high levels of rain. The maximum number of plots was 12 (Table 1). Additional plots were added to both larger stands and stands with irregular boundaries to ensure adequate coverage.

At each plot, data were collected on the location (GPS) and physical site characteristics (percent canopy cover, depth of peat or muck layer, and physiographic description such as the presence of hummocks). Percent canopy cover was taken using a spherical densiometer at roughly breast height (1.27 m) and captures all vegetation greater than this height. A nested plot design was used to quantify vegetation. A 0.02 ha fixed radius circular plot was used for measuring woody individuals greater than 2.54 cm DBH. Overstory trees were defined as individuals greater than 10 cm dbh; in the clearcut and the gaps of the group selection treatment these would represent residual trees. Large saplings were defined as trees between 2.54 and 10 cm dbh; large saplings would include regeneration established after harvesting and advance regeneration. There are also large woody shrubs that can reach diameters greater than 2.54 cm but will never reach an overstory position (i.e. *Alnus*); these species were recorded but have been coded as shrubs. Within the overstory plot, species, status (live or dead), dbh, canopy position, crown ratio, and height of every 4th tree was measured. Any forest health concerns were noted. Three 0.0004 ha circular fixed radius plots located three meters from plot center at 0°, 120°, and 240° were used to measure tree and shrub regeneration. Tree and shrub regeneration was defined as any woody species greater than 0.3 m in height but less than 2.54 cm dbh. Trees were defined as an individual that could reach a future overstory position (dbh > 10 cm); woody shrubs were defined as individuals that would not reach overstory position (dbh < 10 cm dbh). The regeneration layer was tallied by species, status (live or dead), and height class (0.3 to 1.5 m or > 1.5 m). There was no attempt to classify individuals as stump or seed origin since both seed origin and stump spouting black ash are both vulnerable to EAB (Herms and McCullough 2014; Klooster et al. 2014); additionally, stump spouting does occur for oaks (*Quercus* spp.), basswood, and paper birch (*Betula papyrifera*). The broad height classes were used because when trees reach 1.5 m in height the terminal bud of the woody species is likely "safe" from browse from ungulates (i.e., white-tailed deer (*Odocoileus virginianus* Zimmermann) (Anderson et al. 2002). At the center of the regeneration layer subplots, a 1-m^2 quadrat was used to assess percent cover by vegetation type. Broad vegetation types included forbs, mosses/lichens, shrubs, trees, coarse woody debris, bare ground, and water. This level of detail on the sampled understory vegetation did not allow for further classification of the ECS of each stand.

Data analysis

Data were summarized at the stand level with the exception of the group selection stands. The group selection stands were sub-divided and summarized based on plots that fell in the gap/or group opening and those that fell in the matrix since the light environment and impact from harvest (or lack of harvest) influence the structure and composition of the overstory and regeneration layer. Density measures were calculated for trees per hectare (TPH) and basal area per hectare (m^2 ha^{-1}) for overstory and large saplings and TPH for the regeneration. Differences among the silviculture systems were analyzed in R using analysis of variance (R Core Team 2019). Assumptions of normality and homogenous variance were confirmed with visual examination of the residuals. An alpha level of $p<0.1$ was used due to the high variability within and among field sites, and post hoc comparisons were made using Tukey HSD. Relationships between regeneration abundance and environmental and site variable were explored using linear regression (Fig. 1).

Additional analysis was completed on the large saplings between 2.54 and 10 cm dbh to explore structure and composition. This cohort represented new seedlings established or advance regeneration released after harvesting. Additionally, given their size, these individuals are representative of the future forest since individuals are well established compared to the seedling class which may be more ephemeral (Madsen and Larsen 1997).

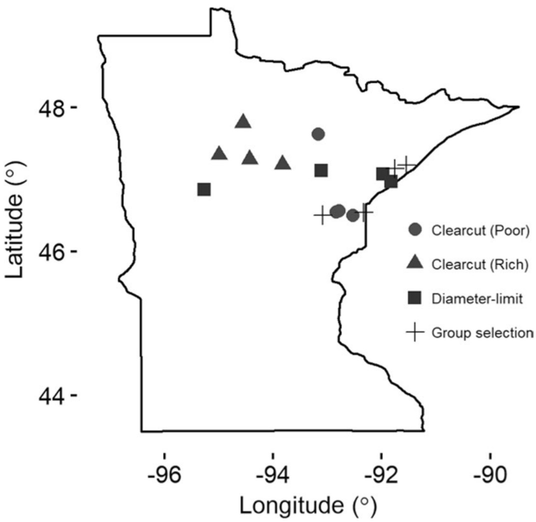

Fig. 1 Distribution of stands by harvest type across the state of Minnesota. Additional details regarding on individual stands can be found in Table 1

