A Science Agenda to Inform Natural Resource Management Decisions in an Era of Ecological Transformation

SHELLEY D. CRAUSBAY, HELEN R. SOFAER, AMANDA E. CRAVENS, BRIAN C. CHAFFIN, KATHERINE R. CLIFFORD, JOHN E. GROSS, CORRINE N. KNAPP, DAVID J. LAWRENCE, DAWN R. MAGNESS, ABRAHAM J. MILLER-RUSHING, GREGOR W. SCHUURMAN, AND CAMILLE S. STEVENS-RUMANN

Earth is experiencing widespread ecological transformation in terrestrial, freshwater, and marine ecosystems that is attributable to directional environmental changes, especially intensifying climate change. To better steward ecosystems facing unprecedented and lasting change, a new management paradigm is forming, supported by a decision-oriented framework that presents three distinct management choices: resist, accept, or direct the ecological trajectory. To make these choices strategically, managers seek to understand the nature of the transformation that could occur if change is accepted while identifying opportunities to intervene to resist or direct change. In this article, we seek to inspire a research agenda for transformation science that is focused on ecological and social science and based on five central questions that align with the resist–accept–direct (RAD) framework. Development of transformation science is needed to apply the RAD framework and support natural resource management and conservation on our rapidly changing planet.

Keywords: climate change adaptation, ecological scenarios, ecological transformation, ecological trajectories, resist–accept–direct framework, transformation science

Directional environmental changes, especially intensifying climate change, are fundamentally transforming Earth's ecosystems through persistent changes in ecological composition, structure, and function within management-relevant time frames (years to decades; Steffen et al. 2018, NAS 2019, Coop et al. 2020, Williams et al. 2020). Natural resource managers around the world understand that the rates and magnitudes of modern global change challenge the viability of longstanding management philosophies, cultures, and mandates built on the assumption that the climate of the future—and therefore what is ecologically possible in a given place—will reflect the past (e.g., US Forest Service's 2012 Forest Planning Rule, US Fish and Wildlife Service policies on habitat management in wildlife refuges, USFWS 2002; as was discussed in Schuurman et al. 2021; see also Millar et al. 2007). Managers of systems as divergent as water supplies, rangelands, and marine fisheries are now contemplating a broader spectrum of responses to rapid directional change and are gravitating toward forward-looking management approaches that reckon with nonstationarity (e.g., Milly et al. 2008, Brown et al. 2017, Ingeman et al. 2019). While a new paradigm to guide and support twenty-first-century natural resource stewardship slowly forms, a three-part decision-oriented framework has emerged through a broad collaborative effort among multiple US federal and state agencies, nongovernmental organizations, academics, and international partner organizations (Schuurman et al. 2021). This framework aims to inform natural resource managers' decisions in a nonstationary world to strategically resist, accept, or direct ecological trajectories. Resisting change means sustaining existing conditions or, where change has occurred, restoring historical or "natural" characteristics via actions including increasing or maintaining ecological resistance and resilience (Connell and Ghedini 2015, Crist et al. 2019). Accepting change accommodates new suites of species and ecological conditions in a site without intervening. Directing change involves intervening to guide the trajectory toward preferred ecological outcomes that differ from historical or current conditions. Such states would ideally be sustainable, at least for a while, under ongoing climate change and other directional stressors. This three-part concept of deciding to resist, accept, or direct ecological transformation (box 1) is the resist–accept–direct (RAD) framework for natural resource management (Schuurman et al. 2020, 2021, Thompson et al. 2021, Lynch et al. 2021a). This framework

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Box 1. What is ecological transformation?

Ecological transformation has been characterized in multiple ways and has been approached from many perspectives. Transformation of a system is a concept that is both theoretically and empirically grounded, from chemistry to climate to economics to politics, and in ecology is variously described as state shift (Barnosky et al. 2012), regime shift (Francis and Hare 1994, Biggs et al. 2018), state change (Stringham et al. 2003), type conversion (Jacobsen and Pratt 2018), tipping point (Selkoe et al. 2015), abrupt change in ecological systems (Turner et al. 2020), ecological threshold (Groffman et al. 2006), social–ecological transformation (Olsson et al. 2004), social–ecological collapse (Cumming and Peterson 2017), ecosystem collapse (Lindenmayer et al. 2016), ecosystem transformation (Huntington et al. 2020), or ecosystem shift (Warszawski et al. 2013), among other terms. Each term has a different focus, based on the particular drivers, rates of change, or hierarchical levels of ecosystems it uses as indicators. Because ecological transformation is a pervasive phenomenon that manifests in myriad ways (Lindenmayer et al. 2016), and at different rates (Hughes et al. 2013, Williams et al. 2020), we take a broad view of this widespread phenomenon. We encompass all the multiple terms above by defining *ecological transformation* to mean "the dramatic and irreversible shift in multiple ecological characteristics of an ecosystem, the basis of which is a high degree of turnover in ecological communities." Species composition of ecological communities is a key characteristic of ecosystems that relates to structure, function, and provision of services. Species turnover, or the number of different species eliminated and replaced over time, is a key commonality for ecological transformation, which is generally exemplified by a shift in dominance among organisms with different life forms (Scheffer et al. 2001). Species are also highly valued by people and remain the most common and clear management target for natural resource managers. Species also tend to be the focus of mandates for natural resource managers (e.g., Migratory Bird Treaty Act of 1918, 16 USC 703–712, Endangered Species Act, 16 USC §1531 et seq., Environment Protection and Biodiversity Conservation Act 1999 (Cth) s 178 (Austl.), Wildlife and Countryside Act 1981, c. 69 (UK), Species at Risk Act, S.C. 2002, c. 29 (Can.)), and many management levers include manipulating species composition and abundance (e.g., setting harvest levels, removing invasive species, restoring apex predators, thinning tree species, reseeding after fire). Climate change is altering the distribution and abundance of many of Earth's species and increasing species turnover rates (Parmesan and Yohe 2003, Foden et al. 2008, Chen et al. 2011, Staudinger et al. 2013, Pecl et al. 2017, Bonebrake et al. 2018, Stanke et al. 2021). With ongoing climate change, natural resource managers perceive, quantify, and anticipate changes in species composition in the areas they manage, including colonization, extirpation, and high species turnover rates (e.g., Wu et al. 2018). Grounding transformation science in species turnover and ecological trajectories can readily connect science to RAD management decisions.

is a simple, flexible decision-making structure that focuses on manager intent, identifies manager actions, and encompasses the entire decision space for stewarding ecological trajectories. The RAD framework could also apply to single-species management, but in the present article, we focus on its application in transforming systems.

Even before natural resource management began to grapple with nonstationarity, a nascent science was developing across diverse ecosystems including forest, grassland, freshwater, and marine systems to characterize and conceptualize ecological transformation (box 1; e.g., Davis 1969, Holling 1973, Berryman and Millstein 1989, Anderson and Piatt 1999, Gunderson and Holling 2002, Bestelmeyer et al. 2011, Biggs et al. 2018), as well as to anticipate it (e.g., Bestelmeyer et al. 2003, Carpenter and Brock 2006, Parks et al. 2019). Social scientists also began documenting the social consequences of climate-related ecological change and investigating the capacity of individuals and institutions to adapt and transform (e.g., Gunderson et al. 1995, Adger 2006, Wilby and Dessai 2010, Pelling 2011). Most notably, the development of the novel ecosystem concept (Hobbs et al. 2009) and the increasing recognition of the challenge of maintaining "natural" conditions (Cole and Yung 2010) suggested that ecological transformation will demand revision of conservation norms that are based on historical baselines. Now that conservation norms are beginning to shift away from a strong basis in historical baselines, managers will increasingly encounter a new set of challenging scientific questions.

