Difficult climate-adaptive decisions in forests as complex social–ecological systems

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Climate change threatens the social, ecological, and economic benefits enjoyed by forest-dependent communities worldwide. Climate-adaptive forest management strategies such as genomics-based assisted migration (AM) may help protect many of these threatened benefits. However, such novel technological interventions in complex social–ecological systems will generate new risks, benefits, and uncertainties that interact with diverse forest values and preexisting risks. Using data from 16 focus groups in British Columbia, Canada, we show that different stakeholders (forestry professionals, environmental nongovernmental organizations, local government officials, and members of local business communities) emphasize different kinds of risks and uncertainties in judging the appropriateness of AM. We show the difficulty of climate-adaptive decisions in complex social–ecological systems in which both climate change and adaptation will have widespread and cascading impacts on diverse nonclimate values. Overarching judgments about AM as an adaptation strategy, which may appear simple when elicited in surveys or questionnaires, require that participants make complex trade-offs among multiple domains of uncertain and unknown risks. Overall, the highest-priority forest management objective for most stakeholders is the health and integrity of the forest ecosystem from which all other important forest values derive. The factor perceived as riskiest is our lack of knowledge of how forest ecosystems work, which hinders stakeholders in their assessment of AM's acceptability. These results are further evidence of the inherent risk in privileging natural science above other forms of knowledge at the science–policy interface. When decisions are framed as technical, the normative and ethical considerations that define our fundamental goals are made invisible.

climate change adaptation | judgment and decision-making | forests | genomics-based assisted migration | British Columbia

Forests are generally adapted to the local climates in which they have historically grown, but climate change is threatening their health, productivity, and myriad social–ecological benefits (1–3). Technology-driven changes in forest policy and management can help forests adapt to expected future climates, protecting these benefits (4). Historically, reforestation after commercial harvest or wildfire has involved the planting of seedlings grown from locally sourced seeds, known as geographically based reforestation, under the assumption that they will perform well in those same environments. Climate change is undermining this assumption by increasing mean temperatures, changing patterns in rainfall and climate variability, changing the distribution of ecological zones, and thereby shifting the places where particular species are likely to grow well in the future (1). Policy makers are now considering new reforestation strategies, such as genomics-based assisted migration (AM), that allow for the selection of seedlings based on expected future climates (climate-based seed transfer or assisted gene flow, more widely known as AM), which they anticipate will lessen the harmful ecological and socioeconomic impacts of climate change (5, 6).

In British Columbia (BC), Canada, forests are vital to the province's social, environmental, and economic well-being. The provincial government has already authorized forestry companies to begin planting seedlings at greater distances from where the seeds were harvested (7). This limited form of AM is based on decades-long provenance trials in which scientists determined the climatic suitability of specific tree populations by growing them in standardized plots across a variety of climates. In contrast, genomics-based AM infers the climatic suitability of individual seedlings by analyzing their genomic information (8) and matching them to future local climates that are projected by locally downscaling global circulation models (9). Commercially important tree species (in the BC case, lodgepole pine, Douglas fir, Western larch, and jack pine) exhibit high levels of genetic diversity and phenotypic plasticity, which has allowed them to grow in a wide range of climates and to survive past climate variability; genomic approaches can harness this adaptability within species by revealing associations between genotype, phenotype, and environmental conditions (10).

This emerging technology is expected to more quickly, precisely, and cost effectively identify suitable seedlings and to evaluate their resistance to common forest pathogens that are likely to co-occur as they are migrated, both within and beyond the species' historic natural range (11, 12). However, AM is not without risks. In the literature, these are typically characterized as the potential failure of the migrated seedlings (i.e., they will not survive, will grow slowly, or will not produce wood of the expected quality), which could make forests less productive and less healthy, and their invasiveness in the receiving ecosystem

Significance

New forest management techniques, like genomics-based assisted migration (AM), can help forests adapt to climate change by maintaining the productivity of commercially important tree species. However, we find that key stakeholder groups tend to be more concerned about the broader health of the forest ecosystem than the success of commercially important species. Because of its uncertain impact on other social, ecological, and economic goals, they have difficulty judging the acceptability of AM and the trade-offs that it implies. While AM may appear to be a technical intervention, many of its implications are not. Decisions about AM and other such adaptations should account for the breadth of values that forests create and the diverse voices of those who depend on them.

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(i.e., the migrated seedlings will outcompete local species), which could jeopardize forest biodiversity and the conservation of other tree species (13, 14). Past studies have also alluded to potential socioeconomic and ethical implications, but these risks have been less systematically explored.

There is growing empirical evidence that climate-adaptive decisions are challenging at all scales, from individuals to institutions and governments (13, 15–18). Such judgments involve at least three sources of intractable uncertainty: the magnitude and direction of future changes in climate (19), the cascading impacts of those physical changes through complex social–ecological systems (3), and the potential nonclimate risks and benefits of the adaptive response (in this case, genomics-based AM) (20). For publicly owned natural resources such as BC's forests, governments must work with the private sector and other stakeholders to use, manage, and protect them, including the management of climate-related risks. However, public and stakeholder perceptions of the potential risks and trade-offs created by climate change adaptation have not been well characterized in the literature, especially for forestry. Brunette et al. (21) found that adaptive actions by forestry professionals in Central Europe were limited by their broader level of risk aversion, but the authors did not conduct a risk elicitation and did not link their results to the specific risks of adaptation. Hajjar and Kozak (22) and Peterson St-Laurent et al. (23) used surveys to assess public acceptance of adaptation strategies in public forests but did not explore the range and implications of the specific risks and uncertainties underlying those judgments.

In such circumstances, characterized by high levels and multiple sources of uncertainty, recent science governance paradigms prioritize "upstream" processes of stakeholder and public engagement to ensure that important concerns are appropriately considered and adequately mitigated during technological development (24). Forest governance has also been historically divisive in BC, with low levels of public trust in decision-makers in government and the forest industry, making stakeholder and public engagement even more important (25, 26). In 2017, we conducted a survey of the broader public that showed that, while support for AM is high when respondents are asked to make an overarching judgment (23), their attitudes toward AM are surprisingly unstable and sensitive to new information (27). In particular, our respondents were quite likely to report a change in attitude when told that there would or would not be an ongoing program of research and monitoring to ensure AM's benefits and lessen its risks (27), which is reflected in stakeholders' logics of support and opposition (28).

The complexity and instability of these judgments of support and opposition suggest the need for methodological approaches that better reveal the underlying and deeply contextualized logics by which participants make them. Where public and stakeholder surveys may neglect important nuance and context, qualitative and mixed-methods approaches can allow participants with diverse and sometimes incompatible values to explore the range, and elaborate on the implications, of the potential risks and benefits created by changes in public policy. Deliberative methods, in particular, encourage participants to elaborate and rationalize the logics underlying their initial assessments in relation to their values and preferences and, as a group, engage in social learning and negotiate a shared understanding of key issues (29, 30).

