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Methods to Improve Survival and Growth of Planted Alternative Species Seedlings in Black Ash Ecosystems Threatened by Emerald Ash Borer

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Abstract: Emerald ash borer (EAB) continues to spread across North America, infesting native ash trees and changing the forested landscape. Black ash wetland forests are severely affected by EAB. As black ash wetland forests provide integral ecosystem services, alternative approaches to maintain forest cover on the landscape are needed. We implemented simulated EAB infestations in depressional black ash wetlands in the Ottawa National Forest in Michigan to mimic the short-term and long-term effects of EAB. These wetlands were planted with 10 alternative tree species in 2013. Based on initial results in the Michigan sites, a riparian corridor in the Superior Municipal Forest in Wisconsin was planted with three alternative tree species in 2015. Results across both locations indicate that silver maple (*Acer saccharinum* L.), red maple (*Acer rubrum* L.), American elm (*Ulmus americana* L.), and northern white cedar (*Thuja occidentalis* L.) are viable alternative species to plant in black ash-dominated wetlands. Additionally, selectively planting on natural or created hummocks resulted in two times greater survival than in adjacent lowland sites, and this suggests that planting should be implemented with microsite selection or creation as a primary control. Regional landowners and forest managers can use these results to help mitigate the canopy and structure losses from EAB and maintain forest cover and hydrologic function in black ash-dominated wetlands after infestation.

Keywords: EAB; *Fraxinus nigra*; underplanting; mitigation; microsite

1. Introduction

Since the confirmation of emerald ash borer ((EAB) *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae)) in 2002 [1,2], quarantine zones and other management recommendations have not slowed the pace of EAB infestation and it has spread across 31 American states and two Canadian provinces (Emerald Ash Borer Information Network 2017). It is projected that the invasive exotic insect will continue to move across North America, continuing to alter forest landscapes by killing host ash (*Fraxinus* spp.) trees [3]. While some studies indicate that there are certain ash trees that may be resistant despite the infested condition of the surrounding forest [4], EAB-induced mortality in ash species in infested forests is approximately 99% [5]. The outlook for North American ash trees is bleak as the confirmed range of EAB continues to expand. One forested ecosystem that is severely impacted by EAB's continued expansion is black ash (*Fraxinus nigra* Marsh) wetlands.

Black ash grows in three ecotypes of the Upper Great Lakes region: depressional headwater catchments, wetland complexes, and riparian corridors [6,7]. All three of these ecotypes have prolonged periods of inundation or saturation throughout the growing season, the time of year when precipitation and temperature are conducive to plant growth. These wetland forest systems provide many ecosystem services. For example, black ash forested wetlands provide habitat and food sources for game birds, small animals, and deer [7], the canopy reduces heat input into streams [8,9], and the root structure maintains soil integrity during rain events, reducing erosion and sediment deposition downstream [10,11]. Current theories predict that cover type changes after EAB infestation will lead to loss of the tree canopy on the landscape and forested wetlands in the short-term will become dominated by a robust herbaceous community [12] and in the long-term possibly a shrub layer consisting of alder (*Alnus* spp.) [13,14].

Planting alternative species within black ash wetlands may be an approach to shift forest composition towards one that will be more resilient to EAB, thereby maintaining ecosystem services provided by forested wetlands. However, artificial regeneration within northern wetlands is a difficult task because of the unique conditions and climate stresses on seedlings [15,16]. For instance, a seedling planted within the region will endure a dramatic annual temperature swing and periods of time when standing water is prevalent. A recent study in northern Minnesota investigated planting in black ash wetland complexes in tandem with forest management practices [17], and their results highlighted a low survivorship among seedlings.

In this study, we used simulated EAB infestations to determine the impacts of EAB on tree seedling survival and used the initial results to subsequently test alternative planting techniques in uninfested ash forests. Our objectives were to (i) compare survival rates among deciduous and coniferous tree seedlings in black ash wetlands where manipulated overstory treatments reflected the timing of EAB infestation, and (ii) compare microsite and herbivory treatments to inform best practices for future plantings to mitigate EAB impact on forest canopy and structure.

2. Materials and Methods

This study consisted of three black ash wetlands that were part of an overstory manipulation study located on the Ottawa National Forest (ONF) and one uninfested black ash riparian corridor located on the Superior Municipal Forest (SMF) (Figure 1). There was some overlap in alternative species planted and details for each forest are presented below.

