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Forest assisted migration and adaptation plantings in the Northeastern US: perspectives and applications from early adopters

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Threats to the future function of forested ecosystems and stability of ecosystem service provisioning due to global change have motivated climate-adaptive forest management strategies that include various forms of tree planting termed "adaptation plantings". Despite the emergence of these strategies, less is known as to how foresters and other natural resource managers perceive or are engaged with adaptation plantings like forest assisted migration (FAM). This knowledge gap is most pronounced in regions like New England and the North Central US (hereafter, the Northeastern US) where tree planting is less common but expected to be an important forest management tool for adaptation. To address this, we surveyed 33 natural resource managers in this region actively engaged in climate change adaptation (i.e., early adopters of the practice) to assess how tree planting for adaptation is currently being pursued against the perceived barriers, opportunities, and potential future engagement with the strategy. Survey respondents overwhelmingly (93.5%) forecast increases in the future use of adaptation plantings in their work in the region, attributed to increased awareness, acceptance, and interest in the practice. Respondents expressed notable interest in strategies related to diversification and most types of FAM (e.g., assisted population expansion and assisted range expansion), but hesitancy to engage with more contentious planting types like afforestation or FAM linked to the long-distance translocation of exotic species (e.g., assisted species migration). Although examples of local enrichment plantings (i.e., non-FAM) proliferate, nineteen of the top twenty most common tree genera planted contain at least one example of FAM in the study region. The most notable barriers reported were themed as 1) biotic and abiotic, 2) information and material, and 3) policy, social, and economic factors. While most respondents report difficulty obtaining adequate planting material from nurseries (i.e., seedlings), over 80% placed orders shortly before planting (< 1 year) which likely generates difficulty in sourcing seedlings suited for a specific site and future range of environmental conditions. Although this study is limited by focusing on subset of natural resource managers who are early adopters of climate change adaptation within the region, valuable inferences into the barriers and trends are possible from this population serving on the front lines of forest adaptation. Together, these results from early adopters suggest a potentially growing need for allocating resources that engage forest stewards in adaptation planning and serve to refine policy, financing, and management practices to support this adaptation strategy in this region and beyond.

KEYWORDS

assisted migration, managed relocation, silviculture, forestry, assisted colonization, climate adaptation

1 Introduction

Global climate change is expected to affect forested ecosystems worldwide, with impacts to community structure, composition, and ecosystem function (Dale et al., 2001). Consequently, these challenges have given rise to forest management strategies that emphasize ecological maintenance and restoration (Palik and D'Amato, 2023), climate change adaptation (Millar et al., 2007; Bowditch et al., 2020), and greenhouse gas mitigation (i.e., natural climate solutions; (Griscom et al., 2017). Understanding how to implement these strategies, along with associated barriers and opportunities, will be important for moving towards operational implementation of climate-smart and adaptive management strategies in the face of global change (Nagel et al., 2017; Verkerk et al., 2020).

Among a suite of climate-smart and adaptive forest management strategies, artificial regeneration (i.e., tree planting) has increasingly become viewed as a critical tool for global change adaptation (Verdone and Seidl, 2017; Domke et al., 2020; Holl and Brancalion, 2020). Termed here as "adaptation plantings", these tree planting strategies differ from traditional artificial regeneration techniques that largely prioritize commodity and timber production and focus on a limited set of commercially valuable species (Bennett, 2015; Martin et al., 2021). In contrast, adaptation plantings emphasize one or several aspects linked to global change adaptation and correspondingly often involve a greater variety of species and genotypes (see Table 1 for detailed descriptions of adaptation planting types). For instance, adaptation plantings may include strategies aimed at a) promoting the adaptive capacity of ecosystems by diversifying, restoring, and/or sustaining ecologically and culturally important foundational species or ecosystem functions (Stanturf et al., 2014; D'Amato et al., 2023), b) encouraging the functional replacement of species degraded by disturbances (D'Amato et al., 2018), c) mitigating greenhouse gas emissions through increased carbon stocks (Domke et al., 2020; Lefebvre et al., 2021), or d) the use of forest assisted migration (FAM) to adaptively respond to shifting habitat conditions caused by climate change (Pedlar et al., 2012; Palik et al., 2022). Notably, forest assisted migration aims to intentionally augment genotypes or introduce tree species from warmer (e.g. southern latitudes, lower elevation) or otherwise future climate-adapted regions to offset lags in natural migration rates relative to the pace of climate change (Sittaro et al., 2017; Iverson et al., 2019). Despite a long legacy of planting being used in forest management globally as a means of achieving various regeneration objectives (Bennett, 2015), less is known about how natural resource managers are engaged with adaptation planting as part of various forest management strategies (McGann et al., 2022; Himes et al., 2023; Schattman et al., 2024). This is particularly apparent for more "novel" adaptation planting strategies like forest assisted migration that have long been perceived as risky (Hewitt et al., 2011; Findlater et al., 2022) but potentially timely and necessary in some forests where the risk of inaction may lead to greater ecosystem vulnerability (Palik et al., 2022).

Artificial regeneration is commonplace globally and employed in many regions of the United States, such as the southeastern and western states, where tree planting is either a primary silvicultural activity, such as in plantation forestry or complementary to reliance on natural regeneration as part of different silvicultural systems (Nyland, 2007). In other regions like New England and the North Central US (hereafter, the Northeastern US, in accordance with the USDA Forest Service region 9), artificial regeneration has traditionally been of lesser importance due in part to the silvicultural practices and dominant forest types that support abundant natural regeneration of ecologically and economically desired species. Nevertheless, recent interest and a growing recognition for practices that transition beyond "business as usual" approaches have led to growth of adaptation plantings in this region (Muller et al., 2019; Etterson et al., 2020; Clark et al., 2021; Palik et al., 2021). In fact, in 2022 forest nurseries in this region produced over 52 million seedlings supporting reforestation efforts on approximately 16,000 hectares of forest lands (Pike et al., 2022). Moreover, given the high species richness of forests in the Northeastern US, this region is expected to be fertile grounds for forest assisted migration where over 40 tree species are forecast to either decline or increase in habitat suitability due to climate change over the next century (Peters et al., 2020; Prasad et al., 2020). Yet, adaptation plantings like forest assisted migration are not a mainstream practice with few, but a growing number of examples of practice. Therefore, generating an understanding as to how and why natural resource managers in the Northeastern US are engaged with adaptation plantings, including but not limited to assisted migration, will be critical in refining policy, attracting financing, and improving best management practices in this region and beyond (Clark et al., 2023). Lastly, given the need for actionable, translational research during a time of unprecedented change

TABLE 1 A list of planting terms (e.g., types), grouped among commonly associated climate adaptation objectives, along with definition of terms in the context of global change applications and examples of their use.