In the present study, we use data from 16 deliberative focus group sessions conducted across BC to explore the specific values, benefits, proximate risks, and uncertainties underlying broad judgments about AM made by participants from four stakeholder groups (forestry professionals, environmental nongovernmental organizations [eNGOs], local government, and local business communities). Here, we ask, "How do stakeholders perceive the risks, benefits, and uncertainties of AM as a climate-adaptive forest management practice? How do their AM risk perceptions relate to their perception of important forest values and preexisting risks?" Expanding on these results, we discuss the difficult trade-offs that stakeholders must navigate when making overarching judgments about climate change adaptation in complex social–ecological systems.

Materials and Methods

The purpose of this study is to characterize the risk perceptions of key stakeholder groups within forest-dependent communities with respect to their forest-related values, existing threats to those values, and proposed climate-adaptive reforestation strategies (i.e., genomics-based AM within and outside of natural range). By values, we mean those aspects of forests or the benefits they provide that people deem important to protect or enhance. We expected that these expressed values would represent more fundamental latent values that are difficult to reveal in a group setting. We also expected that elicited risks would represent risk objects: those things that are deemed to be the proximate sources of risk or cause of disaster (31), which may stand in for latent values and other unexpressed concerns. Furthermore, we expected that uncertainties (e.g., around gaps in lay knowledge, scientific uncertainty, monitoring and evaluation, conflicts of interest, etc.) would shape participants' risk perceptions and that these expressions of uncertainty would also stand in for other unexpressed concerns (e.g., related to trust, protected values, and difficulty in articulating deeply held values). The study design was approved by the Behavioural Research Ethics Board of the University of British Columbia (H17-00565), and all participants agreed to participate through a process of informed consent.

We conducted four focus group sessions in each of four communities (Campbell River, Cranbrook, Kamloops, and Prince George) organized by stakeholder group: professional foresters and forest biologists (hereafter referred to as the forestry participants), local officials from municipal and district governments (government participants), members of the local business communities (business participants), and members of eNGOs (eNGO participants). The study design was therefore a 4×4 matrix of communities and stakeholder groups totaling 16 sessions. During the preliminary analysis, we determined that regional differences were less pronounced than those between stakeholder groups and chose to focus our analysis on the latter. In particular, there were differences related to specific elements of local ecology (e.g., spruce in Prince George and forest versus grassland cover in Cranbrook), but these were nuanced and did not produce meaningful patterns in the higher-level analysis of themes and subthemes. The small-sample nature of focus groups and the interaction among participants within each session limit our ability to elucidate statistical patterns in demographic variables (e.g., age, education, income, and political worldview) that may provide insight in larger-sample studies—a trade-off of depth versus breadth.

The absence of focused Indigenous engagement is the most notable limitation of this study. In BC, First Nations are legally and culturally important to the governance of land and natural resources. We initially intended to conduct separate focus groups with representatives from BC's First Nations; however, following pre-engagement activities with two First Nations, we decided that such an approach would be misleading and potentially harmful, especially given the limited time that we had to foster meaningful relationships. Each nation contains a diversity of individuals with varied interests, values, and priorities; First Nations do not, therefore, understand themselves to be a stakeholder group with a singular perspective. Appropriate engagement activities would ideally be codeveloped with each First Nation and would foreseeably include a diversity of stakeholders equivalent to those engaged in the broader population. Though Indigenous members of the relevant stakeholder groups were welcome to participate, the recruitment methods did not specifically seek Indigenous representation in each focus group. We also chose not to ask our participants about their race or ethnicity and, therefore, do not know how many identified as Indigenous. For context, census data from 2016 (32) indicates that 6.6% of BC residents identified as Aboriginal (First Nations, Inuit, or Métis).

Limitations created by the absence of focused Indigenous engagement are most important in the context of emerging models of cogovernance between Indigenous and non-Indigenous governments within Canada and internationally. Furthermore, there has been judicial and legislative movement toward recognizing the inherent jurisdiction of Indigenous communities over natural resource projects within their ancestral lands. In the long term, these factors are likely to change the structure of governance of natural resources in BC, which may affect some aspects of risk perception, particularly in relation to decision- and policy-making processes. We cannot, therefore, speak to the implications of stakeholder risk perceptions for such emerging models of

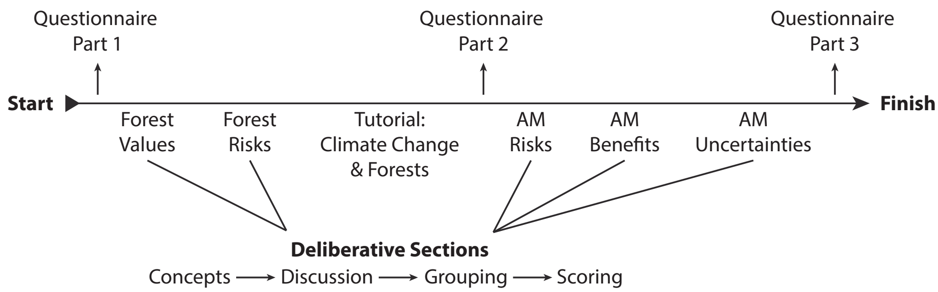

Fig. 1. Focus group structure. Each focus group comprised five deliberative sections, a three-part questionnaire, and a short tutorial on anticipated climate change in BC's forests and reforestation strategies that might help forests adapt. Each of the deliberative sections began with the individual elicitation of concepts on sticky notes followed by deliberation and grouping of concepts and ending with an individual scoring exercise to judge the relative importance of the grouped concepts.

governance or to the unique perspective that Indigenous participants may have on climate change adaptation.

Recruitment and Sample. Participants were recruited through a combination of direct emails and phone calls (using publicly available contact information on organizations' websites), distribution through email listservs (e.g., those of provincial industry associations and local chambers of commerce), and snowball sampling. To achieve adequate participation, each group was recruited using all three methods. Such methods do not ensure a diverse and representative sample; there is little reliable data about the membership of these local stakeholder groups, making it difficult or impossible to define an adequate frame for random sampling. Recruitment was geographically limited to an hour's drive from each community to ensure that participants tended to reside in the geographic area associated with that community.

There were 103 individuals who participated in the elicitations, deliberations, and scoring exercises across the 16 sessions. There was, therefore, a mean of 6.4 participants per session, though there tended to be more participants in eNGO sessions (M = 8.8) and fewer in business sessions (M = 4.3).

