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PRACTICE OF FORESTRY

Tree Planting for Climate Adaptation and Emerald Ash Borer in the Lake States, US: Motivations and State of the Practice

Lucia A. Fitts[1] · Rebecca A. Montgomery[1] · Brian J. Palik[2] · Peter W. Clark[3] · Josh Kragthorpe[7] · Mike R. Reinikainen[4] · Gregory J. Edge[5] · Stephen Handler[6] · Bradley M. Hutnik[5] · Anthony W. D'Amato[3]

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Abstract

Climate-driven stressors, non-native insects, and emerging diseases increasingly impact forest health across the Great Lakes region. Forest management strategies are required to mitigate these impacts. We examined one strategy, tree planting for adaptation to climate and emerald ash borer (hereafter referred to as adaptation plantings), as an approach for establishing tree species possibly better adapted to these stressors. Our goal was to assess the state of the practice of adaptation plantings by organizations across Minnesota, Wisconsin, and Michigan, US, and Native Nations sharing this geography. We conducted surveys, informational interviews, and focus groups. We found adaptation plantings are mostly exploratory rather than operational in scope; organizations have different policies, constraints, capacities, levels of comfort, and budgets allocated for adaptation planting work; and managers have limited experience with implementing adaptation plantings. Despite these challenges, adaptation planting is a priority in the region, with increasing interest, funding, and collaboration potential.

Keywords Climate adaptation · Emerald ash borer · Assisted migration · Adaptive management · Seed source movement

Introduction

Global change (i.e., climate change and associated stressors and disturbances) is expected to have profound impacts on forest ecosystems, generating significant management challenges (Dale et al. 2001). Threats to forests from climate change, including drought, invasive insects, and wildfire, have generated interest in adaptive management practices to maintain productivity and other ecosystem functions (Millar et al. 2007; Swanston et al. 2016; Schuurman et al. 2022). Altering/augmenting composition through

Extended author information available on the last page of the article

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tree planting has emerged as one of the key adaptation strategies to mitigate or adapt to the effects of climate change (Stanturf et al. 2014; Domke et al. 2020). Despite a long history of using tree planting as a tool for reforestation in the US (Dumroese et al. 2005) and globally (Bennet 2015), less is known about how the practice is being used by forest stewards to address adaptation needs.

Tree planting for adaptation can take many forms, but our focus is on planting species or genotypes that may be better suited to future climate and associated disturbances, including invasive species, such as emerald ash borer (Pedlar et al. 2012). Taken together, we refer to artificial regeneration to address global change (e.g., climate change and non-native invasive species) as "adaptation plantings" (Clark et al. 2023). Given that adaptation plantings will likely play an important role in shaping forests in the future, it is timely to gain a better understanding of the motivations, decisions, and lessons learned from stewards already exploring the practice.

We addressed this need by focusing on one region in the US, the western Lake States of Wisconsin, Michigan, Minnesota, and numerous Native Nations that share this geography. We focused on this region given its unique location in a transition between boreal and temperate forests, the importance of both climate change and invasive species in the region, and the potential for adaptation plantings to address these threats (Palik et al. 2022). Documented and predicted challenges to regeneration in this region, including synergistic impacts of elevated herbivory, non-native earthworms, and greater drought frequency (Frelich and Reich 2010), have increased the urgency for identifying strategies that can secure regeneration under novel and uncertain future conditions. Our overall objective was to assess how adaptation planting is being practiced by forest stewards in different organizations (hereafter referred to as "state of the practice"). Specifically, we summarized 1) the characteristics, level of implementation, and current state of the practice of adaptation planting among stakeholders and 2) the institutional support, policies, and guidelines for adaptation plantings among organizations. To address these objectives, we used a combination of surveys, focus groups, consultations, and document reviews. Our focus was specifically on adaptation planting intended to address concerns related to climate change and non-native emerald ash borer (*Agrilus planipennis*; hereafter EAB), given the prominence of these threats in the region.

Methods

Data collection

Within our study region, we used several information-gathering techniques to better understand the practice of adaptation planting in the region among organizations and forest stewards. Our data collection was extensive but not exhaustive, so our study represents a review of entities that participated in our project. Figure 1 shows the study population and characterizes participation. Table 1 illustrates the distribution of respondents across the study region.

