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Incorporating experiments into management to facilitate rapid learning about climate change adaptation

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ABSTRACT

Conservation agencies worldwide are adapting their management plans to climate change. Dozens of climate change adaptation strategies have been proposed in the literature, and practitioners are already implementing many of these strategies. However, very few strategies have been tested empirically to determine if and when they will be effective. Hence, conservation agencies could be investing significant resources in strategies that fail to produce the desired results or cause harmful unintended consequences. Rigorous tests of climate change adaptation strategies are likely lacking because of a tradeoff between the time and resources necessary to implement these tests, and the urgent need for action. Here, we suggest that management actions should be designed as experiments to test climate change adaptation strategies without delaying action. Specifically, we suggest that practitioners employ multiple climate change adaptation strategies simultaneously following the tenets of experimental design. Using this experimental approach will not only provide the evidence necessary to support future actions, it also has many other benefits, including: (1) increasing resilience of the managed system through the portfolio effect, (2) providing tests of our knowledge in climate change biology, (3) helping practitioners and funders overcome the fear of failure, (4) resolving stakeholder conflicts, and (5) providing opportunities for highly effective science and management communication. We provide two case studies to demonstrate how ecological restorations can be designed as experiments to test commonly proposed climate change adaptation strategies. We conclude by suggesting creative ways to implement and fund experimental approaches through co-production of research and unconventional funding strategies.

1. Introduction

Climate change is already impacting species and ecosystems around the globe, which is challenging the efficacy of conventional conservation strategies and complicating the goals of ecological restorations (Harris et al., 2006; Hobbs et al., 2009; Jackson and Hobbs, 2009). It is therefore imperative that we adapt biodiversity conservation and restoration strategies to ensure investments we make today continue to provide benefits in an uncertain future. Dozens of papers propose strategies to adapt management plans to climate change, and practitioners around the world are already implementing many of the proposed strategies (Heller and Zavaleta, 2009; LeDee et al., 2021; McLaughlin et al., 2022; Prober et al., 2019). For example, Prober et al. (2019) identified 23 potential climate change adaptation strategies that are commonly recommended in the peer-reviewed literature, a number that has been increasing over the last 20 years (LeDee et al., 2021). However, very few strategies are being implemented in a way that allows for an understanding of if and when they will be effective (Heller and Zavaleta, 2009; LeDee et al., 2021; McLaughlin et al., 2022; Prober et al., 2019). Only 16.1 % of the 473 papers reviewed by Prober et al. (2019) described implementation, field data, or other empirical evidence to support the use of particular strategies. Even fewer studies provide experimental support, especially at the scales relevant to management and conservation. Rigorous tests of proposed climate change adaptation strategies

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are therefore needed so that practitioners do not waste limited resources on strategies that fail to produce the desired results or cause harmful unintended consequences (Pullin and Knight, 2001; Sutherland et al., 2004).

The most effective tests of climate change adaptation strategies will follow tenets of experimental design – including replication, randomization, and proper controls – so that the results of tests are robust and generalizable to climate change adaptation in other locations and ecosystems (Lindenmayer, 2020; Ockendon et al., 2021). However, studies designed to test conservation strategies often lack these tenets (Ockendon et al., 2021). For example, less than one third of studies included in the Conservation Evidence Database (i.e., a large synthesis of studies evaluating the effectiveness of conservation actions; Sutherland et al., 2020) employ both controls and randomization, and 25 % of studies are simply descriptive case studies of what happened after a management intervention (Christie et al., 2020). Moreover, experimental tests of conservation strategies often require significant resources and time (Månsson et al., 2023; Westgate et al., 2013). Yet, resources are limited and practitioners must often implement climate change adaptation strategies now to address urgent conservation needs and spend available funding. How then do we overcome the tradeoff between the need for rigorous experimental tests and the urgency faced by practitioners?

Adaptive management - a strategy designed to learn without delaying management actions (Holling, 1978; Walters and Holling, 1990) - is commonly suggested as an approach for learning under climate change (Heller and Zavaleta, 2009; McLaughlin et al., 2022). However, in the context of climate change, adaptive management is often described as implementing a single strategy, monitoring over time, and changing strategies if there are signs of failure. This form of adaptive management has been repeatedly criticized in the adaptive-management literature (Kwasniak, 2010; Murray and Marmorek, 2004; Walters and Holling, 1990) because it is unlikely to result in rapid and generalizable learning about which climate change adaptation strategies will be effective and why. Moreover, employing only one management strategy at a time and waiting to observe the outcome before trying an alternative strategy makes learning slow (Kwasniak, 2010; Murray and Marmorek, 2004; Walters and Holling, 1990). Slow learning might not be sufficient to solve critical management issues as climates rapidly change. Hence, we think a new strategy is needed to improve the rate and generalizability of learning without delaying action on climate change adaptation.

Here, we suggest experimental climate change adaptation as a solution that maximizes learning without delaying action. Specifically, we suggest that practitioners employ multiple management strategies simultaneously following the tenets of experimental design (Ockendon et al., 2021). Our definition of experimental climate change adaptation is similar to active adaptive management, however, we avoid that term here due to ambiguity in its use (Kwasniak, 2010; Murray and Marmorek, 2004; Walters and Holling, 1990; Williams, 2011). We first highlight different ways to implement our proposed approach. We then discuss the secondary benefits of an experimental approach, before highlighting two case studies applying an experimental approach to habitat restoration. Experimental climate change adaptation might be particularly feasible for many restoration scenarios where establishment costs (e.g., plants, planting, and personnel) often dominate the required resources (Powell et al., 2017), so experimentation might not add significantly to the cost. Moreover, there is a growing call for experimentation in ecological restorations (Dybala et al., 2017; Howe and Martínez-Garza, 2014; Lindenmayer, 2020). However, our recommendations might also be valuable in other management contexts where uncertainty in climate change responses is hindering management decisions and experimentation can be added to ongoing management (Westgate et al., 2013). Last, we discuss common barriers to implementing experimental management approaches and how we might overcome them to allow experimental climate change adaptation to be adopted more widely.