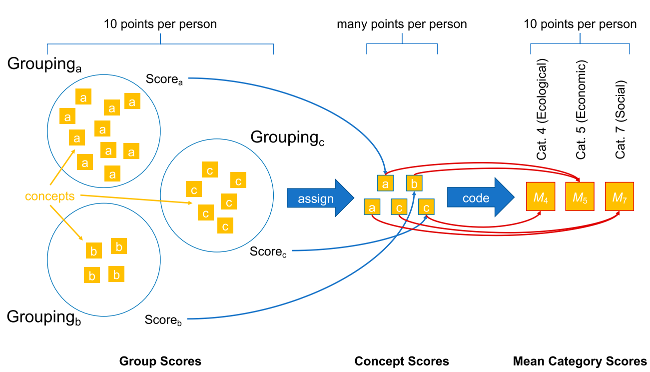

Fig. 2. Calculating mean scores for coding categories. In each of the five deliberative sections (forest values, forest risks, and AM risks, benefits, and uncertainties), each participant was provided with 10 points with which to judge the importance of the deliberatively grouped concepts. During the analysis, these scores were corrected (i.e., inversely weighted by the number of groupings, which varied from three to five) to ensure that the expected mean score (2.5) was constant across all sessions regardless of the number of groupings. Otherwise, sessions in which there were only three groupings would have had mean scores of 3.3, while sessions with five groupings would have had mean scores of 2.0. These corrected scores were then assigned to the underlying concepts within each grouping. Once the concepts were coded into subthemes, themes, and overarching categories, mean scores were calculated for each participant in each section and overarching category. Categories for which no concept was raised (and, therefore, none were grouped and scored) were assigned a score of zero. Each participant therefore had 45 mean scores for the overarching coding categories (e.g., five deliberative sections in the focus group structure multiplied by nine overarching coding categories). However, coding categories for which no concepts were raised in a section by any participants were excluded from further analysis (e.g., no participants mentioned "AM" or "None" in the forest values section, and nobody mentioned "Intrinsic" in the uncertainties section).

These differences in participation corresponded to the relative difficulty in recruiting participants from these stakeholder groups. Of the total, 74% of participants self-identified as male, 24% as female, and 2% as nonbinary. They ranged in age from 23 to 76 y with a mean age of 53. Most (77%) had completed at least a bachelor's degree or equivalent, and 97% had at least some college or university education. Our sample was older, more highly educated, and more male than the general population. Census data from 2016 (32) shows that the broader provincial population was 49.0% male and 50.9% female with a mean age of 42.3 y. One quarter (24.6%) of individuals (15 y of age or older) held a bachelor's degree or higher, and 55.0% had some form of postsecondary certificate, diploma, or degree. In contrast with the focus groups, the sample in our recent public survey (23, 25, 27) was closely aligned with census demographics because it was designed to reach a broader population, and quotas were used to ensure representative sampling for age, gender, and urban/rural residence.

The gender imbalance in our focus group sample appears to be driven, at least in part, by underlying gender imbalances in natural resource-related occupations. Based on participants' comments during the focus group sessions, there may have been self-selection bias toward those with forestry-related experience or education in the eNGO, government, and business groups. In the 2016 census, people who classified their occupation as "Natural resources, agriculture, and related production occupations" were 74.0% male and 26.0% female. Those who declared their industry to be "Agriculture, forestry, fishing, and hunting" were 65.7% male and 34.3% female. Those who had completed a degree in "Natural resources and conservation" were 71.2% male and 28.7% female.

Focus Group Structure. Our approach was adapted from the method developed in Findlater et al. (33) to elicit the numerous and multicausal risks faced by individual farmers along with their highly networked mental models of climate-adaptive decision-making. Each focus group session lasted about 3 h and was audio recorded. The focus group structure, illustrated in Fig. 1, comprised five major deliberative sections: 1) forest values, 2) forest risks, and the 3) risks, 4) benefits, and 5) uncertainties arising from genomics-based AM. Each section began with an individual exercise to contribute three to five key concepts on sticky notes, which were then placed on a poster board and were the focus of a facilitated group discussion of their interrelationships, importance, causes, and effects. Participants were asked to collectively organize the sticky notes into three to five groupings of related concepts (e.g., economic, ecological, spiritual, etc.). They were then individually given 10 points, represented by physical tokens, with which to score the groupings by their relative importance. This produced four datasets: two qualitative and two quantitative. The qualitative data consisted of transcripts and contributed concepts. The quantitative data comprised a three-part individual questionnaire and the scores that each participant assigned to the grouped concepts. Further details of the protocol may be found in *SI Appendix*.

Analysis. The quantitative analysis in this paper includes the use of inferential statistical methods applied to the concepts, scores, and questionnaires. We then interpret the results in relation to the broader literature and our recent public survey (n = 1,926) (23). The transcripts are qualitatively analyzed in more depth in Findlater et al. (28) to reveal underlying logics of support and opposition to AM, interpreting them through a broader lens to identify and reconceptualize potential maladaptation risks in relation to common frameworks in the literature.

The ideas captured in the sticky notes (n = 1,670) were roughly grouped by topic and then iteratively refined into unique concepts (484). These concepts

Table 1. Coding categories, their descriptions, component themes, and examples of prominent subthemes

Category	Description	Themes	Subthemes (example)
AM	Related to AM science and implementation (selecting, planting and growing trees from seedlings). This includes the science underlying tree selection (apart from the climate science) and factors related to their successful establishment and growth in the new location.	AM science, ecology AM science, general AM science, trees Climate change adaptation	AM science, pests AM science, timeframe AM science, genomics AM science, general
Climate/weather	Related to weather, climate variability, and/or climate change, including the climate science underlying the implementation of AM.	Climate change, abiotic Climate change, biotic Climate change, general Climate change, mitigation Climate science Weather/climate variability	Climate change, drought Climate change, diseases Climate change, existence Carbon sequestration Climate change models, extremes Flooding
Decision/policy-making	Related to the processes of decision making (by individuals and organizations) and policy making (by government) and the policies that result.	Control/power Decision making Policies Policy making	Control/power, engagement Decision, objective setting Policies, funding Policy making, public perceptions
Ecological	Related to ecological dynamics (including both abiotic and biotic factors) beyond the planted seedling or tree. Primarily related to the health, structure, and/or function of the receiving ecosystem.	Ecological, abiotic Ecological, biotic Ecological, ecosystem	Abiotic, water Biotic, wildlife/habitat Ecosystem, health/resilience
Economic	Related to economic (largely financial) drivers and effects, including those in the forestry sector.	Economic, forestry Economic, general	Forest, productivity Economic, land use
Forest industry, other	Related to other aspects of the forestry sector, not directly tied to economic drivers and effects, success of the planted seedlings, broader health of the forest, or forest policy. May be related, for example, to the implementation of forest management practices or to the knock-on (noneconomic) effects of changes in forest policy.	Forest industry	Forest management, harvesting
Social	Related to societal processes, drivers, barriers, and impacts more broadly than the forestry sector.	Lifestyle/well-being Societal/cultural	Lifestyle, recreation Societal, values
Intrinsic*	Related to the intrinsic (existence) value of forests.	N/A	
None*	Explicit expressions of denial of risks/benefits.	N/A	

*Intrinsic and None are excluded from most statistical analyses because of their low prevalence.

were coded into emergent sets of exhaustive and mutually exclusive subthemes (134), themes (24), and overarching categories (9) (Table 1). The scores that participants assigned to each grouping were delegated to the coded concepts as illustrated in Fig. 2 and detailed in the caption. The interview data that support these findings are not publicly available because they contain information that would compromise participants' confidentiality and undermine the process of informed consent. An anonymized version of the coded data is available upon reasonable request from the corresponding author under limits established by the Institutional Review Board.