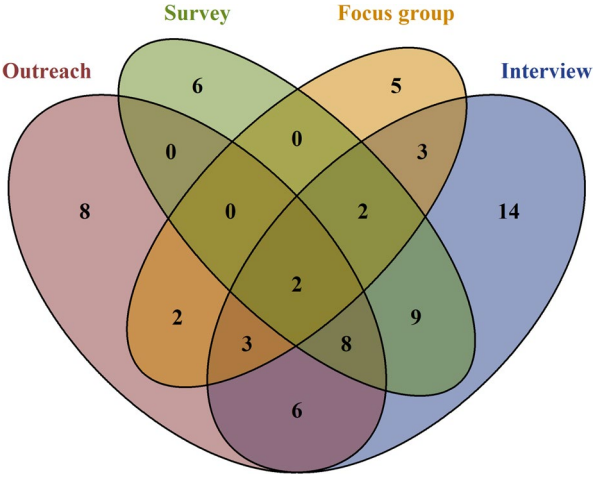

Fig. 1 Study population categorized by the different data collection techniques in which they participated. The intersections in the Venn diagram represent people that participated in more than one technique

Table 1 Study population divided by organizations and geographies

Category	Minnesota	Wisconsin	Michigan	Other geographies	Total
Consultant	0	1	0	0	1
County	1	2	0	0	3
Federal government	5	2	0	1	8
NGO	8	1	2	1	12
Native Nation	6	0	5	0	11
Private company	1	0	0	0	1
Forest family owner	0	2	0	0	2
State	13	7	3	0	23
University	2	0	6	0	8
Total	36	15	16	2	69

Initial outreach

To better understand how forest stewards pursue adaptation planting projects, we emailed 48 forest management entities that we suspected were likely to employ adaptation plantings. This encompassed a diverse group including Native Nations, state and federal agencies, and NGOs. The email included an outreach document explaining our project details and objectives and inviting participation in our project. Recipients were identified using a snowball sampling approach (Noy 2008) to ensure sufficient outreach. This snowball approach consisted of emailing our respective networks and asking contacts to forward our outreach email to their own networks, creating a cycle. In total we received 29 responses from 19 different organizations, with some organizations having multiple unique responses.

In-depth surveys

After our initial outreach, we conducted a more detailed project-oriented survey using Qualtrics software. The survey was emailed to the 29 respondents from our initial outreach and was also published in the Northern Institute of Applied Climate Science (NIACS) Northwoods Climate News newsletter in March and April 2022. This newsletter is distributed to more than 700 forest managers and researchers, covering a broad audience across the forestry community in the Lake States. This survey included up to 30 questions that varied depending on the participant's level of involvement with adaptation plantings. The questions were related to the following topics, including but not limited to: current or future project location, planting year, project objectives, species and densities planted, and monitoring plan (Supplement 1). In total, we received 33 complete surveys and 21 incomplete surveys from 27 individuals. Some participants entered more than one response when they had more than one project to share.

Informational interviews

To augment the surveys, we conducted 47 informational interviews with forest stewards from different organizations. The goal of the interviews was to understand how adaptation planting was pursued among organizations. Most interviews were structured and conducted online, with some less-structured conversations taking place while visiting adaptation planting projects. This was an opportunity for forest stewards to provide supplementary information related to project motivations, decisions, and challenges.

Focus groups

We conducted three focus groups to better understand institutional policies, trends, opportunities, and challenges for adaptation plantings. The 17 participants were chosen to represent diverse geographies and organizations due to their involvement in adaptation planting practices or because of their affiliation with an institution or organization working on developing climate adaptation policy.

We used a semi-structured focus group questionnaire that consisted of up to 16 questions divided into four sections: 1) General background and experience with adaptation plantings, 2) Institutional trends and policies for adaptation plantings, 3) Opportunities, and 4) Challenges (Supplement 2). Recognizing the potential data sensitivity and sovereignty for Native Nations and other stakeholders, we followed, when applicable, FPIC (free, prior, informed consent) principles and guidance from the Indigenous Tribal Data Sovereignty Network including CARE (collective benefit, authority to control, responsibility and ethics) (Carroll et al. 2020) during our data collection phase.

Document review

During our interactions, participants often shared internal reports, policies, or other documents they considered relevant to addressing our objectives. We reviewed 49 documents, including guidelines and/or policies, strategic plans, vulnerability assessments, and internal project reports (Supplement 3). These documents included information about species, planting density, treatments, background information on specific projects, and policies, which helped complement information gathered from our other methods.

Results and discussion

Use of adaptation planting among organizations

Native Nations

Natural resource managers from four Native Nations participated in our study: Fond du Lac Band of Lake Superior Chippewa, Leech Lake Band of Ojibwe, Pokagon Band of Potawatomi, and Gun Lake Tribe. The information described in this section, reflects their perspective and participation in adaptation planting projects.