Results

Tree and shrub regeneration

Five to eleven years after harvests, there was high levels of tree regeneration (> 1 m height, < 2.54 cm dbh) across all silvicultural systems in black ash stands in northern Minnesota (Table 3). There was no relationship between time since harvest and tree regeneration ($p = 0.99$). Total tree regeneration averaged 16,766 ± 7618 (mean ± standard error) TPH within the matrix of the group selection to 37,853 ± 11,560 TPH in the clearcut (rich) system (Table 3). There was high variability within the silvicultural systems and no significant differences were detected in total tree regeneration ($p = 0.246$; $F_4 = 1.522$). Shrub regeneration was also highly variable; there were no significant differences among the different silvicultural systems ($p = 0.544$; $F_4 = 0.706$) (Table 3).

A total of thirty tree and shrub species were observed in the regeneration layer ("Appendix"). Black ash was the most dominant tree species in the regeneration layer; it composed 25% to 42% of regenerating individuals on average across all silvicultural systems (Table 4; Fig. 2a). There was no significant difference among silvicultural systems in the percent of black ash regeneration ($p = 0.74$; $F_4 = 0.49$) or the average TPH ($p = 0.83$; $F_4 = 0.36$) (results not shown). Red maple and *Populus* species—trembling aspen (*Populus tremuloides* Michx), bigtooth aspen (*Populus grandidentata* Michx.), and balsam poplar (*Populus balsamifera* L.) were two of the most other common tree species regenerating (Fig. 2a). *Alnus* spp., *Cornus* spp., and *Corylus* spp. were observed across all silvicultural systems to varying degrees (Fig. 2b). Other conifer, hardwoods, and shrub species composed on average less than 10% of the total density across all silvicultural treatments.

Composition and Structure of Large Saplings

Twenty-seven woody tree and shrub species between 2.54 cm and 10 cm dbh were observed across all sites and silvicultural systems ("Appendix"). The vast majority of those stems were composed of six species: black ash, *Alnus* spp., and three species within the *Populus* genus (Fig. 3a). Black ash was a large component of all sites ranging from an average of 175 ± 37 TPH in the clearcut (poor) to 763 ± 301 TPH in the clearcut (rich). There was no significant difference among silvicultural systems for average black ash TPH ($p = 0.41$; $F_4 = 1.07$), black ash basal area ($p = 0.50$; $F_4 = 0.73$); percent black ash TPH ($p = 0.36$; $F_4 = 0.83$) and percent black ash basal area ($p = 0.49$; $F_4 = 0.74$) also were not significantly different among silvicultural systems (Table 4).

Alnus spp. was a relatively consistent component of all sites with approximately 85 to 300 TPH. There was greater variability in the number of stems of the *Populus* genus across sites. This ranged from a high of 1027 ± 330 TPH in the clearcut (rich) to a low of 3 ± 3 TPH in the matrix of the group selection (Fig. 3a). Other hardwood and conifer species varied but were generally less than 150 TPH except for other hardwoods in the clearcut rich sites and other conifers in the group selection matrix (Fig. 3a). There were no significant differences for each species or species groups across silvicultural systems.

Site characteristic and relationships to large saplings

Site characteristics were highly variable and had large standard errors; there were no significant differences observed among the silvicultural treatments (Table 5). Average muck

Table 3 Mean values of stand structural characteristics by treatment (standard errors in parenthesis)

	Clearcut (poor)	Clearcut (rich)	Diameter-limit	Group selection (gaps)	Group selection (matrix)
Live overstory (dbh > 10 cm)					
Diameter (cm)	7.22^{a} (1.31)	12.64^{ab} (1.21)	17.48^{b} (1.18)	8.6^{ab} (3.77)	22.92^{bc} (3.54)
TPH	70.8^{a} (27.4)	196^{a} (28.1)	737.2^{b} (170.8)	52.3^{a} (38.6)	530.2^{b} (127.6)
Basal area ($m^2 ha^{-1}$)	2.52^{a} (1.1)	3.8^{a} (0.6)	19.1^{b} (4.4)	1.7^{a} (1.3)	20.9^{b} (2.0)
Live large saplings (dbh 2.54–10 cm)					
Diameter (cm)	3.71^{a} (0.24)	3.88^{ab} (0.07)	5.03^{bc} (0.24)	3.21^{a} (0.39)	5.14^{bc} (0.51)
TPH	1066.3 (535.7)	2391.1 (450.5)	1237.2 (215.2)	1232.3 (830.1)	1429.8 (293.9)
Basal area ($m^2 ha^{-1}$)	2.0 (1.2)	3.3 (0.6)	2.8 (0.6)	1.7 (1.4)	3.22 (0.9)
Live small saplings and seedlings (> 1 m height < 2.54 cm dbh)					
TPH	16,839.6 (1771.5)	37,852.9 (11,559.8)	17,197.9 (5044.8)	21,441.0 (7052.1)	16,766 (7618.1)
Woody shrubs (> 1 m height < 2.54 cm dbh)					
TPH	11,818.6 (5507.2)	6546.4 (2528.7)	13,854.2 (1510.9)	11,691.0 (5102.8)	10,887.7 (1390.5)