Results

The elicited values, risks, and uncertainties (n = 1,670) were refined into 484 unique concepts and then coded into nine exhaustive and mutually exclusive categories (Table 1), 24 themes, and 134 subthemes (see *SI Appendix* for lists of subthemes and their frequencies). The prevalence and scoring of these categories revealed differences between stakeholder groups as well as relationships between the perceived risks and uncertainties of AM. Throughout this section, the prevalence of subthemes across focus groups is reported as the number of focus group sessions, out of 16, in which each subtheme arose.

To complement the detailed analysis of differences between stakeholder groups, Table 2 summarizes patterns within groups (i.e., the values, risks, and benefits prioritized by each stakeholder group).

Forest Values and Preexisting Risks. Fig. 3 shows the prevalence and scoring of the elicited forest values and risks by category. Participants were first asked to contribute concepts in response to the question, "Why are forests important? What do you value about them?" Participants contributed values within four broad categories (Fig. 3); ecological, economic, and social values were ubiquitous while a few participants also raised carbon sequestration as an important value within the climate/weather category. To identify those values that were widely shared by participants, we assessed the prevalence of narrower subthemes across the 16 focus group sessions. Specifically, 11 subthemes were raised by participants in more than half of the sessions: biotic, wildlife/habitat (15/16 sessions); lifestyle, recreation (15); abiotic, air (13); abiotic, water (12); economic, general (12); economic, jobs (12); carbon sequestration (11); ecosystem, health/resilience (11); forest, products (11); biotic, biodiversity

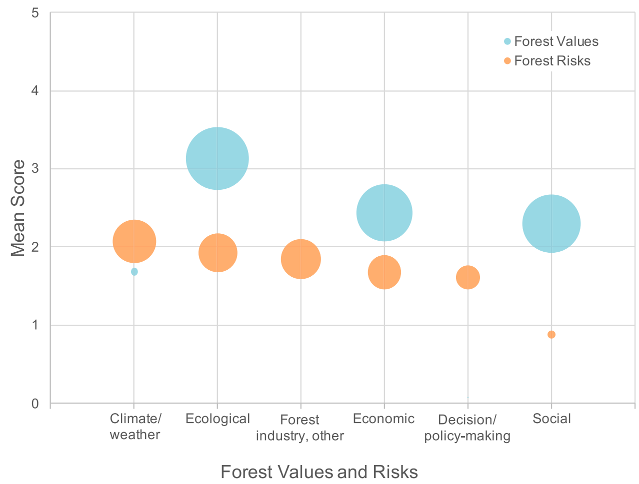

Fig. 3. Importance of forest values and risks aggregated across all stakeholder groups (n = 103). The diameter of each bubble corresponds to the proportion of total elicited values or risks that were coded into the corresponding category. Participants contributed forest values corresponding to four of the coding categories, which overlapped with the six categories of elicited forest risks; the remaining three categories are therefore excluded from this figure. The stakeholder groups were weighted to account for the different number of participants in each.

(10); and well-being, spiritual (9). Note that because participants used some terms interchangeably or linked them inseparably during elicitation, a small number of subthemes include paired terms that might, in other circumstances, be considered conceptually distinct (e.g., "biotic, wildlife/habitat").

The overall significance of the scoring differences between the four categories of forest values was confirmed by one-way ANOVA [$F(3, 408) = 22.789$, $P < 0.001$]. A Tukey post hoc test showed that ecological values were scored significantly higher than economic and social values ($P < 0.001$), while there was no significant difference between scores for economic and social values. Intrinsic values were not included in this analysis because of their very low prevalence. There were no significant differences across stakeholder groups for ecological values, but eNGO participants scored economic values lower than did participants from other groups ($P < 0.001$) and social values slightly lower than did business participants ($P = 0.04$).

Participants were then asked, "What kinds of threats or risks will forests face in the next 20 or 30 y? What might threaten these things that you've said are important?" They contributed a wider variety of concepts here than in the forest values section, with six main categories of preexisting forest risks: climate/weather, ecological, forest industry (other), economic, decision/policy-making, and social. Climate/weather and economic risks were raised in all 16 focus group sessions, while ecological and other forest industry risks were raised in all but one session. Decision/policy-making risks were raised in all business and eNGO sessions. Specifically, there were seven subthemes representing risks of shared concern (i.e., they were raised in more than half of sessions): forest management, harvesting (14/16 sessions); climate change, general (13); economic, land use (13); forest management, general (12); abiotic, wildfire (10); biotic, pests (10); and climate change, wildfire (9).

Again, the significance of the overall differences in scoring across the six categories of forest risks was confirmed by ANOVA [$F(5, 612) = 11.607$, $P < 0.001$]; however, a Tukey post hoc test showed no significant differences between paired categories except for social risks, which were scored significantly lower than all other categories. There was relatively even scoring across climate/weather, ecological, other forest industry, economic, and decision/policy-making risks. Testing for differences across stakeholder groups, forestry participants scored climate/weather and ecological risks higher and other forestry risks lower than did eNGO ($P < 0.01$) and business participants ($P < 0.05$). eNGO participants scored decision/policy-making risks higher than did forestry participants ($P = 0.002$).

AM Risks and Benefits. There were 301 elicited AM risk concepts coded into 5 primary categories (Fig. 4), 16 themes, and 50 subthemes. The most prevalent category comprised "ecological risks" to the receiving ecosystem in which the introduction of a new species may disrupt existing ecological processes: impacts on wildlife, habitat, and biodiversity; broad impacts on the health, resilience, structure, and function of the forest ecosystem; the potential for unexpected or unknown effects because of the complexity of the forest ecosystem; effects on biotic factors like pests, diseases, invasive species, competition, and genetic diversity; and abiotic factors such as water, air, soil, and shade. The second most prevalent category comprised risks related to "failure in AM's implementation"—the failure of the planted seedlings to survive and grow productively—which would have economic and ecological consequences. Factors that were identified as related to AM failure included failure in the science of tree selection; inadequate research and monitoring; susceptibility to pests, diseases, and abiotic factors in the new location; and the knock-on economic effects of tree failure. The third most prevalent category comprised risks related to "decision making and policy making," including inadequate processes of policy making, decision making, and objective setting for AM; inadequate policies in general, and forestry and science policies in particular; politics in general and political stability; control, power, engagement, and trust; and public perceptions. The fourth most prevalent category comprised risks related to weather and climate: that the "climate models" on which AM's implementation depends may be wrong, that they insufficiently capture temporal and spatial variability in future climates, and that weather extremes may harm the migrated trees regardless of climate change. The fifth and least prevalent