Planning and implementation of adaptation projects by these Native Nations are guided by several documents associated with intertribal organizations, including the 1854 Treaty Authority Climate Change Vulnerability Assessment and Adaptation Plan (Stults et al. 2016), the Great Lakes Indian Fish & Wildlife Commission Vulnerability Assessment (GLIFWC Climate Change Team 2023), and the Tribal Adaptation Menu (Tribal Adaptation Menu Team 2019). These documents highlight climate-related vulnerabilities and outline possible actions to create more climate-resilient ecosystems, setting the stage for considering adaptation planting strategies.

Adaptation-related projects implemented by these Native Nations blend the best available western science on climate change, invasive species, and adaptation with traditional ecological knowledge to achieve a more holistic approach (Whyte 2013). These projects are first proposed to Tribal councils, outlining management goals and potential species to plant. Councils then approve them based on the project efficacy and how well it represents the Nation's interest, including desired future conditions of forests and cultural practices.

At the time of our work, adaptation planting among these Native Nations was done to address the threat of emerald ash borer on black ash (*Fraxinus nigra*) wetlands. The Fond du Lac Band (FDL) of Lake Superior Chippewa and the Leech Lake Band of Ojibwe (LLBO), who share geography with the state of Minnesota, are focusing on identifying replacement species for black ash, in anticipation of expected widespread mortality of ash trees as EAB moves into north central Minnesota. As of 2024, EAB has been detected near the LLBO reservation within the Chippewa National Forest ("Emerald Ash Borer (EAB) in Cass County Alert" 2023). Both FDL and LLBO are evaluating the potential for replacement species, including swamp white oak (*Quercus bicolor*), bur oak (*Q. macrocarpa*), silver

maple (*Acer saccharinum*), river birch (*Betula nigra*), and northern white cedar (*Thuja occidentalis*) to replace black ash.

The LLBO is also working with the Chippewa National Forest to transition quaking aspen (*Populus tremuloides*) dominated stands to more diverse mixed species forest. Strategies include enhancing native tree species' diversity and restoring cultural fire. Adaptation plantings are being considered for this project where advanced regeneration from climate-adapted species is not abundant.

Pokagon Band of Potawatomi and Gun Lake Tribe, who share geography with the state of Michigan, are not actively using adaptation plantings to address EAB at the time of this publication. They are currently focused on combining biocontrol and chemical treatments to inhibit EAB given the importance of black ash as a cultural resource (Costanza et al. 2017; Galvas et al. 2020).

USDA Forest Service national forests

The USDA Forest Service (Forest Service) has taken a conservative approach to adaptation plantings on national forests, especially related to assisted migration for climate change. Partially this is a result of policies that limit use of non-native species and genotypes (e.g., USDA Forest Service Reforestation Policy FSM 2472.03, Native Plant Material Policy FSM 2070.3, Genetic Resources Management FSM 2475.03). However, the latest National Reforestation Strategy (Forest Service 2022b) points to a shift toward the inclusion of future-climate adapted planting material.

From our outreach to all National Forests in the study region via a formal request from the Forest Service Region 9 geneticist, we received responses from the Superior National Forest (SNF) and the Chippewa National Forest (CNF), both in Minnesota. Both are actively engaged in planning for adaptation plantings and involved in some on-the-ground trials. The CNF has adaptation plantings in black ash wetlands in anticipation of EAB invasion into the forest's large black ash resource. (Looney et al. 2015; D'Amato et al. 2018; Palik et al. 2021).

The SNF has an approved Assisted Migration Plan to set clear guidelines for how adaptation planting will occur across the forest (Frerker et al. 2023). This plan is the first such example for a national forest in the US. The SNF initiated the process of formalizing an assisted migration plan partially due to its geography in a boreal/north temperate transition zone, and the urgency associated with climate change in this region. This plan will help managers on this national forest make decisions about facilitating movement of populations and species considered suitable for evolving climate conditions. Development of the plan has been a collaborative effort involving at least 100 participants from more than 20 partner organizations including Native Nations, intertribal organizations, universities, and federal and state agencies. More formal and widespread implementation of assisted migration on the SNF is expected after its Assisted Migration Plan is put into action.

States

Michigan, Minnesota, and Wisconsin Departments of Natural Resources (DNR) are at different stages of climate adaptive forestry, including use of adaptation plantings.

All three DNRs are increasing efforts to build collaborations and develop staff capacity with climate adaptation experts. These experts are expected to help develop on-the-ground projects and attract funding to support these projects.

