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ORIGINAL PAPER

Practitioner Perspectives on Assisted Migration and Adapting Reforestation for Climate Change in the Western US

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Abstract
Climate change is creating an urgent need to implement adaptation strategies in forest ecosystems. Assisted migration (AM) of species or genotypes adapted to future climate is one promising strategy, but operational implementation is challenging and likely varies across ownerships. We conducted an online survey ($n=174$) of federal, state, Tribal and private industrial forest managers in Washington, Oregon, and California to understand individual and organizational practices around climate adaptation, perceived barriers to AM, and differences between private industry and public agencies. Most respondents expressed personal concern about climate change, and 77% have adjusted their reforestation practices as a result. Over half have implemented AM; species mix changes, increased vegetation control, and decreased planting densities were also common. Individual respondents often indicated multiple changes, suggesting inclination toward bet-hedging approaches to adaptation. Although > 90% of respondents indicated organizational concern about climate change, a similar number identified organizational barriers to AM, most commonly availability and knowledge of seed sources and uncertainty of outcomes, with policy and social barriers more common for public agencies. If barriers are addressed, there is greatest potential to increase AM on private industrial land given lower current use than on public land and high planting rates (89% of reforestation) at high densities (> 300 trees per acre). These findings highlight the need for research to support AM implementation across tree species, decision support tool training, and increased seed transfer among organizations. Addressing implementation barriers is critical for supporting appropriate use of AM for climate adaptation in western US forests.

Study Implications Across public and private industrial ownerships, forest managers we surveyed generally expressed concern about effects of climate change on forests, with most reporting changes to reforestation practices for climate adaptation, including use of AM. Support and use of AM varied by specific practice, with greater favor for those that may mimic natural processes or reflect bet-hedging with historical practices. Despite relatively high levels of past AM use, most respondents desire more research on outcomes, trainings on tools, and greater access to seed for AM, indicating barriers that must be overcome to support managers planning to use AM for climate adaptation.

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Keywords Assisted migration · Climate change adaptation · Forest management · Tree planting · Reforestation · Silviculture

Introduction

Disturbance and change are inherent to forested ecosystems, but the pace of change has greatly accelerated with climate warming (IPCC 2022). In the western United States, early twenty-first century increases in both fire activity (Abatzoglou and Williams 2016) and drought have been attributed to climate change (Williams et al. 2015). Increased fire extent (Abatzoglou et al. 2021) and severity (Parks and Abatzoglou 2020) coupled with post-fire droughts that inhibit natural regeneration (Stevens-Rumann et al. 2018) are eroding the inherent capacity of forests to recover post-fire (Coop et al. 2020). Fire suppression practices have compounded the effect of warming climate to drastically alter fire regimes – by decreasing fire frequency and increasing fire severity – in many forests in the region (Hagmann et al. 2021). Collectively, these trends have created a backlog of area requiring reforestation (USDA Forest Service 2022). Climate warming and high severity fire are all but certain to continue, and management approaches are needed to ensure forest ecosystem functions can be sustained (North et al. 2019).

Many approaches have been considered for sustaining forests under climate change, covering a wide range of activities that are implemented throughout stand development (Nagel et al. 2017; Royo et al. 2023). Climate adaptation strategies have been framed conceptually as actions to 1) resist ecosystem change, 2) build resilience to change, or 3) promote ecosystem transition (Millar et al. 2007). To be effective, climate adaptation strategies must be implemented across large geographic areas and diverse ownerships with a range of management objectives and associated barriers to implementation (Palik et al. 2022). In the western US, activities during reforestation via planting, which is conducted by most ownerships regardless of resource limitations, offer a tremendous opportunity to implement climate adaptation strategies that sustain functional forests into the future, especially those focused on ecosystem transition. Adaptation strategies may also be designed to avoid reforestation, but these typically have higher costs and constraints (Lydersen et al. 2019) that limit broad implementation across western US forested landscapes dominated by public ownerships.

In general, choice of plant materials, as well as how and where to plant them, are critical decisions when considering climate adaptation through reforestation activities. Populations of forest trees are assumed to be adapted to the climate conditions they evolved under (Leimu and Fischer 2008), and guidelines for reforestation historically emphasized planting with local seed sources (St. Clair et al. 2020). However, tree populations are predicted to become increasingly genetically maladapted to their local environment as the climate continues to warm (O'Neill and Gómez-Pineda 2021). Assisted migration (AM), the facilitated movement of plants from climates they evolved under to areas predicted to have a similar climate in the future, is a promising strategy for selecting species or seed sources (provenances) adapted to future climate (Pedlar et al. 2012; Palik et al. 2022). At the same time, application of silvicultural practices that influence how and where seedlings are planted can enhance seedling survival and may foster resilience of forest stands to future climate. Competing vegetation control, seedling stock type, planting density, and planting season all influence seedling survival and growth depending on site conditions that control plant resource supply (i.e., soils, climate, vegetation community) (Harrington et al. 2009; Dinger and Rose 2009; Aghai et al. 2014; Grossnickle and MacDonald 2021). Although there is evidence that these practices influence reforestation success, how they are applied is less certain and may influence feasibility of AM use (Agne et al. 2025). Understanding how AM and silvicultural practices are being used specifically at the time of reforestation is essential to address barriers to climate adaptation through reforestation.

Scientific support and uncertainty about the potential risks and benefits of AM are likely to influence its implementation by forest managers. There are three distinct AM practices that carry different levels of uncertainty and ecological risk (Williams and Dumroese 2013). Assisted population migration – movement of seed sources to new locations within the historical species range – carries the lowest ecological risk (Aitken and Bemmels 2015). Although information is limited to a relatively small number of species (Bucharova 2017), provenance trials indicate that assisted population migration can produce favorable growth outcomes when safe climatic transfer distances are not exceeded (O'Neill et al. 2014; St. Clair et al. 2020) and the potential for introduction of invasive species is low (Pedlar et al. 2012). Assisted range expansion – movement of species outside but adjacent to their historical range – is characterized by intermediate risk. Although species are introduced to a novel environment in this approach, leading to increased potential for unanticipated ecological interactions, the biotic and physical environment may be similar to the species' historical habitat (Winder et al. 2011). This process is intended to mimic (but increase the rate of) natural migration processes and may be most useful where habitat is fragmented or natural dispersal is otherwise limited (Vitt et al. 2010). Assisted species migration – movement of species outside and geographically isolated from the historical range – carries the greatest risks of maladaptation and invasive species introduction due to high likelihood for environmental differences between the planting site and source locale (Winder et al. 2011). While there is uncertainty in how elements such as soils, vegetation and mycorrhizal communities, insect pests, and diseases may interact with each of these practices (Aitken and Bemmels 2015), uncertainty and risk generally increase with increasing migration distance (Williams and Dumroese 2013). Although social acceptance of assisted population migration is generally higher than that of assisted species migration (Pelai et al. 2021), it is unclear how forest managers weigh uncertainties and potential risks when considering AM implementation, and how its current and future use in reforestation may be affected.