2. An experimental approach to climate change adaptation

Our goals in proposing experimental climate change adaptation are to maximize the rate and generalizability of learning, without delaying management action. We suggest the following steps in designing a climate change adaptation experiment:

1. Clearly articulating the management objectives and the hypothesis (es) to be tested.
2. Developing multiple management actions to achieve the objectives and test alternative hypotheses, including appropriate controls (i.e., do-nothing controls or conventional management strategies that are not climate adapted).
3. Randomly assigning management actions to experimental units.
4. Replicating each management action within a single site and/or distributed among multiple sites to enable robust inferences.
5. Monitoring management and reference sites (if applicable) long term for the outcome of interest, including measuring important variables that help support or falsify the hypothesis(es).

Implementing multiple management strategies simultaneously (e.g., restoring species/genotypes historically present at the site and introducing species/genotypes from warmer locations) should accelerate learning by eliminating the waiting time inherent in implementing a single strategy, monitoring over time, and changing strategies if there are signs of failure (in addition to many other benefits, see below). Employing this process should also help ensure that the observed outcomes are due to the management action and not site- or time-specific factors, while also allowing for a better understanding of why a management action succeeded or failed (Block et al., 2001; Ockendon et al., 2021). Such detailed experiments will facilitate the rapid learning that is required to provide an evidence base for climate change adaptation strategies throughout the world, while also building local knowledge about what strategies are likely to work best. If some of the steps above cannot be achieved because of logistical constraints, compromises can be made that will still facilitate rapid learning (Block et al., 2001; Dybala et al., 2017). Below, we describe a continuum of approaches for implementing experimental climate change adaptation efforts, and suggest ways to better understand how different management actions will perform under future climates.

2.1. A continuum of experimental climate change adaptation approaches

Experimental climate change adaptation can be implemented at multiple scales ranging from single sites to large-scale distributed experiments (Fig. 1), each with advantages and disadvantages (Table 1). A single site can be partitioned into multiple plots, and different management strategies (i.e., treatments) can be randomly assigned to each plot (i.e., a split-plot design; Fig. 1B). If multiple sites are available, two approaches can be used to conduct the experiment. Management strategies can be randomly assigned to each site (Fig. 1C), which can be especially useful when management strategies require large areas, or if there are many small management sites. Alternatively, the split-plot experimental design can be applied at each of multiple sites (i.e., a distributed split-plot design). At larger scales, multiple practitioners can employ a coordinated distributed experiment. Coordinated distributed experiments are experiments run in parallel by multiple groups using standardized experimental designs and monitoring protocols that are often implemented over large environmental gradients (Fraser et al., 2013). Coordinated distributed experiments are designed to maximize site-specific learning and generalizability, and they are the approach we propose as the gold standard for experimental climate change adaptation. Existing coordinated distributed experiments are already contributing to our understanding of climate change adaptation strategies (Broadhurst et al., 2017; Havrilla et al., 2020; Nagel et al., 2017; Whitham et al., 2020). For example, the Adaptive Silviculture for

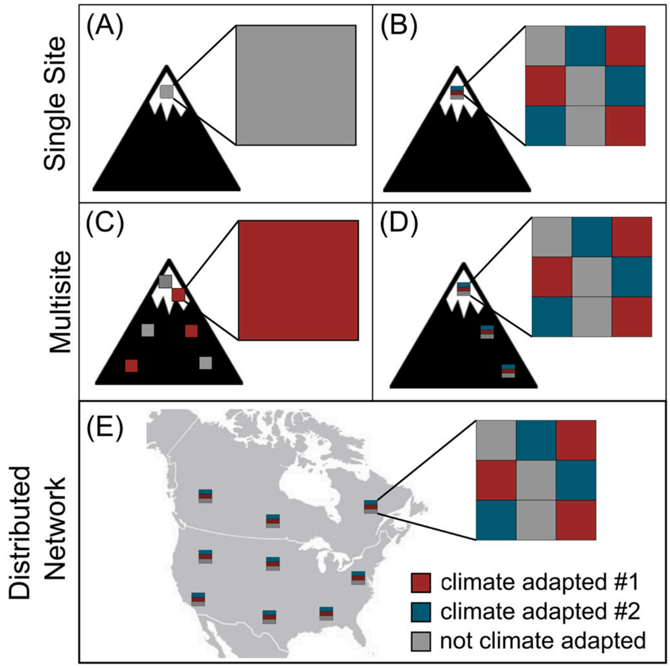

Fig. 1. A continuum of approaches for experimental climate change adaptation. (A) A non-experimental approach where a single method is applied at the site level, which is the typical method for restoration. (B) A split-plot experimental approach at a single site. (C) A multisite approach where a different treatment is applied at each site. Note, in order to achieve sufficient replication this approach requires less treatments (i.e., two in this example) or many sites. (D) A split-plot experimental design implemented at multiple sites. (E) A coordinated distributed experiment where a split-plot experimental design is implemented by many researchers across a large geographic and environmental gradient.

Table 1
Benefits and Limitations to different approaches to experimental climate change adaptation. See Section 3.1 for a description of climate change resilience.

Experimental design	Benefits	Limitations	Climate change resilience
Implementing a single method (i.e., no experiment; Fig. 1A)	• Fewest resources to implement	• Learning is slow or non-existent	None
Split-plot design at one site (Fig. 1B)	• Faster learning than no experiment	• Difficult to generalize results to new sites • Not possible for management strategies that require large areas	Local
Multiple methods each replicated at different sites (Fig. 1C)	• Results can be generalized to new contexts • Applicable to management strategies that require large areas	• Requires a large number of sites to ensure management strategy is not confounded with site	Regional
Split-plot design at multiple sites (Fig. 1D)	• Results can be generalized to new contexts • Management strategy is not confounded with site	• Not possible for management strategies that require large areas	Local and Regional
Coordinated distributed experiment (Fig. 1E)	• Maximizes learning and generalization to new contexts • Minimizes complications with meta-analyses	• Requires significant resources and coordination	Local and Regional

Climate Change project is evaluating the context dependence and feasibility of multiple climate change adaptation strategies using a common experimental design distributed across a network of different forest ecosystems in the United States (Nagel et al., 2017). More of these efforts are necessary to quickly inform our understanding of how best to adapt management practices to climate change.