Letters represent significant differences among treatments. Overstory trees are defined as trees ≥ 2.54 cm dbh. Understory trees are defined as trees < 2.54 cm but > 0.3 m in height. Understory shrub species are non-woody tree species

Table 4 Average relative percent density of overstory and regenerating black ash (FRNI) by treatment with standard errors in parentheses

	Percent FRNI overstory BA	Percent FRNI overstory TPH	Percent FRNI large sapling BA	Percent FRNI large sapling TPH	Percent FRNI regenerating TPH
Clearcut (poor)	26.8[a] (5.8)	26.8[ab] (5.6)	45.7 (11.7)	46.0 (11.3)	31.2 (2.1)
Clearcut (rich)	39.3[ab] (6.9)	39.3[ab] (7.0)	41.5 (13.7)	39.3 (14.0)	42.4 (19.8)
Diameter-limit	77.1[bc] (4.4)	79.3[c] (5.4)	59.4 (5.1)	52.1 (3.8)	34.6 (11.6)
Group selection (gaps)	12.0[a] (7.1)	11.9[a] (7.1)	30.5 (20.4)	29.0 (21.2)	25.1 (5.4)
Group selection (matrix)	55.9[b] (14.0)	59.7[b] (14.0)	42.0 18.1)	39.9 (15.4)	33.4 (8.7)

Letters represent significant differences among treatments

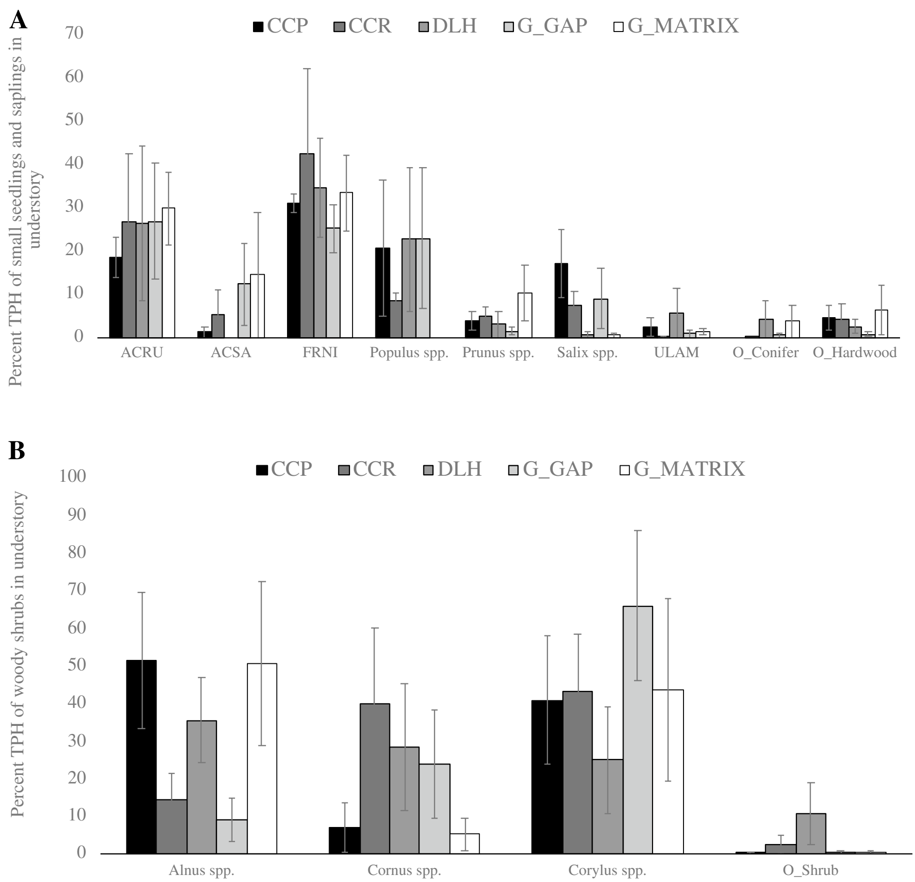

Fig. 2 **a** Percent composition of tree regenerating individuals by silvicultural system. **b** Percent of composition of shrub species by silvicultural species. Many species composed less than 5% of the composition and were grouped into either other hardwoods, other conifers, or other shrubs. A full list of species is located in "Appendix"

