Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change

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Citation: S. M. Prober, V. A. J. Doerr, L. M. Broadhurst, K. J. Williams, and F. Dickson. 2019. Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change. Ecological Monographs 89(1):e01333. 10.1002/ecm.1333

Abstract. Changes in Earth’s climate are accelerating, prompting increasing calls to ensure that investments in ecological restoration and nature conservation accommodate such changes. To acknowledge this need, we propose the term “ecological renovation” to describe ecological management and nature conservation actions that actively allow for environmental change. To evaluate and progress the development of ecological renovation and related intervention options in a climate change context, we reviewed the literature and established a typology of options that have been proposed. We explored how these options address emerging principles underpinning climate-adapted conservation goals and whether the balance of approaches reflected in our typology is likely to be sufficient given expected rapid rates of climate change. Our typology recognizes a matrix of 23 intervention option types arranged on the basis of underpinning ecological mechanisms (“ameliorate changing conditions” or “build adaptive capacity”) on one axis, and the nature of the tools used to manipulate them (“low regrets” or “climate targeted”) on the other. Despite a burgeoning literature since 2008, we found that the majority of effort has consistently focused on low-regrets adaptation approaches that aim to build adaptive capacity. This is in many ways desirable, but a paradigm shift enabling greater attention to climate-targeted approaches is likely to be needed as climate change accelerates. When assessed against five emerging principles for setting nature conservation goals in a changing climate, only one option type could deliver to all five, and we identified a conflict between climate-targeted options and “wildness” values that calls for deeper evaluation. Importantly, much of the inference in the 473 reviewed studies was drawn from ecological reasoning and modeling, with only 16% offering new empirical evidence. We also noted significant biases toward North America and Europe, forest ecosystems, trees, and vertebrates. To address these limitations and help shift the paradigm toward humans as “renovators” rather than “restorers” of a prior world, we propose that ecological researchers contribute by (1) informing societal discourse toward adapting nature conservation goals to climate change, (2) adjusting and upsampling conservation planning to accommodate this suite of climate-adapted goals, and (3) reconceptualizing experimental approaches to increase empirical evidence and expedite innovation of tools to address change.

Key words: assisted colonization; biodiversity conservation; changing climate; climate adaptation; climate ready; connectivity; ecological insurance; ecological renovation; ecological restoration; nature conservation; resilience; typology.

INTRODUCTION

Changes in the Earth’s climate are accelerating, with the Earth’s four warmest years since records began occurring consecutively from 2014–2017, and averaging
0.85°C above the 20th-century global average (NOAA 2018). Global syntheses clearly demonstrate that climate change is already having an impact on genes, species, and ecosystems worldwide, with evolutionary adaptation, shifting species distributions, altered phenology, changing ecosystem productivity, and disruption of ecological interactions already well-documented (Scheffers et al. 2016).

Accordingly, there have been increasing calls to ensure that investments in ecological restoration and nature conservation adequately consider climate change (Heller and Zavaleta 2009, Oliver et al. 2012, Stein et al. 2013, Hagerman and Satterfield 2014, Prober et al. 2017a). This is needed not only to improve outcomes for biodiversity and natural ecosystems, but to support efforts to reduce the negative effects of climate change on social and economic systems (Pecl et al. 2017). For example, ecosystems can help to mitigate climate change by storing carbon and provide adaptation services that improve the capacity of society to respond to climate change (Colloff et al. 2016).

The scientific and practitioner communities have responded with a proliferation of research and activity focusing on planning or management interventions to help nature adapt to climate change. These encompass a wide range of fields from genomic adaptation (e.g., Aitken and Whitlock 2013) and assisted colonization (e.g., Schwartz and Martin 2013) at the species level, through manipulation of ecological and community-level processes (e.g., Greenwood et al. 2016), to disturbance management (e.g., Peterson et al. 2011) and conservation planning (e.g., Beier and Brost 2010) at broader scales. This has resulted in a diverse array of recommendations for adapting nature conservation management to climate change, but there has been limited overarching synthesis to help ecological researchers and land managers navigate this broad range of potential options. Heller and Zavaleta (2009) for example, emphasized the need to organize the current “sea of adaptation ideas” into a structure to guide adaptation planning.

The need for ecological interventions to accommodate impacts of climate change could be viewed as inconsistent with some of the traditional goals and principles underpinning ecological restoration and nature conservation (Corlett 2016, Rohwer and Marris 2016). Indeed, restoration is defined as “to bring back to an original or normal condition” (The Free Dictionary 2017); “to return something to an earlier good condition” (Cambridge Dictionary 2017); and in ecology is widely accepted to incorporate goals directed at the recovery of degraded ecosystems toward a valued historical state (McDonald et al. 2016). Similarly, definitions of nature conservation, for example, the “preservation, protection or restoration of wildlife or natural resources” (The Free Dictionary 2017), similarly invoke goals to avoid ecological change or restore historical states. As the climate changes, ecological restoration and management goals will increasingly need to anticipate future conditions and accommodate characteristics that differ from historical states, such as genetic variants or species better adapted to projected future climates (McDonald et al. 2016, Prober et al. 2017b).

In keeping with the suggestion that a new vocabulary is needed for developing forward-looking conservation principles and goals (Corlett 2016), we propose the term “ecological renovation” to describe ecological management and nature conservation actions that actively allow for environmental change. “Renovate” is defined as “to repair or improve something” (Cambridge Dictionary 2017); “repair or remodel; to impart new vigor, revive” (The Free Dictionary 2017). We view this framing as supporting aspirations to conserve many historical values of ecosystems as expected for both nature conservation management and restoration (McDonald et al. 2016), while also accommodating the inevitability of ecological change associated with climate and other global changes (Higgs et al. 2014, McDonald et al. 2016, Rohwer and Marris 2016); in the same way that a home renovation might restore valued historic character while accommodating modern plumbing, electrical wiring, and heating. In so doing, our aim is to avoid the implication of “anything goes,” which easily arises when goals are decoupled from historical fidelity (Higgs et al. 2014). Our concept is not only relevant to degraded ecosystems but also applies to intact ecosystems undergoing change or species that require facilitation to adapt.

Given rapid research developments in the field of adapting nature conservation to climate change (Heller and Zavaleta 2009, Oliver et al. 2012, Stein et al. 2013, Hagerman and Satterfield 2014), we reviewed the associated literature and assembled a typology of options that aim to help biodiversity and ecosystems withstand or adapt to climate change. We used this analysis to ask how these options address emerging nature conservation goals as the climate changes (Prober et al. 2017b), and whether the balance of approaches reflected in our typology appear sufficient given expected rapid rates of climate change. We focused on options that involve on-ground interventions in terrestrial environments, which we define as actions such as plantings, disturbance management, renovation of ecological processes, or preventative actions (e.g., avoided vegetation clearing through reservation); and strategic location or timing of such actions if relevant. We recognize that policy, planning, and a range of decision support tools are important for guiding and implementing such actions (e.g., Oliver et al. 2012), and social context is central for application and prioritization, but these were generally outside our scope.

METHODS FOR REVIEW AND INFERENCE

Literature survey

We undertook a literature search to identify studies that proposed, implemented, or tested on-ground
options for facilitating persistence or adaptation of species or ecosystems under climate change (hereafter “options”). We searched Web of Science (to 31 December 2016) under the topics of ecology, environmental sciences, environmental studies, forestry, and biodiversity conservation for publications that included at least one term from each of the following three groups: (1) ecolog*, ecosystem, biodiversity, forest, woodland, rangeland, grassland, shrubland, heathland, rainforest, wetland, mangrove, saltmarsh, shore, tidal, dune, river, stream, freshwater, riparian, desert, dryland, species, nature; (2) adapt*, interven*, restor*, engineer*, revegetation, conserv*; and (3) climate change, warming, CO2, aridif*, changing climate. Additional studies known to authors were also included, noting we do not expect to have fully captured specialized literature on some topics (e.g., assisted colonization).

Our search resulted in 16,753 publications, which reduced on screening of titles and abstracts to 640, then on full text to 473 papers reviewed and scored for this analysis (Appendix S1). Criteria for inclusion included (1) an emphasis on biodiversity or nature conservation (rather than livelihoods); (2) an interest in active on-ground management response rather than solely climate change impacts, policy, or social aspects, but including selection of areas for conservation protection or action; and (3) a terrestrial focus (including land-based aquatic but not marine).