Adaptation objective	Adaptation planting term	Definitions and examples
Diversity, restoration, and resilience	Species and ecosystem restoration	*Reestablish or diversify native species and ecosystems to historical conditions and/or conditions that are expected to persist.* • Efforts to reestablish *Picea rubens* (www.restoreredspruce.org) and *Castanea dentata*; www.acf.org) populations, two keystone species threatened or functionality extirpated due anthropogenic disturbances and disease, respectively. • Restoration and diversification of upland and riparian forests to support ecosystem resilience (e.g., supporting riparian area function and flood mitigation potential: www.uppersusquehanna.org/usc/) or restoring native habitat impacted by disturbance where natural regeneration would lead to insufficient recovery targets.
	Functional replacement	*Replacement of threatened or otherwise degraded species with new species that confer similar functional traits.* • The replacement of *Fraxinus nigra* lost due to invasive species with species that may maintain wetland habitat function (Palik et al., 2021). • The Civilian Conservation Corps efforts in the 1930s to plant *Pinus resinosa* in anticipation of declines in *P. strobus*.
Forest Assisted Migration (FAM)	Assisted population expansion (aka assisted population migration)	*Population augmentation of a species currently onsite or within its range using climate-adapted genotypes, commonly from southern or lower elevation seed sources. May also be used to confer disease resistance.* • Supplementary planting of southern genotypes (Palik et al., 2022). • Pine blister rust resistant five-needle pines planted through North America (Schoettle and Sniezko, 2007).
	Assisted range expansion	*Movement of a species outside of its historical range and expanded into adjacent areas in anticipation of increased habitat suitability in the near term, but to territory that the species could realistically establish in via natural dispersal over long timescales.* • Range expansion of *Quercus-Carya* species into northern hardwoods (Clark et al., 2021). • Indigenous North Americans promoted the northward expansion of fruit and mast species (Abrams and Nowacki, 2008).
	Assisted species migration	*Movement of at-risk species or the long-distance relocation (e.g., interregional, intercontinental) of a species beyond areas ever accessible via natural dispersal, necessitating deliberate intervention to establish.* • The movement of *Torreya taxifolia*, an endangered glacial relict species (ww.torreyguardians.org). • Asian *Fraxinus mandshurica* planted in Minnesota as a replacement species for *Fraxinus nigra* (Palik et al., 2021).
Greenhouse gas mitigation	Reforestation	*Increase stocking on low density sites and marginal lands (e.g., under or non-stocked cover types suitable for tree species).* • The Nature Conservancy's Plant a Billion Trees campaign and the Minnesota Million (www.nature.org). • Spatially explicit reforestation decision support tools (www.reforestationhub.org).
	Afforestation	*Establish forests on historically unforested lands to increase forest cover.* • Bottomland afforestation systems with multiple species (Gardiner et al., 2004). • Afforestation on agricultural lands taken out of row crop production.
	Reclamation	*Return degraded sites to forested state.* • Tree planting abandoned mines to increase above and belowground carbon stores (Fox et al., 2020). • Reforestation of degraded forests due to wildfire or human activities (Lefebvre et al., 2021).

Although presented within discrete associated climate adaptation strategies, the grouping only serves to differentiate outcomes as many adaptation planting types may achieve one or multiple objectives related to global change. Moreover, objectives unrelated to global change are also available (e.g., timber) but are intentionally omitted for clarity.

(Enquist et al., 2017), it is particularly important to assess the activities of early adopters of practices, as this population can serve as a critical litmus test on the front lines of application, perception, and knowledge transfer (Rosenzweig and Solecki, 2014; Storbjörk et al., 2024).

With these needs in mind, the objectives of this study are to assess current perspectives, practices, and limitations associated with tree planting for adaptation, principally forest assisted migration, in the Northeastern US. To achieve this, we used a survey tool to solicit responses from regional foresters and natural resource managers actively engaged or interested in climate adaptation (i.e., "early adopters" of these practices) to answer the following questions:

1. *What is the current and anticipated future level of engagement with adaptation plantings among early adopters?*

2. *How and why is tree planting being employed for climate change adaptation?*
3. *What species are favored for assisted migration?*
4. *What factors are most limiting decisions to pursue adaptation planting?*

Our overall goal is to provide a critical baseline of knowledge for informing adaptation plantings and broad reforestation practices, seedling production and capacity building, and the barriers limiting the application of these strategies to address diverse adaptation objectives across the region. Given the apparent novelty of some of these practices (i.e., FAM), we specifically targeted a population of early adopters to gauge the state of the practice among this population and have subsequently constrained inferences within this subset of foresters and natural resource managers.

2 Materials and methods

2.1 Survey design and administration

To gather insights into the perspectives and applications of adaptation planting in the region, we conducted an online survey using the Qualtrics survey tool in the spring of 2022. Survey questions were broadly focused on capturing insights into the practices, levels of experience, and barriers facing natural resource managers related to adaptation plantings (see Supplementary Appendix 1 for complete version of the survey administered). The survey was targeted towards natural resource managers and other professionals (e.g., foresters, conservation professionals, researchers) actively engaged with climate change adaptation. Although we recognize the value of querying a broad sample of forest stewards, we were specifically focused on respondents who are interested in or have engaged with climate change adaptation in forest management for our research purposes of characterizing, assessing, and clarifying the challenges and practices of this subgroup of early adopters.

The survey was tested prior to deployment with three forestry professionals familiar with the topic area and revised according to their feedback. Surveys were designed to be completed in less than 30 minutes. No compensation was offered to participants. We used purposeful informant sampling (Patton, 2002) targeting individuals in the twenty-state Northeastern United States, namely New England and North Central regions (Iverson et al., 2008). To achieve this, we solicited participation through email membership lists and online regional newsletters for the Northern Institute of Applied Climate Science (NIACS; 4,326 potential subscribers) as well as via the National Council for Air and Stream Improvement, Inc (NCASI; unknown number of subscribers). Human subject protection approval was issued by the University of Vermont Institutional Review Board (STUDY00002004).

2.2 Analysis

A total of 44 surveys were returned, but we discarded those responses in which the participant completed less than 50% of survey questions and one respondent from outside of the focal region. This process resulted in 33 valid surveys from natural resource managers working in the Northeastern US and engaged with climate change adaptation. Using these data, we generated summaries of results using numerical, rank ordinal, or proportion of responses and examined differences among populations using ANOVAs followed by Tukey Honesty Significance (HSD) as well as Pearson's correlation coefficient. A significance threshold was set for all tests at $\alpha = 0.05$ and each statistical test was assessed and diagnosed to pass test assumptions including those of linearity and normality of residuals. For written essay responses (one question), we report raw responses as well as coded common themes, informed by grounded theory (Charmaz, 2014). Given the limited sample size, we elected not to employ higher-level multivariate models to assess the role of participant demography (e.g., geography, employment, training, etc.), rather focusing on the outcomes of the overall sample population of early adopters engaged in climate change adaptation.

