# A productive role for science in assisted colonization policy: A productive role for science in assisted colonization policy

**Article** *in* Wiley interdisciplinary reviews: Climate Change · July 2016

DOI: 10.1002/wcc.420



Mark Neff
Western Washington University

Advanced Review

# A productive role for science in assisted colonization policy

Mark W Neff* and Katherine Carroll

*Edited by Josef Settele, Domain Editor, and Mike Hulme, Editor-in-Chief*

Assisted colonization—the intentional movement of species as a climate adaptation strategy—has emerged as a divisive controversy in the conservation biology literature. We review selected scientific literature to understand the nature of the controversy, alongside relevant scholarship on the science-policy interface to highlight ways in which scientists and their work might most effectively and appropriately inform decisions on this management strategy. The scientific literature thus far is problematic in two ways that threaten to undermine the utility of science to actual decision-making processes: As a collection, it contains abundant and seemingly incommensurable insights about assisted colonization. This is at least in part a product of nature, which is sufficiently diverse to provide examples and case studies that appear to justify any number of policy preferences regarding ecosystem management. This first shortcoming exacerbates the second: Scientific authors thus far have not adequately addressed the value-based considerations implicit in their own work, nor acknowledged public's legitimate standing in these inherently value-based decisions. In combination, these attributes of the literature ensure that additional knowledge on assisted colonization will exacerbate public controversy—rather than dispel it—when public attention increases. We propose that if scientists appropriately disentangle value considerations from technical ones, invite public debates over values, and treat proposals individually rather than debating the approach writ-large, they stand to have the greatest influence over technical aspects of decision processes. Scientists would serve themselves well to acknowledge the limits of science and embrace public dialogue about specific management proposals. © 2016 Wiley Periodicals, Inc.

**How to cite this article:**
*WIREs Clim Change* 2016. doi: 10.1002/wcc.420

## INTRODUCTION

Humans have been modifying ecosystems and moving species throughout our collective history and prehistory for purposes including agriculture, aesthetic gardening, and medicine (Ref 1, p. 19). Range seeding and regenerative seeding in forestry have taken place for many years without controversy (Ref 2, p. 32), and stocking of non-native fish species has occurred for centuries. Experimental tree plantings have been taking place in Greenland since 1953, and commercial nurseries in Europe have long encouraged the planting of ornamental plants north of their native ranges (Ref 3, p. 563, Ref 4, p. 736). New Zealand has translocated a number of endangered species to offshore islands that lack non-native predatory mammals to prevent their extinction, including to locations outside of species' documented historical range (Ref 5, p. 799]. Despite this long history of species movements, contemporary proposals to move species to where future climatic and other conditions are likely to be

*Correspondence to: mark.neff@wwu.edu

Environmental Studies, Huxley College of the Environment, Western Washington University, Bellingham, WA, USA

Conflict of interest: The authors have declared no conflicts of interest for this article.

favorable for their survival (known alternately by partial synonyms such as assisted migration, assistant colonization, managed translocation, among others) have inspired passionate and divisive debate over the past decade within the conservation biology literature.[6,7]

Peters and Darling[8] are credited with introducing the idea of assisted colonization to the modern conservation literature. Referencing studies of past fossil records and climate prediction data, they explain the process by which many species will begin to move to higher latitudes to compensate for the changing temperature and weather patterns associated with climate change. Noting the rapidity of projected climatic changes and the extent of habitat fragmentation in many areas, these authors suggest that some 'individuals of disappearing species may have to be transplanted to new reserves' (Ref 8, p. 715). It did not stay a theoretical proposal for long: by 1998, a group of concerned citizens calling themselves the Torreya Guardians was engaged in transplanting the rare conifer *Torreya taxifolia* from its native Florida northward into Georgia to protect the species from extinction (see http://www.torreyaguardians.org/save.html).

Is worth noting that beyond this one citizen effort to save the *Torreya*, other examples of species being moved to novel ecosystems specifically as a *climate adaptation strategy* are relatively uncommon. The published cases of assisted colonization include field trials of translocating Whitebark Pine in Canada for conservation purposes (see Ref 9, p. 761), and the amendment by a number of Canadian provinces of their seed transfer policies to allow seed transfers of greater distances (see Ref 10, p. 29, Ref 11, p. 841). In anticipation of future assisted colonization actions, the United States Department of Agriculture has been working to identify trees in the Northwestern and Southeastern United States suited for translocation (Ref 12, p. 289]. While the research on assisted colonization was initially more limited than the debate over its execution, the number of studies on the practical aspects of implementing assisted colonization is growing (e.g., see Refs 13,14). In addition to the activities of the Torreya Guardinas, the citizen interest in hybridizing and reintroducing the American chestnut[15,16] demonstrates that there is widespread interest in ecosystem management and restoration; we are confident that these passions will generate additional citizen-driven assisted colonization activities as climate change threatens cherished species.

The scholarly attention to the idea was relatively low until 2007, at which point the number of articles on the topic increased significantly (Ref 6, p. 2564), with many articles debating whether it ought ever be considered as a conservation strategy. As the scholarly attention has intensified, authors have explored assisted colonization from many different angles, including enumerating technical and social/political challenges to implementation, proposing decision frameworks, and offering arguments for and against the technique. Clear divides have emerged between authors strongly opposed to its use, and those who believe that cautious implementation may be a viable way to save some species from climate-related extinction. A cottage industry has emerged in reviewing and analyzing this literature to understand the underlying bases of the dispute (e.g., see Refs 2,6,7,17].

We first review the conservation literature on assisted colonization and explore the reasons why the technique is so controversial within that scientific community. We then build from selected humanities and social sciences literatures on the science-policy interface to identify epistemic and social/political reasons why ecology and conservation biology are unlikely to generate a consensus that might dispel disputes over assisted colonization as a species conservation strategy. The debate in the scientific literature, which tends to treat the appropriateness of moving species for conservation purposes as an issue that can be addressed in the aggregate, is not likely to meaningfully influence policy in its current form. This is not to say, however, that science is irrelevant to this issue. In a concluding section, we identify productive roles that scientists might successfully fill in evaluating, learning from, and informing adaptive experimental approaches to ecosystem management in a changing climate. Scientists will, perhaps counter-intuitively, be optimally effective in informing ecosystem management for climate adaptation only by accepting the limited roles of science in public policy and welcoming a political dialogue on the values inherent in conservation decision-making.

## ASSISTED COLONIZATION IS CONTROVERSIAL BECAUSE IT FORCES UNCOMFORTABLE QUESTIONS

The crescendo of debates about assisted colonization in the conservation biology literature suggests that some aspect of this problem differentiates it from otherwise similar species movement activities conducted for other purposes. Aubin et al.[9] suggest that the contention in the literature exists because some authors in conservation work from an ecocentric ethical framework and others an anthropocentric one. In part because of discomfort with the roles of humans in the environment, conservation biology as a discipline has become embroiled in a battle over what to make of ecological dynamism and anthropogenic contributions to ecological change.[18–21] Climate change further forces the issue. Minteer and Collins[22] have a related thesis: they identify tension between—and occasional mutual incompatibility of—positive conservation duties (active management to preserve species and their habitats) and negative conservation duties (the perceived human obligation to minimize our impact on the natural world). Schwartz et al. argue that as a conservation strategy, assisted colonization (their term is managed relocation) would constitute a significant paradigm shift in how ecosystems are managed by expanding the range of techniques used and including 'maintaining biodiversity and conserving ecosystem function' as primary goals (Ref 23, p. 732).

The tensions within the conservation biology community around the role of humans in ecosystem change are present even in Soulé's foundational 1985 essay 'What is conservation biology?' In a single essay, he argues that extinction can be a healthy process of 'replacing less well-adapted gene pools with better adapted ones, (Ref 24, p. 730)' while simultaneously lamenting contemporary extinctions as the product of un-natural human activity. Humans are undoubtedly causing extinctions, but unless we can anticipate that humanity is going to end soon, it is unclear what to make of extinctions that replace species ill-adapted to human activity. Soulé lauds coevolutionary processes, but laments human impacts on evolution. Perhaps most relevant to understanding the divisiveness of the assisted colonization debate, he asserts that 'benign neglect' of natural systems in parks and protected areas is the optimal management strategy for conservation, but, writing about large, rare organisms in nature reserves, acknowledges that 'species diversity must be artificially maintained for many taxa because natural colonization (reestablishment) from outside sources is highly unlikely.' Humans are, to Soulé, external perturbations on natural systems whose impacts should be minimized, but he believes that active management interventions are justified to mitigate anthropogenic damage. This approach creates an ethical ambiguity around this otherwise justified active management for conservation purposes: What are we to make of the unintended impacts caused by our mitigation activities, which necessarily harm some species and ecosystems in attempting to preserve others? The inevitability of future climatic change based on greenhouse gases already in the atmosphere poses a challenge with no clear solution in Soulé's framework. Anthropogenic climate change is causing species extinctions and will continue to do so, but our interventions to protect some species will have undesirable impacts on others (see also Ref 22).