Both Minnesota and Wisconsin DNRs have several on-the-ground adaptation planting projects, but most of these are done as small-scale (1–10 ha) trials. Both states have a strong focus on identifying species that would replace the ecological function of ash, particularly black ash. Both also have small-scale assisted migration projects in other forest types (Box 1). The Wisconsin DNR has a Forest Genetics Program whose goal is to identify and propagate well-adapted genotypes and maintain wide genetic diversity in nursery stock (Wisconsin DNR and University of Madison 2019). While selection and breeding efforts still include production traits, additional emphasis is now placed on adaptation and forest health considerations. Similarly, the Michigan DNR is focusing their adaptation efforts on research identifying suitable genetic sources that will be adapted to predicted climate. This effort focuses on results from long-running provenance trials.

In general, the three state DNRs use seed source control from collection to deployment and focus on maintaining broad genetic representation from their respective seed-collection zones. While growing stock is typically deployed somewhere within its seed-collection zone, the recently published eastern seed-collection zone map (Pike et al. 2020) and seed transfer guidelines have better enabled south-to-north seed transfer for several species. Planting is guided by strategic plans that can support adaptation planting, but that do not include specific details or prescriptions. As such, on-the-ground efforts at adaptation planting are largely grassroots, with individuals experimenting with planting based on personal experiences and levels of comfort.

The policy environment is changing for use of adaptation plantings, as agencies are beginning to develop or revise guidelines that include planting for climate change adaptation. Examples include Minnesota DNR's Climate Adaptation and Mitigation in Natural Resource Management operational order 131, last revised in 2018. This policy has a goal of enhancing ecosystem resilience and reducing negative effects of climate change by developing and implementing adaptation strategies, but does not specify tree planting for climate change adaptation. Another example is the Minnesota DNR's Plant Material Standards for Native Plant Community Restoration operational order 124, currently under revision which includes adaptation strategies for climate change when making plant material decisions.

State-level guidelines regarding EAB and ash management are more developed in Minnesota and Wisconsin as they prepare for wide-spread EAB infestation, as has occurred in Michigan. Minnesota DNR Ash Management operational order 119 aims to mitigate the ecological impacts of EAB and the loss of ash species. This policy highlights the need to plant non-ash species during reforestation to promote species diversity and maintain a forested condition (Bowen and Stevens 2018; Palik et al. 2021). Similarly, the Wisconsin DNR has silviculture guidelines (Wisconsin DNR 2018) that include adaptation plantings as an EAB mitigation strategy, along with lowland ash replacement species guidelines. Both state's guidelines include a framework to help managers in decision-making, providing tools of what to do when addressing ash mortality from EAB.

Family forest owners

Family forest owners are a diverse group with differing interests and experience with adaptation planting. There are wide ranging levels of concern among family forest owners about the impacts of climate change (Butler et al. 2021). According to the National Woodland Owner Survey, more than 74% of the family forest owners in Michigan expressed moderate to high concern about climate change, compared to 60% in Wisconsin, and 50% in Minnesota. These landowners account for management of 63%, 64%, and 57% of forest land respectively in each state (Butler et al. 2021).

Our focus groups and interviews included two family forest owners in northern Wisconsin, each owning about 25 hectares of land (Box 1B). Their focus has been on replacement species for ash, with planting that included swamp white oak and bald cypress (*Taxodium distichum*). Bald cypress represents a large long-distance movement (around 800 km) from its northern range limit in southern Illinois and Indiana (Peters et al. 2020; Pike et al. 2020) and is seen as a replacement species for ash since it can tolerate hydric soil conditions. Private landowners interviewed mentioned having few policy constraints on what they can try, potentially leading to facilitating more novel approaches and nimbler responses than agencies. The downside of this flexibility is less control over source and quality or planting stock, and greater risk of introducing maladapted genotypes, invasive pests, or diseases. Given that private landowners manage the majority of the region's forests, there is an increasing need for education, incentives, and expert assistance targeting climate-adaptive management.

With these needs in mind, the University of Minnesota Extension has developed a *Creating Climate-Ready Woodlands* tree list (Dombeck et al. 2023). This resource provides tree recommendations for woodland owners in MN to help them make informed decisions about species expected to perform well under climate change. Trees selected for the list meet the following criteria: native to Minnesota or nearby eastern deciduous forest, have low risk of mortality from pests or diseases, are beneficial to wildlife, and are adapted to the region's projected climate.