We aim to inspire new science to support the full breadth of potential decisions in the RAD framework. We describe an agenda for transformation science that aligns with the RAD framework and is based on five central questions: Is transformation a threat; how effective and durable are resistance strategies; what are the plausible ecological futures; what are the consequences of the choice to resist, accept, or direct change; and how do managers and society choose among options to resist, accept, or direct change (figure 1)? We organize these five questions and our article around the stages in a generalized decision-making process (e.g., Brest and Krieger 2010). These decision-making stages are similar to those in adaptive management (Allen et al. 2011), structured decision-making (Gregory et al. 2012), climate-smart conservation (Stein et al. 2014) and related frameworks, which all derive from cognitive and psychological decision-making research. We use a generalized model of decision-making in this article to emphasize that the RAD framework and the science to support its application are not tied to any particular resource management decision-making process or set of steps. Any decision-making process begins by defining the problem and stating specific objectives. The first question assesses whether ecological transformation or the prospect thereof necessitates a new management approach in a given location. The second and third questions seek to identify plausible ecological futures, clarify the range of available management alternatives, and understand their associated uncertainties when

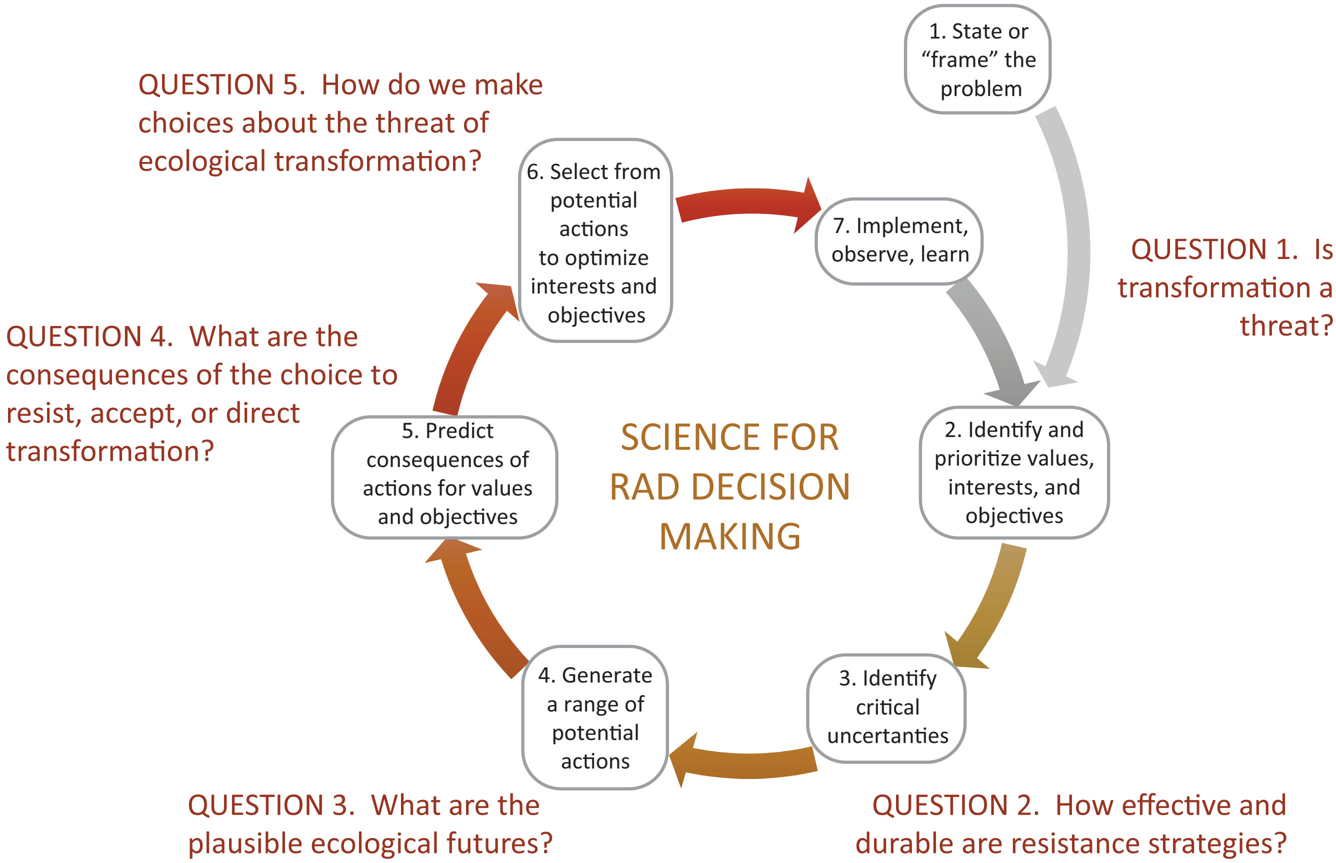

Figure 1. The stages of a generalized decision-making process, and how the five major questions that form the basis for a transformation science agenda fit in. Source: The decision-making stages are adapted from Brest and Krieger (2010).

following decisions to resist, accept, or direct change. The fourth question examines the social consequences expected to result from each alternative. Finally, the last question addresses decision-making itself, including how to choose whether to resist, accept, or direct, as well as higher-order questions about how to learn from past decisions and how to structure decision-making processes to provide desired and fair outcomes for stakeholders and society at large. Social and ecological transformations are highly coupled and interactive, making it challenging to disentangle societal actions, ecological change, and social consequences. We purposefully compartmentalize a complex phenomenon and focus on one aspect at a time to present a clear set of science questions and encourage advances within disciplines that will push the field of transformation science forward.

Question 1. Is transformation a threat?

A starting point in a decision-making process based on the RAD framework is to anticipate whether transformation is a near-term threat, thereby setting the stage for the decision to resist, accept, or direct change. Paleoecological data suggest that transformation is a widespread and real prospect with ongoing climate change, on the basis of past pervasive ecological transformations in response to rapid climate change, as in the dramatic compositional and structural transformation in terrestrial vegetation from the Last Glacial Maximum to the Holocene, roughly 12,000 years ago (Nolan et al. 2018, Williams et al. 2020). Ecological transformations can be anticipated on the basis of knowledge of natural history and landscape dynamics or mechanistic or statistical modeling (e.g., Bestelmeyer et al. 2003, Carpenter and Brock 2006). Knowing that transformation is a threat can be as simple as observing it unfold in adjacent areas. Observational approaches are being developed to remotely sense ecological transformation—for example, with spatial imaging and screening for vegetation transitions common to rangelands: desertification, woody encroachment, and non-native grass invasion (Uden et al. 2019). So far, more than 300 case studies of contemporary ecological transformation have been documented in terrestrial, freshwater, and marine systems (Biggs et al. 2018), with a wide range of triggers, processes, and system attributes that lead to transformation (Biggs et al. 2018, Harris et al. 2018, Ratajczak et al. 2018). Given this complexity, a mechanistic understanding of the nature and rate of change in different ecological systems may provide a way to recognize the potential triggers and signs of transformation in and across systems. Key needs include better understanding the role of amplifying and dampening mechanisms that determine whether transformation will occur and better anticipating rates of transformation.

Amplifying and dampening mechanisms. Feedback loops are the basis for resilience or transformation among alternative stable states under a given set of environmental conditions (Clements and Ozgul 2018). Negative feedback loops are dampening mechanisms that stabilize systems following perturbations but positive feedback loops are amplifying mechanisms that can hasten system change. Feedback loops can affect the physical environment, as when submerged vegetation reinforces water clarity in the clear state of a shallow lake system (Scheffer et al. 2001), or act via trophic interactions, as in an urchin barren in which overgrazing limits kelp growth (Rasher et al. 2020). Our understanding of feedback loops in some systems has grown, but translating this understanding into improved predictions remains challenging. For example, systems with positive feedback loops and alternative stable states may have statistical early warning indicators of impending transformations (Scheffer et al. 2015), but actual applications of this insight in marine and freshwater ecosystems reveal a discouraging success rate, with high false positives (Burthe et al. 2016, Clements and Ozgul 2018).