Application of AM and other treatments for climate adaptation in forests is strongly driven by objectives and policies of a given land management organization (Neff and Larson 2014; Clifford et al. 2022). Specifically, differences between public agencies and private industry in their objectives and management intensity may drive differences in potential use of AM. Generally, private industrial forest lands are primarily managed to optimize timber outputs for maximum return on investment (Bliss et al. 2010), while lands managed by public (federal or state) agencies employ multi-objective management (Pukkala 2002). These objectives result in differing levels of management intensity that may favor (or disfavor) implementation of AM. For example, private industry regularly conducts reforestation at predictable times (i.e., following planned harvest) which could favor implementation of AM logistically, compared to reforestation on public lands which typically occurs after unplanned disturbances (e.g., wildfire; Dumroese et al. 2019), resulting in backlogs in seedling production to meet planting needs (Fargione et al. 2021). Differences in policy or cultural norms may also lead to discrepancies in ability to incorporate changes in management practices – public agencies generally favor the status quo (Wilson 1989) and are slow to undertake novel actions (Kemp et al. 2015; Ontl et al. 2018). Conversely, private companies may be willing to incorporate novel practices if they increase timber production (Rissman et al. 2018), but are unlikely to make changes that carry an increased financial risk (Brunette et al. 2020). Further, there may be organizational differences that influence the ability of individual managers to enact changes in their practices (Clifford et al. 2022). Understanding how differences in organizational management objectives, practices, and policies influence views and implementation of AM is critical for addressing barriers specific to each organization type.

We conducted a survey of practitioners across major forested ownerships in Washington, Oregon, and California with a focus on reforestation in a changing climate. Specifically, we aimed to understand individual managers' perceptions, use, and perceived barriers to AM at the organizations for which they work, as well as general reforestation practices, which have implications for implementation of AM. Further, we were interested in understanding differences between respondents from public agencies versus private companies as differences in management objectives between these groups influence the intensity of forest management activities that each conducts. These differences potentially influence the acceptance and use of adaptation strategies, but there is little quantitative information available to evaluate such potential. Understanding how and where managers are adjusting reforestation through AM and other practices, and what barriers exist, is critical to supporting implementation of climate-informed reforestation practices at an operational scale.

Methods

Survey Design

We collaborated with Western Forestry and Conservation Association (WFCA) to develop an online survey using SurveyMonkey to understand perspectives of forest managers regarding current and future strategies for reforestation under climate change in the western United States. WFCA specializes in interfacing with professional foresters across ownerships in the western US and fosters shared understanding of current research and forest management issues in the region among federal and state governments, industry, and universities. The survey contained 27 questions and included multiple choice, ranking, Likert scale, and open-ended questions (Table 1). The questions were grouped into three sections. Section 1 included general questions about the location and organization at which the respondent works, position title, and years' experience in the field. Section 2 included questions about the respondent's views and practices around forest management, disturbance and/or climate impacts, and climate change adaptation (including AM) as an individual practitioner. Section 3 included questions about the respondent's perspective on their organization's views of climate change and AM, and barriers and resources for implementation of AM. Questions in Sect. 2 intended to capture information on management approaches undertaken as an individual manager while questions in Sect. 3 intended to capture information on policies at the organizational level. We sought input on survey questions from a group of social scientists, forest geneticists, and silviculturists with expertise on the survey topic. We pilot tested the survey with five forestry professionals for survey length and clarity; minor changes were made to questions following feedback.

At the beginning of the survey, we defined AM in general as: "planting seedlings from seed sources adapted to historical (twentieth century) climate conditions at sites that are predicted to have similar climate in the future" (Fig. S1). We further distinguished three distinct types of AM – assisted population migration, assisted range expansion, and assisted species migration – with definitions and a graphical representation of each AM type (Fig. S1) at the beginning of the survey and definitions restated within questions pertaining to specific types of AM. We also asked about planting a seed source from outside the historical seed zone mixed with the historical source as a separate form of assisted population migration. Following best practices for human subjects research, we provided information to all possible participants describing the survey's purpose, time expected to complete the survey, and participant benefits (publicly shared results through reports and webinars). We ensured that participants understood the survey to be voluntary, with all questions other than organization and region of work optional, all responses anonymous, and results reported only in aggregate.

Survey Distribution and Screening of Responses

The target population for this survey was forest land managers from public agencies and private industrial ownerships in California, Oregon, and Washington who make decisions about when and how to conduct reforestation on their organization's land; the target population does not include small private landowners (individuals who own less than 5,000 acres). Prior to survey distribution, we emailed points of contact at USDA Forest Service (Forest Service), Washington Department of Natural Resources, Oregon Department of Forestry, Bureau of Indian Affairs, and Bureau of Land Management describing the survey's purpose and asking for their participation in distributing the survey to their staff. Organizational points of contact were regional silviculturists or foresters who oversee staff who complete reforestation treatments on the ground. Our WFCA collaborators also advertised the survey at conferences and on their website before opening the survey to ensure participation

Table 1 Questions as written in survey by question group – letter in parentheses denotes question type

Personal questions	Individual practitioner views and practices for forest management and climate adaptation	Organizational views and practices for forest management and climate adaptation
Q1. What state(s) do you work in? (A) Q2. Which ecoregion(s) do you work in? (A)	Q7. Please rate your level of agreement with the following statements about climate change and forest management (C) Q8. How much forest land do you manage as an individual? (D) Q9. How much of the forest area that you manage has experienced stand-replacing disturbance (e.g., fire, harvest, insect/disease outbreaks) in total over the last 5 years? (B)	Q21. How concerned is your organization about impacts of drought, fire, insects, diseases, and/or climate change over the next 5 – 10 years? (H)
Q3. Which best describes the organization you work for? (B)	Q10. How much of the total land area that experienced stand-replacing disturbance was reforested by planting? (D) Q11. Please rank up to the top 5 conifer species most commonly planted in your reforestation practices in the last 5 years (E)	Q22. Which of the following statements best describes your organization's perspective on assisted migration treatments for reforestation? (B)
Q4. What title best describes your position? (B)	Q12. What percentage of reforestation by planting was conducted with each of these stock types in the last 5 years? (D) Q13. What planting density is most common in your reforestation practices? (D)	Q23. Which of the following assisted migration treatments have been used or considered at your organization? (A)
Q5. How many years have you been working in your current and similar positions? (B)	Q14. Have you made changes to your reforestation practices in the last 10 years in response to drought, fire, insects, diseases, invasive species or climate change? (B) Q15. Which of the following changes have you made to your reforestation practices in the last 10 years? (A) Q16. How likely are you to make changes to your reforestation practices in response to drought, fire, insects, diseases, and/or climate change in the next 5 – 10 years? (F)	Q24. What barriers to conducting assisted migration exist at your organization? (A) Q25. Are you aware of available resources to identify appropriate seed sources for assisted migration? (B)
Q6. Which of the following statements best reflects your organization's forest management objectives? (A)	Q17. Rate your personal level of support for each of the following types of assisted migration (G) Q18. Have you used assisted migration treatments for reforestation in the past? (B) Q19. Which of the following specific treatments have you used for reforestation? (A) Q20. How likely are you to use assisted migration treatments for reforestation in the next 5 – 10 years? (F)	Q26. Please rate your level of familiarity with the following tools for identifying seed sources (I) Q27. Are you interested in receiving training on using the tools listed above? (B)

A: Multiple choice: multiple answers; B: Multiple choice: one answer; C: Matrix: strongly disagree to strongly agree; D: Short answer; E: Ranking order; F: Matrix: very unlikely to very likely; G: Matrix: strongly oppose to strongly support; H: Matrix: not concerned to very concerned; I: Matrix: no familiarity to high familiarity from private industrial forest land managers. The survey was open from June 12 – July 21, 2023. The survey description and link were posted on the WFCA website and distributed by WFCA through email to organizational points of contact and their member listserv on June 12. Follow-up emails were sent weekly through the listserv during the survey open period. We obtained raw survey data from WFCA after the survey closed.