2.2. *Accounting for climate change*

Often, given high establishment costs in many management scenarios (Powell et al., 2017), practitioners would prefer that climate change adaptation strategies perform well now and under future climates to ensure a long-term return on investments. Hence, to understand the efficacy of climate change adaptation strategies more thoroughly we should test them under potential future climates. Unfortunately, waiting for climates to change in the future undermines the objective of rapid learning. We must therefore find other solutions. Single-site approaches can be implemented in locations that have climates similar to projected future climates, or extreme weather events such as droughts and heatwaves can be used as proxies for the future. Better yet, multisite approaches can be established on climatic gradients to better understand how each strategy performs under different climates (De Frenne et al., 2013; Dunne et al., 2004). However, these solutions have limitations because extreme events are unpredictable, and implementing experiments on climate gradients could confound climate with other environmental differences along the gradient (De Frenne et al., 2013; Dunne et al., 2004).

To overcome these limitations, another solution is to experimentally manipulate climate with methods ranging from easy-to-install passive warming chambers and rainout shelters, to more complex active manipulations such as infrared heat lamps (Hoover et al., 2018; Wipf and Rixen, 2010). Experimentally manipulating climate can better isolate the effect of a specific climate variable on the efficacy of a climate change adaptation strategy. However, climate manipulations also suffer from limitations such as focusing on only a few aspects of climate (e.g., temperature or precipitation), failing to simulate important aspects of climate change, or unintended effects on other environmental variables (Kayler et al., 2015; Wipf and Rixen, 2010). Hence, the strongest experiments will manipulate climate at each site along a climate gradient (Kayler et al., 2015). Obviously, such large-scale experiments will require significant resources and will not be possible for all projects. We provide some advice for how to achieve the most complex experimental designs below.

3. Secondary benefits of experimental climate change adaptation

Implementing multiple methods simultaneously in an experimental climate change adaptation effort can provide many additional benefits, which we outline below. These benefits can be used to justify the extra resources required to achieve experimental climate change adaptation approaches.

3.1. *Resilience through the portfolio effect*

A benefit of implementing multiple management strategies within a single project is an increased likelihood of success through bet hedging or the portfolio effect (i.e., spreading risk among multiple methods). Because many climate change adaptation strategies are relatively novel, the outcomes will be uncertain, and implementing a single strategy could result in complete failure. However, by implementing multiple strategies, the likelihood of at least partial success is increased. Moreover, as climates continue to change, management actions will need to persist through variable climates and extreme events. A recent review suggested that variation in approaches can significantly improve the resilience of habitat restorations to such events (Zabin et al., 2022). Indeed, the advantages of a portfolio effect for natural resource management has been suggested repeatedly, although rarely implemented in practice (Howe and Martínez-Garza, 2014; Jackson and Hobbs, 2009; Schindler et al., 2015). Experimental climate change adaptation can result in local resilience if multiple management strategies are implemented at a single site, and regional resilience if multiple strategies are implemented at multiple sites (Table 1).

3.2. Overcoming the fear of failure

Many management actions have a relatively poor track record for achieving the intended outcomes (e.g., Atkinson et al., 2022). Management failures impact the perception of management agencies and the support for future efforts by the public, policy makers, and funders (Lindenmayer, 2020; Zahawi et al., 2014). Hence, practitioners might justifiably be reluctant to implement novel climate change adaptation strategies for fear of failure. However, such aversion to risk can stifle the creativity that might often be necessary to adapt to climate change (Aslan et al., 2014). Moreover, it is well known from other fields that success is often preceded by repeated failures, because we learn the most from failure (Amabile and Khaire, 2008; Bradshaw, 1987; Lindenmayer, 2020; Yin et al., 2019). Explicitly designing management actions as climate change adaptation experiments, and clearly articulating the learning value of unsuccessful approaches, might help practitioners redefine success and overcome the fear of failure by providing an explanation for unsuccessful approaches to the public, policy makers, and funders. Moreover, as described above, total failure is limited by implementing multiple strategies simultaneously.

3.3. Resolving conflicts and minimizing unintended consequences

Many climate change adaptation strategies go against conventional conservation wisdom and could result in negative unintended consequences. For example, moving species or genotypes outside of their current ranges (i.e., assisted migration or assisted gene flow) is a commonly recommended climate change adaptation strategy that has generated a lot of controversy because of the perceived risks (Aitken and Whitlock, 2013; McLacklan et al., 2007; Waters et al., 2013). Consequently, practitioners, scientists, and other interested parties might often disagree on the appropriate method for climate change adaptation, or be unwilling to implement risky approaches (Vella et al., 2021). Indeed, conflict over climate change adaptation methods has been recognized as a significant barrier to implementation in multiple situations (Archie et al., 2012; Barnett et al., 2015; Bergeret and Lavorel, 2022) and is commonly cited as a barrier to implementing adaptive management (Gillson et al., 2019; Jacobson et al., 2006; Månsson et al., 2023). However, experiments can - and should - be designed to help minimize unintended consequences. Moreover, if management is explicitly designed as an experiment, interested and affected parties might only need to agree on management goals and objectives, and then experiments can be used to hone in on the best solution (Murray and Marmorek, 2004). Trying a novel approach experimentally is often much more palatable to skeptics than employing only one controversial approach (Murray and Marmorek, 2004), especially when precautions are taken to minimize unintended consequences. Co-developing experiments with affected parties, and observing the on-the-ground results together, might therefore help resolve conflicts about the best approach to achieve shared objectives.

3.4. Testing our knowledge in climate change biology

Thirty-six years ago, Jordan et al. (1987) drew attention to the value of ecological restoration as not only a practical solution to environmental degradation, but also a technique for basic research. Bradshaw (1987) built on that idea and suggested ecological restoration could be an acid test of our understanding in ecology. He suggested the strongest test of our ecological theory is to try to reassemble a degraded ecosystem based on our understanding of the key components and evaluate if the ecosystem's structure and function are restored. Failure to restore the ecosystem will expose inadequacies in our ecological knowledge, and could therefore lead to new hypotheses, better theory, and ultimately better restoration success.

Similarly, we think experimental climate change adaptation can be used to test our understanding in climate change biology. Much of what we think will happen to biodiversity and ecosystems under climate change is based on correlative models that make associations between climate and species occupancy (Urban et al., 2016). However, few empirical tests of correlative models exist, despite regular suggestions in the literature that these methods have limitations that could result in inaccurate predictions of climate change responses (Butt et al., 2016; Dawson et al., 2011; de los Ríos et al., 2018; Pacifici et al., 2015; Wheatley et al., 2017). Employing multiple management strategies under an experimental framework (e.g., comparing non-climate-adapted and climate-adapted approaches) could help us understand and improve models and theory in climate change biology, which will feedback to improve the management of biodiversity under climate change.