Fire–vegetation feedback loops, whereby fire affects vegetation flammability and fuel amount (which, in turn, affects fire probability), highlight the need to critically examine the direction, strength, and role of specific feedback loops within a system in order to anticipate ecological transformation (Tepley et al. 2018, McLauchlan et al. 2020). When fire regimes are altered, new fire–vegetation feedback loops can dampen or amplify system change. Recent modeling shows that as burning rates intensify with climate change, forested systems with negative feedback loops (through which fire promotes less flammable vegetation and therefore decreases fire probability) initially resisted forest loss. However, intensifying burning rates ultimately overwhelm these negative feedback loops and across the landscape this dynamic leads to slow incremental forest loss (Tepley et al. 2018, Whitman et al. 2019). In contrast, forested systems with positive fire–vegetation feedback loops exhibited threshold behavior and transformed more rapidly into nonforested systems (Tepley et al. 2018), and this feedback can also be seen in shrublands converting to grassland ecosystems (Syphard et al. 2019). These fire–vegetation feedback loops can act across landscape scales and initiate patterns that persist for millennia, on the basis of the presence and configuration of fuel breaks (Lynch et al. 2014, Calder et al. 2019). Fire is a fundamental component of many terrestrial ecosystems and the push to understand where positive or negative fire–vegetation feedback loops will occur illustrates how understanding specific feedback loops is an important science need.

Another important dampening mechanism is demographic compensation, a phenomenon whereby declines in some demographic rates are offset by increases in others (Doak and Morris 2010). For example, demographic compensation prevents or delays population declines when mortality rates increase with climate change, but survival, growth, recruitment, or reproduction are differentially affected by climate change (Doak and Morris 2010, Lloret et al. 2012). However, these stabilizing mechanisms may be insufficient to maintain positive population growth (Sheth and Angert 2018) or may be altogether absent, as for tree species in the western United States, where recruitment failures accompany large-scale mortality events and result in widespread changes in composition and structure (Stanke et al. 2021). Identifying potential amplifying and dampening mechanisms, including feedback loops and demographic compensation, helps determine whether systems are at risk of transformational change, and may hint at how quickly systems might transform.

Rates of change. Ecological systems differ in their key climatic drivers and in the form of the relationships between key climatic drivers and ecological states (Jackson et al. 2009, Ratajczak et al. 2018). Rates of climate-driven ecological change have been categorized as slow, fast, or abrupt (Williams et al. 2020) and can be visualized in species turnover rates. Slow ecological responses with low species turnover rates occur when lags create mismatches between climatic and ecological states. Lags arise because of limited dispersal, mismatched cues, and long-lived species and can affect population demography and reshuffle communities as species ranges shift at different rates (Visser and Both 2005, Bertrand et al. 2011). Fast ecological response is approximately linearly related to changes in climate, as has been seen in alpine communities in which increases in species richness are accelerating in tight correlation with accelerating rate of climate change (Steinbauer et al. 2018). Abrupt ecological responses have been defined as nonlinear with respect to their climatic drivers because of thresholds or feedback loops (Williams et al. 2020); for example, systems heavily influenced by ice and snow are subject to the physical threshold at 0 degrees Celsius (Littel et al. 2018). Abrupt transformations can also be triggered by pulse disturbances or climate extremes (Turner et al. 2020), and analyses that include ecological resilience in response to extreme events are critical for better understanding whether transformation is a prospect (Smith 2011, Crausbay et al. 2017).

Contemporary climate change-driven transformations often conform to a press–pulse framework, in which gradual, directional climate change sets the stage for a different ecological trajectory, but an acute, mortality-inducing event often triggers transformation. Mortality-inducing events such as heat waves, floods, wildfires, or droughts have triggered ecological transformations across terrestrial, riverine, and marine systems (Lloret et al. 2012, Crausbay et al. 2017, Harris et al. 2018, Parks et al. 2019, Coop et al. 2020). Modern climate change drives more extreme weather and climate events, intensifies disturbance regimes, and promotes the combination of multiple hazards, known as *compound events* (Seneviratne et al. 2012). Understanding how extreme events or compound events might facilitate ecological transformation can guide management expectations of rapid change

(Leonard et al. 2014, Zscheischler et al. 2018, Turner et al. 2020). For example, standard modeling approaches using mean climate variables to map species vulnerability did not capture the reality of giant sequoia (*Sequoiadendron giganteum*) foliage dieback during California's 2012–2016 hotter drought (Stephenson et al. 2018), emphasizing the need to consider acute weather or disturbance events in addition to longer climatic trends. Identifying and understanding the drivers of foundational species' demography and of focal ecological processes is needed to understand the likelihood of abrupt ecological transformation (Turner et al. 2020).

Question 2. How effective and durable are resistance strategies?

Resistance actions work against the ecological trajectory and seek to ensure the continued existence of, or limited change to, current or historical ecological conditions (Schuurman et al. 2021). Resisting human-driven trajectories has traditionally been resource managers' default response and history is replete with successful examples, particularly where local effects could be mitigated and root causes addressed (e.g., Grennfelt et al. 2020). However, the rapid, persistent, and directional nature of intensifying global change requires that managers examine—or reexamine—the efficacy and durability of standard resistance actions. Currently, resistance actions in many ecosystems require constant intervention and their success may be temporary and increasingly expensive (Millar et al. 2007). In addition, resistance actions are becoming increasingly "heroic" with climate change. For example, fish rescue programs that transfer juvenile salmonids to rearing facilities during extreme drought are proliferating, but fish rescue's efficacy at reducing extinction risk is poorly understood (Beebe et al. 2021). Transformation science will be essential to help managers understand the efficacy of new resistance techniques and where resistance is economical, feasible, and durable, given ongoing climate change and other directional stressors (Hobbs et al. 2011).

Research is also needed to characterize important opportunity costs of resistance (Millar et al. 2007, Lynch et al. 2021b). Reflexive (i.e., unexamined) resistance may miss important opportunities to conserve biodiversity and maintain ecosystem services (i.e., the many types of benefits people receive from ecosystems; Leemans and De Groot 2003) by easing transitions instead of resisting them. For example, rather than replanting prefire species on a postfire landscape on public or private land, managers could direct impending forest change by lowering planting density to reduce competition for water and simultaneously favor species adapted to emerging and projected conditions (Millar and Stephenson 2015). In addition, financial resources are almost always limited, and a choice to act in one place or for one resource often means a choice not to act elsewhere. Resisting change in a portion of the range of an ecosystem type may use resources that could be applied in another area in which resistance may be more efficacious. For example, researchers are helping state managers focus specifically on those lakes in the midwestern United States where resistance to warming and nutrient enrichment is likely to retain a keystone prey fish (the cisco, *Coregonus artedi*), the loss of which would likely constitute a transformation (Thompson et al. 2021). Such research is needed to help managers make clear and justifiable decisions about where (and where not) to prioritize their resistance efforts (Jacobson et al. 2013).

Resistance approaches are expected to be viable longer in areas with lower climate velocity or variability (Trumbo et al. 2014, Krawchuk et al. 2020). For example, resistance efforts may be more readily justified at higher-elevation sites in which forests are likely to persist in the near future, as opposed to the lowest-elevation, hottest forest types of western North America that are likely to transform because of high climate velocity plus large wildfires (Stralberg et al. 2018, Parks et al. 2019). In addition to focusing on areas unlikely to soon cross critical ecological thresholds for a given region, a manager could also focus on any areas in which rates of changes are simply very low. Climate change refugia—areas relatively buffered from contemporary climate change over time (Morelli et al. 2016)—represent specific areas in which resistance actions may be viable longer and in which intervention may not even be immediately necessary (because of low rates of ecological change, Schuurman et al. 2021). Headwater stream communities in mountainous environments are an example in which low climate velocities exist because of strong topographically controlled temperature gradients (Isaak et al. 2016).