There were 216 total survey responses, which were screened to exclude response from outside the target population. We excluded respondents who do not work in Washington, Oregon, or California, those who do not directly manage forested lands, and those who occupy roles not involved in reforestation (e.g., wildlife biologist). Finally, we excluded responses that did not include enough questions answered for analysis (e.g., only professional context questions were answered). The final screened dataset contained 174 responses. Some respondents did not answer all survey questions resulting in unequal sample size across questions; sample size for each question is noted when results are reported. We estimate that ~ 725 individuals received direct emails about this survey, for an overall response rate of 24%. However, the WFCA listserv membership encompasses a range of positions that are not directly related to reforestation (but their representation is unknown), so the true response rate is likely underestimated.

Within the screened dataset, we assessed nonresponse bias by comparing responses to questions from Sect. 1 (questions about the respondent's professional context) between early ($n = 117$) versus late ($n = 57$) responders, defined as responses collected in the first four weeks versus last two weeks of the open period. We selected this break point as we made direct follow-up appeals to organizational points of contact in the final two weeks, in addition to weekly follow-up listserv emails. Fisher's exact tests showed greater representation of responses from Washington and the Blue Mountains ecoregion in early responders and greater representation from California and the Sierra Nevada ecoregion in late responders (Table S1), suggesting our survey may underrepresent managers from California (Armstrong and Overton 1977). There were no other significant differences between early and late responders by state, ecoregion, respondent organization, title, years' experience, or organizational forest management objectives (Table S1).

Statistical Analysis

To understand practitioner views on reforestation in a changing climate, we performed three sets of analyses. To evaluate the overall distribution of responses to our questions, we performed chi-square goodness of fit tests on each categorical response variable (i.e., multiple choice and Likert-scale questions) using all responses in the screened dataset. Where global chi-square goodness of fit tests indicated a non-uniform distribution of responses using a significance level $\alpha = 0.05$ (Table S2), we performed Holm-corrected pairwise comparisons to assess differences between response frequencies of each category. We considered frequencies of responses to differ significantly where $P \leq 0.05$.

To understand how responses differed between major land management organizations, we grouped Bureau of Land Management, state agencies, and Forest Service as “public agencies” to compare with responses from those who work for private companies. For this analysis, we omitted responses from local governments, Tribal, and non-governmental organizations (NGOs) as those groups cannot be included with either public agencies or private companies and the sample size in each group was insufficient to include as an additional organization category. Although local governments are public agencies, their forest management is conducted on a smaller scale than that of other public agencies. To compare the distribution of responses between public and private land managers, we used two-sample t-tests for each continuous response variable (Table S3) and Fisher’s exact tests for each categorical response variable. Where Fisher’s exact tests indicated a difference in the distribution of responses between public and private land managers, we performed Holm-corrected pairwise comparisons to assess differences between the proportion of responses in each category between organizations (Table S4, Table S5). We interpreted all statistical tests according to $P \leq 0.05$ as evidence of a difference between organizations.

We also conducted Fisher’s exact tests to understand how past personal use of AM and likelihood of future AM use varied with management area characteristics (i.e., state, ecoregion, recently disturbed area) and organizational perspectives and barriers to AM. Here, we considered binary forms of the variables past use of AM (“yes” vs. “no”) and likelihood of future AM use (“likely” vs. “unlikely”). For likelihood of future use, levels of the binary variable each represent two possible responses from the survey, i.e., “likely” represents all responses of “somewhat likely” or “very likely.” Responses of “not sure” were removed from both variables for these analyses due to small sample size. All analyses were performed in R version 4.4.0 (R Core Team 2024). Linear models were fit with *stats* and chi-square and Fisher’s Exact Tests were conducted with *rstatix* (Kassambara 2023). Results were visualized with *ggplot2* (Wickham 2016), *likert* (Bryer and Speerschneider 2016), and *patchwork* (Pedersen 2024).

Results

Respondent Demographics

Of the 174 responses, 42% of respondents worked for private industrial companies, 36% for federal or state agencies, 14% for Tribal Nations and 8% for other organizations including local governments or NGOs (Table 2). Respondents ranged in experience from under five years to over 25 years. Responses were distributed across experience levels, though greatest representation was from those with over 25 years’ experience. 51%, 44%, and 21% of respondents reported that they work in Washington, Oregon, and California, respectively (percentages sum to greater than 100 because some respondents work in multiple states), which covered all forested ecoregions in our study area (Table 2).

Views on Climate Change and Assisted Migration

Overall, there was a high level of agreement (> 80% of all respondents either somewhat or strongly agreed) with statements that climate change is occurring (Fig. 1a), is currently affecting forests (Fig. 1b), will affect forests in the future (Fig. 1c), and that changes to reforestation practices are needed (Fig. 1d). However, for statements specific to AM, responses were mixed. While 60% of all respondents agreed that AM is needed to adapt to climate change (Fig. 1e), a similar share of respondents agreed that more research is needed prior to implementation (Fig. 1f). Although more respondents disagreed than agreed with the statement "the risks associated with assisted migration outweigh the potential benefits," the greatest share of respondents (40%) were not sure (Fig. 1g), perhaps due to individuals' varying opinions of different assisted migration practices (Fig. 2). The distribution of responses was generally consistent between public and private land managers (Fig. 1). However, public land managers were more likely than private land managers to agree that climate change is occurring (94% vs. 87%), that it is already affecting forests (85% vs. 76%), and AM is needed for adaptation (65% vs. 50%). Public land managers were also more likely than private land managers to disagree that more research is needed before using AM treatments (48% vs. 21%; Table S4). While not compared statistically, the distribution of responses from managers for Tribal governments was generally similar to those of public and private lands, while the distribution of responses from managers at NGOs and local governments (here categorized as "Other"), generally reflected greater concern about climate change and stronger support for AM (Fig. 1).

Personal support for type of AM varied by specific practice (Fig. 2). Of all respondents, most indicated that they strongly or slightly support assisted population migration mixed with the historical seed source (78%) and assisted range expansion (70%), while a smaller share expressed support for assisted population migration alone (47%) and assisted species migration (33%). Personal support for each practice was greater for public versus private land managers (16 – 23% more public managers indicated support), except for assisted population mixed with the historical seed source, for which support was similar between groups (Fig. 2b, Table S4). Responses from managers at Tribal and other organizations generally followed that of public land managers (Fig. 2).