3.5. Science and management communication

Natural resource management and conservation often occur in places of high public value, as this is often a strong justification for funding and management intervention. The heightened public interest in such places creates the opportunity to convey both the rapid changes and multiple uncertainties that natural resource managers are facing. Implementing experimental climate change adaptation in such places can provide an interactive experience for visitors to see first-hand the potential of different management objectives (e.g., resisting, accepting, or directing change; Schuurman et al., 2020) and methods for achieving the objectives. Enhanced public awareness and understanding of the challenges managers face can shape more realistic expectations and support for conservation efforts. Moreover, exposure to carefully designed experiments can help educate the public about the process and value of the scientific method.

4. Case studies: experimenting with genetic diversity through habitat restorations

Two commonly proposed climate change adaptation strategies are increasing genetic diversity and assisted gene flow (Heller and Zavaleta, 2009; McLaughlin et al., 2022; Prober et al., 2019). Increasing genetic diversity by sourcing plants from multiple populations can increase biomass, reduce invasion by unwanted species, and increase resilience to disturbance, even in the absence of climate change (Hughes et al., 2008; Kettenring et al., 2014). Hence, sourcing plants from multiple populations, rather than from a single local population (as has been the traditional practice in habitat restorations), is now regularly recommended (Kettenring et al., 2014). Under climate change, increasing genetic diversity can provide genotypes that recover quickly after disturbances such as heat waves, or increase the chances that populations will evolve in response to changes in climate, in addition to the other benefits (Jump et al., 2009; Reusch et al., 2005). Assisted gene flow is the intentional movement of individuals from locations with climates similar to projected future climates at a restoration site (Aitken and Whitlock, 2013). If individuals are sourced from multiple locations or added to existing local genotypes, then assisted gene flow is a special case of increasing genetic diversity.

Management agencies worldwide are already increasing genetic diversity and implementing assisted gene flow as climate change adaptation strategies. However, little data exists to evaluate whether these strategies are effective. Recent simulations suggest assisted gene flow can be harmful in the short term and that the long-term benefits are often weak (Grummer et al., 2022). Moreover, tests of assisted gene flow might often be conflated with increasing genetic diversity if the experiments are not rigorously designed. Decoupling the two potential mechanisms behind the success of assisted gene flow (i.e., adding genotypes adapted to future climates versus increasing genetic diversity) is important for management because, in contrast to increasing genetic diversity, assisted gene flow often requires significant resources to identify populations adapted to future climates. Here, we present two habitat restoration experiments designed to test and decouple the confounding mechanisms of assisted gene flow and increasing genetic diversity as climate change adaptation strategies.

4.1. The sustainable summits project

At 466 m, Cadillac Mountain in Acadia National Park (Maine, USA) is the highest mountain summit on the coast of the eastern United States. Heavy foot traffic on the easily accessible summit, combined with historical fires, have severely degraded the unique summit vegetation and caused significant erosion and soil loss. Heavy rain events under climate change are likely to exacerbate this degradation, which is also common on other mountain summits in the park and throughout much of the eastern United States.

Between 2015 and 2022, the U.S. National Park Service - in partnership with the Native Plant Trust, Schoodic Institute, and Friends of Acadia - began efforts to restore soil and vegetation to the summit of Cadillac Mountain. The first phase of the project used experiments to identify successful restoration methods and species for restoration (Brumback and Webber, 2021). Three-toothed cinquefoil (*Sibbaldiopsis tridentata*; Fig. 2A) was identified as an important restoration species because it had high survival and growth during the experiments and because it is a stoloniferous plant that could help stabilize soil post-restoration (Brumback and Webber, 2021). However, three-toothed