We systematically scored each of the 473 papers for publication date, ecosystems or organisms studied, geographic regions of study and types of inference used (field observations or experiments, reports of implementation, ecological reasoning, conceptual frameworks, modeling and reviews). “Ecological reasoning” included commentaries or reasoning based on impact assessments, stakeholder workshops and surveys, ecological theory, and/or earlier literature. Modeling studies involved simulation of outcomes of applying adaptation interventions, and reviews focused on assessment of evidence from past literature for outcomes of interventions. An individual study could be scored more than once in any classification.

Creating a typology of intervention options

We derived our typology using an iterative approach. We began by randomly selecting publications from our literature search, extracting information on the interventions they discussed or tested, and trialing organization of the information using insights drawn from overview and synthesis literature. This dual bottom-up and top-down approach allowed us to establish a preliminary, tractable set of “intervention option types” (hereafter option types), and to organize these into preliminary higher-level groupings (see Results). While recognizing there would be many potential ways to classify the information, we aimed for a simple classification that captured some key concepts relevant to underpinning ecological mechanisms and to practical concerns. We continued to build the set of preliminary option types until adjustments and new categories became infrequent, leading to a preliminary typology after 70 publications. Beginning with this preliminary typology, a single operator then systematically scored intervention options proposed, tested, or described in each of the 473 papers, including re-scoring of the initial 70 publications. Refinements were made to the typology where new ideas were encountered, with rescoring of earlier papers if refinements could have affected their scores (e.g., splitting or reconceptualization of a preliminary category). In total, this process led to 1,304 instances of option types scored from the 473 papers.

Using the typology to generate insights

We used two approaches to generate insights from our analysis: (1) a standard data summary approach and (2) an exploration of the potential for options to support climate-adapted goals for nature conservation. The latter approach aimed to generate deeper insights into the potential contributions that the option types in our typology could make toward maintaining what people value in nature. Principles to guide nature conservation in a changing climate are still part of an emerging community debate (Suding et al. 2015, Prober et al. 2017b). For the purpose of our analysis, we assessed option types against each of five principles recently proposed to underpin goal setting for climate-adapted nature conservation (Prober et al. 2017b). Derivation of these five principles was based on the assumption that traditional goals of nature conservation, such as preventing ecological change or restoring ecosystems toward preferred historical states, may no longer be achievable; but that climate-adapted goals could be guided by principles that capture the set of human motivations implicit in such historically focused goals. The five principles included optimize ecosystem functions and processes; maintain evolutionary potential; minimize species losses at realistic spatial scales; maintain the evolutionary character (geographic structuring) of the biota; and maintain or recreate wild, natural systems with minimal human intervention (“wildness”; Prober et al. 2017b).

We used a systematic compilation of author opinion to explore the potential performance of our option types against these principles. Each author of this paper approaches climate adaptation with different perspectives and skills, including expertise in flora and fauna conservation, ecosystem dynamics and processes, conservation genetics, ecological modeling, empirical ecology, and conservation policy and delivery. Taking advantage of this breadth, each author independently scored how they thought each option type would support or work against each of the five principles using a Likert scale (strongly support, weakly support, neutral, weakly work against, strongly work against). To synthesize these responses, we assigned the score given by at least three authors, if
removing scores were in the same direction. Where scores were too discrepant to achieve this, we independently reviewed and rescoring, then repeated the synthesis. Remaining discrepancies were scored as lacking consensus. Given the subjective nature of this methodology and that agreed principles for nature conservation under climate change are still under debate, we view this as a novel exploratory analysis to promote discussion, and limited the insights we drew from it to coarse patterns.

A Typology of Options for Ecological Renovation and Nature Conservation in a Changing Climate

Intervention options were classified in the literature in many ways (e.g., Mawdsley et al. 2009, Gillson et al. 2013), often using confounded ontologies (but see Beechie et al. 2013). In particular, lists of on-ground options commonly included a mix of specific tools or actions (e.g., increase the extent of protected areas, construct coastal barriers), and the intended mechanism or process through which climate adaptation would be facilitated (e.g., facilitate dispersion, ameliorate changes in habitat). Our typology recognizes these two ontologies, leading to 23 intervention option types organized within a matrix of four higher-level intervention classes (quadrants A–D, Table 1, Fig. 1). The axes forming the matrix were chosen to (1) highlight core ecological mechanisms underpinning the option types and (2) to reflect the nature of the tools used to implement these principles (Table 1).

The first axis (focusing on ecological mechanisms) aims to facilitate conceptual planning of intervention options in on-ground management contexts. The two high-level categories along this axis highlight the opportunity to evade or ameliorate changing environments to reduce climate change impacts on species and ecosystems (“evade or ameliorate,” Table 1, Fig. 1) vs. the opportunity to promote or facilitate nature’s inherent resilience or capacity to adapt to change (“build adaptive capacity,” Table 1, Fig. 1; Hagerman and Satterfield 2014, Hajjar and Kozak 2015). Within each of these high-level categories, we also identify nine sub-categories (hereafter, “underpinning mechanisms,” Box 1, 1–9), four contributing to “evade or ameliorate” options and five to “building adaptive capacity.”

“Building adaptive capacity” incorporates concepts of resistance, resilience, and adaptability. We define resilience after Folke et al. (2004) as “the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks,” capturing the concepts of both resistance (absorbing or resisting change) and resilience (recovering from change). Unlike the increasingly applied “resistance, resilience, response” framework that considers these three concepts as fundamental alternatives in climate change response (forestalling impacts, recovering from impacts, and transitioning to new conditions; e.g., Stein et al. 2013), we view resilience and adaptation as linked by the hierarchy of scale, with adaptation or change at a finer scale imparting resilience at a higher scale (Prober et al. 2012). For example, in a drying environment, selection of drought-tolerant individuals at the expense of drought-sensitive individuals (adaptation) imparts resilience to populations and species; and replacement of drought-sensitive species with drought-tolerant species (adaptation) imparts resilience to ecosystem functions. Similarly at higher scales, substitution of ecosystem types, such as replacement of boreal conifer forests with broadleaf forests (adaptation) helps maintain landscape-scale resilience.

The axis distinguishing the nature of the tools used (low regrets vs. climate targeted, Table 1, Fig. 1) was designated on practical grounds, and parallels the “Natural Practice” approach whereby Heller and Hobbs (2014) recommend that ecological renovation decisions favor interventions that would be considered less rather than more intrusive. Social science research has indicated that managers and the general public are more willing to implement intervention options that tend to be beneficial regardless of the rate or extent of climate change (Ausden 2014, Hagerman and Satterfield 2014); often called “low-regrets” options. These typically help natural ecosystems to persist or respond in their own way, for example through amelioration of stressors. However, low-regrets options may be inadequate given the pace of climate change (e.g., Burrows et al. 2014, Millar and Stephenson 2015), and more-interventionist options may be called for (Lin and Petersen 2013, Hagerman and Satterfield 2014). These targeted intervention (hereafter “climate-targeted”) options typically involve higher risk because of potential unexpected adverse consequences (e.g., impact of assisted migration on recipient communities; Schwartz and Martin 2013).

The following sections describe the 23 option types and associated examples from the literature, structured according to four quadrants (intervention classes) in the matrix (A–D, Table 1, Fig. 1) and associated underpinning mechanisms (Box 1, 1–9). We provide examples of specific tools or actions, recognizing that individual tools can enhance adaptation through a range of

### Table 1. High-level structure of the proposed typology of options to facilitate persistence or adaptation of biodiversity and ecosystems in a changing climate.

| Structure | “Low-regrets” options | “Climate-targeted” options |
|-----------|------------------------|---------------------------|
| Evade or ameliorate: Address changing conditions and functions directly | A (4) | B (5) |
| Build adaptive capacity: Enhance the capacity of species and ecosystems to withstand or respond to environmental change | C (10) | D (4) |

**Note:** Numbers in brackets indicate the number of intervention “option types” (see Fig. 1 and Box 1) identified in each high-level intervention class (Quadrants A–D).
different mechanisms and vice-versa. For example, renovation plantings and reserve networks are both tools that can be used to support species and gene migrations by providing connectivity, or to enhance representation of current and future habitats to maximize options for species persistence. The number of papers referring to each option type across our sample of 473 papers is shown in Fig. 2.