Reforestation Practices

Use of a wide range of reforestation practices was reflected in our response pool. Most respondents plant a mixture of stock types, with the average split 55% containerized and 45% bareroot and no significant difference between private and public land managers (Fig. 3a, Table S3). However, there were clear differences in most common planting density and percent area reforested by planting (Fig. 3b), both of which were higher for private companies (mean responses of 372 trees per acre [TPA] and 89% planted area) compared to public agencies (mean responses of 253 TPA and 31% for planted area). 24 conifer species total

Table 2 Response count by organization and experience in position, title, state(s), and ecoregion(s) in which respondents work. Total responses (percent of all survey responses) are reported for each possible response to a question

	Organization							
	Private company	USFS[1,2]	State agency[2]	BLM[2,3]	Tribal Nation	Local agency[4]	NGO[4,5]	Total responses (%)
Experience (years)								
< 5	6	15	2	1	4	1	2	31 (17.8)
6 – 10	13	4	4	3	5	1	2	32 (18.4)
11 – 15	8	4	4	1	5	3	0	25 (14.4)
16 – 25	17	4	5	1	2	2	3	34 (19.5)
> 25	28	10	3	2	8	0	1	52 (29.9)
Title								
Forester	32	8	13	1	10	2	3	69 (39.9)
Regeneration specialist	4	0	2	0	1	0	1	8 (4.6)
Silviculturist	22	26	2	7	4	1	1	63 (36.4)
Other	13	3	1	0	9	4	3	33 (19.1)
State[6]								
Washington	40	4	10	1	22	5	6	88 (50.6)
Oregon	47	10	6	8	1	2	2	76 (43.7)
California	8	25	2	0	1	0	1	37 (21.3)
Ecoregion[6]								
Blue Mountains	9	5	3	0	0	0	2	19 (10.9)
Central/Southern CA	0	4	0	0	0	0	0	4 (2.3)
Coast Range	49	4	10	5	3	0	5	76 (43.7)
East Cascades	15	5	8	1	9	1	3	42 (24.1)
Klamath Mountains	5	6	2	1	0	0	1	15 (8.6)
Northern Rockies	8	1	2	0	1	0	0	12 (6.9)
Puget Lowland	13	0	6	0	2	5	2	28 (16.1)

Table 2 (continued)

	Organization							
	Private company	USFS[1,2]	State agency[2]	BLM[2,3]	Tribal Nation	Local agency[4]	NGO[4,5]	Total responses (%)
Sierra Nevada	0	16	0	0	1	0	1	18 (10.3)
West Cascades	40	8	9	4	2	4	4	71 (40.8)
Willamette Valley	29	0	4	5	0	1	2	41 (23.6)
Total responses	72	37	18	8	24	7	8	174 (100)
(%)	(41.4)	(21.3)	(10.3)	(4.6)	(13.8)	(4)	(4.6)	

[1]USDA Forest Service; [2]Grouped as "public" for comparisons between organizations; [3]Bureau of Land Management; [4]Grouped as "other" where responses are shown by organization; [5]Non-governmental organization; [6]Note some respondents work in multiple states and ecoregions, so these percentages sum to greater than 100

were ranked in the top five planted species (Table S6), with 14 species ranked in the top five by over 10% of respondents (Fig. 3c). Douglas-fir (*Pseudotsuga menziesii*) was most planted – ranked in the top five by 86% of respondents. Ponderosa pine (*Pinus ponderosa*) and western redcedar (*Thuja plicata*) were ranked in the top five by over 50%, while western hemlock (*Tsuga heterophylla*), western larch (*Larix occidentalis*), and western white pine (*Pinus monticola*) were ranked in the top five by at least 25% of respondents. Rankings differed between organizations, although this is likely because most respondents from California, which has a more diverse range of tree species, work for public agencies (Fig. 3c, Table 2). Likelihood of a species being ranked in the top five did not differ by past AM use or future likelihood of AM use (Fig. S2).

Most respondents (77%) reported changes to their reforestation practices (as an individual, not necessarily in response to organizational policy) in the last 5 – 10 years due to climate change and associated disturbances, although a higher percentage of public than private land managers have made changes (89% vs. 65%; Fig. 4a, Table S5). Of those who have made changes to their reforestation practices ($n = 123$), the most common changes included changing the mix of planted species to favor more drought- and fire-tolerant species (67%), increasing control of competing vegetation (52%), and decreasing planting density (42%) (Fig. 4b). Private land managers were more likely than public land managers to have planted species historically not present on the site (30% vs. 10%) or changed the time of planting to fall (35% vs. 10%), with all other changes equally likely in both groups (Fig. 4b). 68% of respondents indicated that they were somewhat to very likely to change their reforestation practices in the next 5 – 10 years, with more responses of very likely from public vs. private land managers (46% vs. 22%; Fig. 4c). Most respondents who are somewhat to very unlikely to change their reforestation practices have already made changes in the past 5 – 10 years; only 5% indicated that they are both unlikely to, and previously have not, made changes to their reforestation practices (Fig. S3).

Individual Assisted Migration Practices

Over half of respondents have used at least one type of AM (Fig. 5a). Of respondents who have used AM, assisted range expansion (59%) and assisted population migration mixed with the historical seed source (54%) were most common, followed by assisted population migration alone (40%) and assisted species migration (22%) (Fig. 5b). There was no difference in past use of AM by ownership type (Fig. 5a-b), state or ecoregion in which the respondent works, or by recently disturbed area managed (Fig. S4). Most respondents (64%) indicated that they were somewhat to very likely to use some form of AM in the next 5 – 10 years (Fig. 5c) with over one quarter of these responses from individuals who have not previously used AM treatments (Fig. S5). Public land managers indicated they are "very likely" to use AM in the future at higher rates private land managers (39% vs. 16%) while "somewhat unlikely" was more common from private vs. public land managers (17% vs. 1%) (Fig. 5c, Table S5). There was no difference in likelihood of future use of AM by state, ecoregion, or recently disturbed area managed (Fig. S4).