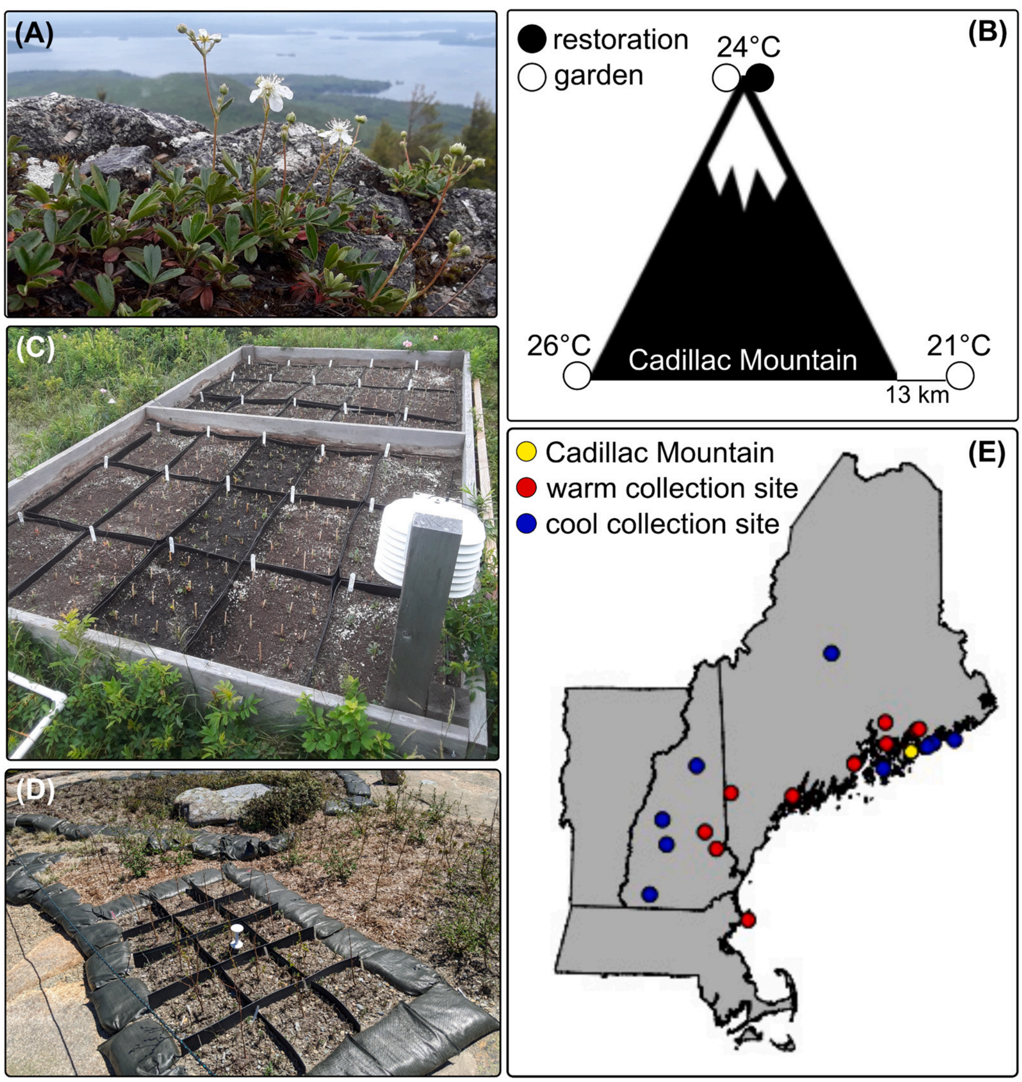

Fig. 2. The Sustainable Summits Project. (A) Three-toothed cinquefoil, (*Sibbaldiopsis tridentata*), the focal species. (B) The location and average maximum summer temperature of raised-bed gardens and the experimental restoration site. (C) A raised-bed garden subdivided into 30 isolated plots, each planted with a population of 20 three-toothed cinquefoil plants from different locations. (D) A picture of the experimental restoration site, subdivided into 15 plots, each planted with 12 three-toothed cinquefoil plants from different locations (photo credit: Tim Watkins, National Park Service). (E) 31 locations where we collected three-toothed cinquefoil to create the experimental populations shown in C and D.

cinquefoil could be highly sensitive to increased temperatures under climate change. Models suggest that three-toothed cinquefoil could lose 98 % of its distribution in Maine by the end of the century due to increased maximum summer temperatures (Smetzer and Morelli, 2019). If these models are correct, then resources invested in three-toothed cinquefoil restoration might only provide short-term benefits, especially if the current practice of restoring local genotypes is used in subsequent phases of the restoration.

The Sustainable Summits Project is an experiment designed to evaluate whether increasing genetic diversity or assisted gene flow are viable climate change adaptation strategies for three-toothed cinquefoil on Cadillac Mountain. The project takes advantage of three existing raised-bed gardens (1.8 m by 3.7 m; Fig. 2C) that were previously installed in Acadia National Park (MacKenzie et al., 2018), including (Fig. 2B): (1) a garden on the summit of Cadillac Mountain, which represents the current climate at the restoration site; (2) a garden at the base of Cadillac Mountain, which represents a future climate that is 2 °C hotter and drier; and (3) a garden 13 km from Cadillac Mountain on Schoodic Point, which represents a benign cool (3 °C cooler than the summit of Cadillac Mountain) and wet climate. The gardens are an excellent proxy for existing summit restoration plots, which are plots surrounded with sandbags and filled with soil (Fig. 2D). Utilizing the gardens in this experiment, rather than utilizing restoration plots, allowed us to evaluate how different genetic management strategies perform in different climates, while better controlling the spread of non-local genotypes into wild populations. We also installed an experimental restoration plot (1.1 m by 1.6 m) embedded within a larger restoration site on the summit of Cadillac Mountain to supplement the garden study (Fig. 2B and D). This design maximizes learning while minimizing potential unintended consequences of introducing non-local genotypes.

In May and June of 2021, we collected adult three-toothed cinquefoil plants from each of 31 locations throughout Massachusetts, New Hampshire, and Maine (Fig. 2E). The locations included Cadillac Mountain (i.e., local individuals), 15 locations where maximum summer temperatures were on average 1.2 °C warmer (SD = 0.8 °C) than Cadillac Mountain (i.e., presumably warm-adapted individuals), and 15 locations where maximum summer temperatures were on average 1.6 °C cooler (SD = 1.5 °C) than Cadillac Mountain (i.e., presumably cool-adapted individuals). We identified collection locations using iNaturalist observations and we assessed the temperature at each location using PRISM climate data (PRISM Climate Group, 2013).

We used these three-toothed cinquefoil plants to create 30 experimentally-restored populations in each of the three raised-bed gardens, and 15 experimentally restored populations in the experimental restoration plot (Fig. 2C and D). We divided the experimental populations into three treatments: (1) a local-only treatment composed of plants from Cadillac Mountain; (2) an assisted-gene-flow treatment composed of a mixture of local plants and plants from each of three locations that are warmer than Cadillac Mountain; and (3) an increased-genetic-diversity treatment composed of a mixture of local plants and plants from each of three locations that are cooler than Cadillac Mountain. The increased genetic diversity treatment is a control to help decouple the effects of adding presumably warm-adapted individuals from the effects of increasing genetic diversity. Hence, we specifically did not add individuals from warmer locations while increasing genetic diversity in this experiment (see the second case study below for a study design that increases genetic diversity without specifically excluding individuals from warmer locations). A stronger design might be to add individuals from locations that have a similar temperature to Cadillac Mountain so that we are not adding potentially maladapted individuals. Unfortunately, we were unable to identify enough locations with a similar temperature to Cadillac Mountain to employ this approach. Nonetheless, our approach could still show many effects of increasing genetic diversity from factors other than maximum summer temperature. We assigned treatments to plots within the gardens and the experimental restoration site using a randomized block design, with treatments blocked by the date of plant collection. We planted all plants within a week of collection and varied the order of collection such that collection time was not associated with the type of collection location. We have monitored percent cover of three-toothed cinquefoil in each population three times annually since we created the populations, and monitoring will continue for at least another year.

The Sustainable Summits Project is a small-scale version of the type of experimental climate change adaptation we propose in this paper and not all of the experimental plots resulted in on-the-ground restoration. However, it demonstrates many of the potential benefits described above, including: a split-plot design in the restoration plot and a distributed split-plot design in the common gardens to test multiple mechanistic hypotheses, evaluation under multiple climates that could help test predictions from correlative models, potential resilience through the portfolio effect, and ample opportunities for science communication. Indeed, the high visibility of the experiment in a national park provided many opportunities for science communication (Carpenter, 2022; Cole, 2022; Watkins, 2022). For example, multiple members of U.S. Congress visited the experiment and provided videos of themselves on social media at the experimental restoration plot describing the goals of the project. This alone demonstrates the enormous potential for such experimental restorations. If increasing genetic diversity or assisted gene flow provide significant benefits over restoring local genotypes, then we plan to compare the most promising method to the local-genotype method at larger scales during future phases of the restoration. Ideally, future experiments will use seeds, rather than transplanting adult plants, to minimize the risk of spreading pest or pathogens, and use lab experiments to understand the impacts of reproduction among the genotypes because removing flowers is costly and not feasible long term.