**QUADRANT A: LOW-REGRETS OPTIONS TO ADDRESS CHANGING CONDITIONS AND FUNCTIONS**

We recognized four low-regrets option types for directly managing climate-induced changes in ecological environments and functions (Box 1, Fig. 1), representing 13% of scored instances across all studies. Mechanisms underpinning these option types involved (1) ameliorating changes in temperature, precipitation or sea level; (2) managing changing disturbance regimes; (3) avoiding or alleviating unfavorable establishment conditions; and (4) ameliorating the loss of specific ecosystem functions (numbering reflects Box 1). There are multiple low-regrets approaches to achieving each, as elaborated below and listed in Box 1.

**Low-regrets options to ameliorate changing temperature, water availability, or sea levels (1A)**

Expected climate change impacts on environmental conditions and functions are often similar to effects of ecological degradation. For example, removal of vegetation can increase local temperatures, reduce soil water infiltration, or increase vulnerability to storm surges, and climate change is likely to compound these impacts. As such, ecological renovation of degraded environments can offer key low-regrets intervention options.

In the context of rising temperatures, renovation has been used to reestablish shade and promote cooling (Greenwood et al. 2016, Thomas et al. 2016), for example riparian plantings have been shown to benefit salmon (Beechie et al. 2013), beach revegetation can reduce turtle egg incubation temperatures by 2–3°C (Fuentes et al. 2012), and rainforest renovation can...
Box 1. Typology of options to facilitate persistence or adaptation of biodiversity and ecosystems in a changing climate (Table 1, Fig. 1§) showing key examples from the literature of tools and approaches that have been proposed to implement each option.

**EVADE OR AMELIORATE: ADDRESS CHANGING CONDITIONS AND FUNCTIONS DIRECTLY**

| A. ‘Low-regrets’, ‘do anyway’ options | B. ‘Climate-targeted’ options |
|--------------------------------------|-----------------------------|
| 1. Ameliorate rising temperatures, altered water availability or rising sea levels | 1A. Ameliorate changing conditions by renovating degraded ecosystems  
*renovate vegetation cover to reduce temperatures  
*renovate soil and landscape biophysical processes to optimize soil water capture in drying environments  
*remove artificial drainage or release water from other uses to increase water availability in drying environments  
*renovate coastal vegetation (e.g. mangroves) to increase sedimentation as sea-levels rise  

1B. Ameliorate changing conditions by engineering environments  
*Bconstruct shade structures to reduce temperatures  
*install solar-powered sprinklers to cool animals  
*manage release of cold water from storage to reduce stream temperatures  
*irrigate or provide water to enhance water availability  
*thin trees to reduce ecosystem water requirements  
*install snow fences or manage forest density to slow snow-melt and regulate water supply  
*engineer topography to create moisture concentrations  
*engineer coastal barriers (including beach nourishment) or flood control systems to limit inundation |
| 2. Adjust changing disturbance regimes to steer change in desired directions | 2A. Manage changing fire or grazing regimes  
*limit increasing frequency or extent of hot fires through suppression and fuel management  
*maintain low intensity fires to constrain shrub invasions where desired  
*manage changing vegetation-grazing interactions, e.g. suppress herbivore increases by managing habitat or re-introducing predators  

2B. Adjust changing disturbance regimes using physical or chemical interventions  
*apply chemical controls or thin trees to ameliorate increases in pest and disease burdens  
*respond to problematic increases in native vertebrate herbivores directly through culling |
| 3. Evade or alleviate deteriorating plant establishment conditions | 3A. Evade or alleviate increasing establishment limitations using strategic planting or renovation tools  
*plant seedlings to avoid vulnerable germination phase  
*use pre-conditioned seedlings in deep containers  
*create cool or moist planting micro-habitats (e.g. using mulches, water crystals, log collectors or hollows)  
*sow seeds that are able to accrue in seedbanks until suitable conditions prevail  
*plant in high precipitation years or over multiple years  
*adjust planting season according to changing climate  
*coppice to rejuvenate mature plants and avoid vulnerable seedling phase  

3B. Ameliorate loss of specific ecological functions  
4A. Ameliorate loss of functions through active in situ selection of resilient functional species  
*e.g. by using resilient local species expected to continue to provide key functions when undertaking plantings or other renovation efforts  
*e.g. by using appropriate disturbance regimes to favour such species  
*e.g. by preferentially retaining such species during routine thinning operations  

4B1. ‘Functional introductions’ of non-local populations  
*source germplasm from climatically-diverse populations of local species for renovation plantings  
*actively facilitate gene flow from adapted populations into natural populations (e.g. pollen introductions, transplants) to promote persistence of functions  

4B2. ‘Functional introductions’ of non-local species  
*plant other tree species to replace shade, tree hollows and other habitat values  
*introduce resprouting species to cope with increasing fire  
*introduce other species to maintain trophic interactions  

4B3. Engineered structures  
*e.g. install tadpole rearing cups, artificial nest boxes, or burrow structures to replace loss of these services |
| C. ‘Low-regrets’, ‘do anyway’ options | D. ‘Climate-targeted’ options |
|----------------------------------------|-------------------------------|
| **5. Promote \textit{in situ} genetic adaptation of local native species** | **5D. Accelerate adaptation through genetic interventions** |
| 5C. Promote adaptation by promoting genetic diversity | * Introduce more diverse or adapted non-local germplasm |
| * manage for large meta-population sizes, e.g. manage connectivity, conserve large areas, infill within populations | * Apply human assisted-evolution (e.g. genetic engineering or screening and culling of non-adapted genotypes) |
| * use genetically diverse germplasm for ecological renovation | * Manage hybridization processes |
| * apply variable management regimes to favour varied genotypes | * Manage for short generation times to expedite adaptation, e.g. using short fire or harvest intervals |

| 6. Insure against loss of species and functions | |
|---------------------------------|------------------------------------------|
| 6C1. Promote site-scale redundancy through species, functional and structural diversity | 6D. Promote site-scale redundancy in ecological functions by promoting diversity of non-local species |
| * Plant a diversity of local species for ecological renovation | * Include a diversity of non-local species in ecological renovation if local species unlikely to persist |
| * Promote diversity through management (e.g. fire regime, thinning operations in a forestry context) | |
| 6C2. Build in spatial redundancy | |
| * Conserve, manage or renovate large areas | |
| * Conserve, manage or renovate multiple sites | |
| * Minimize further loss | |
| * Create ex-situ populations, e.g. zoos/seedbanks | |
| 6C3. Prepare for contingencies by enabling rapid response | |
| * Increase preparedness for response to harmful events such as crown fires, floods or cyclones | |

| 7. Optimize current and future habitat availability | |
|---------------------------------|------------------------------------------|
| 7C1. Protect, manage or renovate a full range of current and potential future habitats | |
| * E.g. representative land facets | |
| * E.g. land for managed coastal realignment | |
| 7C2. Facilitate species’ persistence by targeting climate-resilient locations | |
| * Protect, manage or renovate climate-resilient areas e.g. cooler parts of species’ ranges, areas not prone to coastal inundation, climate refugia | |

| 8. Assist dispersion to suitable habitats or isolate refugia | |
|---------------------------------|------------------------------------------|
| 8C1. Manipulate landscape connectivity | 8D. Assist species to reach and establish in projected suitable environments outside their current range |
| * Plant for connectivity (afforestation, renovation) | * Actively assist dispersal and colonization |
| * Capture climate gradients in reserves | |
| * Create ecological networks | |
| * Reduce dissection by roads, engineer wildlife crossings | |
| * Conserve leading-edge populations | |
| * Maintain isolation to avoid unwanted incursions | |
| 8C2. Promote local spatial heterogeneity | |
| * Protect, manage or renovate to ensure diverse environments are available within close range, e.g. diverse fire regimes or topographies | |

| 9. Alleviate non-climatic stressors | |
|---------------------------------|------------------------------------------|
| 9C1. Control undesired exotic invasions | 9D. Alleviate natural stressors to help highly valued species or ecosystems withstand climate stress |
| * Apply site-focused measures such as nutrient limitation | * Alleviate natural disease, competitor or predator burdens |
| * Use species-focused measures such as biological control | * Feed animals during normal feed gaps to offset reduced survival due to climate stress |
| 9C2. Avoid or ameliorate anthropogenic degradation | |
| * E.g. Reduce salinization, erosion, stream sediments, pollutants or edge effects; re-introduce predators or other keystone species; renovate facilitative relationships (e.g. mycorrhizas to enhance plant nutrient and water uptake) | |
| * Sustainably manage any ongoing utilization | |

*Each intervention option type (1A-9D) is arranged under its higher-level intervention class (A-D, Table 1, Fig. 1) and the ecological principle or mechanism targeted by the intervention (1-9).*
(a) Number of studies referring to each intervention option type across our sample of 473 studies (see Box 1 for detail of option types). (b) (i) Number of studies referring to each option type summed to indicate representation in the four higher-level intervention classes (total number of instances 1,304), and indicating use of different types of inference; (ii) proportional use of different types of inference for data in i. See Methods for detail on the types of inference.