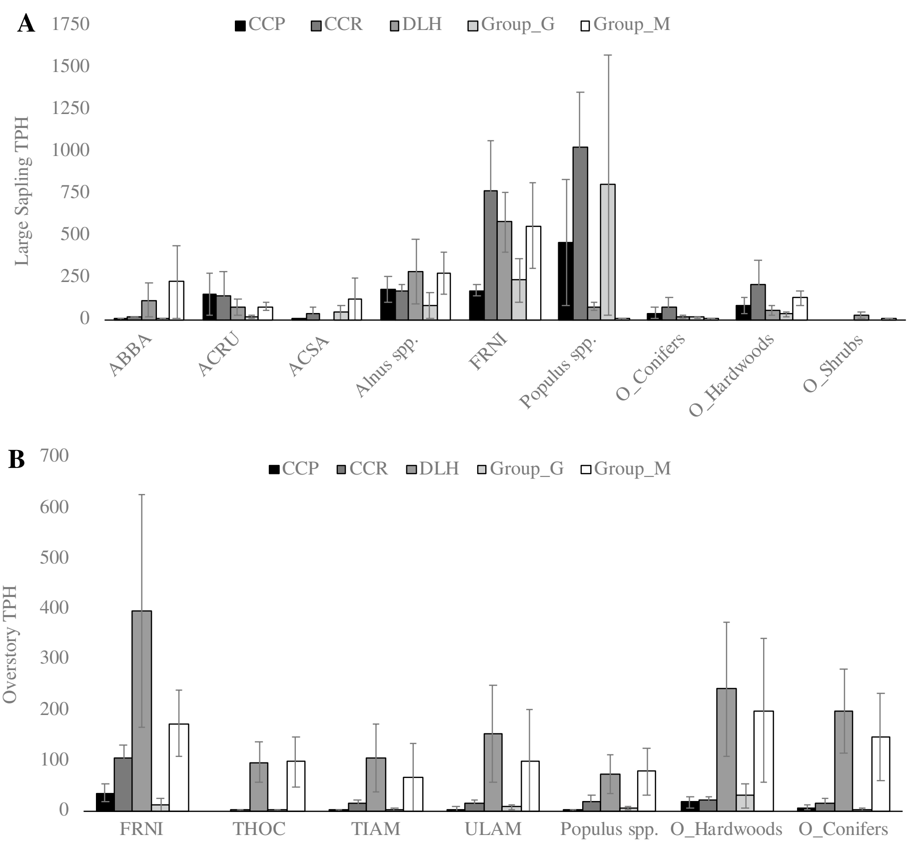

Fig. 3 **a** Average stems per hectare and associated standard errors of large trees and shrubs with a dbh between 2.54 and 10 cm. **b** Average stems per hectare and associated standard errors of overstory trees (> 10 cm). Many species had on average less than 150 woody stems per hectare and were grouped into either other hardwoods, other conifers, or other shrubs. A full list of species is located in "Appendix". No significant differences were observed for any individual species among treatments

depth ranged from 30.07 ± 22.05 cm in the gaps of the group selection to 55.50 ± 24.66 cm in the matrix of the group selection (Table 5). Percent standing water ranged from 16.75 ± 15.13% in the matrix of the group selection to 1.45 ± 0.95% in the clearcut rich stands.

While site characteristics did not vary significantly among sites, there was a significant relationship between the most dominant species (black ash) and species group (*Populus* genus) and average depth to muck (Fig. 4). The relationship was negative between species in the *Populus* genus and increasing muck depth ($p < 0.03$; $F_{18} = 5.40$, $R^2 = 0.19$), versus positive for black ash ($p = 0.002$ $F_{18} = 13.78$, $R^2 = 0.40$).

Overstory structure and composition

As expected significant differences were observed in overstory trees (dbh > 10 cm) for TPH, basal area, and average diameter across the silvicultural systems (Table 3). The

Table 5 Average site characteristics of black ash stands with standard errors in parentheses

	Canopy cover (%)	Hummocks (%)	Average depth to muck (cm)	Bare ground (%)	Down dead wood (%)	Standing water (%)
Clearcut (poor)	10.29 (1.60)	42.72 (9.35)	54.57 (8.32)	0.00 (0.00)	17.30 (4.49)	10.47 (3.96)
Clearcut (rich)	11.63 (3.56)	17.12 (2.54)	35.39 (11.65)	1.36 (0.99)	18.90 (5.52)	1.45 (0.95)
Diameter-limit	18.71 (1.14)	33.31 (11.36)	47.39 (14.83)	1.71 (0.73)	12.18 (1.25)	6.82 (5.14)
Group selection (gaps)	11.72 (2.02)	20.76 (11.22)	30.07 (22.05)	0.31 (0.31)	11.38 (2.93)	11.50 (11.5)
Group selection (matrix)	17.93 (2.80)	32.75 (14.94)	55.50 (24.66)	3.13 (2.36)	13.08 (1.93)	16.75 (15.13)