4.2. Winnapaug pond experimental eelgrass restoration

Eelgrass (*Zostera marina*) is a marine flowering plant that is widely distributed in shallow marine and subtidal areas throughout the northern hemisphere. Eelgrass is a foundation species that provides critical ecosystem functions including providing food and habitat for many species (Thayer et al., 1984; Unsworth et al., 2019; Valentine and Heck, 1999), filtering water (de los Santos et al., 2020; Sandoval-Gil et al., 2016), and preventing coastal erosion (Ondiviela et al., 2014). Like many seagrasses, eelgrass has been declining throughout much of its range, including along the Atlantic coast of North America, due to disease, coastal development, and decreased water quality (Keser et al., 2003; Nahirnick et al., 2020; Orth and Moore, 1983).

Eelgrass is also sensitive to high temperatures and is therefore further threatened by climate change (Hammer et al., 2018; Kaldy, 2014; Marsh et al., 1986). Indeed, the effects of high temperatures have already been observed in many areas (Glemarec et al., 1997; Moore et al., 2014; Moore and Jarvis, 2008). Several practitioners and scientists believe that high temperatures will extirpate eelgrass from many locations throughout its range without active intervention to help populations adapt. Consequently, The Nature Conservancy recently hosted a series of workshops to determine how best to reduce the vulnerability of eelgrass to warming temperatures along the Atlantic coast of the USA (Peterson et al., 2022). A major outcome of those workshops was the need to identify resilient genotypes that can be used for assisted gene flow or selective breeding. Common gardens were proposed as the most efficient way to identify those genotypes (Schwinning et al., 2022).

In response to this outcome, we recently took advantage of an eelgrass restoration in Winnapaug Pond, Rhode Island USA, to create an eelgrass common garden with the objectives of identifying resilient populations, and testing assisted gene flow and increasing genetic diversity as climate change adaptation strategies. Winnapaug Pond is a coastal lagoon that currently experiences diurnal tidal fluctuations due to a permanent breachway established in the 1950s. Eelgrass was historically present in the pond (Renn, 1937; Wright et al., 1949), but was likely extirpated by the mid 1980's due to a combination of stressors, including sedimentation caused by the breachway and impacts from coastal development (Ernst et al., 1999). The U.S. Army Corps of Engineers began restoration in the pond in 2021, as part of the Rhode Island South Coast Habitat Restoration Project, which also includes restoration of three other coastal lagoons in the region (U.S. Army Corps of Engineers, 2002). They created two restoration areas that have been dredged to a depth deemed optimal for eelgrass in coastal lagoons (0.75–1.0 m below mean low water). However, summer water temperatures in Winnapaug Pond are likely close to stressful temperatures for eelgrass due to reduced tidal flushing rates and shallow water depths, and temperatures will certainly become more stressful under climate change. Hence, Winnapaug Pond offers an ideal location to include a climate change adaptation experiment as a component of a planned eelgrass restoration project. Moreover, introducing non-local genotypes into Winnapaug Pond to test different climate change adaptation strategies has a low risk of unintended consequences due to the lack of an existing eelgrass population and the isolation of Winnapaug Pond from existing eelgrass beds.

In August of 2022, we collected eelgrass seeds from 12 sites (Fig. 3B), including: (1) five local sites in Rhode Island, (2) three sites identified as warm by eelgrass experts, and (3) four sites identified as cool by eelgrass experts. We held the seeds in a closed seawater system in a greenhouse and soaked the seeds in a 5 % bleach solution for 5 min prior to planting to prevent the spread of invasive species or disease (Marion and Orth, 2010). In October 2022, we planted the seeds in experimental plots along three transects in one of the Winnapaug Pond restoration sites (Fig. 3C). Experimental plots were randomly assigned to one of four treatments: (1) a monoculture treatment composed of seeds from a single collection site, (2) a traditional, non-climate-adapted treatment