**Fig. 2.**
reduce temperature maxima by 3°C (Shoo et al. 2011b). Likewise, Pike and Mitchell (2013) proposed that renovating populations of burrow-forming animals can in turn create temperature refuges to facilitate the persistence of a range of commensal species.

Declining water availability can be directly ameliorated by reducing environmental water abstraction (Thomas et al. 2016), removing water-drawing plantations or exotic plants such as in-stream willows in Australia (Doody and Benyon 2011), or removing impoundments and artificial drainage. For example, Ausden (2014) removed artificial drainage to reduce summer drying in UK peatlands and maintain habitat for breeding birds. More indirect renovation measures include promoting ecological interactions that facilitate water conservation, such as reinstating beaver dam building (Stein et al. 2013), and restoring soil and landscape biophysical processes that control ecosystem water availability. The latter includes management of ground cover (e.g., through plantings or by reducing grazing) to minimize run-off, soil erosion, and evaporation and enhance soil-water infiltration, or more intensive options such as soil carbon amendments to renovate soil biological activity and water holding capacity (Prober et al. 2014). Minimizing run-off can in turn reduce fluctuations in-stream flow, leading to lower flood risk and greater dry-season stream flow (Bhave et al. 2016).

The impacts of sea-level rise can be ameliorated using vegetation renovation to reinstate natural coastal defenses against erosion and storm surges (Greenwood et al. 2016), or sometimes to directly ameliorate sea-level rise. For example, Kumara et al. (2010) showed that dense replanting of mangroves promoted surface sediment accretion at rates of 13 mm/yr.

**Low-regrets options to adjust changing disturbance regimes (2A)**

Climate change is likely to alter fire regimes (Peterson et al. 2011), in turn influencing the composition and structure of ecosystems. Despite the importance of climate as a driver of fire regimes, it is feasible to manipulate them to influence the way climate change impacts on species and ecosystems. These interventions are often considered low-regrets because they commonly involve redirection or refinement of existing effort, or offer worthwhile benefits regardless of climate change. We acknowledge that they may at times better fit the climate-targeted category depending on context (e.g., where there are substantial increases in risk or management trade-offs), but do not distinguish among these here.

In productive, fire-prone ecosystems such as the conifer forests of the western United States, dry tropical forests of southern Amazonia, and ash eucalypt forests in Australia, warmer temperatures and longer fire seasons are expected to increase the extent and frequency of fire (Abella et al. 2007, Colloff et al. 2016, Devischer et al. 2016). Management tools to limit potentially transformative crown fires include different types and intensities of fuel treatments (e.g., control burns); allowing naturally ignited fires to burn in mild conditions; rapid fire suppression (Raftoyannis et al. 2013); managing for lower densities or less flammable species mixes (Abella et al. 2007, Cross et al. 2013); or limiting ignitions by restricting visitor access (Baron et al. 2009). Human responses to changing fire regimes can also be managed to reduce cascading impacts such as biodiversity loss due to post-fire salvage logging (Driscoll et al. 2012).

By contrast, propensity for fire can decrease in drying environments when fuel production becomes limiting. In such cases, fire may be strategically applied to promote desired species or ecosystem characteristics such as open grassy woodlands (Prober et al. 2017a). Alternatively, as resilience to fire may decline in drying environments, the frequency of applied fire or related disturbances may need to be adjusted (Maalouf et al. 2012). For example, Ausden (2014) excluded burning and grazing as one of a suite of measures to reduce impacts of drying in peatlands.

Climate change is also expected to influence disturbance regimes other than fire, in particular, the frequency of storms, and herbivore, pest, and disease dynamics. Changing vegetation–herbivore interactions may be managed through context-dependent, low-regrets measures such as controls to prevent overgrazing in production settings (e.g., Driscoll et al. 2012), managing herbivore habitat preferences (e.g., minimizing edge habitat preferred by deer; Frelch and Reich 2009), or managing predator populations (Ritchie et al. 2012). Minor disease or pest outbreaks can be addressed using traditional low-regrets management such as sanitation (Frelch and Reich 2009, Six et al. 2014), but in more severe cases, may require climate-targeted measures (see Quadrant B).

**Low-regrets options to evade or alleviate deteriorating establishment conditions (3A)**

Given that the establishment phase is one of the most vulnerable periods in a species’ life cycle (Chmura et al. 2011), a suite of interventions to limit exposure of juvenile stages to unfavorable environments have been proposed to promote the persistence of valued, long-lived plant species. As they are relatively easy to apply during efforts to reestablish plant communities, these options are typically considered low-regrets in nature. Options already commonly used include planting seedlings rather than seed, pre-conditioning seedlings to improve drought tolerance, or actively engineering cool or moist planting environments (e.g., using planting furrows, mulch, water crystals, or seed coatings; Chmura et al. 2011, Vallejo et al. 2012). Emerging low-regrets options include targeting windows of opportunity for interventions, such as sowing seeds that accrue in seedbanks until suitable establishment conditions occur (Bonebrake et al. 2014), or planting during high-precipitation years or over multiple years. For example, by planting a
perennial prairie grass at moderate density over repeated years until a favorable year was encountered. Wilson (2015) was able to achieve native species dominance in a semiarid North American old field. Another suggestion has been to avoid vulnerable seedling phases altogether by reinstating the historic practice of coppicing to rejuvenate mature plants (Sjolund and Jump 2013).

Low-regrets options to ameliorate loss of specific ecological functions (4A)

As climate change becomes more severe, it is likely that species performing important ecological functions will be unable to persist in situ, threatening the ongoing viability of dependent species. Where other local native species can perform these functions, low-regrets ecological renovation may aim to favor such species; for example, by promoting competitive advantage through disturbance management (Creutzburg et al. 2015), selecting resilient local native species for plantings (Prober et al. 2017a), or in a forestry context, favoring resilient species for retention during routine thinning (Dumroese et al. 2015). Where local native species may not be able to replace these functions, alternative, climate-targeted approaches may be called for, as discussed under 4B1–3.

QUADRANT B: CLIMATE-TARGETED OPTIONS TO EVADE OR AMELIORATE CHANGING CONDITIONS AND FUNCTIONS

Climate-targeted options to ameliorate climate-induced changes in environmental conditions and functions represented 20% of scored instances across all studies. Mechanisms underpinning these interventions paralleled three of the four low-regrets option types (ameliorating changes in temperature, precipitation, or sea level; managing changing disturbance regimes; and ameliorating the loss of specific ecosystem functions), but tools used to manipulate them focused on engineering approaches or other methods that may not be considered desirable in the absence of significant threat of environmental change (Box 1).

Climate-targeted options to ameliorate changing temperature, water availability, or sea levels (1B)

A diverse array of climate-targeted interventions have been proposed to ameliorate climate change-associated environmental change. To ameliorate rising temperatures these include constructing shade structures (Capon et al. 2013), for example for amphibians (Shoo et al. 2011a) or fish (Kurylyk et al. 2015), managing release of cold water from storage to reduce stream temperatures (e.g., Beechie et al. 2013); introducing solar beach sprinklers or “cooler” (paler, coarser) sand to support nesting turtles (Fuentes et al. 2012, Capon et al. 2013); and providing cooler artificial nest boxes for Penguins (Alderman and Hobday 2017).

Climate-targeted interventions proposed to regulate water availability include irrigation (Brang et al. 2014), mechanical tree thinning (Millar and Stephenson 2015), engineering topography to create run-on zones (e.g., benefiting butterflies and plants; Greenwood et al. 2016), and building fences to slow snowmelt (Maurer and Bowling 2014). For example, a series of water storage reservoirs were constructed in UK lowland wet grasslands, to store increasing cool-season precipitation for release in increasingly dry summers (Ausden 2014). Artifical provision of water has also been proposed to support African game species under increasing drought stress (Markham and Malcolm 1996).