Strategically resisting directional change in a nonstationary world, however, requires a deeper understanding of low-change areas and their shelf life. For example, working to preserve relict populations (i.e., populations that have persisted in place for a long time) to maintain seed diversity for long-lived species may be a viable resistance strategy only temporarily if compounding changes in disturbance regimes and climate ultimately render these habitats inhospitable (Harvey et al. 2016, Turner et al. 2019). Effectively predicting where resistance is viable likely requires considering changing climate extremes and compound events, not just trends in climate. Climate change refugia are diverse in their attributes; some are maintained by inherent topographic or physiographic factors that protect an area from burning (Wilkin et al. 2016, Stralberg et al. 2020), whereas others involve constant inputs such as groundwater supply in freshwater ecosystems (Briggs et al. 2018). A refugium maintained via an ecological property of the system may disappear if that ecological property is susceptible to change. For example, loss of a shade-producing canopy could remove the buffering element that maintains cool stream temperatures (Stralberg et al. 2020). Understanding the shelf life, risks and the vulnerabilities of strategies to resist transformation is a key science need.

Question 3. What are the plausible ecological futures?

Where transformation is a threat, the RAD framework relies heavily on the ability to characterize the range of plausible ecological trajectories toward new communities and ecological conditions. Ecology has a rich history covering more than a century of describing community assembly and coexistence. But a predictive science remains elusive because of myriad complex mechanisms behind assembly and coexistence, including environmental filtering, biotic interactions, and neutral processes, as well as stochastic drivers and abundant contingencies (Götzenberger et al. 2012, Jackson and Blois 2015, D'Amen et al. 2017, Lasky et al. 2020). Moreover, the redistribution of foundational species critical to habitat formation or maintenance can have cascading effects through trophic levels (Hoegh-Guldberg and Bruno 2010, Wernberg et al. 2016), whereas theory on species coexistence focuses primarily on how environmental filtering and competition act within a trophic level (Chesson 2000). This complexity of interacting processes and trophic levels, and the diversity of possible dynamics, leads to multiple potential ecological trajectories and plausible futures (Blonder et al. 2017). A key science need is to characterize the range of plausible ecological futures for RAD planning processes (Magness et al. 2021).

Novelty, stochasticity, and diverse processes. Understanding the range of plausible ecological futures is challenging for three reasons: abiotic and biotic novelty, the roles of stochasticity and contingency, and the complex set of processes underlying community assembly.

First, climate change is leading to novel climate conditions, which has resulted in novel ecological communities in the past and reduces our ability to forecast ecological conditions of the future (Fitzpatrick et al. 2018). Approaches for considering biotic novelty include using measures of species turnover—for example, to assess the current rate of novelty and identify the environmental drivers of novelty in a large marine system (Ammar et al. 2021) or ensemble species distribution modeling to map and quantify novel communities in the future—for example, in Ecuadorian hummingbird communities by 2070 (Graham et al. 2017). Models focused on species traits (e.g., leaf economic traits) hold promise because traits shape species distributions (Brown et al. 2014, Ovaskainen et al. 2017, Vesk et al. 2021) and underlie community assembly and coexistence (Chesson 2000, Laughlin et al. 2012) and thereby shape ecosystem function (Violle et al. 2014, Funk et al. 2017, Lee et al. 2017). For example, plant traits can predict plant community response to precipitation changes in a semiarid grassland (Wilcox et al. 2021). The effects of species traits on population and community processes will be context dependent (Yang et al. 2018), and although traits will not be a panacea, they are a promising approach to predicting biotic novelty. Another approach involves mapping features of climate change that are expected to lead to novel communities: the emergence of novel climate states and rapid climate changes (Ordonez et al. 2016, Burke et al. 2019). A fundamental scientific challenge is to continue developing ways to anticipate novel ecological communities composed of range-shifting native species or encroaching nonnative species (Chen et al. 2011, Hobbs et al. 2018, Wu et al. 2018).

Second, ecological trajectories are strongly influenced by stochastic weather and demographic events (Chase 2003, Jackson et al. 2009, Chisholm et al. 2014, Groves et al. 2020, Werner et al. 2020). Episodic climatic events interact with stochastic demographic and colonization events in contingent ways that serve as idiosyncratic drivers of ecological trajectories (Jackson et al. 2009). For example, recent work shows the critical importance of weather-dependent regeneration in determining the long-term consequences of drought-induced or wildfire-driven mortality events (Martínez-Vilalta and Lloret 2016, Davis et al. 2019, Coop et al. 2020, Davis et al. 2020). Understanding the dynamics of supporting processes (e.g., hydrology, soil water retention, soil fertility, pollination) with stochastic weather events and how these dynamics control ecological trajectories is increasingly important. A promising new framework for generating and applying quantitative climate stress-test scenarios provides one way to address this issue (Albano et al. 2021). Incorporating different forms of demographic and environmental stochasticity into modeling approaches can strengthen the understanding of links between population and community levels and lead to predictable community-level outcomes (Shoemaker et al. 2020). Developing approaches that consider stochastic events and contingencies in ecological trajectories is an important component of transformation science.

Third, the complex milieu of processes that drive ecological trajectories and structure communities is a challenge to integrate, and ecologists are grappling with how to realistically model and understand the future dynamics of populations and communities. Lasky and colleagues (2020) make an ambitious call for a hierarchical integration of genetic, phenotypic, and demographic data and processes along environmental gradients, which provides a path to improved forecasting under novel conditions for intensively studied foundational species. Similarly, recent convergence of community ecology and macroecology presents an organizing framework to iteratively focus on one of Vellend's (2010) high-level processes of community assembly at a time (e.g., dispersal) and then integrate another (e.g., selection; Rapacciuolo and Blois 2019). Still other new approaches recommend a major shift to focusing on ecological trajectories themselves, rather than static endpoints of different ecological communities (De Cáceres et al. 2019). Trajectory analysis provides a generalized way to characterize and compare ecological trajectories. These kinds of approaches that are explicit about the pathway between one ecosystem state and another can be particularly useful for supporting decisions under the RAD framework because they illuminate possible management intervention points to direct ecological trajectories. Strong science–manager partnerships will help teams identify the most important ecological processes and ways to effectively integrate them into management-relevant ecological scenarios (box 2). This process can illustrate the range of what accepting an ecological trajectory might look like, and spark ideas for directing ecological trajectories on a preferred course (box 2).

Box 2. Ecological scenarios.

Characterizing the range of potential ecological outcomes is necessary to help managers avoid surprises, understand what accepting ecological transformation looks like, and determine whether intervention (either to resist or direct the ecological trajectory) is warranted. Some potential ecological outcomes might be more desirable and offer ideas for how to direct the ecological trajectory. Decisions to resist, accept, or direct ecological trajectories and transformations (i.e., RAD decisions) must be made despite incomplete information and substantial uncertainty. Much of this uncertainty is irreducible. The complexities and contingencies of how ecological trajectories play out preclude a science that can precisely describe what accepting transformation would look like. This reality suggests that considering a broad range of plausible ecological trajectories and outcomes is important.

As managers try to visualize and plan for unprecedented change, a structured approach that uses a set of science-based narratives or storylines to characterize and work with uncertainty can help (Star et al. 2016b). Scenarios can provide such storylines and support decision-making in situations of consequential and irreducible uncertainty (Peterson et al. 2003). Use of scenarios is well developed in natural resource management, generally as part of a scenario planning process, to address the challenges of understanding and managing resources under a diverse set of possible climate change outcomes (Rowland et al. 2014, Gross et al. 2016, Star et al. 2016b, Miller et al. 2017, Symstad et al. 2017, Runyon et al. 2020, USNPS 2021). Guidance about how to craft scenarios to support resource management planning processes is proliferating, and typically focuses on selecting and using downscaled climate model projections and other climate data to develop divergent and plausible climate futures (figure 2; Runyon et al. 2020, Albano et al. 2021, Lawrence et al. 2021). As a result, climate futures that underlie natural resource management decisions are increasingly sophisticated.