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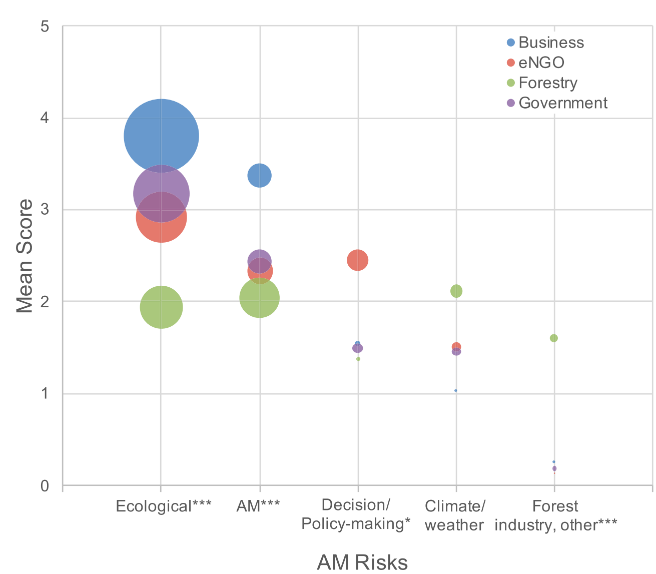

Fig. 4. Importance of AM risks by stakeholder group (n = 103). The diameter of each bubble corresponds to the proportion of elicited uncertainties in the corresponding stakeholder group. The difference in mean score across stakeholder groups for each risk category was tested using a one-way ANOVA (*$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$).

Table 2. **Stakeholder group profiles**

	Forest values	Forest risks	AM risks	AM benefits	AM uncertainties
OVERALL	Prioritized ecological values above social and economic values	No consistent priorities but least concerned about social risks	Most concerned about ecological and AM failure risks above all other categories	Equal potential for economic and ecological benefits above all other categories	Judgment equally limited by climate/ weather, ecological, and AM science uncertainties
Forestry	Prioritized ecological and economic values equally above social values	Most concerned about climate/ weather and ecological processes above all other categories	No consistent priorities but least concerned about decision/policy-making risks	Equal potential for economic and ecological benefits above all other categories	Judgment limited by climate/weather above all other categories and least limited by other economic uncertainties
eNGO	Prioritized ecological values above social and economic values	No consistent priorities but least concerned about social risks	Equally concerned about ecological, decision/policy-making, and AM failure risks	Equal potential for economic and ecological benefits above all other categories	No consistent priorities, but judgment least limited by other economic uncertainties
Government	Prioritized ecological, economic, and social values equally	No consistent priorities but least concerned about social risks	Most concerned about ecological and AM failure risks above all other categories	No consistent priorities	Judgment most limited by ecological uncertainties
Business	Prioritized ecological, economic, and social values equally	No consistent priorities	Most concerned about ecological and AM failure risks above all other categories	Equal potential for economic and ecological benefits above all other categories	No consistent priorities, but judgment least limited by other economic uncertainties

Descriptions are drawn from statistical analyses of differences in mean scores across the coding categories within each stakeholder group (one-way ANOVAs with Tukey post hoc tests, the details of which may be found in *SI Appendix*). Where a relative difference is described (e.g., above, below, most, least), both the ANOVA and the relevant post hoc test were significant. Where categories are described as equal or where no indication is made, the differences were not statistically significant.

category comprised “other risks related to the forest industry,” including the commitment, capacity, and adaptability of the industry to implement AM. Finally, a few participants raised the prospect of social risks, and one participant suggested that there are no risks at all.

Ecological and AM failure risks were raised in all 16 focus group sessions, while climate/weather and other forest industry risks were raised in all forestry sessions. Specifically, there were five AM risk subthemes of shared concern: AM science, tree selection (15/16 sessions); biotic, wildlife/habitat (13); ecosystem, structure/function (13); biotic, biodiversity (11); and biotic, disease (9). Participants in business and government groups more often raised ecological risks than did eNGO and forestry groups. Participants in eNGO groups more often raised decision/policy-making risks than did other participants, while forestry participants more often raised risks related to AM failure than did other groups.

AM’s potential benefits, beyond climate change adaptation, were elicited in the fourth section of the focus group structure and were mainly ecological and economic. However, participants had more difficulty thinking of potential benefits, and the concepts and deliberations were framed more speculatively than in the risks and uncertainties section. We have, therefore, not included their statistical analysis in this paper beyond *SI Appendix*, Fig. S3, which shows the relative prevalence and importance of the different categories of potential benefits. Ecological and economic benefits were raised in all 16 focus group sessions, and there were six shared AM benefit subthemes: forest, productivity (13/16 sessions); biotic, biodiversity (12); ecosystem, health/resilience (12); economic, general (11); economic, sustainability (10); and biotic, wildlife/habitat (9).

AM Uncertainties. Uncertainties related to AM science were raised in all 16 focus group sessions, while climate/weather and decision/policy-making uncertainties were raised in all but one session (Fig. 5). Ecological uncertainties were raised in all but two sessions (14) and economic uncertainties in all but three sessions (13). Specifically, there were five AM uncertainty subthemes of shared concern: climate change models, general (13/15 sessions); ecosystem, complex/unknown (13); AM science, research and monitoring (9); AM science, tree selection (9); and economic, markets (9).

The range of elicited AM uncertainties was broadly similar to the range of elicited AM risks. However, there were differences in how often they were raised and how participants scored their importance (Fig. 6). In the risk section, participants most often mentioned ecological factors, but, in the uncertainty section, they most often mentioned climate/weather factors. The proportion of risks and uncertainties captured in each category differed significantly by stakeholder group as indicated by the width of the bubbles in Fig. 4 [X^2 (12, n = 295) = 29.461, P = 0.003] and Fig. 5 [X^2 (12, n = 294) = 32.159, P = 0.001].

Levels of Support for AM and Other Reforestation Strategies. Fig. 7 shows the overall levels of support, before and after deliberation, for six possible reforestation strategies. The six strategies may be thought of as falling on a spectrum of human intervention in the forest ecosystem from least interventionist on the

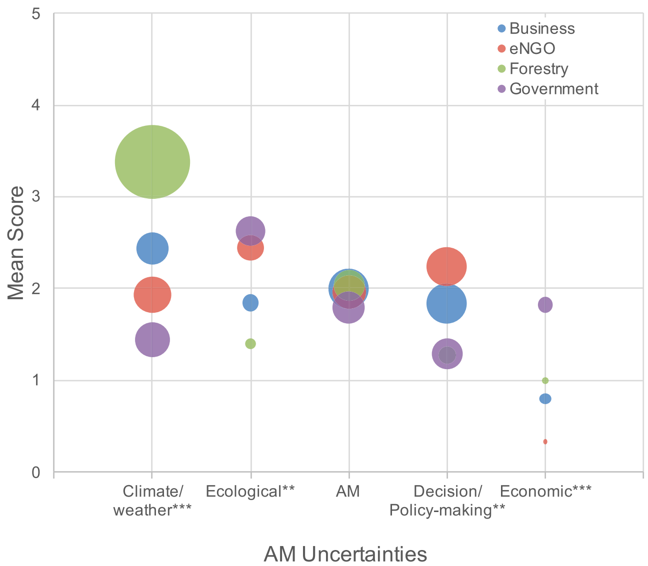

Fig. 5. Importance of AM uncertainties by stakeholder group (n = 103). The width of each bubble corresponds to the proportion of elicited uncertainties in the corresponding stakeholder group. The difference in mean score across stakeholder groups for each uncertainty category was tested using a one-way ANOVA (*P < 0.05, **P < 0.01, and ***P < 0.001).

left (natural regeneration and local tree breeding) to most interventionist on the right (using nonnative species or genetically modified organisms [GMOs]). AM within and AM outside of natural range represent more human intervention than historically practiced but less than nonnative species or GMOs, and AM outside of natural range represents more intervention than AM within natural range. The two AM strategies and nonnative species roughly form a gradient representing the movement of trees increasingly distant from their historical range. This corresponded to a gradient in perceived risk and uncertainty as described by participants during deliberation (e.g., "The further you go, the greater the risk." [Participant CE, Prince George, eNGO]), which is reflected in decreasing support in Fig. 7.

