Management Foundations for Navigating Ecological Transformation by Resisting, Accepting, or Directing Social–Ecological Change

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Despite striking global change, management to ensure healthy landscapes and sustained natural resources has tended to set objectives on the basis of the historical range of variability in stationary ecosystems. Many social–ecological systems are moving into novel conditions that can result in ecological transformation. We present four foundations to enable a transition to future-oriented conservation and management that increases capacity to manage change. The foundations are to identify plausible social–ecological trajectories, to apply upstream and deliberate engagement and decision-making with stakeholders, to formulate management pathways to desired futures, and to consider a portfolio approach to manage risk and account for multiple preferences across space and time. We use the Kenai National Wildlife Refuge in Alaska as a case study to illustrate how the four foundations address common land management challenges for navigating transformation and deciding when, where, and how to resist, accept, or direct social–ecological change.

Keywords: climate change adaptation, ecological transformation, social–ecological system, natural resource management, nonstationary

Ecological systems are not static through time but, rather, exist in a state of fluidity with novel communities replacing the previously stable community as climate change unfolds (Jackson and Hobbs 2009, Hobbs et al. 2013). When climate changes rapidly, as is occurring today, ecological systems are more likely to transform within the timeframes for which managers plan. Under these circumstances, future-oriented management strategies can guide transformation toward more desirable outcomes, including outcomes that maintain ecological functioning, avoid ecological collapse, and minimize loss of critical ecosystem properties, such as biotic diversity (Chapin et al. 2010, Colloff et al. 2017, Díaz et al. 2019, Ceballos et al. 2020). In this article, we present four foundations that scientists and managers can use to support management planning for natural resources undergoing transformative change.

Management practices have generally assumed stability within a historical range of variability (Jackson and Hobbs 2009, Young and Duchicela 2021). To date, most management agencies have not established norms and implementable practices that are specific enough to navigate transformation to novel states (LeDee et al. 2021, Schuurman et al. 2021). Shifting from historical baselines that are generally observable, knowable, and agreed on to nonstationary conditions that are novel, uncertain, and contested will likely require changes in decision-making practices and criteria (Jones et al. 2014, Hirsch 2020). Faced with global climate change and ecological transformation, managers have a decision space in which they can resist, accept, or direct (RAD) change (Lynch et al. 2021a, Schuurman et al. 2020, Thompson et al. 2021, Clifford et al. 2021).

This special issue is about using RAD as a framework to help natural resource managers respond to *ecological transformation*, which is defined in the present article as "the dramatic and irreversible shift in multiple ecological characteristics of an ecosystem" (Crausbay et al. 2021). RAD expands response options beyond the status quo management of stationary conditions to the realities of managing nonstationary and novel conditions (Schuurman et al.

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Table 1. Helpful concepts in identifying and describing plausible ecological trajectories (developed from Chapin et al. 2009, Chapin et al. 2010, Walker and Salt 2012, and Hobbs et al. 2013).

Concept with definition	How concept relates to ecosystem trajectory
State factors—ecological factors (e.g., climate, soils, biota, disturbance regime, topography) that govern both geographic patterns of ecosystem structure, composition, and functioning and ecosystem responses to environmental changes	• **Position** of management unit or ecosystem within the historical range of variability and in relation to the trajectory of change. For example, leading or trailing edge, widely distributed, or rare. • **Landscape features,** such as land use and topography, that isolate or connect ecosystems and create spatial variability • **External drivers** such as climate change and global economic incentives that influence the system, but are outside of management control. • **Directional change,** also known as press disturbance (Harris et al. 2018), can be variable across space and time
Ecological legacies—ecosystem properties that reflect past events and have the potential to constrain or influence ecological change	• **Biodiversity** reflecting the history of establishment events and extirpations, resulting in what is available to adapt to and fill emerging conditions. • **Geodiversity:** the abiotic conditions that are slow to change and provide the context within which biotic processes unfold (i.e., conserving nature's stage; Beier and Brost 2010, Lawler et al. 2015) • **Historical events:** the sequence of past events, often referred to as historical contingencies
Alternative stable states—idea that ecosystems can be found in one of several possible states and that shifts between states are possible (Beisner et al. 2003)	• **Amplifying feedbacks:** ecosystem dynamics that accelerate an ecological trajectory of change. For example, warming temperatures reduce snowpack, which reduces albedo and further reduces snowpack • **Reinforcing feedbacks:** ecological interactions of key internal variables that reinforce the current state such as predator–prey relationships that maintain both populations within limits.
Ecological contingencies—future events or circumstances that are possible but have unpredictable timing. These events can influence ecological stability or trajectories of change (Turner et al. 2020)	• **Pulse disturbances:** extreme events, including novel disturbances (Harris et al. 2018) • **Dispersal or extirpation events** alter the community assemblage • **Thresholds and tipping points** occur at boundaries of the ecosystem operational space or initiate an amplifying feedback to a new state. • **Timing:** cycles in ecological systems influence likelihood of transformation. For example, ecosystems are more likely to reorganize into novel states after disturbance.