No significant differences were observed among sites

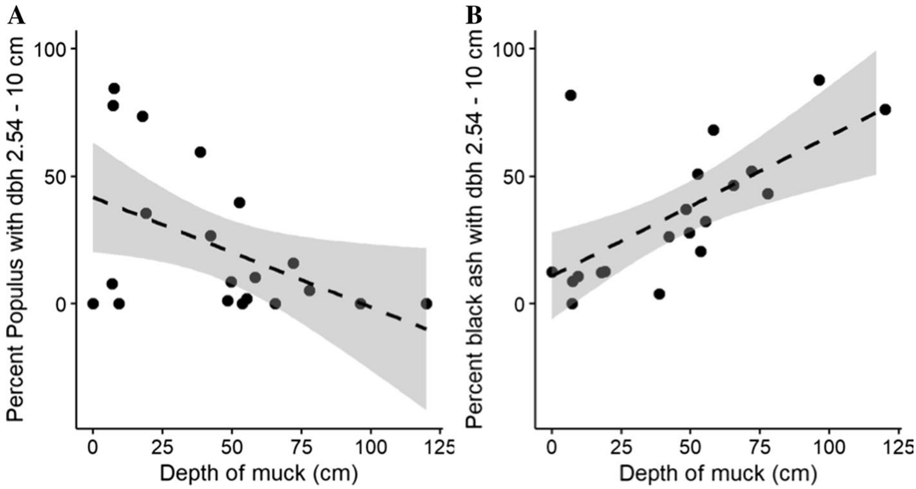

Fig. 4 **a** Relationship between the depth of muck (cm) and the percentage of TPH in the *Populus* genus between 2.54 and 10 cm and **b** relationship between the depth of muck (cm) and the percentage of black ash TPH between 2.54 and 10 cm in dbh across all black ash treatment sites in northern Minnesota

average diameter of overstory trees in the matrix of the group selection (22.92 ± 3.54 cm) and the diameter limit (17.48 ± 1.18 cm) were significantly larger than overstory trees in the clearcut poor site (7.22 ± 12.64 cm) ($p = 0.003$; $F_4 = 6.71$). The diameter-limit harvest and the matrix of the group selection had significantly greater average overstory TPH ($p < 0.001$; $F_4 = 9.47$) and average overstory basal area ($p < 0.001$; $F_4 = 17.53$) compared to the clearcut rich, clearcut poor, and gaps of the group selection (Table 3). There was no relationship between overstory basal area and tree regeneration density ($p = 0.25$) (Fig. 5).

Overstory black ash was observed in all silvicultural systems (Table 4; Fig. 3b). Other common species include northern white cedar, American basswood, American elm, and *Populus* species (Fig. 3b). There were no significant differences observed among any of the species or species groups and silvicultural systems. A total of twelve other species (five

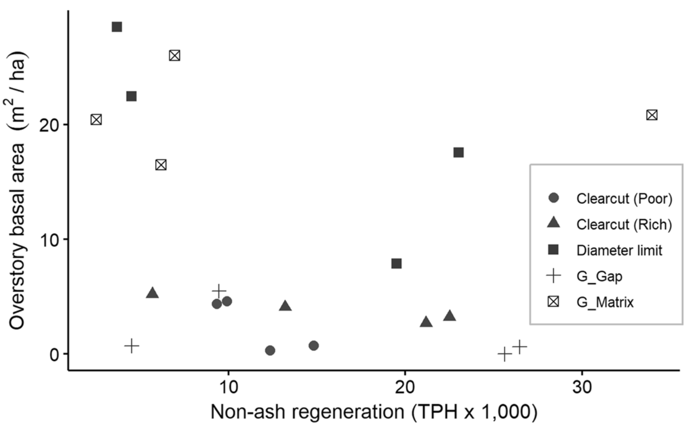

Fig. 5 No relationship was observed between overstory basal area (m^2 ha^{-1}) and regenerating non-black ash tree seedling TPH measured in 2018 across all black ash sites in northern Minnesota ($p = 0.25$)

conifers and seven hardwoods) were observed in lesser amounts across silvicultural systems ("Appendix"). Percent black ash overstory basal area ($p < 0.001$; $F_4 = 9.96$) and TPH ($p < 0.001$; $F_4 = 9.37$) were significantly different among silvicultural systems (Table 4). The diameter-limit harvesting retained a greater percentage of black ash for basal area (77.1 ± 4.4%) and TPH (79.3 ± 5.4%) compared to the percent black ash basal area (12.0 ± 7.1%) and TPH (11.9 ± 7.1%) in the gaps of the group selection (Table 4).