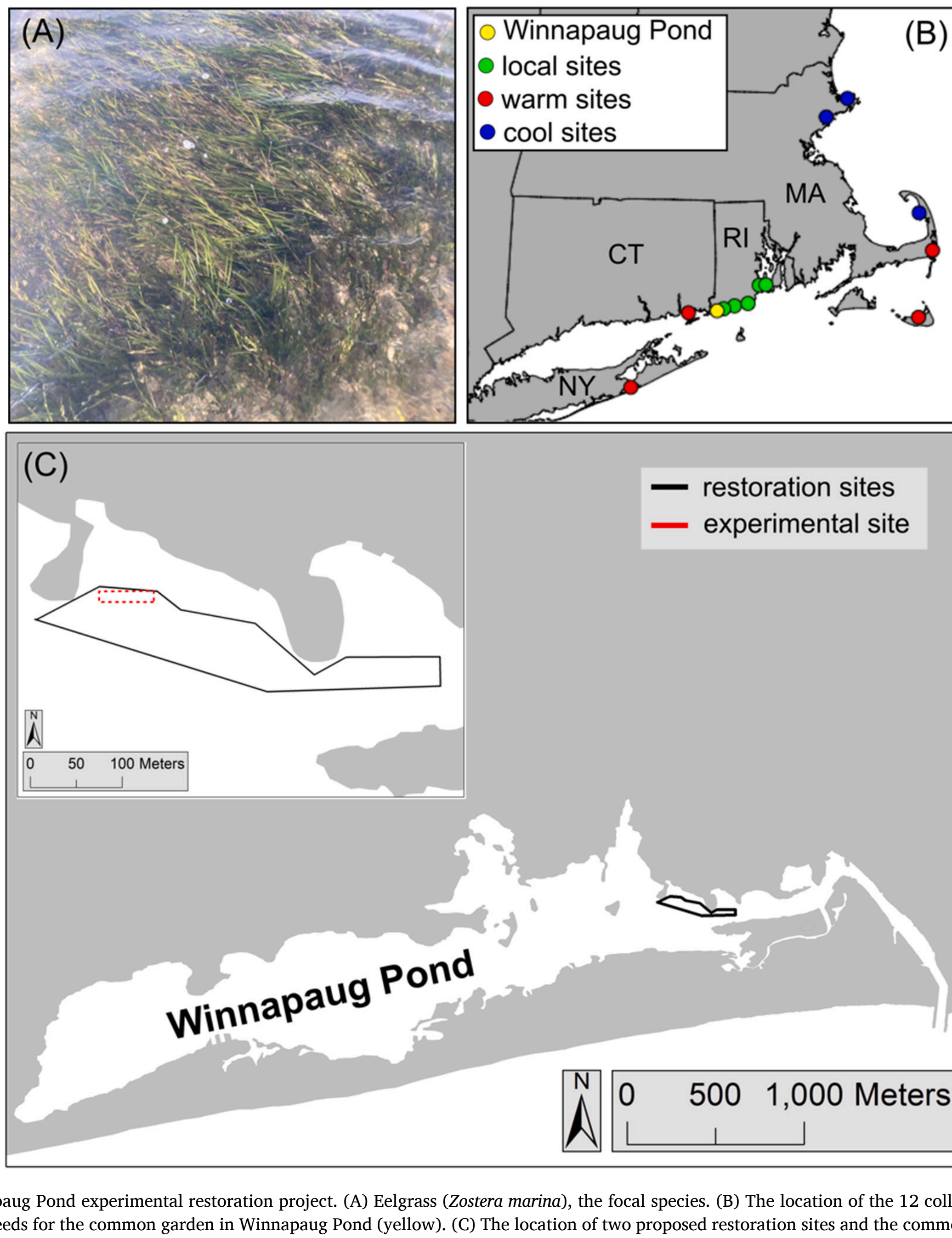

Fig. 3. The Winnapaug Pond experimental restoration project. (A) Eelgrass (*Zostera marina*), the focal species. (B) The location of the 12 collection sites where we collected eelgrass seeds for the common garden in Winnapaug Pond (yellow). (C) The location of two proposed restoration sites and the common garden experiment in Winnapaug Pond. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

composed of a mixture of seeds from each of four Rhode Island sites, (3) an assisted-gene-flow treatment composed of a mixture seeds from each of two Rhode Island sites and two warm sites, and (4) a latitudinal-range treatment composed of a mixture of seeds from each of four sites spanning the latitudinal gradient of our collection sites. The latitudinal-range treatment increases genetic diversity, without a specific focus on presumably warm-adapted individuals, and will therefore help us decouple the effects of increasing genetic diversity from assisted gene flow (see the first case study for a different study design that better decouples these two possible mechanisms). We plan to monitor shoot density in each experimental plot twice annually starting in 2023.

The Winnapaug Pond Experimental Eelgrass Restoration also demonstrates many of the potential benefits described above. As with the Sustainable Summits Project, we employed a split-plot design that included replication, randomization, and a non-climate-adapted control. We also extended the traditional common garden approach (Schwinning et al., 2022) to test multiple mechanistic hypotheses, including using monocultures to identify resilient populations for future restoration, and decoupling the effects of genetic diversity and assisted gene flow. The experimental restoration might also increase the resilience of the site by employing multiple restoration strategies and by sourcing eelgrass from multiple populations. We expect the results to help inform eelgrass restoration on the Atlantic coast of North America by identifying resilient populations and to provide evidence for or against commonly recommended restoration techniques. Moreover, the design of this common garden can serve as a model for restoration efforts in the area to take an experimental approach.

5. Overcoming the costs and barriers to experimental climate change adaptation

Despite the benefits of experimental approaches to management outlined above and elsewhere (Dybala et al., 2017; Howe and Martínez-Garza, 2014; Lindenmayer, 2020), barriers to experimental approaches in natural resource management and conservation are well documented and have hindered widespread implementation (Gillson et al., 2019; Jacobson et al., 2006; Månsson et al., 2023; Westgate et al., 2013). We must therefore overcome commonly cited barriers for experimental climate change adaptation to be adopted widely. Here we discuss three commonly reported barriers that are particularly relevant to experimental climate change adaptation and suggest potential ways to overcome them. We focus on examples from the United States, where the authors are from, but the general sentiments should be relevant to many other countries.

5.1. Building inclusive teams through coproduction and collective learning

Many scientific and management organizations lack the range of expertise required to successfully implement experimental management approaches, which leads to implementation barriers such as experiments that do not address management issues, poor experimental design, and lack of sufficient monitoring (Hughes et al., 2018; Månsson et al., 2023; Westgate et al., 2013). Moreover, many interested and affected parties often occur outside scientific and management organizations. However, relevant parties are not always included in the design and implementation of experimental management, which can weaken experimental designs and prevent the acceptance of experimental results (Månsson et al., 2023). When affected parties are merely informed of a decision after the fact, there is a greater likelihood of dissatisfaction with the process and lack of support of the outcome (National Oceanic and Atmospheric Administration, 2015). Thus, in order to be effective and sustainable, experimental climate change adaptation must be carefully designed with social and ecological input from interested and affected parties beyond scientists and practitioners (Ban et al., 2009; Knight et al., 2008; Villamor et al., 2014). Developing diverse teams will therefore be necessary to successfully implement effective experimental climate change adaptation efforts (Månsson et al., 2023; Westgate et al., 2013). Indeed, the case studies described above, and much of the progress in climate change adaptation to date, has been accomplished through collaborations among organizations with diverse expertise (Halofsky et al., 2015).

Existing models of effective knowledge exchange can facilitate relationship building and increase the collaboration necessary to implement experimental climate change adaptation (Cook et al., 2021; Hughes et al., 2020). For example, coproduction of knowledge relies on direct communication and collaboration among scientists and practitioners to develop and implement experimental climate change adaptation (Beier et al., 2017). The case studies described above were developed through regular communication between scientists and practitioners. Two-eyed seeing approaches (i.e., viewing issues through both Indigenous and Western worldviews) can also help bring together Indigenous and Western science approaches (Bartlett et al., 2012; Denny and Fanning, 2016; Kutz and Tomaselli, 2019). In some settings, having separate individuals (knowledge brokers) or organizations (boundary organizations) that play an intermediary role to facilitate knowledge exchange between scientists and practitioners may be most effective (Cook et al., 2021). For example, Schoodic Institute is a boundary organization that played an important role facilitating the collaborations necessary for the Sustainable Summits Project (described above) to be successful. In addition to facilitating exchange between scientists and practitioners, boundary workers/organizations can be particularly effective at promoting shared knowledge that is usable by all, thereby gaining trust among interested and affected parties (Clark et al., 2016). Note, however, that it is important that management priorities be explicitly stated first, before science opportunities are determined, to allow for the true value of the partnership among managers and scientists to be realized (Bisbal, 2019).