A dynamic world is one in which conservation biologists cannot speak with a unitary voice in responding to management questions because management to help individual species may in some cases undermine efforts to conserve threatened species or ecosystems, and vice versa. Thus, with an acknowledgement that ecosystems change and that humans contribute to those changes, the value considerations inherent in ecosystem management decision-making come directly to the fore.

The prominence with which conservation authors feature the *Torreya* case study[25–28] suggests another reason why assisted colonization has become so controversial: it demonstrates that management activities are not waiting for a consensus from the conservation biology community. A recent Q-method study seeking to pinpoint the sources of controversy among conservation scientists and managers offers empirical evidence that scientists and managers are concerned about the locus of decision-making for these management activities.[17] That study found that central to the dispute are: questions of who has decision-making authority, the extent to which the general public should participate in the process, and whether political jurisdictions need to rethink endangered species protection laws in order to facilitate this form of conservation management. The statement that elicited the lowest score, averaged across the four ideal types the study identified, was one that suggested that citizen groups with proper expertise should be allowed to conduct assisted colonization activities if official processes are not able to sanction them. The *Torreya* case demonstrates that at least some members of the public are willing to actively intervene in ecosystems for conservation purposes without waiting for a consensus from the conservation biology community on either the wisdom of their approach or on the legitimacy of their claim of decision-making authority. The Q-method study suggests that this is highly unnerving to scientific and management communities.

Any embrace of active management for the sake of conservation invites the questions of what is being conserved or restored and how best to conduct that work.[5,21,22] What is the appropriate state of an ecosystem? What are the best methods of achieving that outcome? And, importantly, who gets to decide? These are especially difficult questions when people have different ways of interacting with and valuing ecosystems and the goods and services they produce. In much of the New World, conservation scientists defaulted to the position that we ought restore ecosystems to their conditions prior to European settlement,[29,30] though some authors would have us strive to replicate ecosystems as they existed prior to all human settlement, and advocate employing transcontinental introductions of species well outside of their historic ranges to accomplish that goal (e.g., see Ref 31). Selecting a management goal such as any of these is a highly subjective decision that is not in its essence scientific.[21] And many of these objectives are likely not possible: The climate prior to European settlement was different than it is today (as indeed were the suite of extant species and the dynamics connecting them with other system components and processes), and predicted future climatic conditions will in many cases be unsuitable to the ecosystems of hundreds of years ago.[21,32,33] These changes in ecosystems and climatic influences thereon make it clear that the default restoration goal of pre-European conditions is unattainable, and it thus forces a discussion about goals: What ecosystem goods, services, or conditions do we value and should we manage toward? This blatantly normative question is an uncomfortable one for conservation biology, which, like ecology, is frequently subjected to charges of being political or advocacy oriented.[34] And, it suggests that professional scientists are not the only ones whose opinions have standing.

The ambiguous ethical status of assisted colonization and the departure that it requires from conservation biology orthodoxy exacerbate and highlight contention about technical considerations and aspects of the debate. Much of the debate, and indeed many of the proposed decision frameworks center on biological considerations, and there is plenty of uncertainty in this realm.[6,13] Technical considerations invoked within this dispute include obvious ones—such as predicting climatic conditions through time and determining distances that various species would have to be translocated to account for climatic changes—as well as more esoteric but certainly important ones, such as the need for transferred tree species to have appropriate mycorrhizal fungi species present in the soil at the host site (Ref 4, p. 734). Much of the conservation biology debate centers on invasion considerations, such as the risk of a translocated species becoming invasive and the relative biological impacts if and when a species does become invasive. Sax et al. (Ref 35, p. 249], for example, argue that most invasions have relatively small impacts, while Ricciardi and Simberloff (Ref 27, p. 472] emphasize uncertainty, arguing that even planned introductions can backfire in terms of invasion. Most of these technical considerations are open questions, yet to be settled by science; in fact, many are questions that are not answerable without specifying a region and applying values to identify which species merit consideration in the scientific assessment and what constitutes 'acceptable' risk. Thus, even these more technical considerations are unlikely to be adjudicated by science alone because nature is sufficiently diverse to offer examples that could justify any number of positions (an argument we further develop in later sections), and risk is an inherently subjective concept on which rational people differ.[36,37]

Schwartz et al.[23] and indeed many other authors suggest that the debate cannot be limited to biological considerations, though most frame the question as a technical rather than a democratic one. Several authors have weighed, in purely economic terms, how much translocation programs would cost versus the economic benefits they may provide when implemented for various forestry-related species (Ref 11, p. 840). Others have offered more explicit explorations of economic trade-offs to justify their preferred policy orientation. Fazey and Fischer[38] argue that diverting funding toward assisted colonization efforts would detract from important large-scale restoration projects attempting to reduce habitat fragmentation, one of the primary drivers for climate change extinction, and that it might divert resources and attention from efforts to address climate change more broadly.

Any proposed transfer of species is unique, and the proliferation of terms for species translocations hints at the substantial variety of situations and factors within those situations that might be considered (Ref 39, p. 726). In the broadest sense, assisted colonization is the translocation of species threatened by climate change to new locations where temperature, precipitation, and other conditions are projected to match the species' needs in the future. Authors have attempted to sort through the broad spectrum of actions assisted colonization that may encompass by creating typologies to differentiate between these activities. Schwartz et al.[23] develop a typology distinguishing, for example, between 'assisted migration' and 'assisted colonization' based on the degree of management attention a species receives to assure post-introduction success. Iverson et al. (Ref 2, pp. 25–27) build upon that same typology, but distinguish between 'species rescue' and 'forestry assisted migration,' which comprises similar activities, but undertaken explicitly for the purpose of ensuring viable forests and the continued provision of ecosystem services.[11] Hoping to add additional precision to the discussion, Ste-Marie et al.[39] distinguish between activities that move populations within a species' range, those that extend the range at its margins, and those that move individuals and populations well beyond established and historical ranges. Although each round of further distinctions in terms is motivated by a desire to add precision to the debates, lack of consistency in definition has made it more difficult to understand to what degree assisted colonization may or may not be accepted in scientific and management literatures and is itself a indicator of the varying concerns that different authors have opinions about the topic.

Several authors have asserted that assisted colonization in forestry is less controversial or problematic than species rescue activities.[2,11,40] Thus far, the writing in the forestry and conservation biology literatures appears confirm that those technical communities are more comfortable with the idea. Writing in the forestry literature, Ste-Marie et al. (Ref 39, p. 724) argue that because of their slow growth and long-generation times, trees are less likely than other biota to be able to adapt quickly enough to survive climate change, making them higher priority for assisted colonization action. Leech et al. (Ref 10, p. 22) believe that assisted colonization in a forestry context involves lower risk translocations because movement distances are often shorter. Adding to that, Williams and Dumroese (Ref 12, p. 289) suggest that the groundwork is already in place to do successful assisted colonization in forestry because practitioners have experience with related techniques, echoing an argument presented by Aubin et al. (Ref 9, p. 762). That authors coming from a forestry perspective would be amenable to these activities and that conservation biologists would be more hesitant is compatible with Sarewitz'[37] observation that disciplines have embedded normative perspectives. Forestry educational programs take a more managerial approach than do conservation biology academic programs.

To further the debate surrounding assisted colonization and dispel many of the concerns raised in the literature, several authors have endorsed the use of, or have created decision frameworks.[6] Hoegh-Guldberg et al.[41] propose a decision tree based upon evaluations of feasibility, extinction risk to the species, and possible costs and benefits, in order to evaluate whether or not assisted colonization should be used in a given case (Ref 4, see also Ref 42). Richardson et al.'s[43] heuristic tool explicitly includes both technical feasibility considerations as well as societal values and ethical considerations. Some frameworks look at decision-making very broadly, while others have focused in on specific aspects of assisted colonization implementation, such Vitt et al.'s[1] proposed strategy for prioritizing plant species for seed banking for possible future assisted colonization action. The question of who is doing the evaluation, and the role, if any, for the public in informing decisions, is left unstated in these proposals. This is a crucial gap in the literature, given that there is ample reason to suspect that decision-making authority is one of the major sticking points in current disputes. It is in the spirit of filling this gap that we devote the remainder of this essay to contextualizing the conservation debate within relevant insights from the philosophy of science and the humanistic and social scientific work examining science in environmental controversies.