Participants scored each option on an 11-point scale with the endpoints and midpoint of the scale labeled "Strongly oppose (−5)," "Neutral (0)," and "Strongly support (+5)." Mean initial support was highest for local tree breeding (M = +2.8; the *status quo* practice) and AM within natural range (M = +2.6; the smallest shift in policy) and lowest for nonnative species (M = −1.7) and GMOs (M = −1.8), practices that are not currently being considered for use in BC. Mean initial support for AM outside of natural range (M = +1.1) was somewhat lower than for AM within but still positive. Furthermore, as seen in Fig. 7, 90% of participants were at least somewhat supportive of AM within natural range, while only 7% were at least somewhat opposed. This supportive share was similar to natural regeneration (87% supportive) and higher than all other options. Two-thirds (67%) were still supportive of AM outside of natural range with only one quarter (25%) opposed.

Overall, these data suggest that participants generally recognize the need for climate-adaptive reforestation practices but are less supportive of options that represent more human intervention in forest ecosystems. When analyzed using paired-samples Student's t tests, levels of support for most strategies did not change after deliberation; however, there was a small but statistically significant drop in support for AM outside of natural range after participants had discussed its risks, benefits, and uncertainties [$t(101) = 2.303$, $P = 0.023$]. This difference was largely driven by a decrease in support among government participants [$t(23) = 2.860$, $P = 0.009$]. The overall difference in initial support across the six reforestation strategies was confirmed by one-way ANOVA [$F(5, 611) = 64.790$, $P < 0.001$]. A Tukey post hoc test showed that initial support for AM within natural range was significantly higher than for AM outside of natural range (P = 0.001), nonnative species (P < 0.001), and GMOs (P < 0.001). Initial support for AM within natural range was not significantly different from support for natural regeneration or local tree breeding. Initial support for AM outside natural range was significantly different from support for all other strategies (P < 0.01) except for natural regeneration.

Overall, these levels of support exhibited similar patterns to those elicited in the earlier public survey (23). However, there were important and statistically significant differences between stakeholder groups as shown in Fig. 8, with each group's support peaking at a different point on the x-axis (roughly corresponding to level of human intervention). Participants in business and government sessions were most supportive of local tree breeding, the status quo practice. Participants in eNGO sessions were most supportive of natural regeneration, which would represent a change in practice in favor of less human intervention in forest ecosystems, and were also less supportive than other participants of all other reforestation strategies. Participants in forestry sessions were most supportive of AM within natural range, which represents a change in practice in favor of more intervention. The most meaningful and statistically significant differences between groups were between eNGO and forestry participants, with eNGO participants being least supportive of the two AM strategies, while forestry participants were the most supportive [AM within: $F(3, 99) = 5.015$, $P = 0.003$; AM outside: $F(3, 99) = 6.743$, $P < 0.001$; Tukey post hoc tests between forestry and eNGO groups: P < 0.001]. Judging from statements made during their sessions, these groups tended to have more specialized knowledge of forestry. On the same basis, it seems likely that government and business sessions were also subject to some degree of self-selection bias toward participants with more forestry knowledge than is typical of the broader membership of those stakeholder groups. Though this information was not directly elicited, many participants across all groups mentioned experience or education in forestry-related fields, certainly higher than the 2.6% of the labor force who reported working in "Agriculture, forestry, fishing, and hunting" in the 2016 Census (32).

Discussion

We asked stakeholders to appraise the potential risks, benefits, and uncertainties of genomics-based AM as a climate change adaptation strategy in BC's forests. Broadly speaking, while they perceive there to be important risks and uncertainties, particularly in the ability to predict broader ecological impacts and specific climate futures, they believe that something must be done to lessen the harm of climate change in forests that are integral to so many valued environmental and societal objectives. The risk of AM failure, that the selected seedlings will not survive or thrive, is perceived as important but even more so are the risks to the receiving ecosystem created by the introduction of a new species that may be disruptive to highly interconnected ecological processes, may displace existing species that are foundational to the structure and function of that ecosystem, and may bring with it new pests and diseases.

Government and business participants may be understood as broad, nonspecialist groups likely to have diverse values (the business groups included only participants from non-forest–related businesses). The forestry and eNGO groups may be understood as specialist groups with more specific interests in particular forest governance outcomes, with some shared values and some that are opposed. Therefore, it is not surprising

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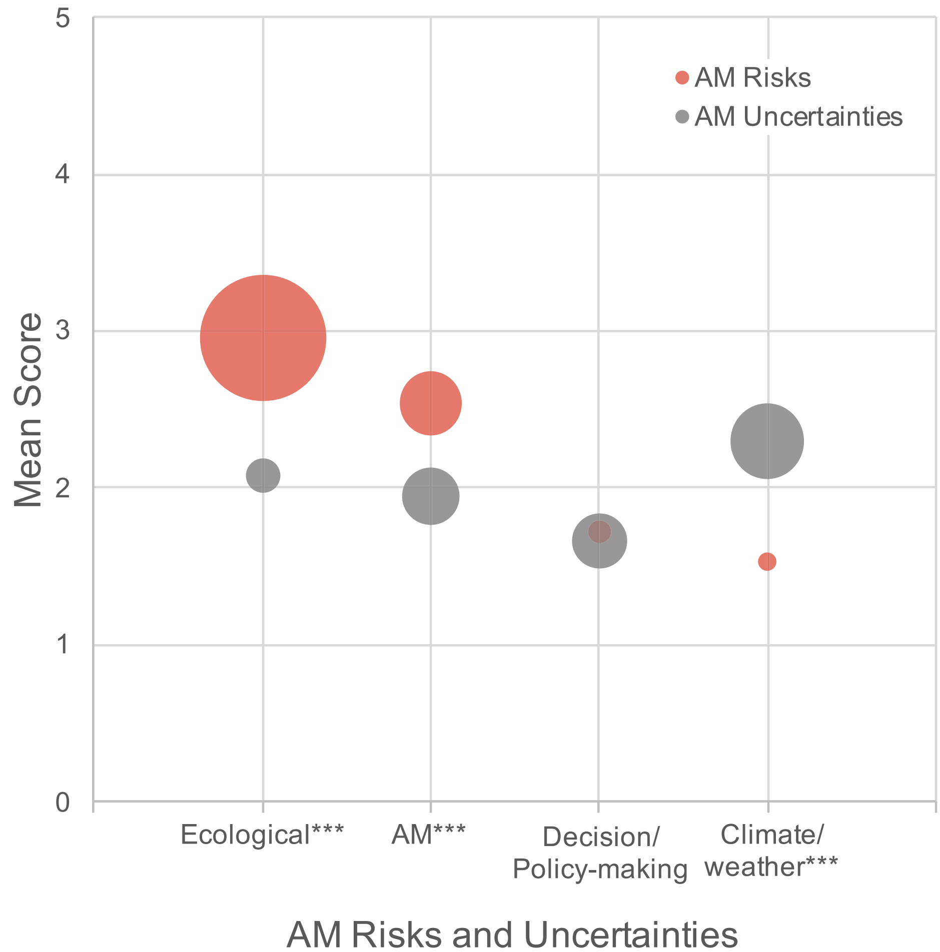