3 Results

Respondents most frequently reported working in New York (33.3%), Massachusetts (21.2%), New Hampshire (12.1%), Vermont (12.1%), and Wisconsin (6.1%). The remaining respondents were from Maine, Maryland, Minnesota, Pennsylvania, and Rhode Island (3.0% each). Participants self-identified to be among various roles engaged in forest stewardship including forester (42.9%), conservation professional (28.6%), landowner (11.9%), researcher (9.5%), and other (7%). Most were employed within conservation agencies (40.5%) while the remaining were employed within state agencies (18.9%), research institutions (13.5%), municipalities (10.8%), federal agencies (8.1%), or in private consulting (8.1%). Respondents reportedly managed varying amounts of forest land, where most oversaw larger land holdings including land exceeding 10,000 hectares (43.3%), 2,000–9,000 hectares (26.7%), and 400–1,999 hectares (13.3%). In terms of forest types, the majority of respondents reported to work in Northern Hardwoods (*Acer-Fagus-Betula*; 26.5%), followed by Oak-Pine (*Quercus-Pinus*; 17.6%), Oak-Hickory (*Quercus-Carya*; 15.7%), Spruce-Fir (*Picea-Abies*; 9.8%), Riparian hardwood (*Ulmus-Fraxinus-Populus; 8.8%*), Aspen-Birch (*Populus-Betula*; 7.8%), and White-Red-Jack Pine (*Pinus strobus-P. resinosa-P. banksiana*; 5.8%).

When asked about their level of experience with tree planting, the majority reported high levels of expertise, with 21.9 and 37.5% self-identified as "very experienced" or "experienced", respectively. The remaining respondents identified as "slightly experienced" (28.1%) or "not at all experienced" (12.5%).

3.1 What is the current and anticipated future level of engagement with adaptation plantings among early adopters?

When respondents were asked if they had used tree planting aimed at global change adaptation, nearly all respondents answered in the affirmative (96.7%), with 54.5% responding "Yes, I have implemented" (*n* = 18), 9.1% responding "No, but I am planning to implement" (*n* = 3), and 33.3% responding "No, but I would consider implementing" (*n* = 11). Only one respondent replied "No, I haven't and don't plan to implement". Of those respondents in the affirmative, the majority (63.6%) reported to have engaged with two – four adaptation planting projects in the last ten years, while 18.2% reported one project, 13.6% reported greater than ten projects, and 4.5% reported five – nine projects.

When respondents were asked how the number of adaptation planting projects that they were engaged with are expected to change over the next 10 years, nearly all reported that relative to present day they expected the number to increase (93.5%) or stay the same (2%). None forecasted a decrease in the number of adaptation planting projects in the future. Among those respondents who provided an optional written response outlining why they expected the amount of adaptation planting projects to change in the future (Figure 1), the most common themes reported were a) *awareness, acceptance, and interest* (*n* = 12, 26%), b) *adaptation and climate resilience* (*n* = 8, 17%), and c) *restoration of species and ecosystems* (*n* = 5, 11%). Only 4% (*n* = 2) explicitly use the term (or related terms) d) *forest assisted migration* as a driver for increasing future adaptation projects, although there are arguably links to the "adaptation and climate resilience" theme noted above. Other themes reported included e) *biotic and abiotic disturbance and stressors*, f) *logistics and best management practices*, g) *research*, h) *invasives, pests and pathogens*, i) *information and resources*, j) *reforestation*, k) *carbon mitigation*, and l) *markets, demand, and forest products*.

3.2 How and why is tree planting being employed for climate change adaptation?

Survey respondents were asked to rank various forest management objectives as to how important they are related to adaptation planting efforts, where very important = 2, important = 1, neutral = 0, unimportant = −1, and very unimportant = −2. In order of mean ranking from most to least important, objectives included a) *to diversify current conditions* (1.4 ± 0.2 SE), b) *to change forest conditions to align with future climate (e.g., FAM;* 1.1 ± 0.2), c) *to change forest conditions to adapt to disturbances (e.g., invasives;* 1.1 ± 0.2), and d) *to store more carbon and greenhouse gasses* (0.9 ± 0.2). Ranked importance among these four strategies did not differ significantly ($p \geq 0.05$ Tukey HSD); however, e) *to maintain historical/existing conditions* (0.2 ± 0.2) ranked significantly lower in terms of importance ($p < 0.05$) compared to all other objectives.

To better understand how different adaptation planting strategies were applied in this region, respondents were asked to rank their level of interest and engagement with ten planting types aimed at global change (Figure 2). Relative to all other levels of strategies, most respondents reported that they have already implemented strategies that included "reforestation of native species", "reforestation to maintain ecosystem functions", and "rehabilitation of degraded sites" (mean proportion of respondents = 43.9%). Additionally, on average 43.5% of respondents reported being interested in the "restoration of historically important [e.g., foundational or keystone] species", "replacing species threatened by disturbance with new species", or "reforestation to increase carbon for climate mitigation" but lack plans or experience in these practices. In terms of assisted migration, 55.6% of respondents report actively having plans or have already implemented assisted population expansion of "climate-adapted genotypes from species currently found onsite" and assisted range expansion of "climate-adapted species not onsite but with ranges found nearby" that would migrate into the region over long timescales (see Table 1 for clarification around terms). On the other hand, most respondents report that they don't plan to implement "afforestation planting on historically unforested lands" (38.7%) or "assisted species migration in the form of long-distance introduction of novel species tolerant of future climate/disturbances" (58.1%).

3.3 What species are favored for assisted migration?

We compared what species were favored for FAM relative to those commonly favored under other non-FAM applications (e.g., local enrichment plantings). Respondents were asked to report which species they plant (or intend to plant), as well as codify each based on three terms relative to seed source location or two FAM types: a) local enrichment of native genotypes (non-FAM), b) assisted population expansion (FAM type 1), or c) assisted range expansion (FAM type 2; Figure 3). Based on responses collected, the most frequently reported deciduous genera were *Quercus* and *Carya* while the most frequently reported coniferous genera were *Pinus* and *Picea*. Overwhelmingly, most plantings are classified as non-FAM local enrichment plantings (71.6% ± 2.7), with only 14.2% (± 1.7) reporting to plant (or intending to plant) under conditions classified as FAM (either assisted population or range expansion). When FAM types are compared, assisted population expansion remains more popular than assisted range expansion strategies (19.6% ± 2.0 versus 8.8% ± 2.1, respectively). In terms of the proportion of plantings coded as FAM, the most common species reported to be planted using FAM (combined assisted population expansion and range expansion) include *Picea* (proportion of plantings reported as FAM = 47%, ranked order of all genera = 9, total number of plantings reported by genera N = 17), *Juglans* (FAM = 46%, rank = 7, N = 18), *Pinus* (FAM = 44%, rank = 2, N = 57), and *Quercus* (FAM = 41%, rank = 1, N = 135). In terms of *Picea*, it is important to note that half of the examples of FAM reported refer to *P. abies* which is non-native to the US (of European origin) and represents the only example of assisted species migration reported in the study.