## MORE SCIENTIFIC HUMILITY MAY ENSURE THE UTILIZATION OF SCIENCE

Javeline et al. recently conducted a survey of environmental biologists as stakeholders with potentially relevant expertise and found that these scientists have views that are more nuanced and middle-of-the-road than that might be expected based upon the debate in the literature.[40,44,45] This survey is helpful in reminding us that the scientific literature is not necessarily an accurate barometer of the range and distribution of opinions in a scientific community. In describing their findings, the authors conclude that:

> A relatively high percentage of respondents justified the use of managed relocation when it is designed to prevent species extinction, overcomes a human-made dispersal barrier, minimizes ecological harm, and responds to specific scientific data. Fewer respondents justified managed relocation to preserve or enable ecosystem functioning, prevent loss of genetic diversity, or overcome natural dispersal barriers, suggesting that managed relocation policy consider these circumstances but give them a lower priority. Very few respondents justified managed relocation if it would put non-target species at risk of extinction or be based on stakeholder arguments about preventing the extinction of the target species, suggesting that managed relocation policy involve careful consideration of the possibility of negative unintended consequences and the rigor of data used as justification. (Ref 40, p. 8)

The survey authors conclude their work with a statement that 'Given the ability of environmental scientists to discern potential benefits and harms specific to a variety of ecological circumstances, these experts should be consulted in the development of principles, rules, and legal guidelines for managed relocation'(Ref 40, p. 9). And they offer the suggestion that self-reported topical knowledge and publication counts are reliable predictors of scientific expertise, and could be used by policy makers to identify relevant experts (Ref 44, p. 672). Doing so, they suggest, would alleviate the problem of think tanks and industry hiring experts and funding science to muddy policy makers' understandings of technical issues and would minimize the related dynamic wherein policy makers select scientists—some of whom have been corrupted by ties to industry and think tanks—who they know will confirm their pre-existing policy preferences.[44] And a survey such as theirs, they argue, is a way of systematically assessing scientific opinion to inform policy processes in areas where science is unsettled and rapidly changing.[45]

While there are certainly instances of groups seeking disingenuously to mislead policy makers and of policy makers intentionally cherry picking experts to justify their pre-existing policy positions,[46,47] and there is no denying that science is frequently underdeveloped in areas where policy makers need information,[48] Javeline et al.'s work is built upon a partial understanding of the problems at the science-policy interface. Briggle,[49] for example, argues that there are two main branches of explanations for why advances in science have done little to reduce or alleviate environmental controversies. The first, which certainly occurs in some cases, is that cynical actors deliberately attack scientific findings and misuse evidence to advance their own interests (e.g., Refs 46,47]. This is the understanding that underlies Javeline et al.'s work and their writing provides suggestions that might, if adopted, be helpful in alleviating problems associated with identifying scientists with substantial expertise.[44] Briggle's other explanation, however, also has merit: Nature is diverse enough to offer robust, scientifically justified evidence to support any number of competing policy proposals. Science does not settle controversies at least in part because science is not unitary; rather, science represents myriad practices to understand diverse systems. When experts disagree, it is frequently because of the diversity of nature and of the scientific approaches that we employ to understand it (see also Refs 37,50).

The Javeline et al. survey included questions not only about generalized trade-off scenarios—such as those in the block quote, above—but also about three briefly described cases that specify target species and recipient ecosystems, and about the specific taxa with which their participants are most familiar. The authors appropriately conclude that 'general questions about managed relocation are less useful to decision-makers than questions targeted toward more specific managed relocation scenarios' (Ref 40, p. 9) and acknowledge that 'No single guideline will apply to all species, ecosystems, and circumstances, because scientists identify different risks and rewards in different contexts' (Ref 40, p. 8). Approaching the issue from these multiple question sets notably better acknowledges the diversity of nature and of disciplinary expertise than treating the proposal as a single issue to be assessed in general terms, and their caveats about context-specificity are important. Nonetheless, each of their question sets asks respondents to generalize across situations in problematic ways. Scientists publishing in environmental biology—the population in their study—may not have any specific knowledge of the systems or species in the specified cases. Asking them how effective species movement activities would be in the briefly described scenarios is to assert that expertise in environmental biology generally lends insights that are meaningful in advising ecosystem management decisions about particular—yet probably unfamiliar ecosystems and species. For this to be true would require substantial homogeneity in ecosystem responses to movements of diverse species. For the survey's taxon-specific questions to have much meaning would require a similar assumption of uniform impacts of translocations across an entire taxonomic category (which in their study were as broad as, for example, 'mammals,' 'woody plants,' 'fungi,' and 'microorganisms') and possible recipient ecosystem types and conditions.[45] While their attempts to move beyond generalized questions about the desirability of managed relocation (their term) and instead ask about specific cases and taxa are laudable, their survey would only have much relevance to actual policy decisions if ecosystems and their responses to species from broad taxonomic categories were quite homogeneous. The literature on assisted colonization repeatedly makes this error of treating the management approach as something that can meaningfully be scientifically evaluated in the absence of a specific proposal. We address this error in the following section.

The second troublesome premise is that asking scientists about the *justifiability* of species movements for conservation purposes asserts that it is a technical question as opposed to a political one with technical considerations. Ecosystem adaptation activities are issues about which scientists undeniably have preferences, but deciding whether managed relocation is *justified* only to prevent species extinction as opposed to being used to preserve ecosystem function—an example of a distinction probed by the Javeline et al. -survey—is at heart a political assessment.[a] In democracies, we have (admittedly flawed and occasionally dysfunctional) systems for weighing decisions such as these. There are times throughout the processes of creating and administering relevant laws, regulations, and policies when expert opinion is legitimately consulted, but determining—in broad strokes—whether moving species is justifiable or appropriate when employed in different management conditions or for particular goals involves weighing competing values within current legal and regulatory structures. Scientists do have expertise to lend, but we need to be very careful about recognizing which questions are appropriate for scientific adjudication, and which are in the realm of political and bureaucratic adjudication. Questions involving the desirability of trade-offs cannot be separated from values and regulatory constraints and thus are not—in their essence—scientific.

Weinberg[51] coined the adjective 'trans-scientific' to denote problems that we cannot meaningfully discuss without the language of science, but that, because of their basis in and connection to value disputes, cannot be settled by science. This controversy certainly fits that bill. Reviews reveal that value-based and policy-strategic considerations underlie the dispute about assisted colonization even amongst technical experts,[7,17] but few would make the case that the disputes lack technical components. As is characteristic of trans-scientific disputes, science clearly has a role to play, but we need the structures of democracy to adjudicate value disputes.

In the following sections, we advance two main arguments in the spirit of furthering the discussion of the proper roles of science in a dispute such as this. First, the world is sufficiently complicated and diverse that ecology and related sciences—including conservation biology—do not generate predictive knowledge sufficiently precise to justify aggregated statements on the technical aspects of assisted colonization. Decisions have to be made in local ecological, social, and political contexts. Broad conclusions on the appropriateness or inappropriateness of assisted colonization represent overreach by scientific authors and are detrimental to scientific credibility in the eyes of the public and of decision makers. Second, the literature on science in controversies demonstrates that additional scientific attention is not likely to defuse political debates on the issue. Indeed, since 2007, when assisted colonization began to receive significant attention in the literature, the disagreement within the literature surrounding its use as a climate change adaptation strategy has only grown (Ref 6, p. 2570). Additional research has done little to settle this dispute. The expectations implicit in the current debate that the scientific literature is the appropriate place to reach a consensus—and indeed that scientists are capable reaching closure on this issue through the additional scientific research—correspond neither to how we use science nor what it is capable of. A more honest and reflective understanding of the role of science might re-empower science to contribute meaningfully to ecosystem management decisions.

## The World Is Too Diverse and Complex to Justify Broad Conclusions about the Impacts of Species Movements

In their 2011 review, Hewitt et al.[6] found nearly half of the articles on assisted colonization and related techniques did not distinguish between taxa, and most discuss its viability/desirability without specifying a geographic or ecosystem context. Of the reviews and commentaries written by that time, all 19 had a global or nonspecified geographic focus. This is remarkable given the species-, ecosystem-, and region-specific aspects of the technical considerations inherent in management decisions of this sort. The appropriateness of assisted colonization as a climate adaptation strategy is not a question that can be resolved at the global or even regional scale. Treating scientific aspects of this as questions that can be answered generally dismisses the importance of situation-specific technical considerations and presupposes a universality of ecosystem characteristics and responses that some philosophers—and indeed ecologists themselves—have suggested is not justified. Ecology as a science is not up to the task of creating generalizations about the outcomes of assisted colonization activities that are sufficiently robust to escape contestation by another scientist working from a different system or perspective.