Non-governmental organizations

Non-governmental organizations also influence forest management for adaptation with The Nature Conservancy (TNC) playing the largest role in the Lake States. While TNC does not own much forest land outright, they pursue adaptation plantings with partners at operational scales across the region. TNC is operationally nimble and has a history of working across institutional boundaries to implement projects (White et al. 2020).

TNC has on-the-ground adaptation planting projects in Minnesota, Wisconsin, and Michigan. Most were installed in 2021 and 2022, ranging from less than 1 ha to 236 ha. The species planted include eastern white pine, northern white cedar, white spruce, red pine, northern red oak (*Quercus rubra*), jack pine, and bur oak. For some, seed sources are from at least one seed zone to the south of the planting location (Minnesota DNR, n.d.), including out-of-state in Wisconsin. TNC

also leads the Minnesota Million program partnering with the University of Minnesota-Duluth. Their goal is to reforest one million acres in Minnesota including climate adapted seedlings.

TNC in Michigan is also increasing capacity to address climate adaptation. One such effort is the Two Hearted Fish Camp adaptation project (Box 1E and Table 2E) in the eastern Upper Peninsula of Michigan. Goals of this project include increasing species diversity, climate resilience, and disease resistance. This project was planted in 2019 and includes northern red oak seed sources from the eastern and southern part of lower Michigan.

Box 1 Examples of adaptation planting projects.

Adaptation planting projects across Minnesota, Wisconsin, Michigan, and the Native Nations that share this geography have diverse objectives, scales, and management strategies. Most focus on climate adaptation or black ash wetlands using a mix of local and non-local seed sources. Deer browse and understory competition were common problems affecting the success of the projects. Based on our surveys, the median area planted was 8.6 ha ranging from <1 ha to 806 ha (Supplement 4). Goals often include diversifying black ash wetlands in anticipation of tree mortality from EAB; maintaining ecosystem functions and forest health in the face of threats; and managing for diverse species and age classes to favor species expected to perform better with climate change. The most common species planted in upland forests are northern red oak (*Quercus rubra*) and eastern white pine (*Pinus strobus*), while the most common species planted in lowlands are silver maple (*Acer saccharinum*) and swamp white oak (*Quercus bicolor*). Photos illustrate several examples. See Table 2 for a description of each project. A) Carlton county planting in ash stands, Minnesota, planted in 2021. B) Family forest owner, Wisconsin, planted in 2021. C) Fond du Lac Band of Lake Superior Chippewa stand 210 planted in 2021-2022. D) Nerstrand Big Woods State Park, Minnesota, planted in 2019. E) Two Hearted River Forest Reserve Planting TNC, Michigan, planted in 2020-2021. F) Great Lakes Restoration Initiative ash project, Wisconsin, planted in 2020-2021