Among the most frequently reported deciduous and coniferous genera (*Quercus*, *Carya*, *Pinus* and *Picea*), 62 species were reported to be planted, of which a subset of 27 are included in Figure 4 (species list truncated to those with at least ≥ 3 observations). Each species in the subset included at least one observation classified as FAM. Nearly all species include plantings classified as assisted population expansion (89.3% of observations), where the only exceptions that lacked examples are *C. alba*, *P. abies*, and *Q. prinoides*. None of the most common species planted among

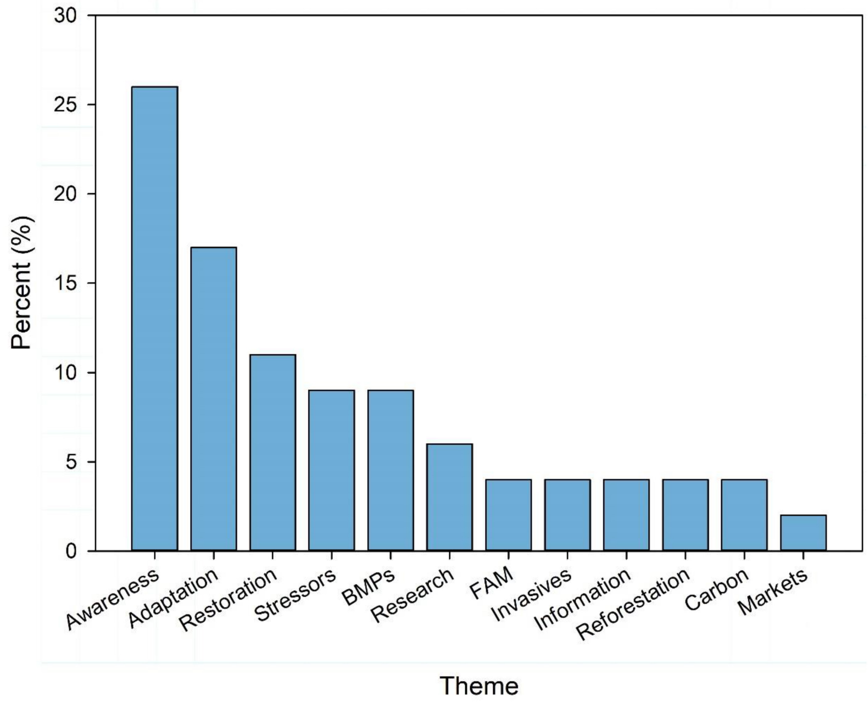

FIGURE 1
Optional text-based responses to the prompt "How do you expect the number of adaptation planting projects that you are engaged with to change over the next 10 years? Why?" Responses are coded by common themes: *Awareness* = awareness, acceptance, and interest, *Adaptation* = adaptation and climate resilience, *Restoration* = restoration of species and ecosystems, *Stressors* = biotic and abiotic disturbance and stressors, *BMPs* = logistics and best management practices, *Research* = Research, *FAM* = forest assisted migration, *Invasives* = invasives, pests and pathogens, *Information* = information and resources, *Reforestation* = reforestation, *Carbon* = carbon mitigation, *Markets* = markets, demand, and forest products. See Supplementary Appendix 2 for raw text-based responses and thematic coding.

each genus were classified as assisted range expansion, including *Q. rubra*, *P. strobus*, *C. ovata*, and *P. glauca*. In fact, species ranked order based on the total number of plantings is inversely correlated with the ranked order of the proportion of assisted range expansion plantings reported per species (mean r = -0.86 ± 0.1, $p \leq 0.01$).

3.4 What factors are most limiting decisions to pursue adaption planting?

Given the important role of species, seedlots, and stock selection in FAM and adaptation plantings, we asked two questions targeted at seedling procurement strategies and availability at forest nurseries. When asked which approach best describes the typical strategy for procuring planting stock, the vast majority (82%) operated on short timelines (< 1 year), electing to place orders several months before planting, based on availability (50%), purchase seedling material immediately before planting (13%), or employ no set strategy (6%). Some respondents did report that they do work with nurseries months to years in advance to grow ideal species, seed sources, or stock types for projects (13%), while 6% employed "other" approaches to procure seedlings. When asked how they would describe their ability to obtain diverse seedlings from forest nurseries (e.g., species, seedlots, and stock types/ages), 66.7% reported to have some or much difficulty in obtaining seedlings. Omitting those who responded that they were unsure to the following prompts, few respondents report having no difficulty obtaining diverse species selection (16.0%), various seed sources (e.g. provenances, genotypes; 4.7%), and different seedling stock (e.g., size/age, containerized vs bare root; 4.2%) in forest nurseries. All remaining respondents reported having some or much difficulty in procuring diverse seedlings (e.g., species, seedlots, and stock types).

Survey respondents ranked seven factors deemed influential in determining adaptation planting decisions, associated with a) biotic and abiotic factors, b) information and material resources, and c) policy, social, and economic considerations (Figure 5). The most important factors in terms of rank order were determined to be related to a) biotic and abiotic (1: *future climate change, disturbances, and novel conditions* and 2: *present-day conditions (e.g., competition, browse, soils, climate)*, then b) information and material resources (3: *access to appropriate planting material (e.g., species, seed sources, stock*) and 5: *information, training, and resources*), followed by c) policy, social, and economic considerations (4: *risk of failure (e.g., maladaptation)*, 6: *economics and labor*, and 7: *policy, regulation, other's perceptions*).

Among the three groups listed above, respondents reported how influential various subcategories are towards informing decisions to plant for climate change adaptation, including eight subcategories linked to biotic and abiotic factors, six associated with information and material resources, and nine related to policy, social, and economic considerations (Figure 6). The most limiting biotic and abiotic factors ranked included *vegetative competition, browse, predation* > *post-planting*