Figure 1. Map of the Great Lakes region with the three study locations in the Ottawa National Forest (●), in the western Upper Peninsula of Michigan, and the one study location in the Superior Municipal Forest (▲), in northwestern Wisconsin. The shaded region is the Great Lakes Watershed with United States and Canadian boundaries.

2.1. Ottawa National Forest Site Description

Three depressional wetland study sites were located in the Ottawa National Forest of the western Upper Peninsula of Michigan, USA (Figure 1, ●). Study site elevations ranged from 371 to 507 m, areas ranged from 0.25 to 1.2 ha, and soils were comprised of Histosols with the depth to clay lens or bedrock between 40 and 480 cm (Table 1). Mean annual precipitation was 836 mm and mean temperatures ranged from −15.7 °C in January to 18.1 °C in July. Study site canopies were dominated by black ash with lesser amounts of red maple (*Acer rubrum* L.), yellow birch (*Betula alleghaniensis* Britton), northern white cedar (*Thuja occidentalis* L.), and balsam fir (*Abies balsamea* L. (Mill)).

Table 1. Treatment and planting years, soil type [18], elevation, and canopy characteristics on the Ottawa National Forest (ONF) and Superior Municipal Forest (SMF) study wetlands.

Site	Percent Canopy Black Ash (%)	Planting Year	Soil Type	Elevation (m)	Canopy Openness (%)
ONF Control	48	2013	Woody peat Histosol	507	19.7
ONF Girdle	88	2013	Woody peat Histosol	499	16.5
ONF Ash-Cut	38	2013	Woody peat Histosol	371	6.6
SMF	90	2015	Arnheim mucky silt loam or Udifluvents	183	Closed–open

2.2. Ottawa National Forest Study Design

Treatments in the three wetlands were an untreated control (“Control”), girdling (“Girdle”), and felling of black ash (“Ash-Cut”). All black ash greater than 2.5 cm in diameter were treated in the Girdle and Ash-Cut wetlands. This is a similar design to a sister-study [12] and our intention for the Girdle treatment was to simulate the short-term impacts of an EAB infestation, while the Ash-Cut treatment simulated the long-term impacts of EAB infestation [1].

Ottawa National Forest study wetlands were planted with ten tree species suitable for saturated soils in summer 2013 (Table 2). Seedling ages ranged from two to four years and were purchased from the USDA (United States Department of Agriculture) Forest Service J.W. Toumey Nursery in Watersmeet, MI, USA. A series of ten transects were established across each wetland and seedlings were planted in pairs in high (hummock) and low (hollow) planting microsites within 1 m every 2 m along each transect, totaling 60 trees of each species in each wetland. Seedings were measured each year of the study during the last week of July.

Table 2. Ottawa National Forest species and seedling ages and planting stock type (BR—bare root, P—plug).

Common Name	Scientific Name	Age (Years)	Stock Type
American elm	*Ulmus Americana* L.	2	P
basswood (linden)	*Tilia americana* L.	3	BR
burr oak	*Quercus macrocarpa* Michx.	3	BR
red maple	*Acer rubrum* L.	2	BR
silver maple	*Acer saccharinum* L.	4	BR
yellow birch	*Betula alleghaniensis* Britton	2	P
balsam fir	*Abies balsamea* (L.) Mill	2	BR
black spruce	*Picea marina* (Mill.) Britton	2	P
northern white cedar	*Thuja occidentalis* L.	2	P
tamarack	*Larix larcinia* K. Koch	2	BR

2.3. Superior Municipal Forest Site Description

The study area was along the riparian corridor of the Pokegama River that meanders through the Superior Municipal Forest in northwestern Wisconsin, USA (Figure 1, ▲). Soils were one of two distinct types: a sandy berm adjacent to the river that was created by deposits of coarse sediment, and clay-loams in adjacent lowland "back bays" (Table 1). The riparian corridor overstory was comprised of black ash and green ash (*Fraxinus pennsylvanica* Marsh) with lesser amounts of northern white cedar, balsam fir, and trembling aspen (*Populus tremuloides* Michx.).

2.4. Superior Municipal Forest Study Design

Tree species were chosen for their suitability in saturated or inundated soils as well as their projected range within forecasted climate models [19]. Seedling species were red maple, hackberry (*Celtis occidentalis* L.), and northern white cedar (Table 3) obtained from the Wisconsin Department of Natural Resources nursery in Hayward, WI, USA. Planting groups were established in different microsite, herbivory deterrence, and elevational conditions. The three microsite conditions were natural flat areas ("Natural"), constructed hummocks ("Con. Hummock"), and cleared soil ("Scarification"). The constructed hummocks were created by placing a shovel-blade full of local soil on top of the forest floor and then fortifying it by covering it with burlap matting. The cleared planting locations were created by removing existing vegetation with a spade.