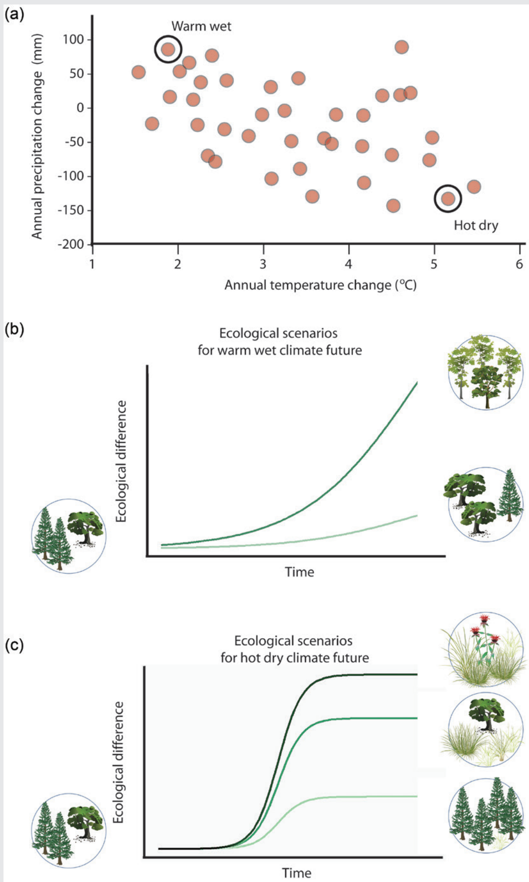

Figure 2. (a) Hypothetical set of climate projections (after Lawrence et al. 2021) showing change in average annual mean temperature and average annual total precipitation for 2080 (2065–2095) relative to the 1950–2000 historical period. Two projections are selected to represent a "warm wet" climate future and a "hot dry" climate future. Each of these climate futures may have its own set of ecological futures. (b) Hypothetical set of two scenarios for species turnover and ecological trajectories under warm wet conditions, where trajectories play out relatively slowly, and (c) a hypothetical set of three scenarios for species turnover and ecological trajectories under hot dry conditions, where trajectories play out abruptly. The y-axis in (b) and (c) could be depicted by various measures of species turnover—for example, multivariate distance measures between the baseline ecological community and subsequent ecological communities. Plant images: IAN Image Library, https://ian.umces.edu/imagelibrary.

Box 2. Continued.

We suggest that planning processes making RAD decisions consider *multiple* ecological storylines or scenarios within each *individual* climate future (figure 2). This suggestion differs from norms of ecological modeling by explicitly seeking to develop divergent ecological responses. Intentionally developing divergent scenarios is unlike typical sensitivity analyses based on parameter uncertainty or variation among statistical algorithms. Developing divergent ecological scenarios is also distinct from work that simply shows a range of uncertainty or that varies additional drivers, such as management practices, within a single climate future (e.g., Miller et al. 2017).

Operationalizing ecological scenarios within climate futures is not trivial because of constraints on the number of scenarios that scientists and managers can realistically use for decision-making. A potentially useful first step is to use ecological theory to classify ecosystems and contexts likely to have many potential ecological futures (e.g., biodiverse ecosystems with high productivity; Chase 2003). Developing and delivering useful ecological scenarios will rely on both strong scientist–manager partnerships and a scientific team that is more interdisciplinary than usual (Meadow et al. 2015). For example, participatory approaches to model development that integrate local knowledge can help to clarify the most relevant processes and scales of change (Clifford et al. 2020a).

Directing toward preferred futures. Managers may intervene to shape and change the emerging ecological trajectory when the outcome of accepting change is undesirable (box 3). Directing ecological trajectories toward a preferred future requires a vision of the target ecological composition and information about how and when management actions could facilitate particular ecological trajectories, including the series of interventions needed. A vision of the target starts with an examination of the range of plausible ecological futures. Targets can include novel communities, particularly if ecologists and managers believe those communities will be resilient or resistant in future climates, or will maintain priority ecosystem functions or services (e.g., Ostertag et al. 2015).

Understanding both how and when to intervene to direct ecological trajectories is a bold and exciting but daunting critical new science need. Managers can draw from experiences with ecological restoration and similar management actions aimed at achieving particular ecological communities and functions. However, directing ecological trajectories under a continually changing climate differs from traditional restoration because it is premised on understanding a moving target and knowing what prevents a particular ecological trajectory as climate changes (e.g., dispersal, moisture availability). A nascent science is forming around how to steer community assembly to attain a particular target or trajectory—for example, by including ecosystem engineers or manipulating processes that reduce dominance or facilitate new arrivals (Baer et al. 2016, Yeakel et al. 2020). New practices, such as translocating entire species assemblages or loading the systems with species to increase adaptive potential at the community level, need development via well-designed experimentation (Thomas 2020). Identifying intervention points or windows of opportunity for manipulating a trajectory, such as immediately before or after major disturbances such as fires, storms, or pest outbreaks, or during a certain climatic event, is a key research need (Chapin et al. 2009, Bradford et al. 2018). These windows of opportunity may rely on key supporting conditions (e.g., abundant soil moisture) that can broadly maintain species. Particular methods and practices to accelerate change, enhance an emerging novel system, or reinforce an ecological function can link to specific intervention points to develop management pathways, by which we mean the sequence, timing, and methods of interventions necessary to achieve a preferred future condition. Developing these pathways is a major challenge for directing change (Magness et al. 2021). Pilot studies and experiments are needed to better understand management pathways, explore unintended consequences, and test intervention efficacy (Lynch et al. 2021b).

Question 4. What are the consequences of the choice to resist, accept, or direct transformation?

Our fourth question is key to evaluating different RAD strategies and to creating operational models for adaptation. Although climate change impacts and adaptation are a robust research area (Field et al. 2014), ecological transformation may yield different character, scope, and scale of social consequences than climate change writ large. The impacts of ecological transformation are an emerging field of study (Chaffin et al. 2016, Barnes et al. 2017, Roy-Basu et al. 2020) and foundational research is needed to understand how ecological transformation affects society and is in turn shaped by human activities. Climate change impacts and adaptation literature provide a guide to these questions: climate change affects economics and livelihoods, emotional and psychological well-being, cultural and spiritual values and practices, human health, and risk and hazards (Clifford et al. 2021). But how, or whether, the social consequences of ecological transformation differ from the impacts of other types of environmental change is unknown. Transformation can offer opportunities to imagine more just futures (Inderberg et al. 2014, Castree 2015, Hulme 2015), but can also drive novel or increased risks of inequitable or unsustainable pathways (Blythe et al. 2018). We identify four broad categories of the social consequences of ecological transformation that deserve greater focus in order to help natural resource managers decide among RAD options. These categories include

Box 3. Science for RAD decisions in Acadia National Park.

Acadia National Park's application of the RAD framework illustrates the need for diverse transformation science. Managers recognize that transformation of the park's forest is inevitable under a range of plausible climate futures, exacerbated by other global change factors, including the increasing abundance of nonnative invasive species (Star et al. 2016a). Sixteen percent of the park's flora has been lost over the past 125 years, likely because of climate change and invasive species (Greene et al. 2005, McDonough MacKenzie et al. 2019). Nine of the park's ten most common tree species are expected to lose climatically suitable habitat over the next 80 years, including red spruce (*Picea rubens*), which makes up 40% of the park's tree stems (Fisichelli 2013). Red spruce is still recruiting in the forest understory (Wheeler et al. 2015), and therefore the timing and spatial pattern of forest transition is uncertain. However, abrupt and widespread declines in red spruce could be triggered by the combination of drought and an insect, pathogen, or parasite outbreak. For example, nearly all the park's red pine (*Pinus resinosa*) died recently with a simultaneous outbreak of nonnative red pine scale and two native fungi, exacerbated by drought. Interactions such as these are intensifying with climate change and are increasingly likely to initiate abrupt transformations (e.g., Crausbay et al. 2020).