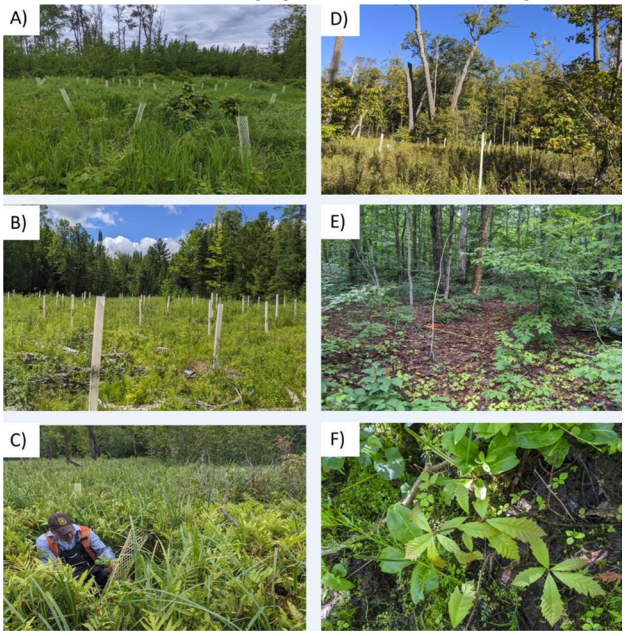

Table 2 Examples of adaptation planting projects in the Lake States region

Institution / organization	Location	Goal	Area (ha)	Planting year	Seed source	Collaborating institutions	Funding
A) American Bird Conservancy	Carlton, St. Louis (MN)	Diversify and increase resilience of black ash stands in preparation for EAB. Reduce loss of ecosystem function and maintain hydrological systems	13	2021	Local	Minnesota DNR, Carlton County, Fond du Lac Band	Grant (GLRI)
B) Family forest owner	Marinette (WI)	Replace harvested black ash	1.6	2021	Non-local / southern	-	Internal
C) Fond du Lac band	Fond du Lac lands	Increase resilience to emerald ash borer in black ash dominated stands. Increase the presence of underrepresented species used by the tribe	7.3	2004. Most recent plantings 2021–2022	Local	-	Grant
D) Minnesota DNR Division of Parks and Trails	Rice (MN)	Restore forest cover after climate-related die-off of > 200 acres of mature mesic hardwood forest	2	2019	Local	University of Minnesota Forest Resource Program	Internal
E) The Nature Conservancy, Michigan	Pine Stump Junction, Luce (MI)	Bolster tree species diversity, improve climate resilience, disease resistance	50.2	2020–2021	Non-local / southern	-	Internal
F) Wisconsin DNR	Ashland, Iron, Douglas, Bayfield, (WI)	Develop strategies in maintaining resilience in black ash wetland forests by mitigating losses and maintaining forest cover and hydrologic functions	40.5	2020	Local	-	Grant (GLRI)

*Letters A-F reference the projects in Box 1

Adaptation planting themes

Adaptation as a priority

Adaptation and mitigation, including adaptation plantings, are current priorities across all sectors (Forest Service 2022a). Of the 33 planting projects in the Lake States Region identified in our surveys (Table 2, Supplement 4), 17 were initiated after 2017. Participants in our focus groups indicated that there is more funding available for projects with an adaptation component. Funding comes from diverse sources including the Great Lakes Restoration Initiative (GLRI), Wildlife Conservation Society Climate Adaptation Fund, state DNRs, the Minnesota Environment and Natural Resources Trust Fund, and the Forest Service.

Current efforts are exploratory

Despite the growing prioritization, adaptation planting is not a routine practice in the region. To date, adaptation plantings have largely been exploratory efforts, demonstrations, or proof of concept, rather than an operational tool to adapt and sustain vulnerable forests (Palik et al. 2022). This reflects caution among natural resource managers. Moreover, most agencies are bound by institutional policies and resource constraints that may not yet allow for operational-scale adaptation planting. A common goal of planting trials is determining suitable species and genotypes that may be adapted to future climates and to gain experience needed to increase the scale of plantings (Fig. 2).

Perceptions of effectiveness

There has been variable success among the adaptation planting projects we surveyed. While some interviewees noted that they had good survival and growth rates, others mentioned high mortality. We note that the definition of success varies among projects and organizations and can be subjective based on the manager's own experience. There are several factors that affect the success of plantings through influence on survival and growth. Factors include soil conditions, hydrology, microtopography, competing vegetation, and resource availability as affected by canopy trees. The extent that these can be controlled varies among projects. Interviewees noted that smaller projects allow for greater control of external factors and ecological variability. The recent (< 5 year) implementation of the projects we surveyed limits evaluation of success. An example is the Two Hearted Fish Camp adaptation project (Box 1E and Table 2E), which despite having an 80–100% survival in 2022, it is still too early to evaluate success.

Adaptation to emerald ash borer

Plantings to address the loss of ash species from EAB are common across the region. Climate change is exacerbating this threat; warming winters lead to greater overwinter survival of larvae and increased spread to non-colonized areas (Iverson et al.