The prospect that science might yield generalizable truths sufficiently precise and universal to guide policy—an expectation implicit in a literature that discusses the appropriateness of the issue without specifying even a particular continent or an ecosystem, let alone an actual proposal—is not something that we can take for granted; rather, it is a hypothesis that can be philosophically and empirically evaluated. Indeed, some philosophers argue directly against that proposition. Dupré,[52] for example, argues that the world is far too varied to be adequately described (let alone explained) by science. There are, he suggests, pockets of nature that are comparatively amenable to exploration by one particular scientific methodology or another, but that these pockets of clarity lead us to expect, falsely, that the world—given adequate scientific attention—will yield universal truths. Any disunity in nature is a barrier to the unity of science: 'Since science does, presumably, presuppose some kind of preexisting order in the phenomena it attempts to describe, limits to the prevalence of order may entail limits to the applicability of science' (Ref 52, p. 11). And, there is so much diversity, flexibility, and ambiguity in nature that even our definitions of what constitutes a species only work with respect to particular scientific, management, or cultural questions; different questions require even that we operationalize the concept of 'species' differently (Ref 52, ch. 2, Ref 53). This interpretive and linguistic flexibility, an inevitable artifact of the quest to fit fixed categories onto a world that lacks fixed 'natural kinds' that correspond to our tidy linguistic distinctions, precludes the development of universally applicable ecological laws of nature (Ref 52, see also Ref 54, ch. 2). Universally applicable truth claims about ecosystems would require uniformity of nature, and we cannot assume either.

Key aspects of Dupré's arguments are shared by Nancy Cartwright,[55] who, building from a related premise about the heterogeneity of the 'dappled' world we inhabit, warns that when we expect greater universality of our scientific understandings than is warranted, the resulting policies remake the world in unintended and detrimental ways. These authors join an interdisciplinary chorus of voices in arguing that claims of scientific universality obfuscate critical political deliberation about how things ought to be.[50,56–59]

It is worth noting that none of the aforementioned authors deny either the existence of a 'real' world or that science yields correct factual insights about that world. Their arguments, rather, stem from the insight that the world is hugely diverse and any glimpses of order that we identify via scientific research (or other means) should not be taken to suggest that the revealed order and pattern is universal. Cartwright[55] argues that even the laws of physics, which are colloquially held to have the broadest and most universal application, in fact are best thought of as *ceteris paribus* laws; that is, they only accurately predict physical phenomena in a limited range of natural conditions or in tightly controlled laboratory settings. Thus, their ability to help us predict complex natural phenomena is limited. She cites the following example, originally from Otto Neurath: Though the laws of mechanics apply everywhere, they cannot be used to predict the trajectory of a thousand-dollar bill in a windy public square (p. 27). The laws of mechanics are at play, to be sure, but the complexity of the situation renders them useless in predicting the outcomes that we care most about.

That the laws of physics are so limited in their ability to predict outcomes in situations with real-world complexity suggests that the utility of the laws and generalizations of ecology and conservation biology in guiding policy deserve similar levels of scrutiny. Lotka-Volterra equilibrium-based models of predator–prey interaction serve as an apt example: This type of model has great explanatory power, but only for a very limited set of natural systems. And importantly, we cannot know *ex ante* which systems under what conditions will follow these patterns. Thus, though they are helpful for scientists trying to understand drivers of observed system dynamics (particularly when outcomes do not match expectations), they are of little use for generating real-world predictions relevant to policy making.[54,60,61]

Furthermore, ecological predictions, whether built around numerical modeling or derived from ecological theory, are necessarily built upon past experience and conditions. This reliance on the past for guiding our expectations of the future may focus us on too narrow a set of potential outcomes—particularly when we recognize that climatic contexts (and species assemblages) are changing—and blind us to surprise and emergent phenomena.[62] Relying on generalized ecological knowledge rather than contextualized understanding of a particular ecosystem may in fact make us more vulnerable to the surprises and unexpected dynamics that characterize the history of ecological management.[63] There is no reason to expect any of these challenges will diminish in the face of changing climatic contexts.

As Kai Lee[64] points out, any ecosystem larger than an aquarium and smaller than the globe is inherently an open system. And even within the necessarily arbitrary boundaries we assign to ecosystems, many ecologists now recognize that ecosystems are dynamic, with unknown and moving thresholds, and that drivers of change operate at different temporal and geographic scales.[63,65,66] Some drivers are intertwined via complicated and possibly poorly understood feedbacks, but others (or those same drivers at other times) operate more or less independently. Acknowledging that humans play a role in ecosystems complicates things even further, given that humans actively yet unpredictably respond to the changes they observe, and management activities may introduce additional complexity that may change or overwhelm the system drivers that we understand from past experimentation, research, or experience.

Treating the prospect that ecological science can provide policy-relevant generalizations as a hypothesis to be empirically explored, Shrader-Frechette and McCoy were unable to find any general theory that yields—in actual policy situations—predictions sufficiently precise to guide policy. They conclude that, 'insofar as ecology is required for solving practical environmental problems, it is more a science of case studies and statistical regularities, than a science of exceptionless, general laws' (Ref 54, p. 1). Keller and Golley, a philosopher and an ecologist, respectively, reach the conclusion that 'Ecological science, like other modern sciences, aspired to identify general laws that would explain its observations. However, as generalizations have been proposed and even applied, inevitably exceptions have been found. The specific replaces the general. Currently ecological science exists in a schizophrenic state: ecologists want to find generalizations, but increasingly ecology has become a science of case studies' (Ref 67, p. 10, see also Ref 68). The laws and generalizations that ecology has produced have innumerable *ceterus parabis* clauses, and they are frequently left unspoken (Ref 69, p. 116).

Ecological theories are frequently invoked in conservation debates, including the current dispute over assisted colonization. That professional conservation biologists, building their arguments upon ecological principles and generalizations, disagree with one another about the wisdom of assisted colonization suggest that ecological theory is insufficiently settled or precise to adjudicate disputes such as this (e.g., see Refs 27,28,38 see also Ref 45]. Ecological theory has historically been invoked in on the successful side of policy debates. One prominent example is diversity-stability hypothesis, which was widely cited as a justification for the United States Endangered Species Act. That this theory was cited in policy debates leading to this widely lauded conservation policy, however, should not be taken as evidence that ecological theory does or should drive policy. In the time, since that act was signed into law in 1973, counter examples have been discovered and described, and the theory has been dismissed by a number of scholars (Ref 54, ch. 2). Debunking the diversity-stability hypothesis did not cause policy makers in the United States to reconsider the Endangered Species Act, suggesting that generalized ecological theory is not a necessary foundation for environmental policy.[54] Furthermore, different ecological theories of the causes and consequences of ecological diversity appear to point to different and occasionally mutually incompatible conservation strategies (Ref 54, pp. 52–54). Thus, even if technical ecological considerations were accepted to be the only legitimate inputs to policy debates, a situation that is not likely to frequently occur, ecological science does not provide that form of consensus on conservation issues.

We cannot expect ecology, conservation biology, or related sciences to yield insights that would enable us to say much meaningful about the impacts of assisted colonization, generalized across taxonomic groups or recipient ecosystems, without assuming a great deal of order in nature. As the dispute that began with Clements (who held that ecosystems develop along particular trajectory determined by abiotic factors) and Gleason (who saw ecosystems as haphazard assemblages of species that happen to be available) demonstrates, ecologists themselves have long been divided on the extent to which natural systems are characterized by inherent order.[70–73] This debate, which began over 100 years ago, is not conclusively settled today. As Worster[72] documents, not only has ecology not settled debates such as this, it has in fact splintered into factions that do not substantially communicate with one another nor challenge each other's frameworks and theories. As such, we deem it unlikely that conservation biology will reach policy-relevant consensus about the ecological impacts of moving species (or even particular taxa), let alone within a time frame that might be useful in informing climate change adaptation strategies.