With the knowledge that ecological transformation of the park's forests is inevitable, concerns center on how to manage this anticipated transition. Climate envelope modeling suggests that one plausible ecological trajectory leads to a temperate deciduous hardwood forest, constituting a dramatic change that would alter ecological processes, wildlife habitat, and ecosystem services. However, drought-triggered dieback of boreal forest creates another plausible ecological trajectory: rapid colonization and expansion of invasive shrubs and vines that prevent recruitment of both longstanding indigenous species and regionally native species undergoing range shifts, leading to a nonnative, nonforested state (Miller and McGill 2019, Miller et al. 2021). This second plausible ecological outcome is unacceptable for many park managers and stakeholders, increasing openness to intervention and unconventional approaches despite uncertainty. Managers have engaged extensively with park staff, stakeholders, and local communities to discuss management options, and they have worked with the media to communicate the issues, science, and decision-making process (e.g., Abel 2014, Ostrander 2018). This engagement is essential because of the novelty of this challenge and the role of human values in identifying preferred future conditions (Clifford et al. 2021, Magness et al. 2021).

Managers at Acadia now have a spatial portfolio that integrates decisions to resist, accept, and direct ecological transformation (figure 3). To understand the spatial opportunities to most easily resist change, researchers mapped potential climate change refugia for priority species (Smetzer and Morelli 2019) and are evaluating the stability of high-elevation refugia using paleoecological analyses. Across the entire landscape, managers are resisting the ecological trajectory that leads to a nonnative, nonforested system (figure 3e) by prioritizing aggressive management of invasive plants. Invasive plant control supports maintenance of historical forest communities (resist) or creation of novel assemblages of regionally native species (direct), and therefore keeps options open. Meanwhile, park managers are innovating strategies to direct ecological trajectories, including testing the establishment of more southerly deciduous hardwoods better suited to emerging climatic conditions (McDonough MacKenzie et al. 2018, Fisichelli et al. 2019). This experimental approach helps evaluate translocation techniques, assess viability under current climate conditions, and identify species that show invasive characteristics.

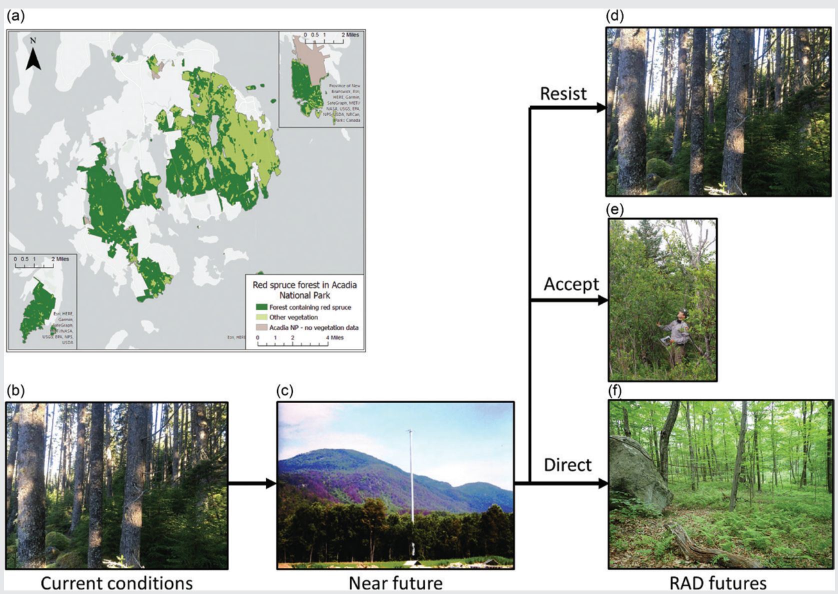

*Figure 3. A diagrammatic outline of the RAD decision-making process regarding red spruce (***Picea rubens***) forests in Acadia National Park showing (a) the distribution of red spruce in the park, (b) current healthy spruce forest conditions, and (c) likely future conditions depicting forest dieback, as well as potential futures depending on the management strategy: (d) resist to keep healthy spruce forests in climate change refugia, (e) accept and allow invasive species, such as glossy buckthorn (***Frangula alnus***), to choke forest regeneration and create shrublands, or (f) direct forest transition to temperate hardwood forest. Images: USNPS (a, f), Schoodic Institute at Acadia National Park (b, d, e); McNulty et al. (2013) (c).*

resource use (market and nonmarket), nonmaterial impacts (emotional, psychological, and cultural), hazards and risk, and equity and justice.

Material interactions. Changing ecosystems alter how people materially interact with the environment. Human communities rely on ecosystems for diverse resource needs. Documented shifts in harvesting patterns (Moerlein and Carothers 2012) and resources disappearing from certain locations, seasons, regions, or even globally (McNeeley and Shulski 2011, Herman-Mercer et al. 2019) show that resource use is already shifting in many areas as the climate changes. Research characterizing how ecological shifts interact with changes in resource use and other material, human–environmental relationships remains a key gap in many locations, especially those just beginning to experience transformation. A related question is the extent to which these shifts provide opportunities for new ways of using resources (versus simply causing the disappearance of valued uses). Furthermore, it is important to understand how transformation will affect other ecosystem services on which resource use indirectly depends, such as water quality or pollination necessary for crop production (MA 2005, Butler and Kosura 2006).

Emotional, psychological, and cultural implications of transformation. The many salient nonmaterial interactions between people and ecosystems (e.g., Adger et al. 2011, Overland and Sovacool 2020, Clifford et al. 2021) include a second category of consequences: the emotional, psychological, and cultural implications of transformation. Scholars studying protected areas and resource management have long recognized that people form strong emotional attachments to places through subsistence use (Rearden and Fienup-Riordan 2016), work such as ranching (e.g., Sayre 2005), recreational uses such as fishing or surfing (e.g., Reineman and Ardoin 2018), and sometimes even without physically interacting with a place because its existence holds cultural value (e.g., Richardson et al. 2017). For example, rising sea levels threaten Small Island Developing States with inundation, which will not only reshape ecological communities but also result in social and cultural losses arising from impacts on communities' social structures and capacity for self-governance (Zellentin 2015). More recent work documents that climate-induced changes can lead to climate grief, an emerging term describing the multifaceted loss from the disappearance of, or unrecognizable change in, important places (Randall 2009, Cunsolo and Ellis 2018). For indigenous communities, specific places are linked to community continuity, spirituality, sovereignty, and cultural knowledge, which means that climate-driven loss or change of ecosystems and associated traditional practices can have deleterious cultural consequences (Voggesser et al. 2013, Bark et al. 2015, Maldonado et al. 2016). Therefore, an important set of questions relate to understanding the emotional, psychological, or cultural consequences of transformation in particular locations, and teasing out the specific impacts of changing ecosystems from wider climatic and societal shifts.

New hazards. Environmental systems also pose threats or represent hazards, a third important type of consequence of ecological transformation. Projections and empirical observations show how climate change alters, intensifies, or accelerates hazards and extremes (Westerling et al. 2006, Field et al. 2014, Cutter 2020). Similarly, the scope and scale of transformative ecological change will likely bring new and greater threats. For example, an ecological transformation that alters the fire regime and increases fire recurrence will increase risk to society. Many environmental changes pose critical threats to public health, such as increased wildfire smoke (McKenzie et al. 2014) and dust storms, as in the 1930s Dust Bowl in the United States (Cook et al. 2009, Romm 2011, Tong et al. 2017), which reduce air quality. Importantly, the intensity of an extreme event (e.g., a wildfire) does not always correlate with the intensity of human impact (Cutter 2016), because social vulnerability arises from social, historical, political, and economic processes—all nonenvironmental factors that manifest in structural inequalities and marginalization (Wisner et al. 2004, Adger 2006, Wisner 2016). Cascading hazards are another important focus because they affect human well-being and can entrain multiple and interacting impacts throughout social systems, especially in more tightly coupled human–natural systems (Cutter 2018, 2020). Although robust research exists on hazards, vulnerability, and adaptation, further questions arise in the context of ecological transformation. Will novel ecosystems include the potential of new hazards? How might ecological transformation alter the intensity and frequency of existing hazards, and confidence in hazard forecasting? What are the changing health risks that result from ecological transformation? How will ecological transformation affect vulnerability of individuals or communities (i.e., the characteristics that influence capacity for human communities "to anticipate, cope with, resist or recover from the impact of a natural hazard" Wisner et al. 2004, p.11)?