Table 3. Superior Municipal Forest species and seedling ages and planting stock type (BR—bare root, P—plug).

Common Name	Scientific Name	Age (Years)	Stock Type
hackberry	*Celtis occidentalis* L.	2	BR
red maple	*Acer rubrum* L.	2	BR
northern white cedar	*Thuja occidentalis* L.	2	BR

The three herbivore exclusion treatments were no treatment ("Control"), herbivore repellant ("Repellant") (Plantskydd®, Tree World Plant Care Products Inc., St. Joseph, MO, USA) and fencing

("Fence"). The herbivore repellant was applied in the spring and fall each year following manufacturer instructions and fenced planting locations were 1.3 m tall. Each combination of microsite (3) and tree species (3) was replicated 36 times in a low elevation and 36 times in a high elevation planting zone, each approximately parallel to the river channel. One-third, or 12 planting groups per elevation zone, were assigned an herbivore treatment. Each of the 72 planting groups had three seedlings of each of the three species, for a total of nine seedlings per group or 648 seedlings. Seedlings were planted in fall 2015. Seedlings were measured each spring and fall for each year of the study period.

2.5. Field and Laboratory Procedures

Field measurements included seedling height and root collar diameter, microsite characteristics including hummock material (mineral soil or coarse woody debris and decay class), mortality, and disease. When cause of death was clear (e.g., fungus), it was recorded. Canopy openness for the ONF study was measured during the early morning, late evening, or under cloudy conditions in early July 2015 using hemispherical photography (Nikon P5000, Nikon FC-E8 fisheye lens, Nikon, Tokyo, Japan). Nine digital photographs were processed using WinSCANOPY software (Pro Version, 2010, Regent Instruments, Inc., Quebec, QC, Canada) [20] and were averaged for each planting site. Canopy openness for the SMF study was categorized from visual observations as one of three coverages: open, partial, or closed canopy and the canopy composition was recorded.

2.6. Analysis

Differences in seedling establishment and survivorship among groups of species, microsite, and treatment were tested for significance using contingency tables via Fisher's exact test. Analysis of variance (ANOVA) was used to assess species growth metrics, and relative height and diameter (calculated by $RH/RD = (W_2 - W_1)/(W_1/(t_2 - t_1))$; where RH = relative height, RD = relative diameter, W = size, and t = time), among treatment, microsite, herbivore deterrent, zone, and canopy openness. Significance level was 0.05 for all statistical tests. All statistical analyses were performed using R: A Language and Environment for Statistical Computing (Version 3.3.1, 2016, R Foundation for Statistical Computing, Vienna, Austria) [21].

3. Results

3.1. Ottawa National Forest

The planting year experienced elevated water tables throughout the growing season because of an unusually high snow pack and delayed snowmelt [22]. Additionally, standing water was present during the initial growing season at intermittent times due to high intensity rain storms [22].

Overall seedling survival across all treatments and microsites (n = 1800) after the first winter for the ONF planting study was 36% and after three years 22% of the planted seedlings survived. The second- and third-year survivorship was significantly higher than seedling establishment. Overall seedling survivorship from years 1–2 and years 2–3 was 75% and 87%, respectively. The hardwood species with the highest survivorship across the study period were silver maple, American elm, and basswood with 74%, 53%, and 40%, respectively (Table 4). The softwood species with the highest survivorship across the study period was northern white cedar at 23% (Table 4). None of the tamarack survived the 3-year study period. We found no statistical difference in seedling survival or growth from bare root stock or plug seedlings.

Initial survival rates for seedlings planted on hummocks and hollows were 44% and 29%, respectively. Over the course of the study, seedlings planted on hummocks survived better than those planted in hollows (Table 4). On average, there was a 19% (range: 4–47%) greater rate of survival than the corresponding paired seedling in the hollow over the 3-year span. However, of the top performing species, only silver maple did not display a preference between hummock or hollow and survived well on both microsites after three years with 76% and 72% survival, respectively. The ONF results indicate that survivorship and growth were not statistically different when canopy treatment was compared.