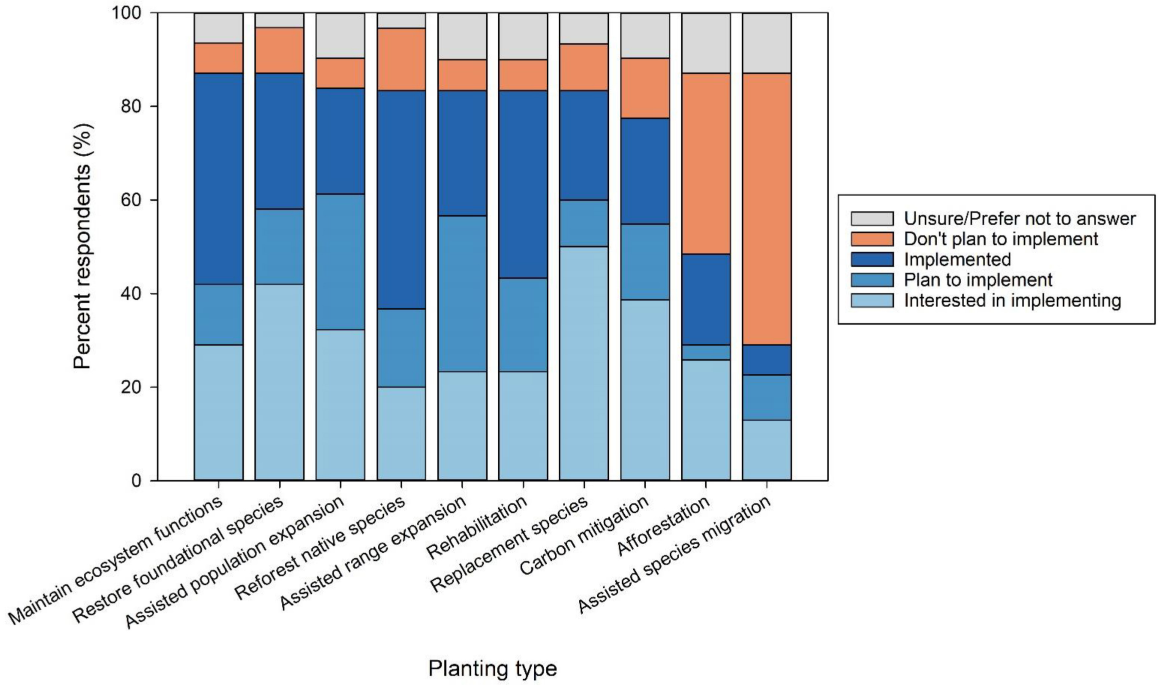

FIGURE 2
Respondent engagement among various adaptation planting types for global change. Planting types are presented from left to right in terms of level of implementation. Given the emphasis on understanding forest assisted migration (FAM) in this work, the three types are FAM are presented here: assisted population expansion, assisted range expansion, and assisted species migration.

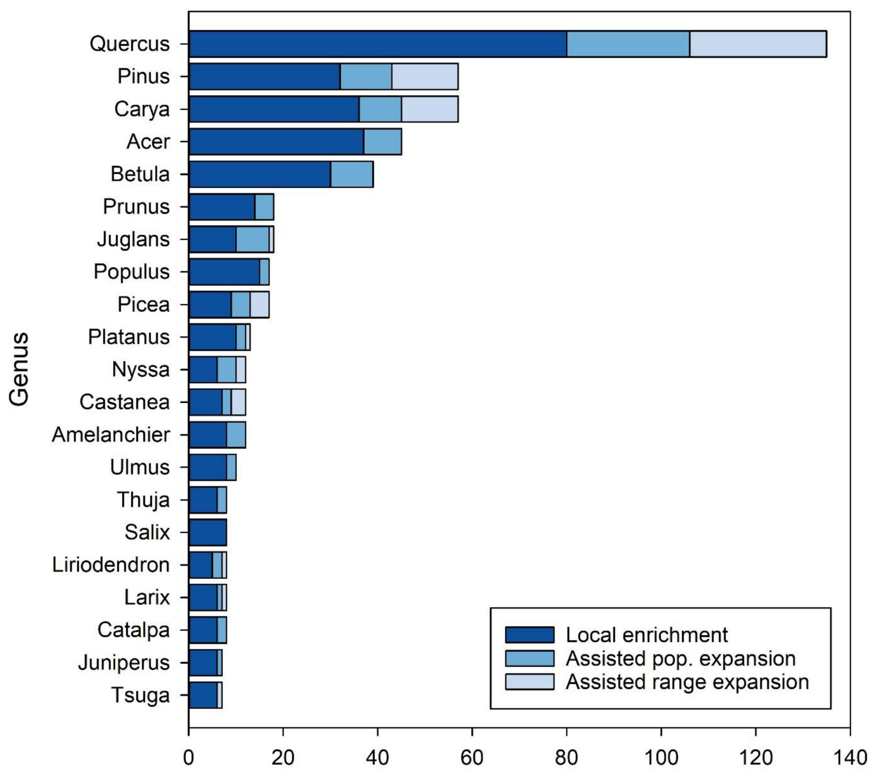

FIGURE 3
Top twenty genera of trees reported or forecasted to be planted by survey respondents. Planting types are presented in terms of the number of plantings binned by (a) local enrichment (non-FAM) and the most common forest assisted migration (FAM) types, (b) assisted population expansion, and (c) assisted range expansion.

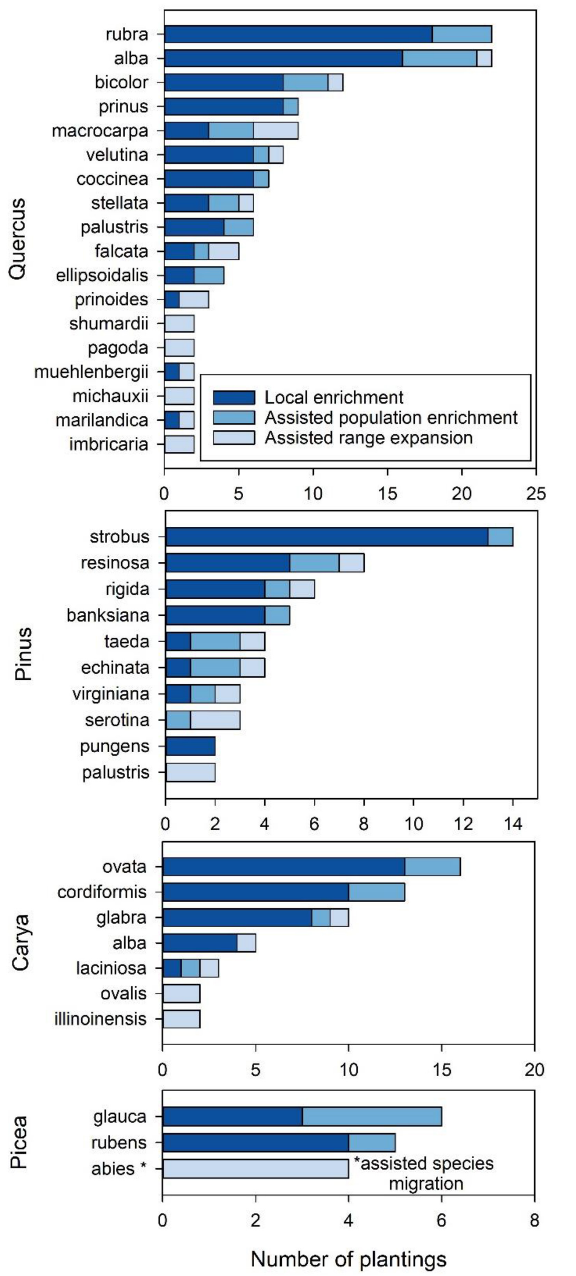

FIGURE 4
The most common species reported (or intended) to be planted among the top two deciduous and coniferous genera. Planting types are presented in terms of the number and percent by (a) local enrichment, and the most common forest assisted migration types, (b) assisted population expansion, and (c) assisted range expansion. Note that *Picea abies* is non-native to the United States and is an example of assisted species migration, but for clarity the figure is coded as assisted range expansion.

management > *invasive plants, pests, and pathogens* > *future projections for climate* > *projected shifts in species habitat* > *site preparation management*, while the least important (based on Tukey HSD tests) were *new, novel, or changes in disturbances* > *current climate (e.g., temperature, precipitation).* The most limiting information and material resources ranked included *stock type availability at nurseries* > *obtaining enough seedlings from nurseries* > *species availability at nurseries* > *seed source availability at nurseries* > *resources for planting climate-adapted species* while the least important was the respondent's *experience with planting.* The most limiting policy, social, and economic considerations ranked included *planting failure occurring* > *funding the practice* > *labor* > *risk of biological invasion,* while the least important were *public perceptions* > *supervisors/landowner directives* > *peers/other manager perceptions* > *policy/regulations* > *economic returns.*