Equity and justice. Ecological transformation will interact with, and possibly exacerbate, existing inequalities and reorganize existing power relations with two possibilities. Transformation may usher in new, more radical and just futures (Bennett et al. 2019) or it may worsen or introduce new environmental injustices, structural inequalities and uneven distribution of harms (Blythe et al. 2018). The range of consequences described above will not be uniformly distributed. The impacts will be unequal, and each management decision and corresponding set of ecological conditions will produce winners and losers. For example, resources relied on for subsistence are particularly important in many rural or indigenous communities (Lynn et al. 2013) and changes in these resources may impose disproportionate harm (see Lynch et al. 2021b). In other words, managing transforming ecosystems and making RAD decisions is, in part, a justice issue (Sayre et al. 2013, Adams and Charnley 2020). For example, wildfire management and response are known to be unequally available along lines of class and race (Lynn and Gerlitz 2006, Adams and Charnley 2020) and new conditions from transformation may only exacerbate these patterns. Therefore, a key research gap is investigating how losses (and likely to a lesser extent, gains) from ecological transformation and changes in resource use are distributed and highlighting the power relations that reinforce inequity (Blythe et al. 2018). Will particular groups bear disproportionate burdens (or realize benefits)? How do the consequences of RAD decisions differ for diverse stakeholder groups? Furthermore, it is not only important to examine the outcomes of transformation, but also to engage larger questions of climate justice, including considering which parties contributed most to the climate changes driving transformation (Harlan et al. 2015).

Question 5. How do managers and society make choices about the threat of ecological transformation?

The fifth question we highlight is decision-making itself, including questions about how and by whom choices about responding to ecological transformation are made, the processes that are used to choose, and how best to weigh and evaluate trade-offs in the face of the consequential uncertainties described above. For the sake of clarity, we present consequences and decision-making in separate sections, but we note that they are intertwined and in practice happen iteratively.

Describing ecological transformation decision-making. Although natural resource managers have long responded to anthropogenic change (e.g., Loomis 2002, Allen et al. 2011, Wilson 2020), managing climate change-driven ecological transformation is still relatively new or yet to come in many locations (e.g., Clifford et al. 2020b). As individual managers and agencies implement new approaches (box 3; Lynch et al. 2021b), empirical social science that documents their experiences will be vital to ensure wider learning about what constitutes successful management and decision-making in a transforming world (Chaffin and Gosnell 2015). A key need is describing decision-making processes and their efficacy across varying contexts. Evaluating effectiveness requires linking outcomes to decision-making processes (Thomas and Koontz 2011, Ulibarri 2015), which will be important for understanding results of particular decisions and how outcomes can be influenced by factors such as spatial or jurisdictional scale, agency culture, individual manager background, regulatory context, stakeholder participation, and other social and institutional aspects (Clifford et al. 2021). These factors highlight a range of variables that potentially interact with decision-making processes and outcomes, suggesting the need for comparative studies across ecological systems, rates of ecological transformation (i.e., fast, slow, or abrupt; Williams et al. 2020), agency type, and particular RAD strategy.

Examining how managers make decisions about transformation can help improve future management (see Clifford et al. 2021). Choosing between alternative ecological futures when selecting a RAD strategy will involve difficult trade-offs and weighing different groups' values, preferences, and potentially losses (Bliss and Fischer 2011, Hirsch 2020). For example, although government and industry forest managers in British Columbia, Canada view managed relocation as important for helping forests adapt to climate change (Pelai et al. 2021), public opinion in the same region is mixed (St-Laurent et al. 2018), leaving managers to weigh important ecological and social trade-offs when considering strategies that direct ecological trajectories. It remains unclear whether new methods for weighing trade-offs will have to be developed, or whether existing methods are adequate for a management future that requires more frequent and more difficult trade-offs. Another question relates to information for making these decisions. Will RAD decisions be based on the "best available science" as is currently the norm (Murphy and Weiland 2016), or are there other ways of knowing that might need to be incorporated—for example, the experiential knowledge of stakeholders (Knapp et al. 2013) or traditional ecological knowledge (Berkes et al. 1994)? Similarly, what role do cognitive biases or heuristics play in RAD decisions (Kahneman 2011)?

Balancing preferences of diverse communities and ensuring meaningful participation. Ecological transformation also raises normative or human-value-based questions about how RAD decisions can and should be made to ensure acceptable, inclusive, and equitable choices and outcomes (e.g., O'Donnell and Talbot-Jones 2018). These types of normative questions are the focus of research on the design of stakeholder engagement processes, public participation, procedural justice, and related topics (e.g., Fiorino 1990, Davidson 1998, Wondolleck and Yaffee 2000, Cosens 2013, Reed et al. 2018), and this expertise may aid those designing processes for making transformation decisions. Individuals view the RAD strategies differently (Clifford et al. 2020b), and decision processes influence trust (Molden et al. 2017). For example, indigenous knowledge systems question core assumptions of western management paradigms and offer new perspectives about ecological transformation (Whyte 2018) or human connection to natural systems (Berkes 2008, Chapin et al. 2013, Schuurman et al. 2021). Ensuring the legitimacy of decisions requires that those affected have seats at the table (i.e., a role in decision-making) and the capacity to meaningfully participate (Cosens 2013), raising questions about the optimal design of stakeholder engagement. To what extent do all relevant stakeholders have both roles in decision-making and the capacity to participate, particularly marginalized groups and those that will live with the burdens from proposed strategies? By whom will the success of RAD decisions be evaluated and in what forums?

Individual and organizational adaptation. Managing ecological transformations over time requires human adaptive capacity, whereby diverse factors support people's confidence in and ability to make RAD decisions (Engle 2011, Whitney et al. 2017). The factors that influence individual and organizational adaptive capacity are not completely understood, although much recent attention has focused on human adaptive capacity in the context of social–ecological transformation (Cinner et al. 2018, Cinner and Barnes 2019), and in particular, identifying the governance mechanisms needed to navigate such change (e.g., Chaffin et al. 2016, Garmestani et al. 2019). Scholars have found that organizational cultures, specifically those that support government resource managers, are often slow to change, lack general creativity, and reinforce status quo power relations (Gunderson and Light 2006, Gunderson et al. 2018), reflecting what is often a dominant discourse of risk aversion and protection of current resources and dynamics. Such scholarship suggests that individual RAD decision-makers will need support from a culture of change, and raises questions about how to foster organizational learning.

Institutions to manage ecological transformation. Institutions (i.e., laws, policies, rules, and social norms) are dynamic, and the ways they develop, adapt, and evolve over time have been extensively studied (e.g., Mahoney and Thelen 2009, Micelotta et al. 2017). Natural resource management decisions have always had ramifications for social systems that depend on both decisions and the resources themselves (Ostrom 1990, Young 2002). Choices about how to respond to challenges such as ecological transformation, in turn, influence the creation of institutions that guide human interactions with ecosystems (Young et al. 2008, Cleaver 2012). Laws and policies create boundaries to action (Fidelman et al. 2019, Clifford et al. 2021) that may need to shift to match changing realities, or else managers will likely need to find creative ways forward despite intractable policies (McNeeley 2012, Oakes et al. 2016, Garmestani et al. 2019). Long-standing goals may also need to change (see Lynch et al. 2021b). For instance, many environmental policies and regulations use the ambiguous term *natural* as part of directives (Cole and Yung 2010), which raises questions of how mandates to manage for "natural conditions" will be implemented in transforming ecosystems. Institutional change may involve allowed or prohibited resource uses, laws and policies, management goals, governance processes and structures, and roles of decision-makers (Clement and Standish 2018). There is a broad and rich diversity of questions at the intersection of ecological transformation and institutional change (e.g., Knapp et al. 2020). Because the selection of RAD options likely influences the scope and viability of sequential RAD decisions, the continual interplay between decision-making, outcomes, and subsequent institutional change needs examination (e.g., Subalusky et al. 2019, also see Clifford et al. 2021).