2021). Preparing for and facilitating ecological transformation will often require a corresponding transformation in the management regime, which may include shifts in the values, rules, and knowledge that govern how humans interact with the resource (Chapin et al. 2010, Olsson et al. 2014, Gorddard et al. 2016, Colloff et al. 2017). We lay four foundations to conceptualize practices that can be used to implement RAD. We developed the foundations on the basis of our experiences implementing future-oriented management, and we present a case study from Southcentral Alaska, where on-the-ground lessons occurred. The four foundations can stimulate critical thinking about implementation such as how ecological transformation may occur on the landscape, how to apply the RAD framework, and how management regimes may shift to effectively accommodate novel conditions. Although the four foundations are depicted as separate, they are complementary and designed to be integrated, which might necessitate moving iteratively among them and focusing on the most relevant pieces as implementation proceeds.

Foundation 1: Scenarios of plausible social–ecological trajectories

Foundation 1 builds a shared knowledge about the range of future conditions that could occur in the management landscape as climate change unfolds. It explicitly acknowledges the uncertainty associated with moving outside of historical conditions and envisions several plausible futures. Explicitly describing plausible futures enables managers, scientists, and stakeholders to build a shared knowledge about what, where, when, and how it may be possible resist, accept, or direct these anticipated changes (foundations 2 and 3; Gorddard et al. 2016). Predictions of the most likely future, although they are useful, are not sufficient as disturbances, tipping points, and thresholds can alter the social–ecological trajectory away from historical conditions, sometimes rapidly. Novel social–ecological trajectories are possible and favor practices that incorporate uncertainty and the potential for surprise (Walker and Salt 2012). How the social–ecological trajectory unfolds is path dependent and shaped by many factors such as historical and current management practices, environmental conditions, novel ecological community interactions, and human responses (table 1). We build on rich literatures in social–ecological systems, complex adaptive systems, resilience assessment, and novel ecosystems to help managers develop knowledge about the range of plausible future conditions in their landscape of interest (Chapin et al. 2009, Chapin et al. 2010, Walker and Salt 2012, and Hobbs et al. 2013).

In some cases, a plausible trajectory may be observable within the landscape. For example, sea-level inundation maps can identify upland ecological communities that are at risk of salt-water intrusion and transformation to nearby or lower-latitude coastal marsh ecosystems (Lynch et al. 2021a). In other cases, high uncertainty about ecological response may suggest multiple plausible trajectories that can only be generalized to broad ecological types, such as a biome. These are still useful for bounding plausible future states and identifying key indicators for tracking the emerging trajectory (see Kenai National Wildlife Refuge case study). The importance of continued and improved monitoring will increase as managers seek to detect ecological changes in real time, decreasing lag time and improving management response (Lynch et al. 2021b). Empirical study of the social–ecological history (Higgs et al. 2014), analogs (Carroll et al. 2018), manipulative experiments (Lynch et al. 2021b), modeling, and qualitative opinions of people with knowledge of the environment can enrich and expand understanding of plausible trajectories (foundation 2). Convergence of multiple lines of evidence, including traditional and local ecological knowledge, can decrease, but not remove uncertainty about ecological response (Michalak et al. 2017, Magness and Morton 2018). When multiple competing conceptual or quantitative models exist, divergent models can be explored as alternative, plausible social–ecological trajectories, some of which may be validated through experiments that mimic the climate driver (Lynch et al. 2021a). Disagreement among models may also identify social–ecological trajectories with more opportunities for management intervention to tip the outcome (Magness and Morton 2018).