Discussion

There is urgent need to identify silvicultural techniques that can be used to maintain and potentially transition black ash stands to more diverse and resilient communities prior to EAB arrival. However, research is limited on how black ash stands will respond to EAB outbreaks (D'Amato et al. 2018). Across all silvicultural systems in our study, there were some broad similarities. The regeneration response 5 to 11 years post-harvest was high with an average of over 15,000 stems per hectare of trees (Table 3). The regeneration response of non-black ash tree species did not vary based on the amount of residual overstory stems (Fig. 5). This is an important consideration since residuals can be used to maintain the hydrological regime (Slesak et al. 2014) without impacting recruitment of new individuals in the short term. In the regeneration layer (< 2.54 cm dbh), black ash was the most abundant tree species. This strong regeneration response of natural black ash regeneration after harvesting is in line with other studies (Davis et al. 2017; Looney et al. 2017; D'Amato et al. 2018) and is likely attributed to prolific stump spouting following harvesting.

While black ash was an important component across all the size classes, there was high variability in the regeneration response of the sixteen black ash stands sampled. This variability was observed in both the amount of regeneration in seedlings, small saplings, and large saplings (2.54–10 cm dbh). The high variability among silvicultural systems highlights the variability of site characteristics within an individual stand, as observed through large standard errors (Table 5). In Minnesota, there are two dominant native plant communities for black ash in the ecological classification system (ECS); Wet Ash forests and Very Wet Ash forests (Aaseng 2003). These ECS forest types vary in soil moisture and nutrient availability and may be useful criteria in determining appropriate silvicultural strategies (D'Amato et al. 2018). However, given the historic lack of management in black ash forests coupled with difficult site access during the growing season (when vegetation can be identified), the ECS designation may not be known for many stands, resulting in some limitations including inventorying during the growing season when assess may be difficult. Based on our findings, a simple measure of muck depth which can be measured outside of just the growing season, including winters when non-frozen conditions are present may provide another tool for foresters to use when developing silvicultural prescription.

Species within the genus *Populus* were observed regenerating across all silvicultural systems. In the Lake States Region, *Populus* species, especially aspen, regenerates so prolifically that it once was considered a weed (Cleland et al. 2001) which is very different than the regeneration dynamics of aspen in the Western United States (Cleland et al. 2001; Long and Mock 2012). Aspen in the Lake States are able to regenerate across a wide range of conditions including aggregated retention harvests (Curzon et al. 2017). Greater densities of species in the genus *Populus* were associated with thinner layers of muck and mineral soils compared to thicker layers (Fig. 4a). There were three stands that had thin layers of muck but low *Populus* species densities. Two of the three sites were in the matrix of the group selection and the DLH; the third site was in a gap of a group selection. The two sites within the matrix likely had less than ideal light environments for *Populus* regeneration since *Populus* species are shade intolerant (Burns and Honkala 1990).

Fitting the silvicultural system with the desired future conditions is important in black ash stands. The clearcut regeneration system in black ash stands on richer and poorer sites were similar in many structural features (Table 1). However, there were key differences in the composition of regeneration, especially in the large saplings. On sites that were classified as richer (having a mesic hardwood component), *Populus* species averaged over 1000 stems per hectare compared to over 450 stems per hectare on average on poorer sites. In other studies conducted on poorer-quality black ash stands (black ash stands classified as very wet forests), the clearcut regeneration system resulted in significant changes in hydrology and elevated water tables, generally causing much wetter conditions (Slesak et al. 2014; Diamond et al. 2018). Survival of artificial regeneration was low and natural regeneration was mostly black ash with a high increase in shrub species like alder (Looney et al. 2017). This general response may make natural resource managers hesitant to use the clearcut system. However, in our study, the clearcut system on richer sites created a stand likely to be more resilient to future EAB impacts. We define resilience at the stand level as desirable future composition and structure that is less susceptible to forest disturbance associated with EAB (DeRose and Long 2014). The higher average TPH of *Populus* species would allow the site to maintain forest cover during and after EAB establishment, and also allow for increased dominance of this species over time given its clonal ability. However, changing climatic conditions and shifting disturbance regimes are likely to decrease *Populus* species fitness and growth in the future (Boucher et al. 2019; Dey et al. 2019). Note that the clearcut rich sites typically had thinner layers of muck (36 cm on average), which was associated with low surface water coverage compared to the other silvicultural systems (Table 5). Because of this, the hydrologic regime of these sites is probably much drier than typically observed in black ash wetlands where an average depth to muck was 54.5 cm. Additionally, there may have been other factors of the sites pre-treatment or from the surrounding landscape that contributed to differing regeneration response between the clearcut rich and clearcut poor sites that were not measured as part of our study.