Conclusions: A transformation science agenda

New science is essential to help managers fully grapple with nonstationarity and choose strategically among options to resist, accept, or direct ecological trajectories and transformations. We have laid out a set of five questions that can form the basis of a transformation science agenda to support RAD decisions (table 1). Is transformation a threat? How effective and durable are resistance strategies? What are the plausible ecological futures? What are the consequences of the choice to resist, accept, or direct transformation? How do managers and society make choices about the threat of ecological transformation? The science needed is diverse. It includes greater understanding of amplifying and dampening mechanisms, rates of ecological change, biotic novelty, and environmental contingencies. It calls for conducting science in a new way to develop multiple ecological scenarios for a given climate future and identify effective pathways for directing ecological change. The science needed includes a greater understanding of the wide-ranging social–ecological consequences of a particular choice to resist, accept, or direct ecological change, from resource use, to equity and justice. Finally, applying the RAD framework requires examining the RAD decision-making process, and institutions that manage ecosystems in the face of ecological transformation. These questions form the basis of a broad new transformation science agenda for a nonstationary natural world, rooted in manager needs and decisions.

Science to support application of the RAD framework requires disciplinary progress within both ecological and social science, and it will benefit from a new scientific approach that involves closer partnerships between researchers and managers, allows for faster and more contextual learning under uncertainty, and considers questions across disciplines. These shifts in the practice of science can increase usability (Dilling and Lemos 2011), better integrate dynamics of scale (Hulme 2010), span barriers to provide more synergistic insights (Rice 2013), respond to stakeholder experiences of climate change impacts (Knapp and Trainor 2013), and ensure that science informs and improves decision-making (Enquist et al. 2017). Complex and dynamic RAD decisions, made under conditions of imperfect knowledge, can be guided by new ways of developing and delivering scientific information, and by shifts in institutional cultures to facilitate risk taking, learning, and increased adaptive capacity (Emerson and Gerlak 2014). Science in this context may include diverse interdisciplinary teams (e.g., box 4), new experimental approaches (e.g., box 3; Lynch et al. 2021b), and advanced development of scenarios (e.g., box 2). Coproduction and translational ecology have emerged as a strategy for creating useful and relevant science that is tailored to applied contexts (Mauser et al. 2013, Beier et al. 2017, Enquist et al. 2017, Djenontin and Meadow 2018). These science–management partnerships may require new types of funding support for applied and context-dependent research (Arnott et al. 2020). The

Table 1. A research agenda for transformation science organized around five major questions that arise in a RAD decision-making process.

Question	Agenda
Question 1. Is transformation a threat?	What feedback loops could amplify or dampen change?
	Is demographic compensation likely to dampen change?
	Will ecological response be slow, fast, or abrupt?
	Will ecological transformation conform to a press–pulse framework, and be triggered by an acute disturbance event?
Question 2. How effective and durable are resistance strategies?	Where and when are resistance strategies economical, feasible, and durable, given ongoing climate change and other directional stressors?
	What are the opportunity costs of resistance?
	What is the shelf life of climate refugia with ongoing climate change and intensifying climate extremes and compound events?
Question 3. What are the plausible ecological futures?	What is the likelihood and nature of a novel ecological community in the future?
	What are the roles of stochasticity and contingencies in driving ecological trajectories?
	How do multiple complex ecological processes drive ecological trajectories and which processes are most essential to integrate in modeling?
	What are the divergent and plausible ecological scenarios for a particular climate future?
	What are the sequence, timing, and methods of interventions that could achieve a preferred future ecological condition?
Question 4. What are the consequences of the choice to resist, accept, or direct transformation?	How does ecological transformation interact with changes in resource use and other material, human–environmental relationships?
	What are the emotional, psychological, or cultural consequences of ecological transformation?
	How will ecological transformation alter existing hazards and vulnerability of individuals or communities?
	How do the consequences of RAD decisions differ for diverse stakeholders and rights-holders and influence equity and justice?
Question 5. How do managers and society make choices about the threat of ecological transformation?	What factors influence the effectiveness of RAD decisions across different decision-making contexts?
	How can decision-makers balance preferences of diverse communities?
	What factors influence individual and organizational adaptive capacity to manage ecological transformation?
	What institutional changes would facilitate management of ecological transformation?

Box 4. Coupled social–ecological realities.

Decisions that address ecological transformation—and by extension, coupled social–ecological dynamics—are just one of many feedback loops between society and ecosystems in the context of transformative change. Over the past several decades, scholars have posited a large and sometimes overwhelming number of theoretical frameworks and analytical approaches to achieve cross- and transdisciplinary integration in studies of human–environment interactions (Pulver et al. 2018). The term social–ecological system (SES) represents one common characterization of this scholarship, and it emphasizes the dynamic connections between human behavior and ecological condition (Gunderson and Holling 2002, Folke 2016). For ecological transformation, one key insight from an SES perspective is the importance of identifying thresholds, which can be essential for recognizing potential transformations and making anticipatory decisions (Foley et al. 2015, Selkoe et al. 2015). SES perspectives particularly underscore the need to understand social–ecological feedback loops to disturbance processes. This kind of focus can reveal how both the consequences and the drivers of disturbance may change as the environment changes, altering a system's vulnerability to ecological transformations (e.g., Gaiser et al. 2020). A key area for future interdisciplinary research is therefore the coupling of ecological and social systems (e.g., Larrosa et al. 2016, Pulver et al. 2018): What are the most important feedback loops between human behavior and ecological dynamics in the context of transformations? Which data, metrics, or indices provide information about changes in connections in SES systems?

RAD framework is supporting the development of a new management paradigm for our rapidly changing planet (Schuurman et al. 2021). Application of the RAD framework calls for a transformation science agenda, focused on ecological and social sciences and centered on the questions encountered in a RAD decision-making process, to effectively support natural resource management in a nonstationary world.

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Shelley D. Crausbay (shelley@csp-inc.org) is a senior scientist with Conservation Science Partners, in Fort Collins, Colorado, and is a consortium partner for the US Geological Survey's North Central Climate Adaptation Science Center, in Boulder, Colorado, in the United States. Helen R. Sofaer is a research ecologist with the US Geological Survey Pacific Island Ecosystems Research Center, in Hawaii Volcanoes National Park, in Hawai'i, in the United States. Amanda E. Cravens is a research social scientist in the US Geological Survey's Social and Economic Analysis Branch, in Fort Collins, Colorado, in the United States. Brian C. Chaffin is an assistant professor of water policy at the University of Montana, in Missoula, Montana, in the United States. Katherine R. Clifford is a postdoctoral social science research fellow in the US Geological Survey's Social and Economic Analysis Branch, in Fort Collins, Colorado, in the United States. John E. Gross is an ecologist with the US National Park Service Climate Change Response Program, in Fort Collins, Colorado, in the United States. Corrine N. Knapp is an assistant professor at the University of Wyoming, in Laramie, Wyoming, in the United States. David J. Lawrence is an aquatic ecologist in the US National Park Service Climate Change Response Program, in Fort Collins, Colorado, in the United States. Dawn R. Magness is a landscape ecologist for the US Fish and Wildlife Service, Kenai National Wildlife Refuge, in Soldotna, Alaska, in the United States. Abraham J. Miller-Rushing is the science coordinator at Acadia National Park in Bar Harbor, Maine, in the United States. Gregor W. Schuurman is an ecologist with the US National Park Service Climate Change Response Program, in Fort Collins, Colorado, in the United States. Camille S. Stevens-Rumann is an assistant professor with the Forest and Rangeland Stewardship Department and assistant director of the Colorado Forest Restoration Institute, at Colorado State University, in Fort Collins, Colorado, in the United States.