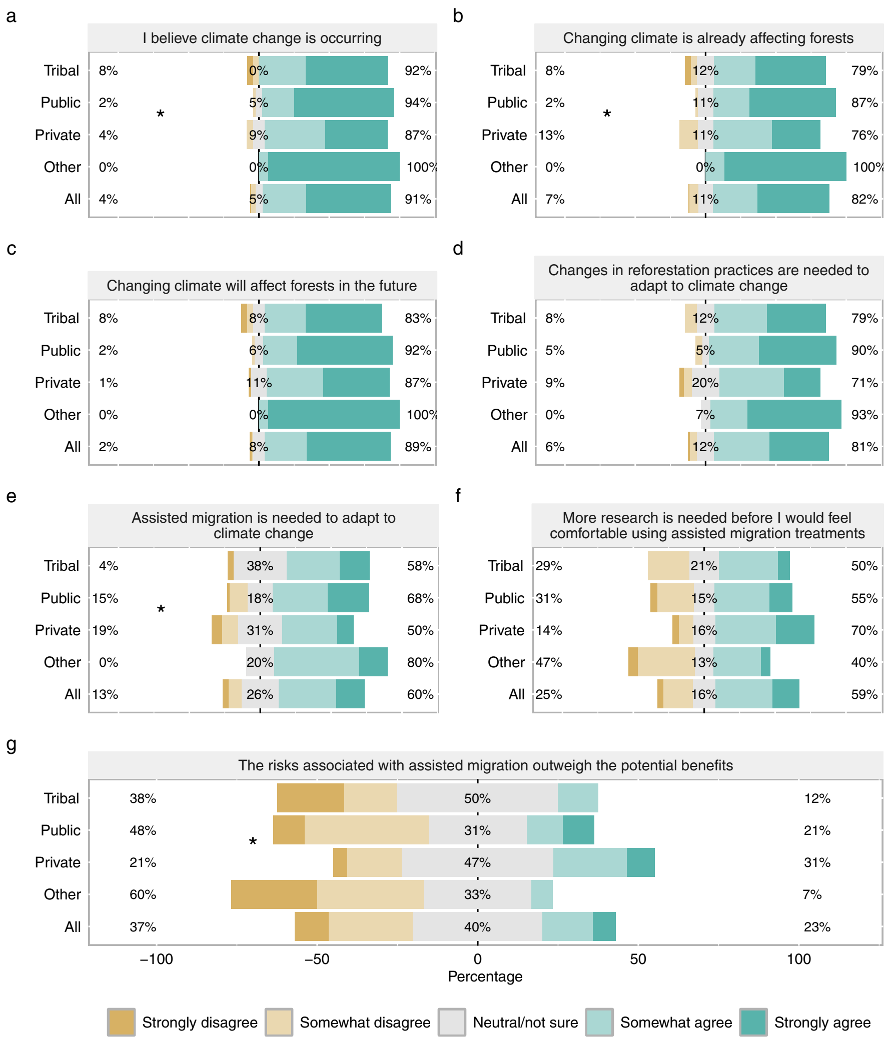

Fig. 1 Survey respondent levels of agreement with statements about climate change effects on forests and adaptation strategies including assisted migration (**a-g**). Bars show the distribution of responses by organization and for all organizations combined ($n = 171$). Percentages represent: strongly and somewhat disagree (left), neutral/not sure (center), and strongly and somewhat agree (right). Asterisks represent significance of statistical differences in the proportion of a given response to a question between private and public land managers only, determined from Fisher's exact tests, according to $P < 0.05$

Organizational Perspectives and Barriers to Assisted Migration

Perceived levels of organizational concern about impacts of climate change over the next 5 – 10 years were very high – 95% of respondents indicated that their organizations had some level of concern (Fig. 6a). Responses varied between groups, with greater frequencies of "very concerned" from public vs. private land managers (68%

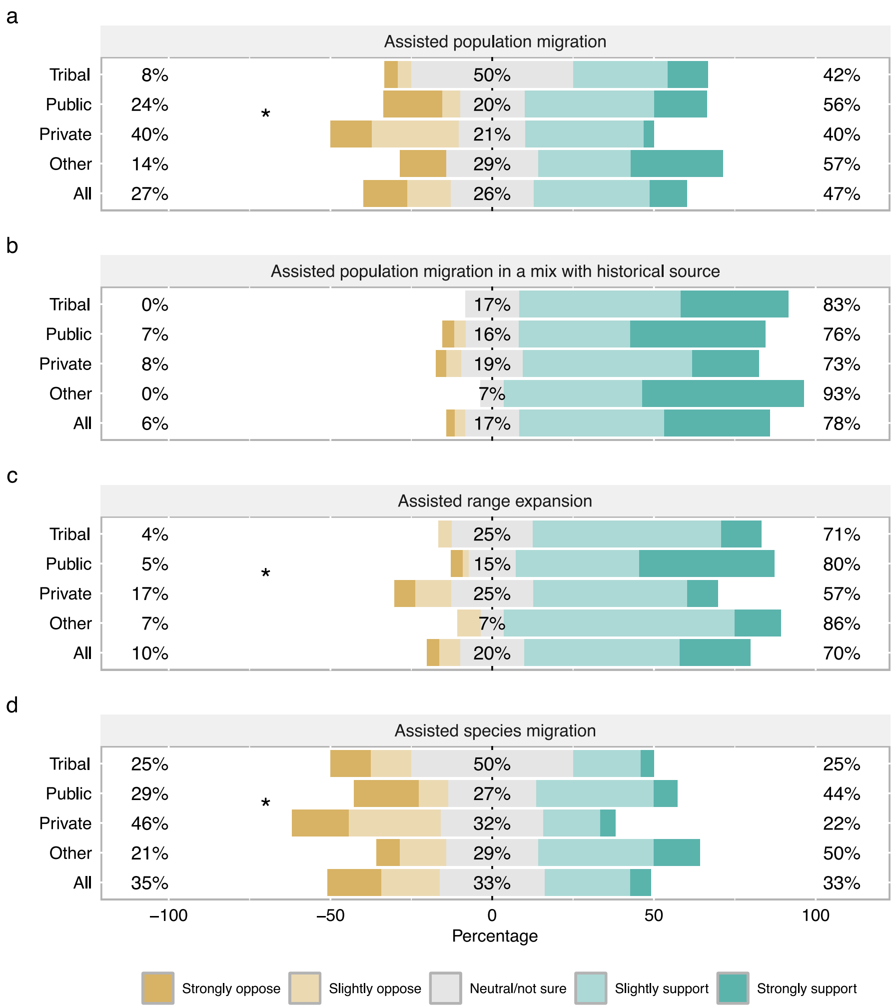

Fig. 2 Levels of personal support for four specific assisted migration treatments (**a-d**). Bars show the distribution of responses by organization and for all organizations combined ($n = 157$). Percentages represent: strongly and slightly oppose (left), neutral/not sure (center), and strongly and slightly support (right). Asterisks represent significance of statistical differences in the proportion of a given response to a question between private and public land managers only, determined from Fisher's exact tests, according to $P < 0.05$

vs. 37%) and "slightly concerned" from private vs. public land managers (19% vs. 2%; Fig. 6a, Table S5). Respondent perceptions of their organization's views of AM were similar between groups except that "discussed but not used [with no plans for use]" was more frequently selected by private vs. public land managers (48% vs. 15%; Fig. 6b). Organizational use and consideration of specific types of AM (Fig. 6c) followed a similar pattern as personal past use (Fig. 5b), though overall rates of use were lower. Individual support for each type of AM was also greater at