## Additional Scientific Knowledge Does Not Dispel Controversy Based in Value Disagreement

That respected scientific authors advocating opposite positions on assisted colonization find justification for their positions in ecological theory is evidence that generalized ecological knowledge is still inadequate for providing that type of policy guidance. It also demonstrates the common cultural inclination to justify our values by invoking scientific claims. Comparative work demonstrates that societies have distinct relationships with and approaches to using science, but in modern liberal democracies (particularly the United States) decision makers invoke science to legitimize their activities and provide the aura of objectivity.[74–78]

Contrary to what we imply when we use science to justify policy positions, scholars of the science-policy relationship suggest science rarely, if ever, determines policy. Most policy dilemmas are constantly shifting, open to multiple mutually incompatible framings, and are nested in other problems, which are themselves dynamic. Policies that might yield (or constitute) satisfactory outcomes to some parties may in fact be problems in-and-of-themselves to others. This is why the tensions inherent in conservation biology have proved so divisive: Human intervention—which is necessary and justified in the eyes of some scientists to help ecosystems to adapt to climate change—is exactly that which other conservation biologists seek to minimize. Problems such as these are termed 'wicked problems' to distinguish them from 'tame' problems, which, no matter how complicated, are unambiguously defined and solvable.[79–81]

When individuals define problems differently, no amount of factual evidence will compel consensus. Evidence that bolsters one argument may do nothing to diminish another if that other argument is based on an incompatible framing. Scholars probing the science—decision-making interface from a number of disciplinary perspectives have come to related conclusions. Collingridge and Reeve[82] express strong skepticism that science could ever significantly influence the direction of public policy decisions. Although their claims neglect the important—but far from exclusive—roles of science in identifying problems and contributing to technological innovation,[83,84] their insights about the dynamics of science in controversies merit consideration. They argue that in cases where it appears that science informs policy, there is in fact a pre-existing value consensus around the policies. Science can be very useful in operationalizing agreed-upon policies, but science does not make us agree upon the policy itself. This situation constitutes what they dub this the 'under-critical' model of the science-policy interface. In what they call the 'over-critical' model, which occurs when there is an underlying value dispute, participants in debates begin to pick apart the scientific explanations of their opponents by questioning assumptions that underlie those studies and critiquing standards of evidence used therein. Because the sciences collectively represent widely varied practices, norms, methods, and standards of evidence—and because natural systems are so diverse—there is never a lack of additional questions that can be asked or counter-examples to offer (cf. Refs 37,85).

When we justify our policy positions by invoking factual claims, disputes over science become proxy arguments that obscure the underlying value disagreements.[37,83] We expect that science 'proves' the superiority of one policy preference over another, but this thinking is misguided. As historian of science Naomi Oreskes puts it, this 'the idea that science ever could provide proof upon which to base policy is a misunderstanding (or misrepresentation) of science, and therefore of the role that science could ever play in policy' (Ref 84, p. 369). And misrepresenting science in this way empowers those who disagree with policy proposals to cite ongoing scientific uncertainty—which is a characteristic of all properly functioning scientific efforts—as a justification for inaction. The scientific community has in many cases accepted the premise that controversy stems from insufficient information and sought to provide greater certainty via additional research.[84]

Additional research, however, may not reduce uncertainty. Sarewitz[37] points out that additional scientific attention comes in the form of additional questions asked from different disciplinary perspectives, employing new methods and standards of evidence. Because the world is varied and the sciences represent a diverse set of approaches to studying that world, additional science yields additional partial perspectives, and there is no single way of assembling those partial perspectives into and an incontrovertible holistic understanding.[37,86] The net result is a larger number of facts that can be invoked by debating parties to further justify any number of mutually incompatible policy interventions, further polarizing existing debates.

Seeking to make sense of the ways in which scientists interact with policy processes and to provide scientists with some guidance on how to contribute meaningfully, Pielke[83] delineates four idealized roles or modes of interaction. The 'Pure Scientist' represents the disinterested researcher who produces knowledge with no consideration for whether or how it is used. The 'Science Arbiter' serves as an expert consultant, answering questions that decision makers have in the course of their work. The 'Issue Advocate' is a scientist who believes that, based upon their expertise, they know the preferable policy action and they advocate for that action. 'Issue advocate' scientists seek to influence policy by trying to limit the scope of options considered by decision makers. And finally, the 'Honest Broker of Policy Alternatives' seeks to clarify and expand the range of policy options available.

Thus far, a significant portion of the conservation biology literature on assisted colonization has fallen into the model of issue advocacy, wherein the scientists are pressing for their preferred policy approaches based upon their underlying values. Scientists can fall into this mode whether or not they acknowledge their values, and those who argue about the desirability of assisted colonization in scientific terms rather than being open about their normative framework become 'Stealth Issue Advocates.'

Pielke suggests that, from the perspective of these scientists, 'stealth issue advocacy is politically desirable because it allows for a simultaneous claim of being above the fray, invoking the historical authority of science, while working to reduce the scope of choice. The Stealth Issue Advocate seeks to "swim without getting wet"' (Ref 83, p. 7).

Ecosystem adaptation to climate change is particularly prone to stealth issue advocacy because the technical considerations relevant to any individual assisted colonization activity are necessarily at least in part ecosystem- and taxon-specific, while journals and the culture of science favor generalizations. Inviting environmental biologists as a group to weigh in on the justifiability of assisted colonization in the abstract, or even regarding specific scenarios outside of those scientists' systems, is an invitation to conduct stealth issue advocacy. The Javeline et al. survey[40] is a good measure of scientists' values regarding active ecosystem management, but decisions in that realm take place within democratic governance structures.

Assisted colonization is not yet a major public policy dispute, but given public passions about all things environmental and the threatened conservation status of some of our most charismatic species, it will likely become controversial when species transfers are proposed or implemented. If at that point scientists have not clearly delineated the value-based considerations inherent in this controversy and ceded them to democratic governance, the public will see that scientists have divergent, and possibly mutually incompatible, policy preferences that 'derive' from their science.[83,87,b] As happens in 'scientized' disputes, actors—scientific and otherwise—seeking to advance their preferences will draw upon scientific claims as justifications.[83] To the public, science and scientists in these instances look like political actors in a political decision-making venue rather than objective purveyors of truth,[89] as they prefer to be seen.[34] When this dynamic emerges, 'political battles are played out in the language of science, often resulting in policy gridlock and the diminishment of science as a resource for policy-making' (Ref 83, p. 10).

Scientific fact flinging does not yield policy consensus. Cultural theorists tell that many of our policy preferences derive not from process of rationally assembling all of the relevant facts, but rather from broadly influential yet frequently invisible cultural notions of what society should look like and how it should be organized.[36] This is true for scientists as well.[57,87,90] Because there are experts providing insights from a diversity of disciplinary perspectives and making any number policy propositions, interested parties can find expert vindications of their preferred policies. We integrate new information into our pre-existing worldviews, and if that information is flat-out incompatible with our pre-existing views, we dismiss it and the experts making those claims as being biased or irrelevant.[91,92] Research based in cultural theory helps to explain, for example, the deeply dissatisfying empirical finding that individuals with the strongest knowledge of climate change are the most deeply divided in their policy preferences.[93] Knowledge does not determine environmental policy preferences; cultural values do. Additional knowledge about assisted colonization is not likely to persuade anyone—technical experts or otherwise—that their prior convictions about humanity's role in conserving nature are incorrect.

## POTENTIAL PATHS FORWARD

The lack of certainty and absence of scientific consensus surrounding assisted colonization does not pose an unprecedented challenge to our decision-making structures. We regularly make decisions and undertake activities under conditions of uncertainty.[37,62,82,94] In fact, our decision-making frameworks are not compatible with the rational-comprehensive model of decision-making presupposed by those who would demand absolute certainty prior to acting. Both as individuals and as institutions, we lack sufficient attention too simultaneously weigh all possible considerations prior to making a decision,[95–97] if indeed that were a logical possibility for issue areas in which people define problems differently. We would not know what to do with comprehensive information even if we were able to obtain it. Luckily, we will never be presented with that situation.

There are, however, better and worse decisions to be made, and there is scholarship to help guide decision processes. The literature on social-ecological system resilience, for example, builds from the premises that ecosystems are dynamic in that there are multiple possible stable states in any ecosystem, that we cannot fully predict thresholds at which systems might suddenly shift to a new state nor fully understand the drivers that affect those changes, and that human activities are part of and complicate these dynamics but are not the sole cause of them (see Ref 65 for a comprehensive introduction). This literature seeks to provide insights to help ecosystem managers make decisions that are robust to unexpected futures and that maintain adaptive capacity such that ecosystems can regenerate after collapse, whether caused by management or other drivers.[98] Resilience scholarship builds from a place of humility, starting from a premise that we do not and cannot know enough about systems to know in advance the outcomes of management activities, but acknowledges that uncertainty cannot preclude action. This literature suggests that we need to treat management interventions as experiments, learn from them, and manage adaptively based upon that learning.[64,99–103] It is worth noting that ecologists have contributed to resilience thinking, and ecological science plays a key role in advising and assessing ecological management experiments; we certainly do not want to make the claim that ecologists' contributions are irrelevant to policy. Rather, the distinction is that resilience scientists typically are not acting as issue advocates, promoting policies that they believe 'derive' from their science. Instead, they are working to devise new management approaches that create learning opportunities and maintain options for the future. Resilience scholarship seeks to expand and characterize policy options, in the model of Pielke's Honest Broker of Policy Alternatives.