Scenario planning is a tool used to imagine plausible futures, which is relevant in systems in which tipping points and surprises are expected (Peterson et al. 2003, Crausbay et al. 2021). Scenario development is flexible and allows for mixed methods such as quantitative, qualitative, expert driven, or participatory approaches (Star et al. 2016). Evaluating how a social–ecological system may respond across divergent scenarios of climate change, land-use change, and other drivers can provide insights into how, when, and where divergent social–ecological trajectories may unfold in the landscape of interest (Delevaux et al. 2018). Scenario methods can also effectively contribute to upstream engagement (foundation 2) by increasing shared knowledge among stakeholders and promoting collective learning (Schoemaker 1995, Malinga et al. 2013). Enhanced stakeholder engagement in scenario planning also provides diversity and equity in decision-making and fosters creativity and social innovations from stakeholders (Oteros-Rozas et al. 2015).

Foundation 2: Upstream, deliberative engagement

Foundation 2 focuses on robust engagement, both within agencies and with stakeholders. Transformation forces reassessment of the values and preferences that managers, agencies, stakeholders and the general public associate with a particular ecosystem and the goods and services it provides. Any choice of desired conditions can create winners and losers (Selkoe et al. 2015), making such choices an inherently value-laden exercise (Ives and Kendal 2014, Clifford et al. 2021). As such, managers may consider engaging stakeholders *upstream* of decision-making processes and use *deliberative* methods that embody two-way dialogue and explore a range of social factors related to various plausible ecological trajectories and potential pathways to shape them.

Upstream engagement entails dialogue among potentially affected parties (stakeholders) about controversial issues in the early stages of developing options and in advance of committing to certain management pathways (Wilsdon and Willis 2004, Pidgeon and Rogers-Hayden 2007). Moving engagement upstream means transitioning from reactionary to proactive stakeholder involvement and taking advantage of the discretion that agencies have within existing policies and mandates in determining how to involve stakeholders (CEQ 2007, NRC 2008). Moving engagement upstream can create space for the use of deliberative methods that promote respectful, two-way dialogue between diverse stakeholders, experts, and decision-makers (Burgess 2014, Pelai et al. 2021). Deliberative methods encourage exploration of social and ethical issues alongside scientific and technical questions, with the goal of producing decisions that all parties view as more legitimate (Gastil 2017).

Upstream engagement in the context of ecological transformation

As Yung and colleagues (2013, p. 254) described it, "upstream public engagement provides an early opportunity for scientists, publics and decision-makers to discuss the values associated with particular ecosystems and approaches towards management. Such discussions make the role of society in ecosystems more explicit and encourage public recognition of the ties between natural and social systems and processes." Where typical public participation asks what people think about agency science, management options, or decisions (often after the fact), upstream engagement explores assumptions underlying science and past management approaches, draws on different forms of knowledge that might be relevant and considers how decisions can be made to ensure more fair and justifiable outcomes (Wilsdon and Willis 2004). Laws and agency policies inform which desired conditions are permitted and the decision space in which managers operate (foundation 3), whereas the best available science can help to identify plausible ecological trajectories (foundation 1) and management pathways to achieve them (foundation 3). But, as managers work to identify desired conditions for a given unit, landscape, region, or resource, considering diverse perspectives throughout decision-making processes can help balance many individual, organizational, and societal values and preferences across nested scales (foundation 4).

Upstream engagement processes can enable managers and stakeholders to explore innovative solutions that might not have otherwise been considered (Stirling 2005). Often, discussing science, values, and priorities in advance or outside of a formal