The use of uneven-aged regeneration methods like group selection provided the opportunity for regenerating both within the gaps and in the matrix (Leak and Filip 1977; Nyland 2016). This type of silvicultural system may be particularly well suited for very wet black ash stands with deep muck layers. The group openings provide a range of light conditions with portions of the opening having a very high light environment required for shade intolerant species including species in the *Populus* genus to regenerate (Poznanovic et al. 2014). Additionally, the openings provide diffuse light into the matrix and can allow for mid-tolerant species like red maple the opportunity to regenerate. Group selection harvests have also shown promise in the survival of artificial regeneration. For example, Looney et al. (2015) observed that swamp white oak (*Quercus bicolor* Willd.), Manchurian ash (*Fraxinus mandshurica* Rupr.), and American elm displayed greater than 75% survival in a group selection treatment dominated by black ash 3 years after planting. However, planting will also likely require protection from white-tailed deer browse, an added investment that may not be feasible across Minnesota's expansive ash forests (White 2012). Fortunately, at least for black ash and *Populus*, these naturally-regenerating species are generally considered only moderately susceptible to browsing by white-tailed deer. However, unlike the clearcut system, a group selection harvest treats only a portion of the stand and would require multiple entries to convert stand composition over time. It is also still unclear how the size of the group opening may influence regeneration response. We saw no relationship between regeneration response and overstory tree basal area. However, as gap size increases especially on poorer sites there may be a threshold where a shift in hydrologic regime could happen. Other aspects to consider with a group selection harvest is if they are also more logistically complicated since some level of marking is required, requires a logger to be more conscious of residual trees, requires more planning for skid trail layout, and may result in additional soil compaction or rutting due to repeated entries.

While we have presented diameter-limit harvest as a silvicultural system in our study, it is generally regarded as high-grading and not recommended for management (Kenefic et al. 2005; Bohn et al. 2011; Nyland 2016). In the context of EAB, the removal of the largest diameter black ash was hypothesized to slow the spread of EAB if certain amount of phloem or basal area could be reduced or removed (Eberhart et al. 2008). However, with further research, EAB was observed to be able to infest trees as small as three cm dbh (Klooster et al. 2014). Due to this, phloem reduction/diameter-limit harvests are not a recommended silvicultural system for EAB management. High-grading in northern hardwood systems can result in a reduction in quality with loss of long-term log value and grade and fewer silvicultural options for the future (Kenefic and Nyland 2005). It is also hypothesized to reduce genetic fitness but this has been difficult to test (but see Hawley et al. 2005). Additionally, while the DLH stands had a similar residual overstory basal area and TPH to the matrix of the group selection (Table 3), there can be important shifts in species composition. In a long-term study in a northern hardwood forests in the Upper Peninsula of Michigan, the DLH treatments shifted the herbaceous community and resulted in an increase in weedy and invasive species compared to single tree selection treatments (Campione et al. 2012). Given the above and the lack of any apparent benefit of DLH on regeneration, we do not think DLH is a viable option to diversify black ash forests.

Conclusion

The expansion of EAB across the Great Lakes region threatens the numerous ecological and cultural resources that black ash stands provide (Costanza et al. 2017; D'Amato et al. 2018; Kolka et al. 2018). While high in ecological and cultural value, there is less of a monetary value for black ash, which increases the need for natural resource managers and foresters to be creative in developing cost-effective silvicultural systems. While group selection systems in black ash would ensure diverse regeneration and reduce the potential for "swamping" out, it also only treats a portion of the stand, requiring multiple entries which is not likely feasible for many black ash stands. Our study observed high regeneration of *Populus* species after a clearcut silvicultural system on sites classified as richer. The clearcut system when used on appropriate sites such as those with a low muck depth would likely have the highest economic return and the lowest cost to agencies in terms of timber harvesting logistics and diversifying regeneration. However, utilizing a clearcut system in poor black ash stands with a high muck depth may likely have long-term consequences including the potential loss of forest cover (Zhang et al. 2019). Additionally, our study highlights the importance of assessing the site prior to developing a silvicultural prescription; variables such as depth to muck, the ECS description, and current species on site and in the surrounding landscape can all aid in determining an appropriate silvicultural system.