Table 4. Three-year mean seedling survival rate, relative height growth, and relative diameter growth across all treatments by microsite hummock and hollow for each planted species in the Ottawa National Forest study. Statistical significance indicated (*) for hummock vs. hollow comparisons within species for survival. Standard deviations are indicated by ± for height and diameter.

Species	Microsite	Survival (%)	Relative Height Growth (cm)	Relative Diameter Growth (cm)
American elm	Hummock	68 *	6.4 ± 15.0	0.1 ± 0.1
	Hollow	38	3.5 ± 10.4	0.1 ± 0.1
Basswood (linden)	Hummock	64 *	2.2 ± 16.0	0.1 ± 0.3
	Hollow	17	−0.1 ± 6.3	0.0 ± 0.2
burr oak	Hummock	38 *	−1.2 ± 7.6	0.0 ± 0.3
	Hollow	11	0.4 ± 2.4	0.0 ± 0.1
red maple	Hummock	11 *	0.2 ± 5.8	0.0 ± 0.2
	Hollow	2	0.1 ± 1.0	0.0 ± 0.0
silver maple	Hummock	76	4.2 ± 14.7	0.1 ± 0.2
	Hollow	72	7.1 ± 17.1	0.1 ± 0.3
yellow birch	Hummock	8 *	−0.3 ± 4.0	0.0 ± 0.1
	Hollow	0	-	-
balsam fir	Hummock	7 *	0.2 ± 1.4	0.0 ± 0.0
	Hollow	0	-	-
black spruce	Hummock	13 *	0.9 ± 2.9	0.0 ± 0.1
	Hollow	2	0.3 ± 1.9	0.0 ± 0.0
northern white cedar	Hummock	39 *	2.8 ± 6.1	0.1 ± 0.2
	Hollow	8	0.3 ± 2.6	0.3 ± 2.6
tamarack	Hummock	0	-	-
	Hollow	0	-	-

* Statistical significance at p = 0.05 level.

Average 3-year relative height growth for all the species except tamarack was 1.3 cm. Three-year relative height growth for six of these species was significantly higher for seedlings planted on hummocks compared to seedlings planted in hollows. In contrast, silver maple and burr oak relative growth rates were greater for hollow microsites than hummocks (Figure 2a). Average relative diameter growth across the study period was 0.3 cm, and northern white cedar planted on hummocks had the greatest increase in diameter, but the growth was highly variable (Table 3, Figure 2b).

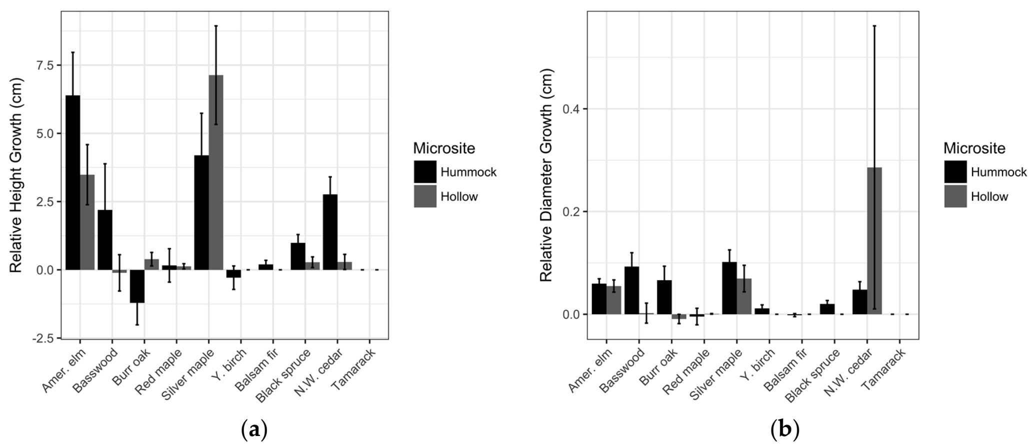

Figure 2. (**a**) Relative growth of height (cm) and (**b**) diameter (cm) of the 10 wetland-adapted tree species (American elm, basswood, burr oak, red maple, silver maple, yellow birch, balsam fir, black spruce, northern white cedar, tamarack) planted across three black ash-dominated wetlands in the Ottawa National Forest over the 3-year study period. The bars represent the mean relative growth rate for each species by microsite condition. The error bars represent ± one standard error.