Fig. 6. Importance and prevalence of the four most common categories of risk and uncertainty arising from the implementation of AM as a climate change adaptation strategy in BC's forests (n = 103). The width of each bubble corresponds to the proportion of elicited risks and uncertainties in all groups. The stakeholder groups were weighted to account for the different number of participants in each. Paired-samples Student's t tests confirmed the significance (***$P < 0.001$) of the differences between mean scores that participants assigned to ecological risks and uncertainties, between risks and uncertainties related to AM science, and between climate/weather risks and uncertainties. A, χ^2 test also confirmed the significance of the differences in prevalence across categories [X^2 (3, n = 559) = 110.294, $P < 0.001$].

that these latter two groups exhibited key differences in risk perception, sometimes taking oppositional positions between which the government and business groups adopted more moderate positions (for instance, in their overall attitudes toward AM in Fig. 8). Forestry participants, for instance, were more concerned than other groups about scientific uncertainty, while eNGO participants were more concerned than others about decision- and policy-making processes. However, all groups perceived forests to be very important to their communities and to the province (mean scores of 9.0 and 9.1, respectively, on a scale from "0, Not important" to "10, Very important"), with no significant difference between stakeholder groups despite differences in the reported personal importance of forests. Alongside similarity in the scoring of forest values across groups (Fig. 3), this shared perception of forests' importance suggests that there may be broader basis for agreement on climate-adaptive action than implied by participants' membership in stakeholder groups stereotypically associated with competing values (e.g., economic values by forestry professionals and ecological values by eNGOs).

Because of the instability in support that respondents exhibited in the public survey (27), we initially expected larger shifts in support after deliberation. However, the stability of participants' attitudes appears to reflect, at least in part, a resignation to the need for adaptive action, which we found in the separate qualitative analysis of participants' underlying logics (28). Though deliberative focus groups encourage social learning that may shift participants' understanding of risks and benefits (34, 35), the format may also underestimate the changeability of participants' attitudes because it encourages them to rationalize and contextualize their initial choices. Based on comments they made in introducing themselves at the beginning of their sessions, the focus group participants also appear to have had more baseline knowledge of forestry than did the respondents in the public survey, even in the "nonspecialist" government and business sessions.

In reviewing arguments about AM risks in the scientific literature, Hewitt et al. (14) found that researchers most commonly foresaw risks related to the potential invasiveness of the migrated species, with knock-on ecological and socioeconomic impacts. Further risks included broader ecosystem impacts, genetic effects, competition for scarce conservation funding, bias in the prioritization of particular species, and other socioeconomic and cultural impacts. In our study, the range of stakeholder concerns broadly covered those described by Hewitt et al. but with more specificity and additional nonscientific risks related to decision- and policy-making processes. Though the tutorial on reforestation strategies emphasized that, in this case, AM would rely on genomic techniques that are currently

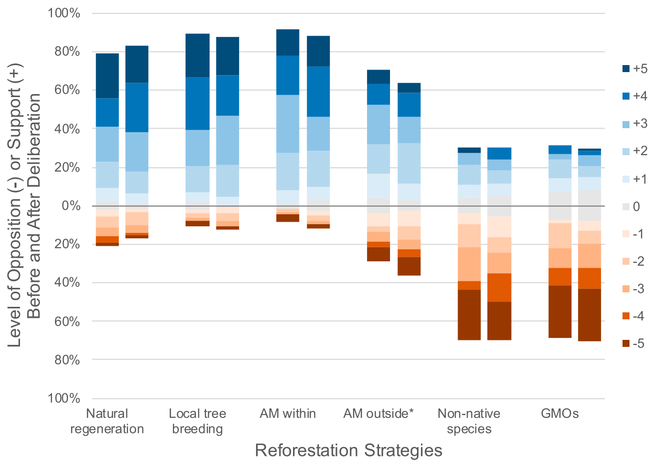

Fig. 7. Overall levels of support and opposition for six proposed reforestation strategies before and after deliberation (n = 103). Participants scored each option on an 11-point scale; the endpoints and midpoint of the scale were labeled "Strongly oppose (−5)," "Neutral (0)," and "Strongly support (+5)." Each pair of bars shows participants' predeliberation (*Left*) and postdeliberation (*Right*) answers. *AM outside of natural range was the only strategy with a statistically significant difference between pre- and postdeliberation support in paired-samples Student's t tests [$t(101) = 2.303$, $P = 0.023$].

under development, participants did not spend much time raising or deliberating factors directly related to those novel techniques. They tended to focus on concerns about AM more broadly, with the genomics-based approach just one source of scientific uncertainty among many, possibly reflecting a lack of understanding or comfort in discussing the technical details.

In Findlater et al. (28), we find that these same participants rationalize and elaborate their statements of support and opposition toward AM using five distinct logics: scientific uncertainty, distrust in decision-making, fear of overconfidence, lost opportunity, and responsibility and resignation. These logics suggest the potential for maladaptation through technical failure, opportunity cost, path dependence, and the too-narrow framing of the adaptation problem (36). These show that participants' concerns are not limited to the specific risks and uncertainties that they raised during the elicitation exercises but also represent broader, longer-standing concerns with the processes and priorities of

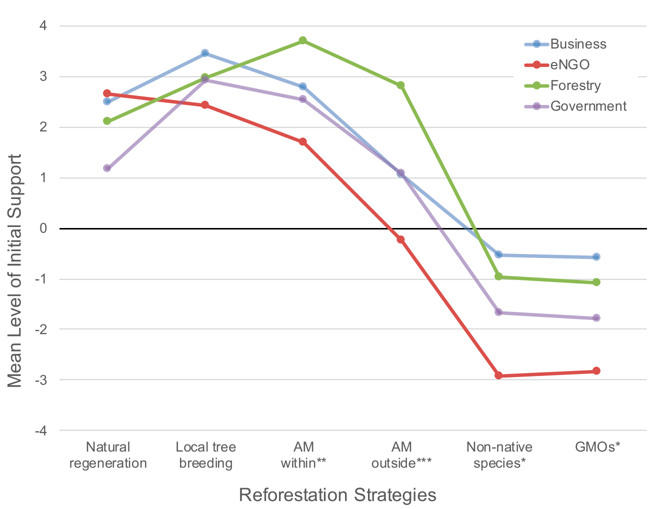

Fig. 8. Mean support for six proposed reforestation strategies by stakeholder group (n = 103). The difference in support across stakeholder groups for each strategy was tested using a one-way ANOVA (*$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$).

forest governance. Forest management itself, for instance, was perceived by participants in all groups to be an important risk to forest values, reflecting a tendency in the BC context to trust scientists in making forest-related decisions but to distrust government and the forest industry because they are perceived to have made poor management choices in the past (25, 26).