Management of sea-level rise (or flooding) commonly includes climate-targeted engineering options such as building physical structures, adding sand or shingle (beach nourishment; Berry et al. 2013), or constructing man-made living reefs (e.g., oyster beds; Lin and Petersen 2013). Engineered structures are highly debated as ecological management tools because, while they can control inundation and help retain riparian or coastal vegetation, they prevent landward migration of tidal vegetation (Hulme 2005, Greenwood et al. 2016). Other novel approaches applied to ameliorate impacts of sea-level rise include creating low-lying coastal islands from shingle to maintain nesting habitat for UK Terns and Plovers (Ausden 2014), and installing culverts to increase freshwater influx, ameliorate rising salinity and conserve saltwater intolerant trees in North Carolina coastal forests (Lin and Petersen 2013).

Climate-targeted options to adjust changing disturbance regimes (2B)

Climate-targeted measures were occasionally proposed in the literature to address climate-induced changes to disturbance regimes. As discussed above, these potentially include adjustments to fire management if they involve high additional costs or risks. More explicitly proposed climate-targeted measures (0.9% of instances) focused on culling to control problematic increases in native vertebrate herbivores, and chemical controls or introduction of disease-resistant varieties and species to achieve outcomes such as suppressing devastating forest die-back (Frelich and Reich 2009, Six et al. 2014).

Climate-targeted options to ameliorate loss of specific ecological functions (4B1-3)

As noted under 4A, it is likely that many species performing important ecological functions will be unable to persist in situ as climate change intensifies. Where local native species are not expected to replace these functions, a suite of climate-targeted interventions can be considered. These include introducing non-local populations or species to maintain ecosystem functions (here termed “functional introductions”; Prober et al. 2012), and provision of engineered structures. We note that “functional introductions” reflect a form of assisted colonization (also...
termed assisted dispersal, managed relocation, or translocation). While assisted colonization is often viewed as a last resort conservation option for at-risk, often iconic taxa (see 8D; Oliver et al. 2012, Schwartz and Martin 2013), assisted colonization measures that aim to replace ecosystem functions are often considered more socially acceptable (Prober et al. 2012, Dumroese et al. 2015). Indeed, functional introductions of non-local populations or species were some of the most commonly recommended options in our sample (summing to 13%, Fig. 2).

First preference may be given to introducing better-adapted provenances or engineered variants of the declining functional species (Prober et al. 2015), variously known as “within-species assisted migration,” “assisted gene flow,” or “genetic translocation” (Sgro et al. 2011, Aitken and Whitlock 2013, Dumroese et al. 2015, Fady et al. 2016). This approach includes a shift from the widely accepted “local is best” paradigm for sourcing germplasm for plantings, to mixed-provenancing strategies that aim to mix local genotypes with non-local genotypes with greater physiological tolerances to future climates (Prober et al. 2015). Such interventions are yet to be proven and need to be undertaken within appropriate genetic risk frameworks (Aitken and Whitlock 2013, Prober et al. 2015, Fady et al. 2016). For example, Benito-Garzon et al. (2013) documented unexpected maladaptation of maritime pine (Pinus pinaster Ait.) populations that had been translocated from warmer to cooler climates, and succumbed to a rare frost event after several decades.

Where a species with valued functions is unlikely to persist (regardless of provenance), replacement species may need to be selected; for example trees and shrubs with strong resprouting capacity (e.g., many oak and eucalypt species) can be introduced to replace predominant obligate-seeding trees (e.g., conifers or ash eucalypts) where changes in fire regime render the persistence of obligate seeders unlikely (Colloff et al. 2016). Along similar lines, non-local, salinity- and flood-tolerant, tree species were introduced into North Carolina coastal forests, to facilitate ongoing provision of habitat for endangered fauna as sea levels rise (Lin and Petersen 2013). Lin and Petersen (2013) called this approach “guided transition,” whereby socially and environmentally important ecosystem functions are identified as a basis for managing change.

Where replacement of functional species is too slow or not feasible, engineered structures may also be considered for replacing some ecosystem functions. For example, artificial roosting, nesting, burrowing, or tadpole-rearing structures can help maintain habitat for associated fauna (Shoo et al. 2011a, Capon et al. 2013, Prober et al. 2017a).

**QUADRANT C: LOW-REGRETS OPTIONS TO ENHANCE CAPACITY TO WITHSTAND OR RESPOND TO CHANGE**

While changed climate conditions and associated changes in ecosystem functions are potential direct targets for climate-adapted conservation management, the most widely promoted suite of interventions involved low-regrets options to increase the resilience and adaptability of native species, ecosystems and landscapes to such changes (56% of suggestions, Fig. 2; Morecroft et al. 2012, Prober et al. 2012). These involved five target underpinning mechanisms, including (5) promoting in situ genetic adaptation capacity; (6) insuring against loss of species and functions; (7) optimizing current and future habitat availability; (8) managing dispersion to suitable habitats; and (9) alleviating non-climatic anthropogenic stressors (numbered as per Box 1). As described in the five subsections that follow, a wide suite of low-regrets tools have been applied or proposed toward facilitating climate adaptation via these mechanisms.

**Low-regrets options to promote in situ genetic adaptation (5C)**

Fady et al. (2016) argue that, where climate shifts are not too steep, the diversity of local genetic resources are likely to be adequate for many tree species to adapt to climate change. Maintaining genetic diversity thus offers a low-regrets means to promote climate adaptation, potentially achieved by managing for large meta-population sizes (at the same time reducing the likelihood that population sizes will fall below critical, non-genetic thresholds; Sgro et al. 2011). Large meta-population sizes in turn can be achieved by protecting or renovating large areas, ensuring connectivity to support gene flow between patches (Sgro et al. 2011, Oliver et al. 2012, Hagerman and Satterfield 2014), or where small populations have not reached carrying capacity, increasing the number of individuals in a population (Maschinski et al. 2011). Other approaches to promoting local genetic diversity include ensuring high quality, genetically diverse propagules are used for ecological plantings (Broadhurst et al. 2008), or by application of variable management regimes that select for diversity by exposing species to varied light, soil moisture, or other environments (Dolan et al. 2008, Brang et al. 2014). For example, in an endangered perennial forb endemic to Florida scrub, Dolan et al. (2008) found that allele frequencies of regenerating populations showed marked shifts after fire.

**Low-regrets options to insure against loss of species and functions (6C1-3)**

Species’ functional and structural diversity are widely recognized attributes for conferring ecosystem resilience, whereby functional redundancies insure against loss of ecosystem functions even where some taxa fail to persist (Folke et al. 2004). A meta-analysis across 46 grassland experiments supported this concept, demonstrating that productivity of depauperate grasslands (1–2 species) declined by an average of 50% under moderate, brief, prolonged, wet or dry climate events, whereas productivity of diverse grasslands (16–32 species) declined by only 25% (Isbell et al. 2015). Similarly, tree stands of mixed species,
age, structure, and functional types are more resistant to disturbances, including wind damage and beetle attack, and are expected to cope better in new conditions (Brang et al. 2014).

Promoting such diversity is thus a commonly proposed measure to facilitate climate adaptation. Low-regrets measures to promote species diversity include use of diverse local species mixes in ecological plantings, or diversity-promoting management. In facilitating forest reestablishment after logging, for example, creating variations in light conditions (including thinning), enrichment plantings, and ungaulate control have been used to increase species’ structural and functional diversity (Neill and Puettmann 2013, Brang et al. 2014, Dumroese et al. 2015). Neill and Puettmann (2013) showed that thinning young stands increased species diversity and consequently increased the probability that wildlife habitat features (such as insect pollination, berry production) were maintained under climate change conditions.

Other low-regrets approaches to insuring against losses are to establish contingencies or plan for rapid response in order to limit impacts of extreme events (Lindenmayer et al. 2010). In particular, maintaining or increasing spatial redundancy increases the chance that at least some examples of a species or ecological community will persist (Oliver et al. 2012). This “bigger, better, more” approach promotes conserving species or ecological communities at multiple sites, conserving large areas, establishing ex situ populations or seedbanks, and avoiding losses through other anthropogenic developments. Rapid response includes readiness to reseed after wildfire, as has been undertaken in sagebrush steppe and fire-sensitive ash eucalypt forest (Creutzburg et al. 2015, Collof et al. 2016).