3.2. Superior Municipal Forest

The growing season monthly temperature (mean 14.8 °C, range 9.4–19.4 °C) and precipitation (mean 7.3 cm, range 4.0–11.5 cm) were within the 30-year average for the Superior, Wisconsin region National Oceanic Atmospheric Administration. In contrast to the relatively low first-year survival rates on the ONF, the overall mean seedling survival across all treatments and microsites at SMF was 82% one year after planting and 54% two years after planting. Red maple had a two-year survival rate of 63%, hackberry's survival rate was 62%, and northern white cedar's survival rate was 38% (Table 5).

Table 5. Two-year mean seedling survival rate, height, and diameter across all treatments by microsite constructed hummock (CH), natural (N), and scarification (S) for each planted species in the Superior Municipal Forest study. There were no significant differences in seedling survival, relative height growth, and relative diameter growth.

Species	Microsite	Survival (%)	Relative Height Growth (cm)	Relative Diameter Growth (cm)
hackberry	CH	66	−0.1 ± 14.6	0.4 ± 5.6
	N	60	−0.9 ± 11.9	−0.6 ± 1.8
	S	58	−1.0 ± 10.4	−0.6 ± 1.7
red maple	CH	68	12.2 ± 20.9	0.2 ± 1.8
	N	57	10.9 ± 19.9	−0.5 ± 1.8
	S	63	6.4 ± 14.1	−0.6 ± 1.2
northern white cedar	CH	39	−1.2 ± 7.9	0 ± 1.4
	N	43	0.2 ± 5.6	−0.1 ± 1.3
	S	32	0.3 ± 9.7	−0.1 ± 1.9

For the SMF study, there were no statistical differences in survivorship or growth among any of our study factors: species, microsite, herbivore exclusion, and zones; therefore, we pooled the planting data and report the results here. There were no statistical differences in survivorship among browse treatments when species were pooled (mean 54%, range 39–65%). Similarly, there were no statistical differences in survivorship between the elevation zones (both 54%) despite the presence of standing water for most lower elevation (Zone 2) seedlings at the time of the 2017 measuring campaign. There were no differences among the microsite treatments when species were pooled (mean 54%, range 51–58%). Height growth for red maple was positive while hackberry showed no growth and northern white cedar decreased in height over the study period (Table 5). Average height growth for red maple was 9 cm, hackberry 0 cm, and northern white cedar −2 cm.

4. Discussion

Survival was greater for seedlings planted on hummocks when compared to seedlings planted in hollows or on cleared ground, except for silver maple at the ONF site which showed no difference between microsite conditions. Mounding has long been used in wetland forestry to establish seedlings [23] as a means to elevate seedlings out of standing water and provide a more favorable moisture regime. While the constructed hummocks in SMF were much smaller than the natural hummocks in ONF and smaller than typical mounding microsites, they still provided a marginal advantage over the hollows and cleared microsites at the two study sites.

The low survival rates on the ONF may be explained by the high amount of precipitation in the 2013 water year [24], which resulted in elevated water tables throughout the growing season and may have masked our ability to detect a difference among the treatments. The higher retention in the later years indicates that successful establishment of plantings greatly increases the probability of survival in the future. These results are similar to a study conducted on the nearby Chippewa National Forest in Minnesota [17] which showed that the successful establishment during the first growing season and

winter are the major hurdles for seedling survival. Winter within the study region typically consists of high snowfall and months-long periods of below freezing temperatures.

Black ash canopy tree species loss has been determined to significantly influence water tables within black ash-dominated wetlands within northern Minnesota [25]. Black ash loss has been determined to significantly lower rates of stand transpiration in the ONF [26], significantly smaller rates of growing season drawdown within the ONF [22], and significantly higher water tables across the upper Great Lakes region [22,25] were detected in ash-dominated wetlands following a simulated EAB infestation or timber harvest. These changes subject regeneration to higher standing water levels for longer periods of time after spring inundation and after episodic summertime precipitation events. The cascading effects of forest cover loss may result in increased erosion and downstream sediment deposition. Therefore, establishing future canopy species in the understory would limit the negative environmental consequences, and provide additional time for understory vegetation to establish itself prior to exposure to the harsh environmental conditions expected following an EAB infestation.

The 4-year old silver maple seedlings had greater survival rates in both the hummocks and hollows compared to other species. The age-related height difference may explain the success of silver maple compared to the rest of the species and may have confounded the results due to the difference in planting stock. While silver maple had the highest survival rates in the ONF planting study, this species is not currently found in great numbers on this landscape, and most of the population's nearest individuals are found ~80 km to the southwest. Adaptation models suggest that future climate conditions may expand the suitable habitat for silver maple into the headwater wetlands of the upper Great Lakes region [27,28]. As global temperatures continue to rise, the cold-intolerant silver maple may shift to northerly latitudes.