Broader Implications. Forestry is vital to the economic, ecological, and social well-being of communities worldwide, and BC is a global leader in forestry research and practice (37). This pivotal case provides important lessons for forest management and adaptation in other contexts, and the major concerns of our participants are not unique to BC. For instance, recent progress in forest ecology has demonstrated that scientific knowledge about the ways in which trees anchor broader ecological processes remains nascent (38, 39), and public trust in decision-making processes is fundamental to the effective governance of shared or publicly managed resources (40). However, public ownership of BC's forests creates an expectation of responsible public stewardship (23) that may not exist in regions where private land tenure is more common.

Climate-adaptive forest policies are necessarily forward looking; trees are at their most productive and most ecologically vital decades after planting, and they must be adapted to those future climatic, ecological, economic, and social conditions. Where forest management has typically assumed that such conditions are stable, however, most never were, and climate change has brought that dynamicity into focus. The renewed need for long-term, multifaceted, and climate-sensitive planning is evident in other social–ecological systems (41), equally so for sectors, like water, that have typically had decades-long planning horizons (42–44) and for those, like agriculture, in which decision-makers are responsive to annual changes in environmental and market conditions (15, 16). For instance, McWethy et al. (45) argue that wildfire regimes are changing so drastically and so quickly that adaptation will never be enough and that we will have to transform our relationship to fire altogether, learning to live with it.

There are also lessons for responsible innovation. Technological choices are inherently political, as argued by Jasanoff (46) and others—no less so for climate change adaptation—and there is danger in the unchallenged primacy of scientific expertise. Public and stakeholder engagement should not be approached as an exercise in unilateral risk or science communication but as a way of achieving normative, substantive, and instrumental objectives (47, 48). Through this broader lens, nonscientific perspectives are equally valid. Because of their diverse sources and kinds of knowledge, stakeholders may collectively understand complex social–ecological systems better than scientists alone (49). Though the application of genomic techniques for tree selection may be the purview of forest geneticists, its acceptability as an adaptation strategy in BC's forests is not. Risk communication is not simply a method by which to alleviate public and stakeholder concerns; it should be a dialogue in which those concerns are treated as legitimate and addressed where needed. While communication is an important goal, upstream engagement should seek to understand the broader implications of what may appear to be technical choices. Engagement can, for instance, improve climate-related decisions by enabling a fuller understanding of the potential impacts of changes in policy while increasing legitimacy and public trust (50).

Recognition of the shortcomings of natural science, in isolation, is reflected in the Responsible Research and Innovation framework of the European Union, studies of which have raised concerns about the enduring primacy of natural science knowledge (51). The norms and institutions of the natural sciences and engineering devalue other ways of knowing and being, including social science and Indigenous knowledge (52).

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For instance, resistance to the integration of social science expertise into climate science has hampered a decade-long, World Meteorological Organization–led effort to create climate services as a user-driven approach to climate information that improves climate-sensitive decision-making (53). This privileging of natural science at the science–policy interface is sustained by cultural, institutional, and financial structures (54).

It is not sufficient that technological interventions for adaptation be technically successful; they must be sensitive to context. Whereas effective mitigation requires international collaboration, adaptation is typically framed as a local process (55). Moser (18) argues that adaptation can be unexpectedly contentious because its context specificity may disrupt legal frameworks, social norms, and institutions. Our results remind us that policy choices framed as adaptations can have implications far beyond climate resilience. They may encounter unexpected resistance from stakeholders where decisions appear not to have accounted for context-specific nonclimate uncertainties and not to have considered the potential for systemic change. Although support for adaptation among our focus group participants (Fig. 7) and the public (23) appears to be high, inclusive and transparent policymaking may go a long way toward ensuring that it does not become unexpectedly contentious.

Conclusions

The successful application of genomics-based AM focusing on commercially important species, as in this case, would protect the current economic benefits of forests, while AM's failure would be a loss of those benefits. However, even if AM succeeds and the migrated seedlings survive and thrive, there may well be other unwanted consequences for the receiving ecosystem and the exacerbation of important nonclimate risks. We have shown that while overall support for genomics-based AM, especially within natural range, may be high compared to other reforestation options and does not change much following deliberation, the factors that stakeholders are generally most concerned about relate not to the risk or uncertainty inherent in the novel genomics-based technology or even the technical success of the adaptation (i.e., whether the migrated trees thrive) but to broader questions about the perceived lack of scientific knowledge of complex forest ecology, the inability to predict precise climate futures, and the need to reconsider broader processes of forest governance. There is, therefore, also a risk in undertaking adaptation strategies that maintain or entrench status quo forest governance priorities and processes that are perceived to be inadequate. These results, building on those in Findlater et al. (27), suggest that public and stakeholder judgments about the appropriateness of climate-adaptive forest management strategies are interconnected with diverse nonclimate objectives. The highest priority objective for most stakeholders seems to be the health and integrity of the forest ecosystem, from which all other important forest values derive, and the factor perceived as riskiest is our lack of knowledge of how forests, as complex social–ecological systems, work.

These results are further evidence of the difficulty of adaptation decisions in complex social–ecological systems in which both climate change and climate-adaptive responses will have widespread and cascading impacts on diverse nonclimate values. Adapting to climate change, in and of itself, is not a useful goal, even more so when the climate risk is intractably uncertain but the nonclimate risks created by adaptation are not. If climate-related decisions are defined only by natural science and taken in reference to climate change alone, we may jeopardize the more fundamental goals that adaptation is meant to help achieve: food and water security, health and well-being, protection of property and livelihoods, ecosystem services, etc. The definition and achievement of these goals depend on normative and ethical considerations that are made invisible by the instrumental and technical approaches most often used to assess new technologies. Climate-adaptive decisions, though they may seem less contentious and less ideological than those related to mitigation (18), must be approached broadly and systematically; otherwise, the framing will predetermine the suitability of proposed solutions. In this case, technical framing (e.g., maintaining tree productivity) implies a narrow solution to protect commercially valuable species, whereas broader framing (e.g., healthy forests) may encourage systemic changes in forest governance to protect and enhance ecosystem integrity and diversify the values for which forests are managed. The former echoes the debunked yet still common understanding of adaptation as rational adjustment to climatic harms (56), while the latter resonates with recent arguments against "adaptation" and toward more inclusive and dynamic concepts such as transformative resilience.

Data Availability. The interview data that support the findings of this study are not publicly available because they contain information that would compromise the research participants' confidentiality and undermine the process of informed consent.

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