Low-regrets options to optimize current and future habitat availability (7C1-2)

Contemporary spatial planning approaches to nature conservation typically prioritize representation of ecological communities to capture the conservation needs of most species. This approach is likely to need adjustment as species reorganize under climate change (Hannah et al. 2002, Strange et al. 2011), hence parallel approaches are increasingly proposed to maximize capture of future species and ecological community distributions (8% of recommendations). In particular, low-regrets approaches propose to protect, manage or renovate a full range of current and potential future habitats through geophysical representation (e.g., using concepts such as land facets or geophysical diversity [Beier and Brost 2010] or by targeting climate diversity [Heller et al. 2013]). This concept incorporates managed realignment of coastlines, i.e., the need to spare land suitable for landward-moving coastal species and ecosystems (e.g., Enwright et al. 2016). Another common approach uses projections of species distributions to identify and ensure representation of future species’ habitats (Jones et al. 2016). These approaches are likely to require greater land area under conservation, so some authors propose concepts such as redirection of resources from currently protected to new sites; however, transaction costs limit potential financial savings in this regard (Strange et al. 2011).

Targeting areas with low projected degrees of climate change is another low-regrets approach that has been a strong focus for helping to maintain habitat for at-risk species and communities. For example, Crossman et al. (2012) identified the coolest and wettest areas in the landscape to target for restoration actions; and investments to conserve European coastal marshes have targeted areas that are not vulnerable to coastal flooding (Ausden 2014). Particular attention is often given to managing or renovating places expected to act as climate refugia, i.e., habitats that “components of biodiversity retreat to, persist in and can potentially expand from” as the climate changes (Keppel et al. 2012). For example, Shoo et al. (2010) demonstrated up to 10°C reduction in thermal extremes in mountaintop boulder fields, suggesting these could be important refugia for critically endangered frogs, and protection of cold water refuges in streams is commonly promoted for conservation of salmonid fish (e.g., Stein et al. 2013).

Low-regrets options to assist dispersion to suitable habitats or isolate refugia (8C1-2)

Supporting natural gene and species migrations toward appropriate climates by ensuring adequate connectivity was the most widely proposed action for helping biodiversity adapt to climate change (12% of instances; Heller and Zavaleta 2009, Sgro et al. 2011, Oliver et al. 2012, Lister et al. 2015). This low-regrets approach aims to connect suitable habitat along relevant environmental gradients, particularly through ecological renovation or protection, as implemented, for example, in reserves in the Cape Floristic Region (Sgro et al. 2011). Other approaches to increasing connectivity include minimizing fragmentation by barriers such as roads or vermin-proof fences (Lister et al. 2015); providing wildlife crossings (Lister et al. 2015); reducing the impermeability of intensively used landscapes, for example by incorporating woody cropping systems or urban green spaces (Oliver et al. 2012, Hagerman and Satterfield 2014); and restoring natural flow regimes to allow cold water fish to find suitable thermal conditions (Baron et al. 2009). Lawson et al. (2014) for example, found that conservation management of fragmented chalk grasslands in the UK facilitated range shifts in the silver-spotted skipper butterfly (Hesperia comma Linnaeus, 1758).

While connectivity is widely promoted, the value of physical corridors for promoting migrations has been questioned, especially in relation to differential dispersal capacities among species (Morecroft et al. 2012). Maintaining isolation or even reducing connectivity could be important in specific situations. For example, rare
species or rear-edge populations with low dispersal abilities may be better protected by isolation to avoid threats such as fire or encroachment by other migrating species, particularly exotics that may be superior colonizers (Morecroft et al. 2012).

At the landscape scale, maximizing local-scale spatial heterogeneity is another low-regrets way to facilitate species’ dispersion to suitable habitat, and may also assist in suppressing extensive wildfires (Peterson et al. 2011, Oliver et al. 2012, Albano 2015). A diverse range of habitats within a landscape can be achieved by targeting ecosystem renovation toward the least-represented habitats (e.g., those most affected by human use), designing reserve networks using geophysical diversity criteria at local to regional scales (Albano 2015) or applying varied fire and other disturbance regimes (Peterson et al. 2011).

Low-regrets options to alleviate non-climatic, anthropogenic stressors (9C1-2)

Climate change represents just one of many anthropogenic pressures on biodiversity and ecosystems, hence it is widely argued that alleviating non-climate-related anthropogenic stressors is a key, low-regrets approach to strengthening the resilience of species and ecosystems to climate change (Baron et al. 2009, Prober et al. 2012, Stein et al. 2013). These include measures such as buffer zones to limit edge effects in agricultural or urban landscapes, pollution control, soil nutrient management, and restoring symbiotic interactions (Ferrazzano and Williamson 2013, Gillson et al. 2013). For example, when reintroducing an endangered herbaceous perennial plant species to Texan savanna woodlands, Ferrazzano and Williamson (2013) found that mycorrhizal inoculation improved its growth significantly during periods of drought, consistent with the capacity of mycorrhizal fungi to enhance water uptake in host plants.

Another important way to alleviate anthropogenic stressors is to control invasive exotic species that are likely competitors or predators of native species (Driscol et al. 2012). Controlling invasive exotics is also important for promoting ecosystem reassembly by native rather than exotic species, given the potential advantage to exotic species that have already demonstrated the capacity to colonize new environments (Sorte et al. 2013). Investments in exotic species control are best supported by prioritization of target species from the perspective of transformer capacity and likelihood of spread under future climates (Gosper et al. 2015). There is also an increasing need to clarify the definition of exotic status as species move in response to climate change (Webber and Scott 2012, Prober et al. 2017b).

Quadrant D: Climate-Targeted Options to Enhance Capacity to Withstand or Respond to Change

As the pace of climate change increases, building the natural resilience and adaptive capacity of species and ecosystems may become insufficient to meet nature conservation goals (e.g., Burrows et al. 2014, Williams et al. 2014). Researchers and managers have thus also implemented or proposed climate-targeted options to facilitate species’ and ecosystem response to climate change (12% of instances, Box 1, Figs. 1, 2). These were underpinned by four of the five mechanisms that underpinned low-regrets options, but involved more intensive interventions and were more restricted in range. The key underpinning mechanisms include (numbered as per Box 1) (5) promoting in situ genetic adaptation capacity; (6) insuring against loss of species and functions; (8) managing dispersion to suitable habitats; and (9) alleviating natural non-climatic stressors. While option types in this quadrant were some of the less frequently mentioned, one such option, assisted colonization, was the second-most widely considered in our sample of studies (9% of suggestions, Fig. 2).

Climate-targeted options to promote in situ genetic adaptation (5D)

By contrast with Fady et al. (2016) who argue that diversity of local genetic resources may be adequate for tree species to adapt to climate change, other authors suggest that many species and populations may not be able to adapt fast enough (Dumroese et al. 2015, Millar and Stephenson 2015). Consequently, they argue that active, climate-targeted, genetic interventions will be needed to facilitate adaptation. Human-assisted movement of better-adapted genotypes can be used in this context to accelerate genetic adaptation in natural populations (e.g., Aitken and Whitlock 2013). Other proposed interventions include artificial selection of adapted individuals within local populations (van Oppen et al. 2015), adaptive hybridization (Becker et al. 2013), or genetic engineering (Dumroese et al. 2015). The latter is already being undertaken for the American chestnut (Castanea dentata (Marshall) Borkh.) in the United States due to devastation by chestnut blight (Cryphonectria parasitica (Murrill) Barr), and in the race to conserve the world’s coral reefs (e.g., van Oppen et al. 2015), but such applications still face regulatory barriers owing to concerns such as potential invasion risk (van Oppen et al. 2015). Another means to accelerate natural adaptation rates is to manage for short generation times; for example, by using short fire or harvest intervals (Joyce et al. 2009).

Climate-targeted options to insure against loss of functions (6D)

Management for species and functional diversity to insure against climate change-driven loss of ecological functions is typically viewed as a low-regrets option, assuming that this diversity is contributed by local native species. Extending from such low-regrets options are more-interventionist climate-targeted options. In particular, where few native species are expected to persist, wider
mixes of local and non-local species could be used in ecological renovation to build resilience to change. While use of non-local rather than local species to promote diversity was rarely explicitly expressed (0.1% of incidences; Duve neck and Scheller 2015), such strategies may be implicit in some contexts (e.g., production forestry; Brang et al. 2014). Introduction of non-local species to mixed plantings could proceed using principles and approaches discussed under “functional introductions.”