American elm and basswood were also relatively successful in the ONF study. These species are commonly found along the hydric to mesic gradient near the black ash-dominated wetlands in the Great Lakes Basin. American elm is more tolerant of extended periods of inundation and saturated conditions, while basswood does not survive well when subjected to standing water [19]. If predicted future climate conditions [29] for the upper Great Lakes region come to fruition, this would put American elm at an advantage and basswood at a disadvantage because of the projected wetter and longer spring season.

Northern white cedar was the only conifer to survive at ONF in both microsite conditions, and it also had high survivorship at the SMF site. Northern white cedar is found within both black ash-dominated headwater wetlands and black ash-dominated riparian corridors. As a long-term management strategy, however, converting hardwood-dominated forests to northern white cedar may not be sustainable as northern white cedar within the region regenerates poorly and may be converted to other species [30]. Also, northern white cedar regeneration is heavily pressured by herbivores [31–33] and while our second-year results did not show a statistical difference among herbivore exclusion treatments, it may be too early to detect herbivore pressure.

Within the SMF, red maple had the highest survivorship and vigor after the first-year and based on our first year vs. third year survival rates from the ONF, we expect the survival rate for red maple to remain high. Red maple on the ONF did not fare well due to the relatively low-quality growing stock. The red maple seedlings often had missing terminal buds and were visibly less hardy when compared to the other planted seedlings. While all of the planting stock were subjected to undesirable conditions (e.g., in and out of cold storage, transport to remote study sites without temperature control) red maple's low survivorship may have been because of its small stature and frailty. Red maple is commonly found within black ash-dominated wetlands as a co-occurring species and survives in a variety of conditions [34], which indicates that red maple is a promising alternative species to plant within black ash-dominated forests. However, red maple is not very shade tolerant [35] and its success therefore will depend on release opportunities, such as those initiated by EAB infestation. As witnessed between these two study locations, if red maple were planted as an alternative species to black ash, quality growing stock and handling care will greatly enhance the success rates of planting efforts.

In a related study on the ONF, natural red maple regeneration was abundant, with density of stems ≤50 cm similar to black ash (21,944 ± 12,638 vs. 21,105 ± 13,017 stems ha^{-1}, respectively). However, the relative density of the species decreased with increasing size class. As historical data from these forests is not available, it is not clear whether this decline in density is due to legacy effects of prior growing conditions, red maple shade tolerance, poor recruitment due to current growing conditions, or some combination of these and other unidentified factors. However, this forest type is dominated by red maple elsewhere in the region [6], which suggests that a future canopy dominated by red maple is a possibility. That red maple seedlings were not negatively affected by increased herbaceous cover in our related study supports this possibility, though declines in natural regeneration may occur in the future as time since disturbance increases. The poor recruitment despite high natural regeneration indicates that the success of planting efforts may rely in part on the conditions in which the seedling establishes, and further highlights the importance of the findings in the current study.

The planting success of hackberry suggests it is a viable alternative species to ash within these systems; however, hackberry is not currently found in great numbers on this landscape, and the northernmost individuals of the defined population are found ~120 km to the southwest. As with silver maple, adaptation models suggest that future climate conditions may expand the suitable habitat for hackberry to move further north in the upper Great Lakes region [27]. In a similar study on the Chippewa National Forest, hackberry had a 52.9% survivorship over a three-year period, indicating high survival in ash-dominated wetlands [17]. While hackberry does not establish well or flourish within very wet sites [36], the hydrology of the riparian corridor may be more suitable to hackberry than the seasonal inundation in the ONF depressional wetlands.

5. Conclusions

This research includes two studies that compared plantings of wetland-adapted tree species survival and growth within black ash-dominated wetlands. In one study, seedlings were planted within black ash wetlands that underwent overstory treatments that simulated our estimated short- and long-term EAB-induced conditions. In the second study, seedlings were planted in an uninfested black and green ash-dominated riparian corridor with manipulated microsite conditions and herbivore browse exclusion treatments.

Our results indicate higher survivorship of planted seedlings when planted on hummocks in ash-dominated wetland sites in the Great Lakes region of the US. These results suggest that perching seedlings on elevated beds enhances their survivorship by providing a more stable environment. The highest surviving species we planted were silver maple, American elm, basswood, hackberry, red maple, and northern white cedar and were determined to be species well suited for alternative species plantings in ash-dominated wetlands when compared to natural regeneration within similar systems.