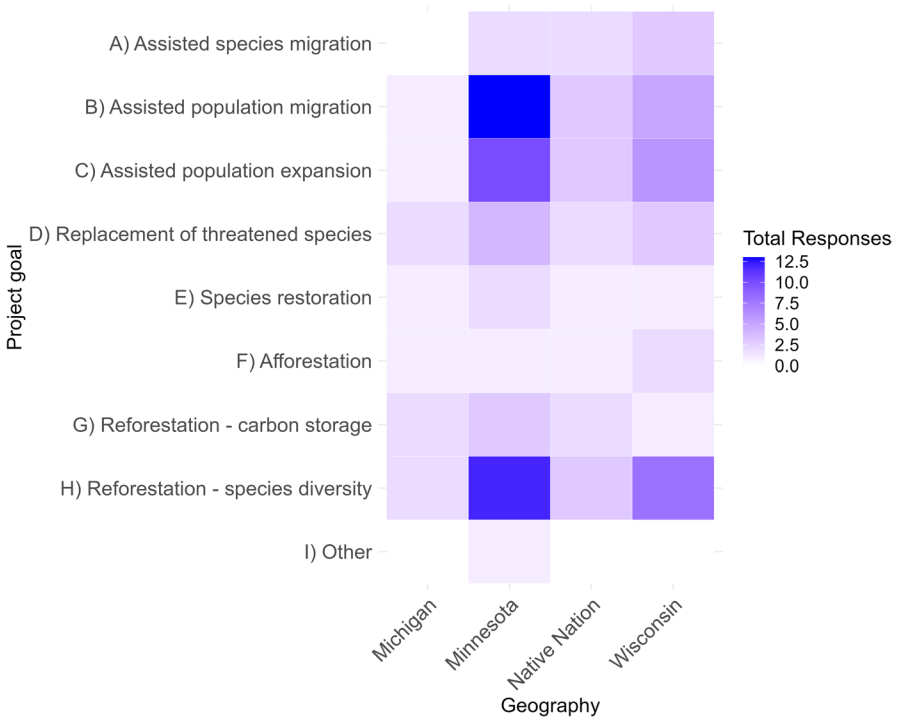

Fig. 2 Heatmap of project goals by location from survey responses

2016). Plantings of non-ash species in the understory (i.e., underplanting) prior to EAB infestation, were the most common types of adaptation plantings we encountered. The main objective is to establish tree species that maintain some aspects of forested wetland function as the current ash-dominated canopy dies.

Challenges for operationalizing adaptation planting

In general, respondents viewed operational-scale adaptation planting as a challenge, although the specifics vary among organizations. Despite a willingness to try adaptation plantings, natural resource managers generally have little experience with the approach, especially when it includes assisted migration. Divisions within the same agency can have different policies, personnel capacities, and budget allocation for adaptation planting projects, hindering operational-scale implementation.

Lack of policy guidance

A challenge mentioned by most survey participants was the lack of formal institutional policy to guide adaptation plantings, especially for assisted migration. There currently is no formal policy on assisted migration for the federal and state

agencies we surveyed, including the Forest Service, which has historically discouraged assisted migration in National Forest plans (Johnson et al. 2013). However, this situation is changing with the recognition of the need to formalize the use of assisted migration (Pike et al. 2020), guided by the best available science as seed sources are moved. Within the Forest Service, there are ongoing efforts to extend policies, like the Superior National Forest Assisted Migration Plan, to the entire national forest system (Frerker et al. 2023). Moreover, interviewees indicated that policy revision is being discussed within the state natural resource agencies in Minnesota, Wisconsin, and Michigan.

Uncertainty about approaches

Uncertainty about the best approach to address adaptation was often seen as a challenge. Some of the uncertainty comes from a lack of specific guidelines and formal policies, best practices when planting new species or genotypes, and information on performance of future climate-adapted species at local scales. Similar challenges were reported by McGann et al. (2023), who noted that some of the greatest barriers for planting for climate change adaptation included a lack of resources for selecting climate appropriate seedlings (e.g., species, seed sources, stock types) and uncertainty about best practices for novel planting strategies (e.g., assisted migration, replacing ecological function of vulnerable species).

There is still much uncertainty regarding which approaches, including which seed sources, are successful when planning an adaptation planting project. Moreover, most organizations in the region have little to no experience planting in forested wetlands, which are common in the region and particularly challenging in the normal spring planting season. The Fond du Lac Band and a private landowner in Michigan have had success in black ash wetlands using a site preparation technique called bucket mounting (e.g. Londo and Mroz 2001) that creates a raised planting site.

Cost of planting

One reason that adaptation plantings are not yet practiced routinely at operational scales is the high cost of planting compared to natural regeneration. For example, planting costs approximately $800–1300 per hectare in Minnesota (species and technique dependent) for a 1500–2000 trees per hectare typical density, with potential additional costs accrued for site preparation ($0–620/ha) and browse protection ($110–185/ha).

As such, natural regeneration remains the primary regeneration strategy for most organizations in the region, especially for state DNRs. Minnesota DNR harvests on average 16,200 hectares annually. Of these, approximately 1,400 to 1,600 hectares are planted per year (9–10%) and in 2023, only 20–40 planted hectares are specifically focused on adaptation (0.1–0.2%) (Minnesota DNR 2023). Wisconsin is similar, where out of 278,903 hectares of state-owned forest land, 6,079 hectares are actively managed (2.2%) and only around 527 hectares per year are planted (0.2%), with an even smaller percentage focused on adaptation.