Current models of co-production to address climate change exist. Notable examples in the United States include the case studies described above, the USGS National and Regional Climate Adaptation Science Centers, the NOAA Regional Integrated Sciences and Assessments Program, USGS Cooperative Fish and Wildlife Research Units, U.S. National Park Service Research Learning Centers, and the Land Grant and Sea Grant university extension systems. These boundary organizations provide frameworks that can be adapted and scaled in other contexts, and they provide lessons learned to inform best practices. For example, key features of their success include: (1) using flexible network structures (Bisbal, 2019); (2) having place-based emphases; (3) incorporating diverse knowledge sources; (4) employing iterative learning approaches; and (5) providing boundary management functions (communication, translation, mediation, convening; Stevenson et al., 2016). These features facilitate a collective and 'learn by doing' approach to climate change adaptation (Combest-Friedman et al., 2019). Further, once in place, boundary organizations can foster bridges among other affected parties, facilitating the knowledge networks and social learning that are critical to responding to the accelerating impacts of climate change (Bidwell et al., 2013). Indeed, working with these organizations is an excellent starting point to create the partnerships necessary to begin a new climate change adaptation experiment.

5.2. Novel funding strategies to overcome limited resources

One of the most widely reported barriers to implementing climate change adaptation is a lack of resources (Halofsky et al., 2015). Similarly, a lack of resources for design, monitoring, and analysis is often cited as a barrier to implementing experimental management approaches (Jacobson et al., 2006; Månsson et al., 2023). Hence, experimental climate change adaptation will undoubtedly suffer from the same problem. Bold, creative, and strategic action is therefore needed to provide the resources necessary for our proposed approach to flourish (Fazey et al., 2018; Wyborn et al., 2020). Given the scale of many experimental climate change adaptation efforts, state (e.g., California

KELP Act H.R. 4458) and/or federal (e.g., O'Halleran Congressional Bill H.R. 5145) legislation to prioritize and fund experimental climate change adaptation can help to ramp up implementation. Partnerships with industry to fund experimental climate change adaptation (e.g., Williams et al., 2019) represents another under-utilized approach. Moreover, a number of early-career fellowships in the United States have been designed with the explicit goal of creating meaningful practitioner-scientist partnerships that can be used to fund experimental climate change adaptation. For example, the Sustainable Summits Project and some of the eelgrass work described above was funded by the David H. Smith Conservation Research Fellowship administered by the Society of Conservation Biology. The Second Century Stewardship Fellowship administered by the Schoodic Institute at Acadia National Park, and the NatureNet Fellowship administered by The Nature Conservancy are other great examples. Importantly, imagination is needed to build the anticipatory capacity to get ahead of the curve, rather than simply reacting to crises (Wyborn et al., 2020). It will also be important to understand the cost of adding experimentation to climate change adaptation approaches to better understand the cost and benefits of experimental approaches.

5.3. Changing values, priorities, and definitions of success to match the new reality

Competing logics among scientists, the public, and funders can act as a significant barrier to implementing experimental management approaches (West et al., 2016). Often, scientists prioritize learning, the public prioritizes accountability, and funders and practitioners prioritize efficiency and effectiveness (West et al., 2016). For experimental climate change adaptation efforts to be adapted widely, these values and priorities will need to shift. For example, traditional academic training and merit processes have prioritized foundational over translational research. Although there are increasing examples of work at the interface of academia and practice and a growing focus on coproduction, an upscaling of research that works more directly with practical domains is needed (Fazey et al., 2018). These efforts must be integrated throughout the academic pipeline - including coursework, training programs, and merit and promotion processes - in order to develop and support scientists who understand that knowledge is more usable when it fits within and draws utility from the existing ideas, technologies, and governing institutions (Clark et al., 2016). The case studies described above, which involved undergraduates, PhD students, postdoctoral researchers, and professors, are an example of how experimental climate change adaptation can be incorporated into the academic pipeline.

Similarly, funding agencies and management organizations often prioritize metrics that are easily reported, such as acres restored, and are often reluctant to fund research, despite requirements to provide evidence supporting proposed actions (Parks et al., 2022). Some experimental climate change adaptation efforts will not maximize these metrics, some portion of the experimental climate change adaptation project might fail, and resources will need to be devoted to experimental design and monitoring. It must be recognized, however, that existing management approaches might also fail under climate change. Hence, in the face of climate change, experimental approaches might be more acceptable to entities that have traditionally focused on other metrics (see Section 3.2 above). To prevent a fear of failure from hindering action, we must evaluate efforts based on the process, and not the outcome, and reward learning and communication of findings (Meek et al., 2015; Wyborn et al., 2020). To maximize and expedite the learning process, practitioners, researchers, funding sources, and peer-review journals should consider the value of failure and reporting negative results from well-designed experiments (Redford and Taber, 2000). The integral role management organizations played in the case studies described above is evidence that priorities are rapidly changing as management organizations face ever growing threats to management success under climate change. Hence, experimental climate change adaptation might be more widely accepted as more of these attitudes change.

6. Conclusion

Implementing untested climate change adaptation strategies could waste limited conservation resources or cause harmful unintended consequences. However, the time and resources necessary to test climate change adaptation strategies is in conflict with the urgent need to adapt management actions to climate change. Here, we suggest implementing multiple climate change adaptation strategies simultaneously using an experimental framework as a solution to this conflict. We show how experiments can be implemented at multiple scales to ensure learning without delaying action, and we outline many secondary benefits to both scientists and practitioners that provide incentives for following our proposed approach. Nonetheless, implementing experimental climate change adaptation will require creative solutions to overcome traditional barriers such as funding restrictions and building effective partnerships. Many examples are emerging that provide road maps for success. We encourage more practitioners and scientists to pursue these creative avenues to ensure that the money we invest in conservation today will continue to provide benefits in an uncertain future.

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Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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