Some resilience thinkers promote the use of scenario planning as a way of exploring the interplay of system drivers in a nonpredictive way, and this approach has the added benefit of creating opportunities for communities to deliberate on shared goals.[104–108] Coming from a different but compatible tradition, the Danish Board of Technology; the Consortium for Science, Policy and Outcomes; and the Loka Institute, among others have been utilizing consensus conferences to create deliberative spaces where citizens can explore both technical and nontechnical components of decisions in order to advise decision makers.[57,109,110] Each of these formats is designed to confront trans-scientific issues without dismissing either the technical or the value-based considerations inherent therein, and each creates mutual learning opportunities for experts and nonexperts.[111] Scientists who participate in activities such as these can learn what types of knowledge might be most relevant to decision makers, and thus have an opportunity to design research agendas that may directly inform future policy. And there are nascent efforts to train ecologists specifically to be more effective participants in and contributors to these iterative, boundary-spanning, mutual learning research efforts,[112] and substantial research has gone into understanding institutional designs that facilitate these relationships.[110,113,114]

Even as scientists frequently complain that their work falls on deaf ears in the decision-making community, policy makers often lament that the science being done is not relevant to the issues with which they must deal. Despite the scale of the global scientific enterprise, there is a problem of a mismatch between the demand for scientific knowledge and the supply thereof.[115] Scientists who are willing to engage in substantive dialogue and negotiation with potential knowledge users, beginning at the formulation of research questions and methods and continuing throughout the research process, can avoid that mismatch and ensure that users see their work as credible, salient, and legitimate—characteristics of useful (and influential) knowledge.[113,114,116–118] The linear 'loading dock' model—wherein scientists produce information with the hope that someone else will pick it up, read it, reconcile it with other available knowledge, and then make the 'right' decision based upon the science—has long been dismissed by those who study the science-policy interface (e.g., see Refs 76,83,116]. Scientists who are willing to participate in joint-learning opportunities with potential users of knowledge stand to create information that is genuinely influential in informing decisions[119]; those who work as issue advocates, stealth or otherwise, will likely find that their work becomes fodder in entrenched policy arguments, but also that their work fails to help those disputes achieve closure.[37,83]

## CONCLUSION

The debate about assisted migration in the scientific literature continues a history of impassioned disputes about the appropriate role of humanity in nature. This not a question that we can justifiably claim to be technical; it is a public policy question with technical components, but is ineluctably tied to values. Value considerations at the core include: the proper human role in systems along a natural-to-anthropogenic gradient; what constitutes a natural system (as opposed to an explicitly managed one); and how to evaluate ecosystem health or well-being, which itself requires a normative consideration of what ecosystems should be, should do, or should produce. Perhaps most contentious but least discussed: What should be the roles of technical experts and democratic processes in structuring and informing decision processes. The nontechnical roots of the ongoing disputes are not amenable to scientific resolution.

Even the technical aspects of the dispute may not be resolvable by scientific study unless authors agree upon study questions, methods, and systems. And even then, shared understandings will be limited to those specific contexts. We cannot expect ecologists, conservation biologists, or other technical experts to reach a consensus about the ecological impacts of species movement activities generally because ecosystem types and taxonomic groups down to the species level are too flexible, ambiguous, and diverse to yield helpful and uncontestable broad-scale conclusions. Although assisted colonization implies breaking through geographic and political borders, relevant knowledge will be inherently placed-based and context-specific.

The ongoing debate in the scientific literature is not likely to yield scientific consensus on the desirability of assisted colonization, and in its current format, it is more likely to exacerbate underlying value disputes than it is to inform public policy in any meaningful way. The format of the scholarly dispute undermines both the relevance of science to this important policy issue because it is premised upon homogeneity of natural systems that does not exist and it ignores the democratically legitimate public interest in contributing to decisions. For science to contribute meaningful insights to ecosystem management decisions in a changing climate, scientific researchers need counter-intuitively to acknowledge that the management decisions are not in their essence scientific questions. Science can play an instrumental role, but not a determinative one.

And if we neglect the contested values that underpin debates about species movements in specific contexts, we will undermine the ability of scientists to contribute meaningful system- and species-specific knowledge to those deliberations. It is instinctively comforting to expect science to be able to identify 'right' or 'best' answers about the proper human role in helping ecosystems to adapt to climate change. If society surrenders what is inherently a political debate to technical experts, we deny ourselves the ability to manage our ecosystems toward the future conditions that we may desire. Neither conservation biology nor any other field can determine the 'right' answer because that is a normative question rather than a technical one.

None of this is to say, however, that ecology and conservation biology cannot make important contributions to these discussions. To make meaningful contributions, the scientific community must disaggregate the layered scientific, value-based, and strategic considerations.[87,90] Writing about the inherent complexity of natural resource management and policy issues, Allen et al. (Ref 60, p. 484) argue that 'scientists need to recognize that the most valuable contributions are not proof and truth, but good judgment achieved in an intellectually honest arena of discourse.' In this spirit, we suggest that the scientific literature might become more policy relevant to the extent that it is able to detangle the nonscientific questions inherent in this realm from technical ones that can actually be settled meaningfully through scientific methods. Part of this might be a thoughtful discussion of what ecological insights are meaningful to discuss in the aggregate, and which are sufficiently variable that they would have to be addressed in specific contexts. These efforts would push value-based considerations squarely back into decision-making venues with clear lines of democratic accountability, and it would allow scientists to pursue the context-specific information that may inform individual decision processes.

When we abandon the notion that science will answer questions about the generalized desirability of assisted colonization once and for all, we enable ourselves to experiment with and learn from active ecosystem management activities (cf. Ref 64), which have always occurred agricultural, aesthetic, and accidental reasons. Ecological science, especially North America, has in recent decades had a significant bias against studying human dominated systems, preferring to study 'nature' as it unfolds absent human intervention.[73] For ecology and conservation biology to make meaningful contributions to ecosystem management, those disciplines need to be willing to participate in and study intensive management activities when and where they occur.[84] As Herrick and Sarewitz argue, 'once science has elevated an environmental issue to a high public priority, the most appropriate role for science is not to resolve the controversy or otherwise control policy deliberations but to support the design and evaluation of effective policies *after* a political consensus has been achieved. In other words, science should be cast not so much in a predictive and adjudicatory role but, rather, as a source of tools, data, and methods to be used in the service of policy evaluation and to aid the process of social learning' (Ref 88, p. 320). It is time to recognize and respect the strengths of democracy in order to take advantage of the strengths of science.

## NOTES

[a] The penultimate paragraph of one of the resulting papers includes the caveat that 'Expert opinion is, of course, only one part of multi-dimensional risk assessment that should involve diverse stakeholders and practical considerations' (Ref 40, p. 9) and the methods section of that paper acknowledges that they are not the only stakeholders in

these decisions. The remainder of their several publications on that survey, however, primarily focuses on scientists' interpretations of justifiability and efficacy and argues for the importance of scientific opinion on this issue without mentioning the other stakeholders.[40,44,45]

[b] The science studies scholarship demonstrates that fully isolating values from technical aspects of scientific processes is never possible (For a thorough review, see Ref 76), but a more humble interaction would allow for a more deliberate and possibly productive discussion.[88]

## ACKNOWLEDGMENTS

We wish to thank the reviewers and editors for their thoughtful and challenging feedback. This material is based upon work supported by the US National Science Foundation (NSF) under Grant Nos. 1158723 and 1465279. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