The seedling supply chain

Another important challenge is a misalignment between seedlings needed for adaptation plantings and what nurseries are currently able to produce. Specifically, a lag between the species, genotypes, stock types, and quantities of seedlings that nurseries are growing and what managers are starting to request for adaptation projects, particularly in the quantities needed for operational scale plantings (Clark et al. 2023; Fargione et al. 2021; Haase and Davis 2017; Tepe and Meretsky 2011). Nursery production and supply is driven by demand; until recently, organizations have not requested the species, seed sources and quantities needed for even moderately sized adaptation projects. There is a broader misalignment of the entire reforestation supply chain to on-the-ground needs, including seed sources and collection, seed processing, nursery capacity, and planting capacities (Clark et al. 2023). For example, interviewees noted that the seed collectors they rely on are reaching retirement age, with little potential for replacement. Moreover, for assisted migration purposes, the need is for seed from seed zones in the central and southeastern US, but this is a region of relatively little public land for collection, and there is little experience with seed collection in general. Interviewees noted the need for investment in attracting and training younger collectors. The Minnesota Million project has begun to offer training.

Overall, responses affirmed the need for more advanced programmatic planning (10 + years) to better align supply and demand of planting stock for adaptation projects (Dumroese et al. 2016). Organizational policy, strategic planning shifts toward adaptation plantings, and economic incentives to nurseries could bridge this planting stock gap.

Staff capacity

Lack of staff capacity was seen as another barrier towards increasing the use of adaptation planting (Haase and Davis 2017; Blinn et al. 2021; Fargione et al. 2021; Clark et al. 2023). For example, managers in state DNRs report being overwhelmed with ongoing other responsibilities, making it hard to experiment with adaptation planting projects. Some institutions are considering reorganization of staff and programs to include specialists focused on climate adaptive management to facilitate operationalizing adaptation plantings.

Conclusions

This project evaluated trends and outcomes of adaptation planting projects across land ownerships in Minnesota, Wisconsin, Michigan, and Native Nations that share this geography. We found that adaptation plantings are generally seen as demonstrations or proof of concept, rather than operational tools for sustaining or adapting vulnerable forests to threats such as climate change and emerald ash borer. At organizational scales, adaptation plantings are not seen as the main management choice due to high costs, high uncertainty in the outcomes under current global

change scenarios, and long traditions of relying primarily on natural regeneration in reforestation activities in this region. Limitations preventing operationalizing adaptation plantings include availability of species and genotypes in sufficient quantities, uncertainty in species selection, and limited guidance within agencies pertaining to adaptation planting.

Despite these challenges, adaptation planting to address climate change and EAB invasion is increasingly seen as a priority by every organization we surveyed and there is an increasing interest in operationalizing the practice among these organizations. Regional collaboration for access to demonstration areas and sharing knowledge, resources, and lessons learned among and within institutions and across geographies was seen as an important opportunity among participants in this project to advance adaptation planting.

Overall, our results will highlight the importance of clear guidance for forest practitioners regarding adaptation plantings and contribute to a more comprehensive understanding of the operational feasibility and outcomes of forest adaptation plantings.

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Author contributions LAF, BJP, AWD, and RM conceived and designed the study. LAF analyzed the data. LAF, RM, BP, PC contributed to writing a first draft of the work. All authors provided input on the analysis and interpretation of results. All authors edited, read, and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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Authors and Affiliations

Lucia A. Fitts[1] · Rebecca A. Montgomery[1] · Brian J. Palik[2] · Peter W. Clark[3] · Josh Kragthorpe[7] · Mike R. Reinikainen[4] · Gregory J. Edge[5] · Stephen Handler[6] · Bradley M. Hutnik[5] · Anthony W. D'Amato[3]

✉ Lucia A. Fitts
fitts010@umn.edu

Rebecca A. Montgomery
rebeccam@umn.edu

Brian J. Palik
brian.palik@usda.gov

Peter W. Clark
peter.clark@uvm.edu

Josh Kragthorpe
jkragtho@umn.edu

Mike R. Reinikainen
mike.reinikainen@state.mn.us

Gregory J. Edge
Gregory.Edge@wisconsin.gov

Stephen Handler
stephen.handler@usda.gov

Bradley M. Hutnik
Bradley.Hutnik@wisconsin.gov

Anthony W. D'Amato
anthony.damato@uvm.edu

1 Department of Forest Resources, University of Minnesota, 1530 Cleveland Ave. N. St, Paul, MN 55108-6112, USA

2 USDA Forest Service, Northern Research Station, Grand Rapids, MN, USA

3 Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT, USA

4 Minnesota Department of Natural Resources, St. Paul, MN, USA

5 Wisconsin Department of Natural Resources, Division of Forestry, Madison, WI, USA

6 USDA Forest Service, Northern Research Station and Northern Institute of Applied Climate Science, Houghton, MI, USA

7 Natural Resources Research Institute, University of Minnesota Duluth, Duluth, MN, USA