4 Discussion

The capacity of forest ecosystems to respond to global climate change may be driven in part by the forest management decisions made today. For instance, the intentional movement of species and genotypes to match shifting ranges (i.e. FAM), the replacement of threated species, or maintenance and restoration of culturally and ecologically important species (and genotypes) are likely to be necessary if not critical tactics in supporting future levels of ecosystem service delivery that are within a socially acceptable range of variability (Seidl et al., 2016). Yet, to date, little is known about how natural resource managers are engaged in these practices, particularly those more novel adaptation strategies like forest assisted migration. The results from this study largely support the limited but growing body of literature that outline the role of operational scale adaptation planting work in the Northeastern US, particularly those emphasizing FAM (Palik et al., 2022; Royo et al., 2023). Moreover, our study further suggests how and why interest in adaptation plantings may be growing, albeit based on a small, subset population of early adopters actively engaged in climate change adaptation and despite the persistence of external factors that influence its application, including adaptation and FAM objectives, biophysical influences, and logistical barriers.

4.1 Perspectives of adaptation plantings

Results from our survey appear to suggest a growing interest and level of application of tree planting for adaptation. Based on results generated from a population of early adopters actively engaged in climate change adaptation, nearly all respondents in our survey (93%) reported that they expect the number of adaptation planting projects that they are engaged with to increase over the following decade. Although many aspects likely contribute to why interest appears to be increasing, factors such as awareness and acceptance of climate change and invasive species impacts, and interest in adaptation and climate resilience (i.e. FAM) are the most common themes reported among the survey population. These results generally point to factors related to knowledge, perceptions, and peer-to-peer influence that have been shown to influence the adoption of some adaptation practices among foresters (McGann et al., 2022; Schattman et al., 2024), but refine these findings in the context of adaptation planting. This pattern is likely most apparent for more "novel" practices related to adaptation, such as FAM, which historically have been perceived as riskier but may now becoming a more fundamental tactic in the adaptation toolbox (Palik et al., 2022). Although our survey was

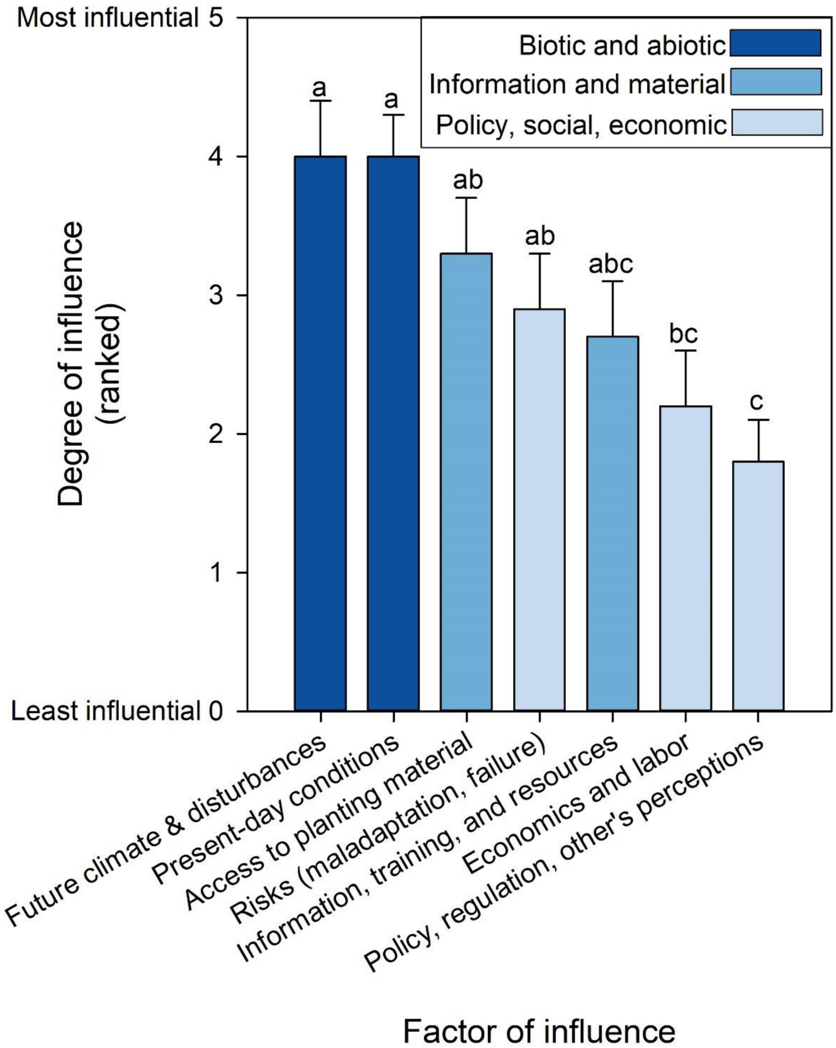

FIGURE 5
Ranked responses to the survey prompt, "What are the greatest influences for your decision to plant for climate change adaptation?", where 5 = *most influential* and 0 = *least influential*. Letters denote groups that are significant different where $p \leq 0.05$.

limited in the number of respondents and focused on a sample population of forest stewards already engaged with adaptation work (i.e., early adopters), the trends in these survey results illustrate that adaptation plantings and FAM may be a key tactic employed in adaptive forest management planning in the future (Himes et al., 2023).

In terms of how adaptation plantings are being pursued, most respondents (over 80%) anticipated the use of planting projects augmented by FAM, specifically assisted population expansion and range expansion. In fact, respondents were twice as likely to report having plans in place to implement FAM in the future relative to all other adaptation planting types queried. One interpretation of this trend is a potential expansion of the application of FAM compared to other adaptation planting types, although more information may be necessary to ascertain directionality. Still, other adaptation planting strategies related to diversifying forest conditions (e.g., restoration of foundational species, the use of replacement species) or carbon mitigation remain important with high levels of interest in future engagement. Although many respondents reported to have had experience implementing strategies related to maintaining historical conditions (e.g., reforestation of native species, maintenance of ecosystem function, rehabilitation of degraded sites), fewer anticipate future projects solely focused on these objectives. This trend is supported by other results in our study that illustrate the population of forest managers sampled here underemphasize strategies aimed at resisting the effects of global change (e.g., planting to maintain historical/existing conditions), rather, they exhibit a preference for planting strategies related to promoting adaptation, resilience, or ecological transition (e.g., to diversify current conditions, to change forest conditions to align with future climate, to change forest conditions to adapt to disturbances, and to store more carbon and greenhouse gasses; (Millar et al., 2007; Palik et al., 2022).