## REFERENCES

1. Vitt P, Havens K, Kramer AT, et al. Assisted migration of plants: changes in latitudes, changes in attitudes. *Biol Conserv* 2010, 143:18–27.
2. Iverson LR, Peters MP, Matthews S, Prasad A. An overview of some concepts, potentials, issues, and realities of assisted migration for climate change adaptation in forests. In: Browning J, Palacios P, comps. *Proceedings of the 60th Annual Western International Forest Disease Work Conference*, Western International Forest Disease Work Conference, Tahoe City, CA, 8–12 October, 2012, pp. 25–34.
3. Mueller JM, Hellmann JJ. An assessment of invasion risk from assisted migration. *Conserv Biol* 2008, 22:562–567.
4. Winder R, Nelson E, Beardmore T. Ecological implications for assisted migration in Canadian forests. *Forest Chron* 2011, 87:731–744.
5. Seddon PJ. From reintroduction to assisted colonization: moving along the conservation translocation spectrum. *Restor Ecol* 2010, 18:796–802.
6. Hewitt N, Klenk N, Smith AL, et al. Taking stock of the assisted migration debate. *Biol Conserv* 2011, 144:2560–2572.
7. Klenk NL, Larson BMH. A rhetorical analysis of the scientific debate over assisted colonization. *Environ Sci Policy* 2013, 33:9–18.
8. Peters RL, Darling JDS. The greenhouse effect and nature reserves. *Bioscience* 1985, 35:707–717.
9. Aubin I, Garbe C m, Colombo S, et al. Why we disagree about assisted migration: ethical implications of a key debate regarding the future of Canada's forests. *Forest Chron* 2011, 87:755–765.
10. Leech SM, Almuedo PL, O'Neill G. Assisted migration: adapting forest management to a changing climate. *J Ecosyst Manag* 2011, 12:18–34.
11. Pedlar JH, McKenney DW, Aubin I, et al. Placing forestry in the assisted migration debate. *Bioscience* 2012, 62:835–842.
12. Williams MI, Dumroese RK. Preparing for climate change: forestry and assisted migration. *J Forest* 2013, 111:287–297.
13. Benito-Garzón M, Fernández-Manjarrés JF. Testing scenarios for assisted migration of forest trees in Europe. *New For* 2015, 46:979–994. doi:10.1007/s11056-015-9481-9.
14. Castellanos-Acuña D, Lindig-Cisneros R, Sáenz-Romero C. Altitudinal assisted migration of Mexican pines as an adaptation to climate change. *Ecosphere* 2015, 6:1–16. doi:10.1890/ES14-00375.1.
15. Freinkel S. *American Chestnut: The Life, Death, and Rebirth of A Perfect Tree*. Berkeley, CA; London: University of California Press; 2009.
16. Thompson H. Plant science: the chestnut resurrection. *Nature* 2012, 490:22–23. doi:10.1038/490022a.
17. Neff MW, Larson BMH. Scientists, managers, and assisted colonization: four contrasting perspectives entangle science and policy. *Biol Conserv* 2014, 172:1–7.
18. Kloor K. The battle for the soul of conservation science. *Issues Sci Technol* 2015, 31:2.
19. Sandbrook C. What is conservation? *Oryx* 2015, 49:565–566.
20. Soulé M. The "new conservation." *Conserv Biol* 2013, 27:895–897.
21. Marris E. *Rambunctious Garden: Saving Nature in a Post-Wild World*. New York, NY: Bloomsbury; 2011.
22. Minteer BA, Collins JP. Species conservation, rapid environmental change, and ecological ethics. *Nat Educ Knowl* 2012, 3:14.
23. Schwartz MW, Hellmann JJ, McLachlan JM, et al. Managed relocation: integrating the scientific, regulatory, and ethical challenges. *Bioscience* 2012, 62:732–743.
24. Soulé ME. What is conservation biology? *Bioscience* 1985, 35:727–734.

25. McLachlan JM, Hellmann JJ, Schwartz MW. A framework for debate of assisted migration in an era of climate change. *Conserv Biol* 2007, 21:297–302.

26. Minteer BA, Collins JP. Move it or lose it? The ecological ethics of relocating species under climate change. *Ecol Appl* 2010, 20:1801–1804.

27. Ricciardi A, Simberloff D. Assisted colonization is not a viable conservation strategy. *Trends Ecol Evol* 2009, 24:248–253.

28. Schwartz MW, Hellmann JJ, McLachlan JS. The precautionary principle in managed relocation is misguided advice. *Trends Ecol Evol* 2009, 24:474.

29. Jackson ST, Hobbs RJ. Ecological restoration in the light of ecological history. *Science* 2009, 325:567–569.

30. Oliveira-Santos LGR, Fernandez FAS. Pleistocene rewilding, Frankenstein ecosystems, and an alternative conservation agenda. *Conserv Biol* 2010, 24:4–5.

31. Donlan J. Re-wilding North America. *Nature* 2005, 436:913–914.

32. Harris JA, Hobbs RJ, Higgs E, Aronson J. Ecological restoration and global climate change. *Restor Ecol* 2006, 14:170–176.

33. Hobbs RJ. Setting effective and realistic restoration goals: key directions for research. *Restor Ecol* 2007, 15:354–357.

34. Kinchy AJ, Kleinman DL. Organizing credibility: discursive and organizational orthodoxy on the borders of ecology and politics. *Soc Stud Sci* 2003, 33:869–896.

35. Sax DF, Smith KF, Thompson AR. Managed relocation: a nuanced evaluation is needed. *Trends Ecol Evol* 2009, 24:472–473.

36. Douglas M, Wildavsky A. *Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers*. Berkeley, CA: University of California Press; 1982.

37. Sarewitz D. How science makes environmental controversies worse. *Environ Sci Policy* 2004, 7:385–403.

38. Fazey I, Fischer J. Assisted colonization is a techno-fix. *Trends Ecol Evol* 2009, 24:475.

39. Ste-Marie C, Nelson EA, Dabros A, Bonneau M-E. Assisted migration: introduction to a multifaceted concept. *Forest Chron* 2011, 87:724–730.

40. Javeline D, Hellmann JJ, McLachlan JS, Sax DF, Schwartz MW, Castro Cornejo R. Expert opinion on extinction risk and climate change adaptation for biodiversity. *Elem Sci Anthr* 2015, 3:57.

41. Hoegh-Guldberg O, Hughes L, McIntyre S, Lindenmayer DB, Parmesan C, Possingham HP, Thomas CD. ECOLOGY: assisted colonization and rapid climate change. *Science* 2008, 321:345–346.

42. Hunter ML. Climate change and moving species: furthering the debate on assisted colonization. *Conserv Biol* 2007, 21:1356–1358.

43. Richardson DM, Hellmann JJ, McLachlan JS, Sax DF, Schwartz MW, Brennan EJ, Camacho A, Root TL, Sala OE, et al. Multidimensional evaluation of managed relocation. *Proc Natl Acad Sci* 2009, 106:9721–9724.

44. Javeline D, Hellmann JJ, Castro Cornejo R, Shufeldt G. Expert opinion on climate change and threats to biodiversity. *Bioscience* 2013, 63:666–673.

45. Javeline D, Shufeldt G. Scientific opinion in policymaking: the case of climate change adaptation. *Policy Sci* 2013, 47:121–139.

46. Oreskes N, Conway EM. *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming*. New York: Bloomsbury Press; 2010.

47. Michaels D. *Doubt Is Their Product: How Industry's Assault on Science Threatens Your Health*. Oxford, New York: Oxford University Press; 2008.

48. Kinzig A, Starrett D, Arrow K, Aniyar S, Bolin B, Dasgupta P, Ehrlich P, Folke C, Hanemann M, Heal G, et al. Coping with uncertainty: a call for a new science-policy forum. *Ambio* 2003, 32:330–335.

49. Briggle A. Nature or neoliberalism? Two views on science and the persistence of environmental controversies. *Interdiscip Environ Rev* 2014, 15:94–104.

50. Latour B. *Politics of Nature*. Cambridge, MA: Harvard University Press; 2004.

51. Weinberg AM. Science and trans-science. *Minerva* 1972, 10:209–222.

52. Dupré J. *The Disorder of Things: Metaphysical Foundations of the Disunity of Science*. Cambridge, MA: Harvard University Press; 1993.

53. Mayr E. *Animal Species and Evolution*. Cambridge, MA: The Belknap Press of Harvard University Press; 1963.

54. Shrader-Frechette KS, McCoy ED. *Method in Ecology: Strategies for Conservation*. Cambridge: Cambridge University Press; 1993.

55. Cartwright N. *The Dappled World: A Study of the Boundaries of Science*. Cambridge and New York: Cambridge University Press; 1999.

56. Bocking S. *Nature's Experts: Science, Politics, and the Environment*. New Brunswick, NJ: Rutgers University Press; 2004.

57. Fischer F. *Citizens, Experts, and the Environment: The Politics of Local Knowledge*. Durham NC: Duke University Press; 2000.

58. Kitcher P. *Science, Truth, and Democracy*. New York: Oxford University Press; 2001.

59. Winner L. The whale and the reactor. In: *The Whale and the Reactor: A Search for Limits in an Age of*

*High Technology*. Chicago, IL: University of Chicago Press; 1986, 164–178.