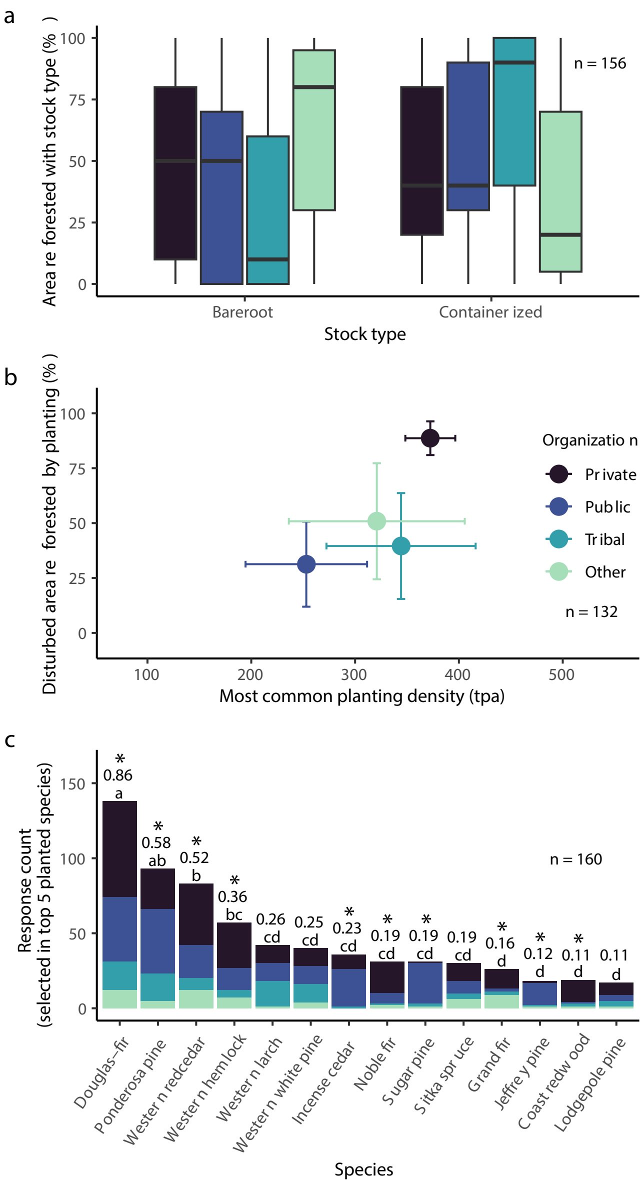

Fig. 3 Mean responses to survey questions about **a**) stock types used for reforestation, **b**) planting area and density, and **c**) top 5 planted species shaded by organization. N represents the total number of responses to the question across all organizations. Boxes show the median and interquartile range of responses – there were no significant differences between private companies and public agencies (**a**). Large points represent mean responses and error bars represent 95% confidence intervals for each organization, while small points represent individual responses (**b**). Numbers above each bar represent the proportion of total respondents that selected the response (**c**). Significant differences in response proportion from chi-squared goodness of fit tests and Holm-corrected pairwise comparison tests are represented by different letters. Asterisks represent significance of statistical differences in the proportion of a given response to a question between private and public land managers, determined from Fisher's exact tests, according to $P < 0.05$

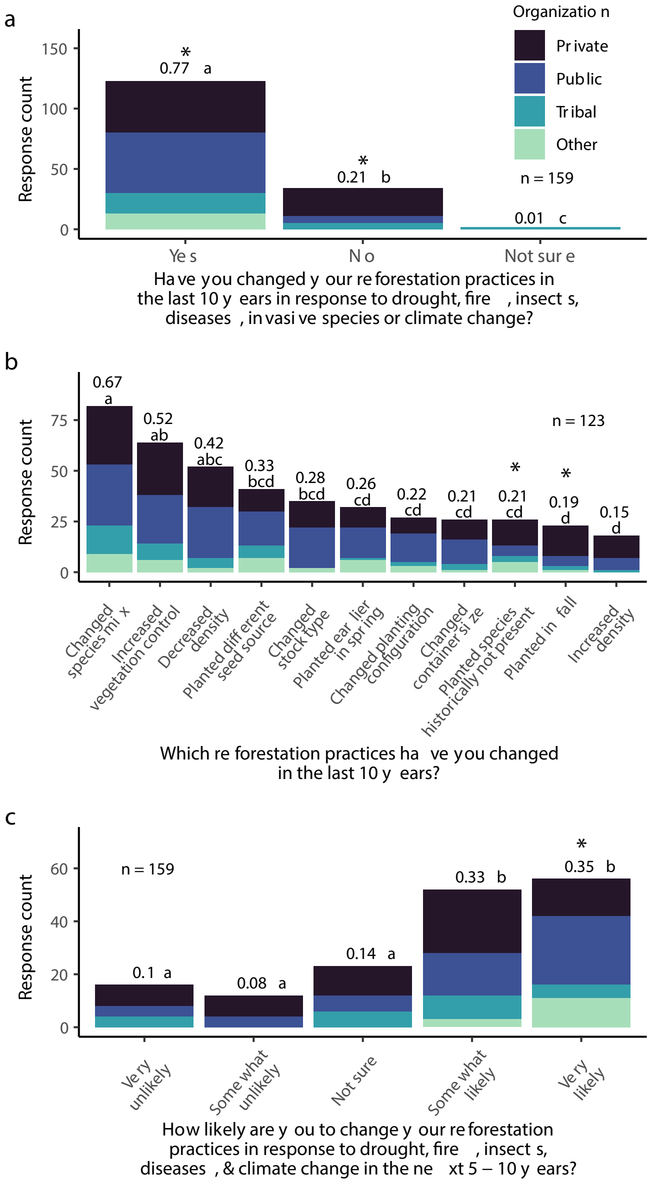

Fig. 4 Distribution of responses to survey questions about respondents' reforestation practices shaded by organization (**a-c**). N represents the total number of responses to the question across all organizations. Numbers above each bar represent the proportion of total respondents that selected the response. Significant differences in response proportion from chi-squared goodness of fit tests and Holm-corrected pairwise comparison tests are represented by different letters. Asterisks represent significance of statistical differences in the proportion of a given response to a question between private and public land managers, determined from Fisher's exact tests, according to $P < 0.05$

organizations that use or are considering use of that type of AM (Fig. S6). Organizational use/consideration of assisted population migration both alone and mixed with the historical source was greater for public vs. private land managers (57% vs. 19% and 64% vs. 37%, respectively; Fig. 6c).

The three most common barriers, each selected by over half of all respondents, were uncertainty of outcomes, knowledge of seed sources suited to the future climate of the planting site, and availability of seed sources for AM (Fig. 6d). Logistical, policy, and social barriers were identified as barriers to AM less frequently (12 – 16% of respondents), and 9% of respondents identified no barriers to AM (Fig. 6d). Public land managers were more likely than private land managers to identify availability of seed sources for AM (63% vs. 29%), policy barriers (25% vs. 5%), and social barriers (16% vs. 2%) as barriers to AM (Fig. 6d, Table S5). Most respondents reported awareness of resources to identify seed sources for AM (63%; Fig. 6e) and also indicated interest in trainings on tools for the same purpose (63%; Fig. 6f). Affirmative responses to both questions were ~ 24% greater from public vs. private land managers (Fig. 6e, f).

Discussion

Given global climate change projections, management practices that facilitate climate adaptation in forests are needed to sustain forests into the future (North et al. 2019). Our survey of a wide range of forest practitioners provides key insights about climate adaptation through reforestation in the western US. Importantly, our results indicated a high level of concern about climate change among practitioners and substantial interest and use of AM across both public and private ownerships. Barriers to implementation of AM are common and may influence the extent to which treatments are applied. Our findings have implications for climate adaptation through reforestation activities in the western US and identify research and capacity needs that will need to be addressed to facilitate appropriate use of AM during reforestation.

Concern about the impacts of climate change on forests was widespread across survey respondents from all ownerships, indicating strong interest among practitioners for climate adaptation through reforestation irrespective of management objectives (Rissman et al. 2018). Despite widespread concern about climate change impacts on forests and desire for climate adaptation measures, application of specific practices often lag behind (Lenart and Jones 2014; Kemp et al. 2015; Anhalt-Depies et al. 2016; Boag et al. 2018; McGann et al. 2023). The vast majority of survey respondents have already made changes to their reforestation practices (or plan to in the near future) in response to climate change, including a broad range of strategies that can foster ecosystem resistance, resilience, or transition (Millar et al. 2007). Beyond individual concern, respondents indicated nearly universally that the organizations for which they work are at least slightly concerned about impacts of climate change and associated changes in disturbance impacts, with this trend consistent across organizations. Further, individual views on AM generally tended to