Our survey points to hesitancy among the sampled population to engage with two planting types, afforestation and assisted species migration, which are likely the most controversial and debated planting strategies presented within the scope of our survey (Pedlar et al., 2012; Di Sacco et al., 2021). Criticism of afforestation in this

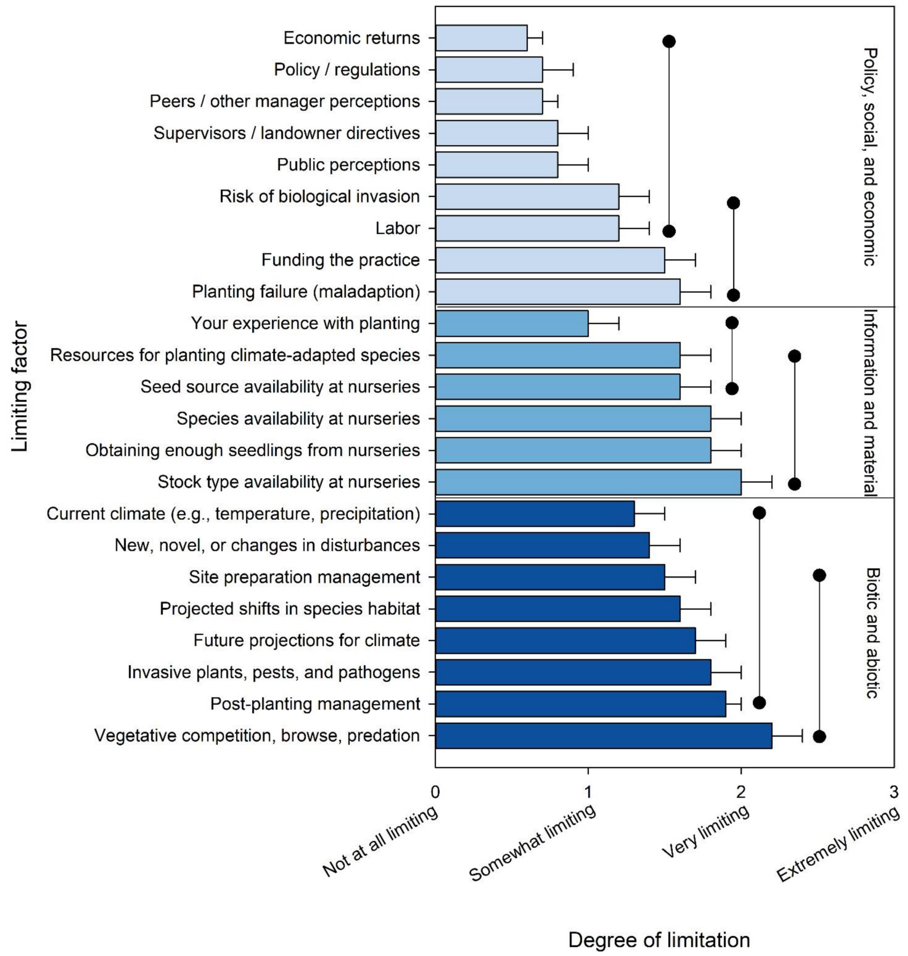

FIGURE 6
Responses to the prompt, "How limiting/influential are the following factors for your decisions to plant for climate change adaptation?". Responses are binned by (a) biotic and abiotic, (b) information and material, and (c) policy, social and economic factors. Horizontal bars denote factors that are not significantly different at $p \leq 0.05$.

region is likely centered around the loss of important herbaceous plant and wildlife habitat as well as ecosystem qualities of fields, meadows, and other historically unforested lands. Additionally, hesitancy to engage with assisted species migration is likely linked to a risk aversion to invasion or other unintended consequences of moving novel or exotic species. Relative to other FAM types like assisted population or range expansion which are regarded more favorably in our survey, manager sentiment toward assisted species migration is much less favorable. Given that adaptation planting types like afforestation and assisted species migration strategies are strongly associated with substantial shifts in ecosystem state, it is likely this generates uncertainty among natural resource managers tasked with sustaining ecosystem functions and services. Yet, as the consequences of global change are increasingly realized and/or uncertainty is minimized through research and implementation, it is possible that adaptation planting types like assisted species migration may become more necessary to adapt, functionally replace, and/or sustain forested ecosystems in the future. Lastly, it is important to note that adaptation planting strategies are not necessarily discrete or isolated from one another and may (or should) be paired to create complementary desired future conditions, such as timber productivity and FAM (Royo et al., 2023), restoration and FAM (Clark et al., 2022), or functional replacement and FAM (Palik et al., 2021). Taken together, the results from this work underscore that tree planting for adaptation appears to be growing in interest and implementation among natural resource managers actively engaged in climate change adaptation, although levels of engagement vary among planting types and objectives.

4.2 Application of forest assisted migration (FAM)

Within the subset population of early adopters sampled, interest in and the application of FAM differs among tree genera and species planted in the Northeastern US. The most commonly planted genera reported in our survey were *Quercus* and *Pinus* (26 and 16 species, respectively), which are highly valued for timber products but also support many critical cultural and ecological functions in the region. Moreover, these genera are some of the most commonly propagated in many forest nurseries in the region (Pike et al., 2018; Clark et al., 2023), likely resulting in relatively abundant inventory and source selection for planting projects. Given the role that these species have historically played in planting practices in the region, it is perhaps unsurprising that they are frequently planted to enrich local populations with native genotypes. This trend is consistent across all genera reported in the study, such that most plantings are classified as local enrichment. Nevertheless, even though engagement (or plans to engage) with FAM is subordinate to plantings for native population enrichment, which is unsurprising given the nascent stage of the practice, FAM still apparently represents up to one quarter of planting efforts reported among the sample population's work.

Among the sample population of early adopters, applications of assisted population expansion appear to be more common compared to assisted range expansion, and with very few examples of assisted species migration. For instance, on average twice as many planting projects reported in this study are coded as assisted population expansion versus those coded as assisted range expansion. Moreover, most genera contain at least one example of assisted population expansion (95%) while fewer genera contain an example of assisted range expansion (55%). One interpretation as to why natural resource managers may be more comfortable with assisted population expansion is that it allows for the accomplishment of multiple goals with more controlled, incremental changes and fewer perceived risks, relative to the other FAM types. For example, the inclusion of a future-climate adapted genotype of a species currently onsite may be considered safer (in terms of maladaptation) while simultaneously promoting climate adaptation and diversification (genotypic). In addition, these applications may be consistent with broader restoration goals to support historical forest and ecological conditions when the species planted represent those that were historically more formerly common in a given landscape (e.g., *Pinus strobus, Picea rubens*). Compared to an assisted range expansion planting, which may carry elevated risks (in terms of maladaptation) given that the target species does not already have a demonstrated site affinity beyond those projected by species distribution models (Iverson et al., 2019), assisted population expansion is more consistent with historical traditions in forest management surrounding matching species to a site based on past experience and current ecological conditions. Still, we only report one species used for assisted species migration, *Picea abies*, a species of European origin having been planted throughout the eastern US since the mid-1800s. Given the long history of planting *P. abies* in the region, it is likely natural resource managers are more comfortable with species as the risks of invasion or other unforeseen consequences of its introduction have been demonstrated to be minimal or unapparent. As threats from global change increase, it is possible that other examples of assisted species migration species like *P. abies* may be applied in broader adaptation context. For example, *P. abies* has been considered to be a candidate species to potentially functionally replace *Tsuga canadensis* in an effort to sustain the critical ecosystem benefits of the ecological keystone species threatened by an invasive pest (Ritter et al., 2023).