Climate-targeted options to facilitate dispersion to suitable habitats (8D)

Assisted colonization is one of the most widely proposed and widely debated options to facilitate nature conservation in a changing climate. This climate-targeted option is typically applied or proposed to help threatened or valued species establish in projected suitable habitat outside their current range (Oliver et al. 2012, Schwartz and Martin 2013). It addresses the same underpinning mechanism as low-regrets approaches that build connectivity (8C1), i.e., facilitating species dispersion to suitable habitats, but is considered where natural dispersion is unlikely to meet conservation goals. The approach is often contested owing to potential negative consequences to the recipient ecosystem or even to the target species; hence much of the literature revolves around methodological, ethical, and legal debate (Schwartz and Martin 2013), with fewer examples of successful application (Willis et al. 2009, Van der Veken et al. 2012). Nevertheless, there are numerous examples of success in non-climate-related translocation efforts (Soorae 2016).

Climate-targeted options to alleviate non-climatic stressors (9D)

Parallel to the concept of ameliorating anthropogenic stressors (see 9C1–2), managing natural stressors such as natural diseases or resource-availability gaps, is a creative, climate-targeted measure occasionally recommended to buffer target species or communities from climate stress (0.8% of instances). For example, reducing natural parasite infestations in chicks of a rare Tasmanian Albatross is compensating for reductions in breeding success due to the warming climate (Alderman and Hobday 2017); and simulations suggest supplemental feeding of threatened New Zealand his (Notiomystis cincta Du Bus, 1839) could delay their extinction under climate change (Correia et al. 2015).

Discussion: Drawing insights from the typology

Our typology provides a synopsis of intervention options to facilitate nature conservation as the climate changes (Box 1, Fig. 1). The following sections highlight four key insights regarding the status of research and thinking in climate adaptation for nature conservation, that we drew from our analyses of patterns in the options recommended (Figs. 2–4), and our assessment of how different option types addressed emerging principles for nature conservation in a changing climate (Prober et al. 2017b) (Fig. 5).

There are no simple solutions to helping nature adapt to climate change

The first clear implication is that most option types are unlikely to adequately address all principles for
nature conservation under climate change (Prober et al. 2017). In particular, maintaining evolutionary character and maintaining wildness were typically the most poorly accounted for, whereas optimizing ecosystem functions and minimizing species losses were more often scored as strongly supported (Fig. 5). Only one of the 23 option types, maintaining high genetic diversity to promote genetic capacity to adapt (5C), was considered likely to strongly support all five principles (Fig. 5). Nevertheless, five option types were considered to
provide some benefit toward all five principles. Most of these (particularly building spatial redundancy [6C2], conserving current and potential future habitats [7C1], and manipulating landscape connectivity [8C1]) require increased area of land managed for nature conservation and coordinated implementation at large scales. This highlights the importance of such approaches despite potential challenges to implement at sufficient scale to effect widespread adaptation. The lack of simple solutions is not surprising but is important to emphasize, given that real-world action requires choosing a limited set of options to pursue (e.g., studies describing on-ground implementation included an average of 3.9 option types). Our analysis (Fig. 5) instead highlights the need for a strategic approach to adequately maintain the basic qualities much valued in nature; for example, by explicitly planning for a range of complementary or even conflicting actions that may not fulfil all needs in one place but collectively could accommodate them at a broader scale.

Certain types of intervention options dominate the literature

A second striking insight is that despite the diversity of ideas for intervention (Box 1), a certain subset of options garner most of the attention in the literature (Figs. 2–4). In particular, low-regrets options intended to build the capacity of species and ecosystems to persist or adapt on their own (category C), have been given about three times the amount of attention in the literature as any other intervention class (Fig. 2b), and include 10 option types compared with four or five in other categories (Table 1). This trend is largely consistent across years, geographic regions, ecosystem types, and species groups (Figs. 3, 4). Across all intervention classes, the scientific literature addressing climate intervention options has burgeoned since 2008, rising in our sample from 0–10 papers per year from 1992–2007, to 49–77 papers per year since 2011 (Fig. 3a). Yet Fig. 2b shows how much of the rise is due to interest in low-regrets approaches that build adaptive capacity. By contrast, Fig. 2a shows that more than one-half of the climate-targeted option types are at the lower end of the frequency distribution, with mentions in <6% of the papers included in the review. Notwithstanding this lower interest, two climate-targeted option types are among those most frequently addressed in the literature (8D, assisted colonization, and 4B2, functional introductions of non-local species).

This pattern of disproportionate attention paid to low-regrets options to build adaptive capacity is in many ways desirable. Low-regrets options tended to be scored as strongly supporting more of the nature conservation principles than climate-targeted options (Fig. 5) and, by definition, were rarely scored as working against them. For these reasons, they are often preferred by managers and researchers and building adaptive capacity may also be more likely to have multiple benefits to a wider range of species and ecosystems (Wilby et al. 2010, Hagerman and Satterfield 2014, Hajjar and Kozak 2015).

However, the strong emphasis on low-regrets approaches to build adaptive capacity raises some
There are inherent trade-offs between climate-targeted options and “wildness”

The final insight we draw attention to is the trade-off between climate-targeted approaches and maintaining or recreating wild natural areas with minimum human intervention. This is evident in Fig. 5, which shows that all climate-targeted options were considered likely to work against the conservation goal of maintaining or recreating wild areas. This is expected because climate-targeted options characteristically involve hands-on intervention, creating an inherent contradiction with concepts of wildness in nature.

A consequence of this trade-off is that, as climate change accelerates, society may be forced to be much more explicit about what is valued in wildness, and consider how core elements of wildness could be maintained despite more-interventionist approaches. For example, it would be possible to replace the simple dichotomy between wild and not wild with a scale from intensive to “light-touch” (including zero) interventions (see also Heller and Hobbs 2014). These challenges are already relevant to the concept of “rewilding” (e.g., Corlett 2016), which typically requires human interventions to reestablish characteristics of wild systems, notably resulting in many ambiguous (no consensus) scores in Fig. 5. More broadly, the issue can again be addressed by planning to capture a variety of values at regional scales, potentially including wildness.

While the focus of this review is on the terrestrial realm, a case in point is the trade-off between wildness and intervention already proceeding for the world’s coral reefs (e.g., van Oppen et al. 2015). If warming and ocean acidification trends continue, it is highly unlikely that low-regrets approaches to build the resilience and adaptive capacity of coral reefs will be enough to support most reefs as currently known. It is pertinent that, as the situation has become more urgent, researchers are indeed increasingly exploring highly interventionist approaches (e.g., genetic engineering) to maintain some of what we currently value about coral reefs (e.g., ecotourism, beauty, biodiversity), even though these approaches challenge societal values regarding wildness (van Oppen et al. 2015).

NEW DIRECTIONS: PREPARING FOR A CONCEPTUAL SHIFT IN ADAPTING NATURE CONSERVATION TO CLIMATE CHANGE

Our review and the insights we have generated from our typology suggest that, while attention to climate change is dramatically increasing in nature conservation research and implementation, there are challenges in shifting the paradigm from ecological “restoration” to “renovation.” A multitude of intervention options have been proposed, but there is limited empirical evidence for their effectiveness. There are unresolved trade-offs in their application and proposed options predominantly focus on supporting the natural capacity of ecosystems and species themselves to adapt. While the latter is an important priority, the pressures biodiversity and ecosystems are...
expected to experience as the velocity of climate change increases (Burrows et al. 2014, Williams et al. 2014) suggest that a broader emphasis is needed.

One reason why the ecological research community is paying less attention to the more challenging climate-targeted intervention options may be because their implementation requires a substantial conceptual shift in how nature is viewed and valued, and thus how nature conservation is approached (Martin et al. 2016, Rosa et al. 2017). The inherent trade-offs we identified between intervention and wildness typify this. As climate change intensifies, these trade-offs will become more apparent and could eventually force a change in thinking and policies that currently preference “restoration” as a goal.

The role of ecological research may thus be to help lay the groundwork that enables this paradigm shift, as well as to overcome other barriers we identified that limit development and testing of the best possible toolkit for ecological management under climate change. The following sections expand on three key pillars of activity where ecological research could best help prepare for these goals.

**Foster discourse about linkages between societal values and conservation in a climate change context**

Our review identified a diverse suite of options regarding how society might act to facilitate nature conservation in a changing climate. However, public discourse about the values society holds about nature as the climate changes, and hence how to decide which options to apply, remains highly limited (Stein et al. 2013, Corlett 2016, Martin et al. 2016, Pascual et al. 2017, Prober et al. 2017b). Shaping new goals will require escalation and expansion of public discourse so that decisions can be grounded in societal values that have been explicitly articulated.