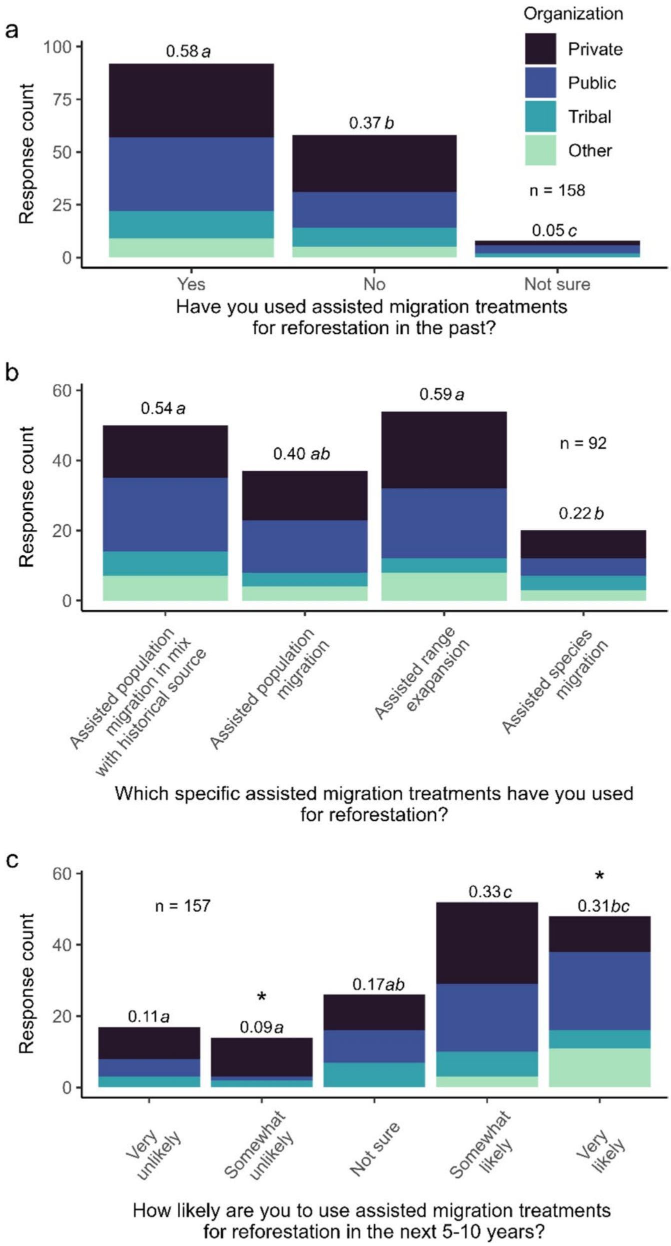

Fig. 5 Distribution of responses to survey questions about personal past (**a-b**) and future (**c**) use of assisted migration shaded by organization. N is the total number of responses to the question across all organizations. Numbers above each bar are the proportion of total respondents that selected the response. Significant differences in response proportion from chi-squared goodness of fit tests and Holm-corrected pairwise comparison tests are represented by different letters. Asterisks indicate significant difference in the proportion of a given response to a question between private and public land managers, determined from Fisher's exact tests, according to $P < 0.05$

align with organizational perspectives (Fig. S6). The institutional context in which a manager works is a key factor that influences decision-making, with organizational policies and norms exerting a strong control on managers' ability to change their practices (Clifford et al. 2022). Collectively, our findings suggest a strong will across organizations represented in this survey to adjust reforestation practices for climate change.

Assisted migration is a key tool that is already being used by many practitioners and across organizations for climate adaptation. Our survey supports the assertion that use of AM in reforestation is increasing (Palik et al. 2022), with most respondents intending to use AM within the next decade. Uncertainty regarding potential risks and benefits highlighted by past work (Neff and Larson 2014; Fontaine and Larson 2016) remains a concern for many practitioners (Fig. 1). However, levels of support and adoption of AM reported here suggest that practitioners have similar concerns about inaction, even when faced with remaining information needs about implementation of AM, similar to findings from forestry professionals in British Columbia (Pelai et al. 2021; Findlater et al. 2022). Assisted population migration, generally perceived as the least risky AM practice (Aitken and Whitlock 2013), had greater support both from individuals and their organizations than assisted species migration, consistent with previous findings from assessments of public perceptions of AM in British Columbia (Peterson St-Laurent et al. 2018; Findlater et al. 2020). Importantly, assisted population migration mixed with the historical seed source had greater support and past implementation than assisted population migration alone. This may reflect a bet-hedging strategy given that many survey respondents expressed both the belief that climate adaptation measures are needed to sustain forests and continued uncertainty regarding the risks of AM. Further, similar levels of support for assisted range expansion to assisted population migration mixed with the historical source suggest managers may view range expansion as a practice that tracks with climate change more intuitively than assisted population migration alone or assisted species migration.

In addition to implementation of AM, survey respondents have made a wide range of non-AM changes to reforestation practices for climate adaptation. Over three quarters of those surveyed have changed at least one element of their planting practices. Many of the non-AM changes reflect resistance or resilience strategies, where the goal is to maintain forests in a similar composition and structure to their historical state (Nagel et al. 2017). The most common changes across organizations were changing the species mix to favor drought- and fire-tolerant species historically present on the site, increasing vegetation control, and decreasing planting density. The likely intent of both increasing vegetation control and decreasing planting density is to achieve greater initial survival of planted seedlings and longer-term resilience as forests mature. While vegetation control can increase resources to individual seedlings by immediately decreasing competition for water, nutrients, and light (Dinger and Rose 2009), the effect of decreased planting densities on competition between trees typically does not appear until much later in stand development (Harrington et al. 2009). Although a small share (~25%) of respondents who have changed their species mix have also planted novel species, changes in species mix generally reflected a change in the proportion of historically present species planted.