It is also possible that species employed under assisted population expansion (or other FAM types) were done so somewhat unintentionally. In our study, many foresters report that one of the greatest challenges related to implementing adaptation plantings is the availability of adequate, diverse planting stock (e.g., species, seed sources) from forestry nurseries, findings consistent with (Clark et al., 2023). Forest nurseries operate on narrow margins and respond to market signals. Given that it can take 1–5 years to grow seedlings for sale, inventories may not change unless buyers work with growers years in advance (see the Target Plant Concept; (Dumroese et al., 2016). Yet, most respondents in our survey report seeking out stock merely months before planting, which likely hinders the ability to refine choices in terms of seed source, species, or stock to match site and climate needs. Under these conditions, if a forester is unable to obtain seedlings from a local nursery or native seed source, it is possible that seedlings may inadvertently come from seed sources outside of the local region but that happen to be representative of a future climate zone.

Although this scenario illustrates the potential for "unintentional" assisted population expansion, it is possible that this may be applied under an assisted range expansion scenario, too. For instance, we had no respondents reporting use of geographically widespread species like *Quercus rubra* and *Pinus strobus* for assisted range expansion, likely attributed to the broad ecological amplitude and breadth of their ranges throughout the study region. Yet, we show an inverse relationship between the frequency a species is planted relative to proportion that the species is planted for assisted range expansion. In other words, uncommon species tended to be planted more frequently under applications termed assisted range expansion. These same species more likely originate from narrower geographic distributions and may be scarcer in forest nursery inventories. Although many factors may contribute to this trend, it is possible that due to a limited nursery inventory and/or failure to place seedling orders early enough, a forester may elect to plant "secondary" species that inadvertently result in the application of assisted range expansion.

4.3 Barriers and limitations of adaptation plantings

Understanding the barriers and limitations that managers face with adaptation plantings, including FAM, has increasingly become an important research focus. Although the perceptions of natural resource managers have been more generally assessed regionally and globally to determine engagement among a broad suite of climate change adaptation strategies in forests (Findlater et al., 2022; McGann et al., 2022; Himes et al., 2023; Schattman et al., 2024), here we illustrate these challenges more specifically in the context of adaptation planting (albeit in a narrower geographic region), which has received considerably less attention. This is particularly timely given the growing interest in the role of tree planting as a natural climate solution (e.g., the World Economic Forum's One Trillion Trees Initiative: https://www.1t.org/; the REPLANT Act as part of the Infrastructure Investment and Jobs Act, 117th US (Congress The 117th U.S., 2021). Some authors report that factors related to policy, social, and economic considerations can be key drivers linked to hesitancy to engage with adaptation practices but find that other factors related to present day threats to forest health may override this hesitancy (McGann et al., 2022; Schattman et al., 2024).

Our findings generally support these assertions such that survey respondents report that factors associated with present and future biotic and abiotic stressors are more important in terms of decision making relative to other facets like policy, social, or economic consideration. More specifically, factors linked to present-day conditions (e.g., vegetative competition and predation or pre/post-planting maintenance activities) or future threats and climate conditions (e.g., invasive pests and pathogens, projected shifts in species habitat) are reportedly the most influential factors in decision making. Still, limitations in funding and labor are also highly ranked in terms of importance under the policy, social, or economic group. Notwithstanding, factors like informational and material resources such as access to planting material (e.g., enough diverse planting stock from forest nurseries) and information, training, and resources (e.g., what and how to select climate-adapted species or genotypes for current and future conditions) rank highly among limiting factors reported among our respondents. Together, these results may narrow the focus as to how to allocate resources that engage forest stewards in adaptation planning. To advance the practice of adaptation plantings and reduce uncertainty under global change, emphasis may need to be placed on developing best practices to address biotic and abiotic factors, increasing research and educational resources to advance to knowledge transfer, expanding forest nursery capacity and ecological diversity, and improving funding and policies available to advance more novel adaptation planting practices like FAM.

4.4 Study limitations

Although climate adaptive management and the potential need for adaptation plantings, including FAM, are a global issue, we were only able to survey the perspectives from foresters and other practitioners from a narrow, albeit critical forest region, the Northeastern US. Moreover, our study is limited by a small number of valid survey respondents, limiting broader inference related to the perceptions and applications of adaptation plantings in the region and beyond. While this work would benefit from a larger sample size, including respondents who are not engaged or interested in climate change adaptation and associated planting activities, many of these perspectives have been captured elsewhere (McGann et al., 2022, 2023; Himes et al., 2023). Moreover, given that many of these planting practices are somewhat new or novel to the study region and associated forest management activities, there are understandably fewer foresters actively engaged with the practice. Nevertheless, despite the small sample size, evidence from adaptation science, technology transfer, public health, and other fields (Gollust et al., 2011; Hardman et al., 2016; Storbjörk et al., 2024) point to the value of assessing the perspectives early adopters who can serve as important litmus tests to understand and refine the state of the practice.

5 Conclusion

In conclusion, interest in tree planting for restoration, FAM, and as a natural climate solution appears to be growing across a diversity of forest stewards. Despite limitations in our study (i.e., a limited number of respondents) which constrain higher level inference, the general trends in the survey population of early adopters of the practice point to an increasing emphasis on adaptation planting as a tool employed by foresters already actively engaged in climate change adaptation in the study region. Further work remains to assess how this population of early adopters compares to other foresters and natural resource professionals not actively engaged in climate change adaptation. While apprehensions remain as to how to best apply adaptation plantings such as FAM, the results from this survey highlight that many forest stewards surveyed have already implemented adaptation plantings, including FAM, or have plans to do so in the near term. Our results also illustrate planting preferences in terms of species used for FAM, potentially serving to inform and refine seedling production needs for future plantings. To ensure success in the future development of adaptation planting projects, emphasis should be placed on developing tools, informational resources, research, and funding to inform best practices. Given the growing importance of these practices in shaping future forest development under climate change, increasing prioritization of training and capacity building to support adaptation planting activities in forest management agencies and organizations across the Northeastern US may need to be considered.

Data availability statement

The datasets presented in this study can be found in online repositories via FigShare.com. See Clark et al. (2023).

Ethics statement

The studies involving humans were approved by the Human subject protection approval was issued by the University of Vermont Institutional Review Board (STUDY00002004). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

PC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review and editing. AD: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – original draft, Writing – review and editing. LF: Conceptualization, Methodology, Writing – review and editing. MJ: Conceptualization, Resources, Writing – review and editing. RM: Conceptualization, Funding acquisition, Methodology, Writing – review and editing. BP: Conceptualization, Funding acquisition, Methodology, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2024.1386211/full#supplementary-material

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