Even with extreme winter temperatures which may slow impacts from EAB, EAB will continue to spread and fundamentally alter black ash wetland forests (Cuddington et al. 2018). To address this threat, natural resource managers should focus on developing resilient forests which can maintain forest cover after EAB impacts, with focus on increasing species diversity prior to EAB arrival when possible (D'Amato et al. 2018). There is no one silver bullet. Rather, foresters must understand the underlying stand characteristics of the black ash stands they are managing to prescribe appropriate treatments. In our study, the density of overstory residuals were not related to the regeneration response which can allow foresters flexibility in designing the size and the shape of the openings to best fit the site. In regions that have the flexibility and time to prepare for future forest health threats, silvicultural treatments can be prescribed that promote the natural regeneration of non-host species that exist in the stand.

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Appendix: Full list of woody trees and shrubs observed in each of the three layers. Many rare species were observed infrequently and in low abundances and were grouped into a hardwood, conifer, or shrub category

Species scientific name	Species common name	Species code	Present in the understory (< 2.54 cm dbh)	Understory classification	Present in the large sapling class (2.54–10 cm dbh)	Overstory classification	Present in the overstory (> 10 cm dbh)
Abies balsamea (L.) Mill.	Balsam fir	ABBA	X	Conifer	X	Conifer	X
Acer negundo L.	Boxelder	ACNE		Hardwood	X	Hardwood	
Acer rubrum L.	Red maple	ACRU	X	Red maple	X	Hardwood	X
Acer saccharum Marshall	Sugar maple	ACSA	X	Sugar maple	X	Hardwood	X
Acer spicatum Lam.	Mountain maple	ACSP	X	Shrub	X	Hardwood	
Alnus spp.	Alder	ALNUS	X	Shrub	X	Alnus	
Amelanchier spp.	Service berry	AMSP	X	Shrub	X	Hardwood	

Species scientific name	Species common name	Species code	Present in the understory (< 2.54 cm dbh)	Understory classification	Present in the large sapling class (2.54–10 cm dbh)	Overstory classification	Present in the overstory (> 10 cm dbh)
Betula alleghaniensis Britton	Yellow birch	BEAL	X	Hardwood	X	Hardwood	X
Betula papyrifera Marshall	PAPER birch	BEPA	X	Hardwood	X	Hardwood	X
Cornus spp. L	Dogwood	CORNUS	X	Shrub			
Corylus spp.	Hazel	COSP	X	Shrub	X	Hardwood	
Crataegus spp. L.	Hawthron	CRSP	X	Shrub			
Fraxinus nigra Marshall	Black ash	FRNI	X	Black ash	X	Black ash	X
Fraxinus pennsylvanica Marshall	Green ash	FRPE	X	Hardwood			
Larix laricina (Du Roi) K. Koch	Tamarack	LALA			X	Conifer	X
Ostrya virginiana (Mill.) K. Koch	Ironwood	OYVI	X	Hardwood	X	Hardwood	X
Picea glauca (Moench) Voss	White spruce	PIGL	X	Conifer	X	Conifer	X
Picea mariana (Mill.) Britton, Sterns & Poggenb.	Black spruce	PIMA	X	Conifer	X	Conifer	X
Pinus strobus L.	Eastern white pine	PIST		Conifer	X	Conifer	X
Populus balsamifera L.	Balsam poplar	POBA	X	Populus spp.	X	Populus spp.	X
Populus spp.	Aspen	POSP	X	Populus spp.	X	Populus spp.	X
Prunus spp.	Cherry	PRSP	X	Hardwood	X	Hardwood	

Species scientific name	Species common name	Species code	Present in the understory (< 2.54 cm dbh)	Understory classification	Present in the large sapling class (2.54–10 cm dbh)	Overstory classification	Present in the overstory (> 10 cm dbh)
Quercus alba L.	White oak	QUAL	X				
Quercus bicolor Willd.	Swamp white oak	QUBI	X	Hardwood	X	Hardwood	X
Quercus macrocarpa Michx.	bur oak	QUMA	X	hardwood	X	hardwood	X
Quercus rubra L.	Northern red oak	QURU	X	Hardwood			
Rhamnus cathartica L. *	Common buckthorn	RHCA	X	Shrub			
Salix spp.	Willow	SALIX	X	Hardwood	X	Hardwood	
Sambucus spp.	Elderberry	SASP	X	Shrub	X	Hardwood	
Thuja occidentalis L.	Northern white cedar	THOC			X	Conifer	X
Tilia americana L.	American basswood	TIAM	X	Hardwood	X	Hardwood	X
Unknown hardwood					X	hardwood	
Ulmus americana L.	American elm	ULAM	X	Hardwood	X	hardwood	X
Zanthoxylum americanum Mill. *	Common prickly ash	ZAAM	X	Shrub			

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