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References

1. Haack, R.; Jendek, E.; Liu, H.; Marchant, K.; Petrice, T.; Poland, T.; Ye, H. The emerald ash borer: A new exotic Pest in North America. *Newslett. Mich. Entomol. Soc.* **2002**, *47*, 1–5.
2. Siegert, N.; McCullough, D.; Liebhold, A.; Telewski, F. Dendrochronological reconstruction of the epicentre and early spread of emerald ash borer in North America. *Divers. Distrib.* **2014**, *20*, 847–858. [CrossRef]
3. MacFarlane, D.; Meyer, S. Characteristics and distribution of potential ash tree hosts for emerald ash borer. *For. Ecol. Manag.* **2005**, *213*, 15–24. [CrossRef]
4. Marshall, J.; Smith, E.; Mech, R.; Storer, A. Estimates of *Agrilus planipennis* infestation rates and potential survival of ash. *Am. Midl. Nat.* **2013**, *169*, 179–193. [CrossRef]
5. Herms, D.; McCullough, D. Emerald ash borer invasion of North America: History, biology, ecology, impacts, and management. *Annu. Rev. Entomol.* **2014**, *59*, 13–30. [CrossRef] [PubMed]
6. Erdmann, G.; Crow, T.; Ralph, M., Jr.; Wilson, C. Managing black ash in the Lake States. In *General Technical Report NC-115*; U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: St. Paul, MN, USA, 1987.
7. Wright, J.; Rauscher, H. *Fraxinus nigra* marsh. Black ash. *Silv. N. Am.* **1990**, *2*, 344–347.
8. Hewlett, J.; Fortson, J. Stream temperature under an inadequate buffer strip in the southeast piedmont. *J. Am. Water Resour. Assoc.* **1982**, *18*, 983–988. [CrossRef]
9. Bourque, C.A.; Pomeroy, J.H. Effects of forest harvesting on summer stream temperatures in New Brunswick, Canada: An inter-catchment, multiple-year comparison. *Hydrol. Earth Syst. Sci. Discuss.* **2001**, *5*, 599–614. [CrossRef]
10. Sheridan, J.; Lowrance, R.; Bosch, D. Management effects on runoff and sediment transport in riparian forest buffers. *Trans. Am. Soc. Agric. Eng.* **1999**, *42*, 55–64. [CrossRef]
11. Lowrance, R.; Altier, L.; Newbold, J.; Schnabel, R.; Groffman, P.; Denver, J.; Correll, D.; Gilliam, J.; Robinson, J.; Brinsfield, R. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. *Environ. Manag.* **1997**, *21*, 687–712. [CrossRef]
12. Davis, J.; Shannon, J.; Bolton, N.; Kolka, R.; Pypker, T. Vegetation responses to simulated emerald ash borer infestation in *Fraxinus nigra*-dominated wetlands of Upper Michigan, USA. *Can. J. For. Res.* **2017**, *47*, 319–330. [CrossRef]
13. Palik, B.; Ostry, M.; Venette, R.; Abdela, E. *Fraxinus nigra* (black ash) dieback in Minnesota: Regional variation and potential contributing factors. *For. Ecol. Manag.* **2011**, *261*, 128–135. [CrossRef]
14. Palik, B.; Ostry, M.; Venette, R.; Abdela, E. Tree regeneration in black ash (*Fraxinus nigra*) stands exhibiting crown dieback in Minnesota. *For. Ecol. Manag.* **2012**, *269*, 26–30. [CrossRef]
15. Ponnamperuma, F. Effects of flooding on soils. In *Flooding and Plant Growth*; Academic Press, Inc.: New York, NY, USA, 1984; pp. 9–45.
16. Roy, V.; Bernier, P.; Plamondon, A.; Ruel, J. Effect of drainage and microtopography in forested wetlands on the microenvironment and growth of planted black spruce seedlings. *Can. J. For. Res.* **1999**, *29*, 563–574. [CrossRef]
17. Looney, C.; D'Amato, A.; Palik, B.; Slesak, R. Overstory treatment and planting season affect survival of replacement tree species in emerald ash borer threatened *Fraxinus nigra* forests in Minnesota, USA. *Can. J. For. Res.* **2015**, *45*, 1728–1738. [CrossRef]
18. Staff, S.S. Natural Resources Conservation Service Web Soil Survey, United States Department of Agriculture. 2017. Available online: http://websoilsurvey.sc.egov.usda.gov/ (accessed on 26 April 2017).
19. Burns, R.; Honkala, B. *Silvics of North America: 1. Conifers; 2. Hardwoods*; United States Department of Agriculture: Washington, DC, USA, 1990.
20. *WinSCANOPY*, Pro Version ed; Regent Instruments Inc.: Quebec, QC, Canada, 2010.
21. R Development Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2016.
22. Van Grinsven, M.; Shannon, J.; Davis, J.; Bolton, N.; Wagenbrenner, J.; Kolka, R.; Pypker, T. Source water contributions and hydrologic responses to simulated emerald ash borer infestations in depressional black ash wetlands. *Ecohydrology* **2017**, *10*, e1862. [CrossRef]
23. Londo, A.; Mroz, G. Bucket mounding as a mechanical site preparation technique in wetlands. *North. J. Appl. For.* **2001**, *18*, 7–13.