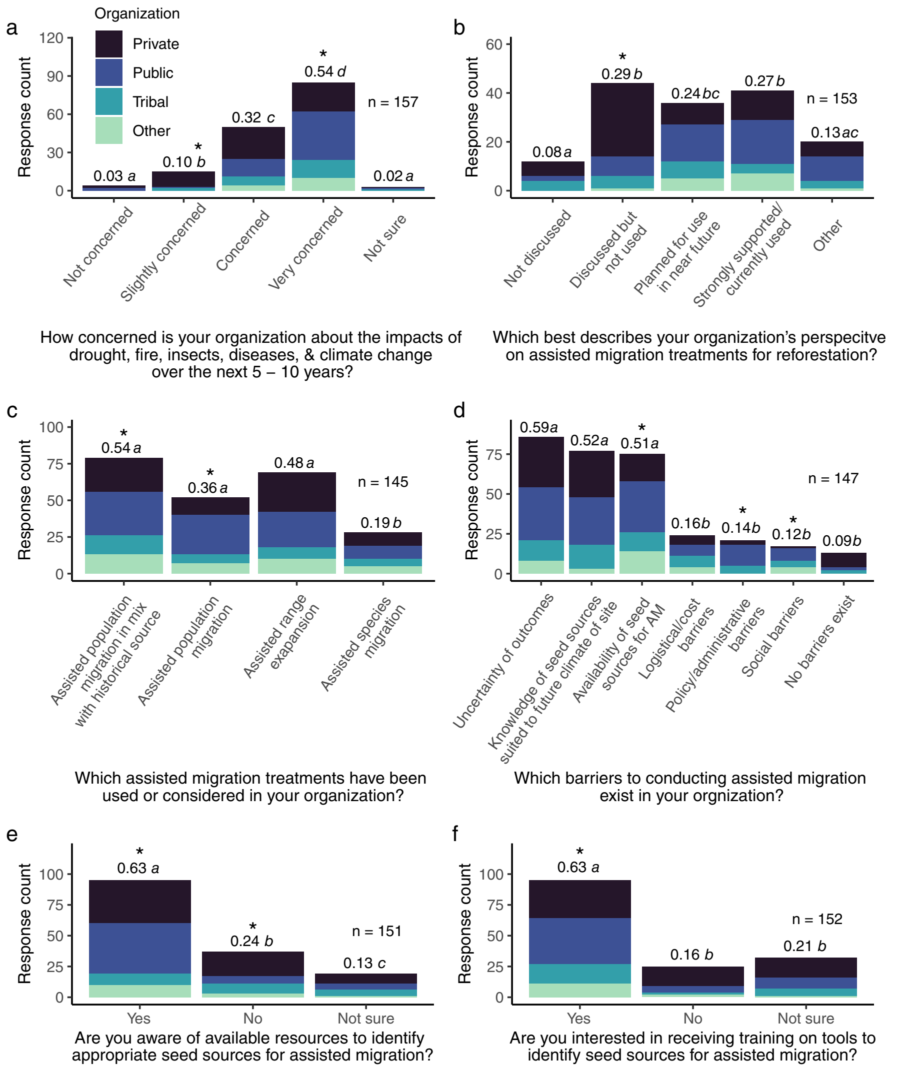

Fig. 6 Distribution of responses to survey questions about organizational perspectives and barriers influencing assisted migration use shaded by organization (**a-f**). N is the total number of responses to the question across all organizations. Numbers above each bar are the proportion of total respondents that selected the response. Significant differences in response proportion from chi-squared goodness of fit tests and Holm-corrected pairwise comparison tests are represented by different letters. Asterisks indicate significant difference in the proportion of a given response to a question between private and public land managers, determined from Fisher's exact tests, according to $P < 0.05$

Therefore, changing the planted species mix may also reflect a resilience strategy and bet-hedging approach, that deviates from typical stand composition while refraining from a transition to entirely novel species compositions. Notably, both reforestation changes that reflected resistance or resilience strategies and ecosystem transition strategies (i.e., AM) were commonly conducted by the same individuals (Fig. S7). This suggests a combination of approaches may be most favorable (Ontl et al. 2018) and highlights a need to understand how silvicultural practices combine with AM to influence overall reforestation success (Agne et al. 2025).

Most survey respondents indicated a desire for more technical information regarding AM, with uncertainty of outcomes the most common barrier to its implementation across organizations (Fig. 6d). This finding is in line with past evaluations of manager perspectives on AM and use of other novel management practices (Neff and Larson 2014; Kemp et al. 2015; Fontaine and Larson 2016; Pelai et al. 2021). A primary concern with AM is that trees will experience a range of climate conditions across their lifespans, requiring a balance between early seedling establishment and long-term performance. Planting of seedlings adapted to late-century climate may cause establishment failure or lower seedling survival following extreme events (Aitken and Bemmels 2015), while decreases in survival and productivity in adult trees can take decades to appear (St. Clair et al. 2020). Further, the influence of AM on insect and pathogen dynamics remains poorly understood (Wilhelmi et al. 2017). In light of these uncertainties, the need for additional long-term common garden studies to inform population transfer guidelines for climate adaptation has been well-documented (Park and Talbot 2018; Twardek et al. 2023). Further, while common garden experiments of species native to western North America have generally focused on commercially important species such as Douglas-fir (O'Neill et al. 2014), ponderosa pine (Rehfeldt et al. 2014; Martínez-Berdeja et al. 2019), and lodgepole pine (Wang et al. 2006; Gray et al. 2016), respondents, including those who plan to use AM in the near future, plant a wide range of conifer species (Fig. 3c, Fig. S2), many of which have limited information regarding seed transfer. Although generalized methods for seed transfer exist (St. Clair et al. 2022; Richardson et al. 2024), their use carries additional uncertainty of outcomes that may be unacceptable, particularly for managers who are interested in optimal stand productivity. Given the wide range of species planted by individuals intending to use AM for reforestation, new studies that encompass a broader range of species, such as the Assisted Migration Adaptation Trial (Government of British Columbia 2024), are necessary to address this uncertainly.

Increasing resources and capacity for AM implementation is just as important as developing new technical information (Neff and Larson 2014; Fontaine and Larson 2016). One of the top barriers identified was related to matching seed sources to future climate of a site (Fig. 6d). Although tools exist to address this barrier, including the Seedlot Selection Tool (St. Clair et al. 2022) and the Climate Adapted Seed Tool (https://reforestationtools.org/climate-adapted-seed-tool/), most respondents, including both those who have and have not implemented AM in the past, indicated interest in trainings on seed identification resources (Fig. S7). More workshops that directly engage practitioners on the use of existing and new planning tools for seed transfer may be an effective means to address this need (Schmitt et al. 2021). Furthermore, the barrier related to availability of specific seed sources to conduct AM was highlighted as a key issue (Fig. 6d), particularly among those who have conducted AM in the past (Fig. S7). Seed availability in general (regardless of AM) is a large barrier to seedling production which needs to more than double to meet reforestation needs (Fargione et al. 2021; Dobrowski et al. 2024). Development of infrastructure to support seed acquisition and transfer among regions and across organizations, as well as increased seedling production for a wide range of species, is a critical barrier that needs to be addressed to implement AM broadly in reforestation practices.

As we expected, there were distinct differences between public and private land managers in how they have adjusted, or plan to adjust, reforestation practices for climate adaptation. However, these differences were more muted than anticipated, and there may be opportunities to increase implementation on private industrial ownerships. Relatively high rates of perceived risk (Fig. 1) and uncertainty of outcomes (Fig. 6d) suggest that technical information is a greater requirement for AM implementation on private industrial ownerships. If true, technical assessments that are relevant to forest industry, such as those that evaluate transfer of genetically improved seed (Ye and Jayawickrama 2024), may facilitate their use of AM in reforestation. Industrial land represents the greatest potential to expand use of AM, given the higher planting densities and area planted (Fig. 3b) and generally shorter rotation lengths. Private industry may also be better positioned to handle the logistics necessary for implementing AM including acquisition of suitable seed, production of seedlings, and use of reforestation practices that ensure establishment success.

Conclusion

Assisted migration is currently being used or considered for use by individual managers and organizations across major forested ownerships in the western US. Common barriers that hinder AM implementation include 1) general uncertainty of outcomes, 2) a lack of information on suitable seed transfer distances, and 3) the acquisition of seed. Despite these barriers, managers across ownerships appear to be open to expanded use of AM and other changes in reforestation practices, notably bet-hedging approaches that address the inherent uncertainty associated with climate adaptation strategies. In a landscape context, private industry may offer the greatest opportunity for increased implementation of AM given the higher proportion of area planted and planting densities reported by that ownership group. These findings provide a framework for addressing research and technology transfer needs to support climate adaptation through reforestation across forest ecosystems in the western US.

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Author Contributions All authors contributed to study conception, design, and data collection. Data analysis and visualization were performed by Michelle Agne. The first draft of the manuscript was written by Michelle Agne and Robert Slesak commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The data underlying this study will be shared upon reasonable request to the corresponding author.

Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

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