This discourse could be facilitated by an interdisciplinary research context (e.g., Bennett et al. 2017), within which ecological researchers can contribute by helping to predict potential futures associated with different intervention scenarios (Rosa et al. 2017). This includes understanding the consequences of “do-nothing” options; a key question, for example, is whether even large, wild areas will suffer substantial decline in diversity, loss of functional types (e.g., slow dispersers), and/or deterioration of key functions. Clearly articulating or visualizing possible futures, grounded in foresighting and projections that acknowledge uncertainty, can be a powerful tool for fostering conversations about values (Ferrier et al. 2016, Rosa et al. 2017]). In many instances, projections may involve biodiverse, functioning, ecological systems that simply look and feel very different from those of today, and so may not garner widespread support for what are likely to be confronting interventions. However, a likelihood of undesirable outcomes such as catastrophic biodiversity decline, loss of iconic species, desertification, or plummeting recreational and economic values (e.g., Newbold et al. 2016, Bland et al. 2017), may intensify demand for more climate-targeted ecological interventions.

**Adapt and upscale conservation planning to accommodate climate-adjusted conservation goals**

Comparison of our typology against potential nature conservation principles in Fig. 5 highlighted that it may be difficult to pursue all values in any one location or with any small set of adaptation approaches. Rather, it is likely that even more so than has been required to date, different conservation goals will need to be met in different places, and coordinated planning will need to be upscaled to permit broader contexts that accommodate inevitable movements of species and biomes (Prober et al. 2017b). This calls for ecological researchers and land managers to actively extend and experiment with traditional conservation planning tools to explicitly accommodate new nature conservation principles as the climate changes (e.g., Reside et al. 2018), in turn helping to ensure active participation in societal discourse (e.g., Hill et al. 2015).

Planning for this bigger picture view also has critical implications for research into intervention options. Modeling and field studies most frequently explore the utility of intervention options individually or in limited combinations (on average in our data set, field and empirical studies addressed 1.2 and modeling studies addressed 1.7 intervention options types per study). For example, analyses might target the value of protecting climate refugia (e.g., Kurylyk et al. 2015) but not incorporate how that might interact with other actions like manipulating landscape connectivity. As a part of the paradigm shift in how we approach nature conservation, increasing the breadth of options researched and implemented could best be achieved by integrating the adaptation perspective into all nature conservation activity rather than viewing it as a set of discrete additional actions (Burch et al. 2014).

**Expedite innovation and testing of intervention options**

Work ahead of the curve to develop viable options.—

Given the looming choices society faces as climate change increasingly impacts species and ecosystems (Burrows et al. 2014, Williams et al. 2014) and the limited empirical evidence available for the effectiveness of intervention options, it is critical for ecological researchers and managers to stay “ahead of the curve” to assemble a well-substantiated suite of options. This includes thinking of creative new alternatives, refining emerging options, and investigating their efficacy, to avoid accidentally being left with a very slim tool kit when change accelerates and/or catastrophic climate-change-related events inevitably arise.

Empirical observation and experimentation can be key pathways not only for testing efficacy, but for revealing the unexpected, leading to greater understanding and triggering new directions (Mariani 2008). A greater emphasis on empirical investigation, for example, how
best to direct land use change to favor rather than com-
pe with nature conservation [Popp et al. 2017]), how to
manipulate soil microbial communities to promote
ecosystem adaptation (Bardgett and van der Putten
2014), or whether emerging technologies such as
CRISPR/Cas9 and gene drives can be used to control
emerging transformer exotic species (Piaggio et al. 2017),
may therefore in itself help to generate new ideas and
solutions. It goes without saying that the application of
leading-edge capabilities such as CRISPR/Cas9 require
substantial ethical discourse prior to implementation.
Proven processes for eliciting innovation and stimulating
creativity, including collaborations among disciplines and
other deliberative learning processes (Aslan et al. 2014)
could also be used to generate new ideas.

Focal areas for future investigation could also aim to
fill gaps identified by our analysis, including improved
geo-graphic and biotic representation and greater atten-
tion to developing and testing creative climate-targeted
options within an appropriate risk management frame-
work. The latter might favor options that help set sus-
tainable and desirable future trajectories (e.g.,
provenance and species introductions; 4B1, 4B2, 6D),
rather than those requiring repeated application (e.g.,
repeated culling or chemical controls; 2B).

Reconceptualize empirical approaches to generate evi-
dence for effectiveness of interventions.—While we pro-
spose that empirical observation and experimentation
offer dual solutions to both stimulate and test adapta-
tion ideas, we have already recognized that empirical
research on climate adaptation faces serious challenges.
Efforts to build empirical evidence may only be success-
fu by reconceptualizing empirical approaches to
account for these challenges. Effective learning systems
suited to this context could include (1) establishing pro-
cesses to rapidly but intensively test intervention options,
for example, by identifying early indicators of success or
increasing the use of climate controlled facilities; (2)
building conceptual models of ecosystem dynamics to
ensure that the range of interacting drivers are factored
in when testing options; (3) capitalizing on the growing
global network of ecosystem observatories monitoring
ecosystem responses to trending climatic averages and
extreme events (e.g., Karan et al. 2016); (4) using deci-
sion frameworks such as adaptation pathways
approaches (Colloff et al. 2016, Prober et al. 2017a) to
structure research, for example, by identifying and moni-
toring decision points then documenting ecosystem
responses to actions triggered by these decision points;
(5) testing renovation options in degraded sites or land-
scapes (e.g., fragmented agricultural landscapes) to capi-
talize on existing investment in ecological restoration
and limit risk to areas of high ecological integrity; (6)
actively integrating relevant empirical evidence drawn
from studies undertaken in a non-climate-change con-
text; and (7) learning from space-for-time substitutio-
ners, i.e., from the social and ecological methods that help
pave the way forward in parts of the globe that are
forced to confront the paradigm shift early.

CONCLUSIONS

Impacts of climate change on species and ecosystems
are escalating worldwide (Scheffers et al. 2016, Pecl
et al. 2017), demanding urgent investment to learn how
best to facilitate adaptation (Heller and Zavaleta 2009,
Oliver et al. 2012, Stein et al. 2013, Hagerman and Sat-
terfield 2014). This review and our use of a typology to
explore the fast-moving field of climate adaptation in
nature conservation have shown that there has been bur-
goeing attention to a diverse and creative array of cli-
mate-adapted intervention options in the literature since
2008, including options to evade or ameliorate climate-
induced change in environments or ecological functions,
and options to build the inherent resilience and adaptive
capacity of species and ecosystems.

Notwithstanding this growing attention, the climate
adaptation toolkit is still limited by a notable lack of
empirical evidence for effectiveness, unresolved trade-offs
in application, bias toward studies focusing on forests,
trees, and vertebrates, and substantial gaps in geographic
evidence. Further, proposed options predominantly focus
on supporting the natural capacity of ecosystems and spe-
cies themselves to adapt, with much less exploration of
bolder adaptation responses. Low-regrets responses such
as these are justifiable, but the possibility that this may
not be enough needs to be confronted, shifting the para-
digm to humans as “renovators” of dynamic systems
rather than “restorers” of a prior world.

To achieve this, ecological researchers in climate change
and nature conservation need to take some deliberate new
directions, including (1) playing an active supporting role
in public and policy discourse about what society values in
nature, (2) actively advancing planning approaches that
help to accommodate a range of values, and (3) expediting
the generation and testing of new ideas through experi-
ment, interdisciplinary interactions and reconceptualizing
empirical approaches.

ACKNOWLEDGMENTS

This review was co-funded by the Australian Government
Department of the Environment and Energy, and the Common-
wealth Scientific and Industrial Research Organisation (CSIRO)
Australia as part of its partnership on the Biodiversity
Knowledge Projects series (https://research.csiro.au/biodiversity-
knowledge/). We thank Carl Gosper and Emma Woodward for
helpful comments on an earlier version of this manuscript. All
authors assisted in designing the study, establishing the typology
and writing the manuscript. S. M. Prober undertook the litera-
ture search and scoring, and led the writing; V. A. Doerr and S.
M. Prober led the data interpretation and assessment against cli-
mate-adapted nature conservation principles.

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SUPPORTING INFORMATION
Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecm.1333/full

DATA AVAILABILITY
Data are available from the CSIRO Data Access Portal: https://doi.org/10.25919/5b8861aa54b88b