24. Van Grinsven, M. Implications of Emerald Ash Borer Disturbance on Black Ash Wetland Watershed Hydrology, Soil Carbon Efflux, and Dissolved Organic Matter. Ph.D. Thesis, Michigan Technological University, Houghton, MI, USA, 2015.
25. Slesak, R.A.; Lenhart, C.F.; Brooks, K.N.; D'Amato, A.W.; Palik, B.J. Water table response to harvesting and simulated emerald ash borer mortality in black ash wetlands in Minnesota, USA. *Can. J. For. Res.* **2014**, *44*, 961–968. [CrossRef]
26. Shannon, J.; Van Grinsven, M.; Davis, J.; Bolton, N.; Noh, N.; Pypker, T.; Kolka, R. Water level controls on sap flux of canopy species in black ash wetlands. *Forests* **2018**, accepted.
27. Williams, M.; Dumroese, R. Preparing for climate change: Forestry and assisted migration. *J. For.* **2013**, *111*, 287–297. [CrossRef]
28. Iverson, L.; Knight, K.S.; Prasad, A.; Herms, D.A.; Matthews, S.; Peters, M.; Smith, A.; Hartzler, D.M.; Long, R.; Almendinger, J. Potential species replacements for black ash (*Fraxinus nigra*) at the confluence of two threats: Emerald ash borer and a changing climate. *Ecosystems* **2016**, *19*, 248–270. [CrossRef]
29. Janowiak, M.; Iverson, L.; Mladenoff, D.; Peters, E.; Wythers, K.; Xi, W.; Brandt, L.; Butler, P.; Handler, S.; Shannon, P.; et al. *Forest Ecosystem Vulnerability Assessment and Synthesis for Northern Wisconsin and Western Upper Michigan: A Report from the Northwoods Climate Change Response Framework Project*; General Technical Report NRS-136; U.S. Department of Agriculture, Forest Service, Northern Research Station: Newtown Square, PA, USA, 2014; Volume 247.
30. Chimner, R.; Hart, J. Hydrology and microtopography effects on northern white-cedar regeneration in michigan's Upper Peninsula. *Can. J. For. Res.* **1996**, *26*, 389–393. [CrossRef]
31. Cornett, M.; Frelich, L.; Puettmann, K.; Reich, P. Conservation implications of browsing by *Odocoileus virginianus* in remnant upland *Thuja occidentalis* forests. *Biol. Conserv.* **2000**, *93*, 359–369. [CrossRef]
32. Rooney, T.; Waller, D. Direct and indirect effects of white-tailed deer in forest ecosystems. *For. Ecol. Manag.* **2003**, *181*, 165–176. [CrossRef]
33. Russell, F.; Zippin, D.; Fowler, N. Effects of white-tailed deer (*Odocoileus virginianus*) on plants, plant populations and communities: A review. *Am. Midl. Nat.* **2001**, *146*, 1–26. [CrossRef]
34. Abrams, M.D. The red maple paradox. *BioScience* **1998**, *48*, 355–364. [CrossRef]
35. Kobe, R.; Pacala, S.; Silander, J.; Canham, C. Juvenile tree survivorship as a component of shade tolerance. *Ecol. Appl.* **1995**, *5*, 517–532. [CrossRef]
36. Krajicek, J.; Williams, R. *Celtis occidentalis* L. Hackberry. *Silv. N. Am.* **1990**, *2*, 262.