60. Allen TFH, Tainter JA, Pires JC, Hoekstra TW. Dragnet ecology—"Just the Facts, Ma'am": the privilege of science in a postmodern world. *Bioscience* 2001, 51:475–485.
61. Sagoff M. Are there general causal forces in ecology? *Synthese* 2015:1–22. doi:0.1007/s11229-015-0907-x.
62. Sarewitz D, Pielke RA, Jr. Byerly R. *Prediction: Science, Decision Making, and the Future of Nature*. Washington, DC: Island Press; 2000.
63. Bennett EM, Carpenter SR, Peterson GD, Cumming GS, Zurek M, Pingali P. Why global scenarios need ecology. *Front Ecol Environ* 2003, 1:322–329.
64. Lee KN. *Compass and Gyroscope: Integrating Science and Politics for the Environment*. Washington, DC: Island Press; 1993.
65. Gunderson LH, Holling CS. *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington, DC: Island Press; 2001.
66. Scheffer M, Carpenter S, Foley JA, et al. Catastrophic shifts in ecosystems. *Nature* 2001, 413:591–596.
67. Keller DR, Golley FB. Ecology as a science of synthesis. In: Keller DR, Golley FB, eds. *The Philosophy of Ecology: From Science to Synthesis*. Athens: University of Georgia Press; 2000, 1–19.
68. Drake JM. Whence explanation? The diversity of practices in ecology. *Biol Philos* 2004, V19:801.
69. Cooper GJ. *The Science of the Struggle for Existence: On the Foundations of Ecology*. Cambridge: Cambridge University Press; 2003.
70. Barbour MG. Ecological Fragmentation in the Fifties. In: Cronon W, ed. *Uncommon Ground*. New York: W.W. Norton Company; 2003, 233–255.
71. McIntosh RP. *The Background of Ecology: Concept and Theory*. Cambridge and New York: Cambridge University Press; 1985.
72. Worster D. *Nature's Economy: A History of Ecological Ideas*. Cambridge: Cambridge University Press; 1994.
73. Kingsland SE. *The Evolution of American Ecology, 1890–2000*. Baltimore, MD: The Johns Hopkins University Press; 2005.
74. Ezrahi Y. *The Descent of Icarus: Science and the Transformation of Contemporary Democracy*. Cambridge, MA: Harvard University Press; 1990.
75. Jasanoff S. *Designs on Nature: Science and Democracy in Europe and the United States*. Princeton, NJ: Princeton University Press; 2005.
76. Jasanoff S, Wynne B. Science and decision making. In: Rayner S, Malone EL, eds. *Human Choice and Climate Change. Volume 1: The Societal Framework*. Columbus, OH: Battelle; 1997, 1–87.
77. Porter TM. Objectivity and the politics of disciplines. In: *Trust in Numbers: The Pursuit of Objectivity in Science and Public Life*. Princeton, NJ: Princeton University Press; 1995, 193–216.
78. Rosenberg CE. *No Other Gods: On Science and American Social Thought*. Baltimore: Johns Hopkins University Press; 1997.
79. Hulme M. *Why We Disagree About Climate Change: Understanding Controversy, Inaction and Opportunity*. Cambridge and New York: Cambridge University Press; 2009.
80. Nisbet MC. Engaging in science policy controversies. In: *Routledge Handbook of Public Communication of Science and Technology*. New York, NY: Routledge; 2014, 173–185.
81. Rittel HWJ, Webber MM. Dilemmas in a general theory of planning. *Policy Sci* 1973, 4:155–169.
82. Collingridge D, Reeve C. *Science Speaks to Power: The Role of Experts in Policy Making*. New York: St Martin's Press; 1986.
83. Pielke RA Jr. *The Honest Broker: Making Sense of Science in Policy and Politics*. Cambridge: Cambridge University Press; 2007.
84. Oreskes N. Science and public policy: what's proof got to do with it? *Environ Sci Policy* 2004, 7:369–383.
85. Latour B. *Science in Action*. Cambridge, MA: Harvard University Press; 1987.
86. Sarewitz D. Against holism. In: Frodeman R, Klein JT, Mitcham C, eds. *The Oxford Handbook of Interdisciplinarity*. Oxford: Oxford University Press; 2010, 65–70.
87. Neff MW. What research should be done and why? Four competing visions among ecologists. *Front Ecol Environ* 2011, 9:462–469.
88. Herrick C, Sarewitz D. Ex post evaluation: a more effective role for scientific assessments in environmental policy. *Sci Technol Human Values* 2000, 25:309–331.
89. Ezrahi Y. The political resources of american science. *Soc Stud Sci* 1971, 1:117–133.
90. Neff MW. Research prioritization and the potential pitfall of path dependencies in coral reef science. *Minerva* 2014, 52:213–235. doi:10.1007/s11024-014-9250-5.
91. Kahan DM. Cultural cognition as a conception of the cultural theory of risk. In: Roeser S, ed. *Handbook of Risk Theory*. New York: Springer; 2012, 8–20.
92. Kahan DM, Braman D. Cultural cognition and public policy. *Yale Law Policy Rev* 2006, 24:149–172.
93. Kahan DM, Peters E, Wittlin M, Slovic P, Ouellette LL, Braman D, Mandel G. The polarizing impact of science literacy and numeracy on perceived climate change risks. *Nat Clim Change* 2012, 2:732–735.

94. Benedick R. *Ozone Diplomacy: New Directions in Safeguarding the Planet*. Cambridge MA: Harvard University Press; 1998.
95. March JG. Theories of choice and making decisions. *Society* 1982, 20:29–39.
96. Simon HA. *Reason in Human Affairs*. Stanford, CA: Stanford University Press; 1991.
97. Lindblom CE. The science of muddling through. *Public Adm Rev* 1959, 19:79–88.
98. Gunderson LH. Ecological resilience—in theory and application. *Annu Rev Ecol Syst* 2000, 31:425–439.
99. Walters CJ, Holling CS. Large-scale management experiments and learning by doing. *Ecology* 1990, 71:2060–2068.
100. Walters CJ. *Adaptive Management of Renewable Resources*. Caldwell, NJ: Blackburn Press; 2001.
101. Holling CS, ed. *Adaptive Environmental Assessment and Management*. Caldwell, NJ: Blackburn Press; 2005.
102. Lee KN. Appraising adaptive management. *Conserv Ecol* 1999, 3:3.
103. Moore SA, Wallington TJ, Hobbs RJ, Ehrlich PR, Holling CS, Levin S, Lindenmayer D, Pahl-Wostl C, Possingham H, Turner MG, et al. Diversity in current ecological thinking: implications for environmental management. *Environ Manage* 2009, 43:17–27.
104. Bonnett TM, Olson RL. How scenarios enrich public policy decisions. In: Fahey L, Randall RM, eds. *Learning from the Future: Competitive Foresight Scenarios*. New York: John Wiley & Sons; 1998, 308–324.
105. Nassauer JI, Corry RC. Using normative scenarios in landscape ecology. *Landsc Ecol* 2004, 19:343–356.
106. Peterson GD, Cumming GS, Carpenter SR. Scenario planning: a tool for conservation in an uncertain world. *Conserv Biol* 2003, 17:358–366.
107. Wollenberg E, Edmunds D, Buck L. Using scenarios to make decisions about the future: anticipatory learning for the adaptive co-management of community forests. *Landsc Urban Plan* 2000, 47:65–77.
108. Neff MW. Scenario planning for wildlife management: a case study of the National Elk Refuge, Jackson, Wyoming. *Human Dimens Wildl* 2007, 12:219–226.
109. Fischer F. *Democracy and Expertise: Reorienting Policy Inquiry*. New York: Oxford University Press; 2009.
110. Guston DH. Building the capacity for public engagement with science in the United States. *Public Underst Sci* 2014, 23:53–59.
111. Andersen I-E, Jæger B. Scenario workshops and consensus conferences: towards more democratic decision-making. *Sci Public Policy* 1999, 26:331–340.
112. Brunson MW, Baker MA. Translational training for tomorrow's environmental scientists. *J Environ Stud Sci* 2015, 6:295–299.
113. Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, Jäger J, Mitchell RB. Knowledge systems for sustainable development. *Proc Natl Acad Sci* 2003, 100:8086.
114. Guston DH. Boundary organizations in environmental policy and science: an introduction. *Sci Technol Human Values* 2001, 26:399–408.
115. McNie EC. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environ Sci Policy* 2007, 10:17–38.
116. Cash DW, Borck JC, Patt AG. Countering the loading-dock approach to linking science and decision making. *Sci Technol Human Values* 2006, 31:465–494.
117. Cash D, Clark WC, Alcock F, Dickson N, Eckley N, Jäger J. Salience, credibility, legitimacy and boundaries: linking research, assessment and decision making. John F. Kennedy School of Government Faculty Research Working Papers Series No. RWP02-046. John F. Kennedy School of Government, Harvard University, 2002.
118. SPARC. *Usable Science: A Handbook for Science Policy Decision Makers*. Report prepared by Science Policy and Assessment for Research on Climate, 2010. Available at: http://sciencepolicy.colorado.edu/sparc/outreach/sparc_handbook/index.html.
119. Funtowicz SO, Ravetz JR. Science for the post-normal age. *Futures* 1993, 25:739–755.