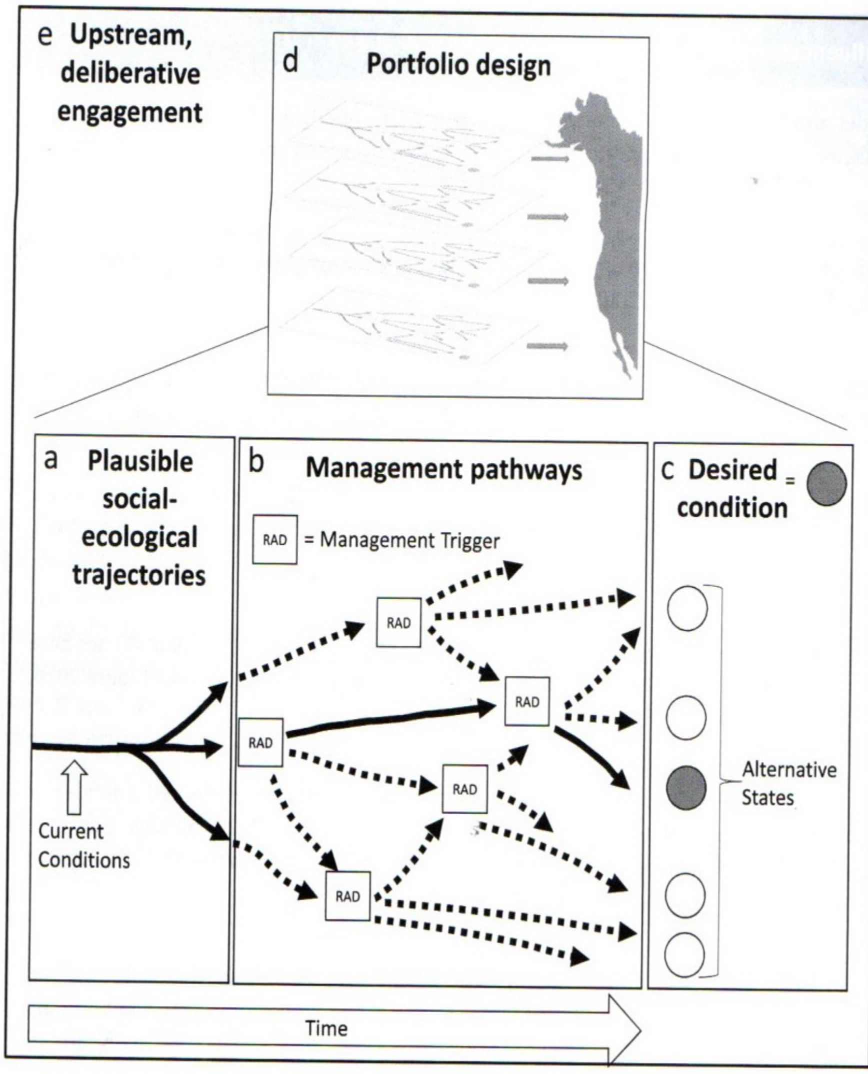

Figure 1. Conceptual diagram of the four foundations used to implement the RAD framework. (a) Plausible social-ecological trajectories (foundation 1) are used to (b) identify how RAD choices could shape future conditions and provide management pathways (foundation 3) to (c) desired conditions. Management triggers identify opportunities to change RAD strategies. Multiple pathways may be possible depending on which management triggers occur in the future. (d) Different management pathways applied across the landscape create a portfolio (foundation 4). (e) Transparent and upstream engagement (foundation 2) provides the deliberative space to consider options and identify desired conditions.

and potential trade-offs. Conflict is not always negative; it is required to change the status quo. Upstream engagement processes can help foster constructive dialogue before conflict spirals out of control. Situation and stakeholder analyses can help managers identify key parties to include those who have the ability to affect the outcome of a deliberative process. For more on stakeholder analysis and related methods see Reed and colleagues (2009).

Deliberative engagement methods also can encourage managers and stakeholders to listen to one another and acknowledge the human side of transformation (Chopyak and Levesque 2002). Building new lines of communication and more deeply understanding how various stakeholders perceive and respond to change can position agencies to be more nimble in responding to transformation. Where consensus on desired future conditions is impossible, upstream, deliberative engagement can help stakeholders know that their perspectives were heard and may at least help to identify plausible outcomes to avoid if possible because they are highly undesirable to multiple stakeholder groups (Chapin et al. 2010). A portfolio approach (foundation 4) may be a strategy to moderate losses and inequities.

One key to being effective is transparency with stakeholders about agency or institutional constraints, legislative mandates, areas of uncertainty, information used, key assumptions, and how stakeholder feedback will be used in the decision-making processes (Clifford et al. 2021). Overpromising stakeholders regarding their involvement and influence in a decision process can be worse than not including them at all (Creighton 2005).

Foundation 3: Management pathways

Foundation 3 emphasizes designing interventions that can be used to shape a social–ecological trajectory toward desired conditions or away from unwanted outcomes. Planning when, where, and how to resist, accept, and direct change can be more successful when managers visualize and communicate these choices as alternative pathways to divergent futures. Explicitly designing pathways can clarify the regulatory constraints, the actions and preferences of stakeholders, and other governance issues that influence the options available to managers (foundation 2). The beliefs, attitudes, and knowledge of individual managers also influence how they develop and consider management pathways (Clifford et al. 2021). Diversity in institutional and individual pathway development can provide a more comprehensive and creative set of pathway options (Wise et al. 2014). This foundation explicitly recognizes the benefit of creating space for managers to play a proactive role in developing and considering future-oriented alternatives, including novel and creative options to direct a system away from historical conditions. In multijurisdictional landscapes, the mosaic of alternative pathways chosen can create a regional portfolio of RAD choices (foundation 4).

Pathway planning explores the sequence of management interventions that could be used to shape the ecological trajectory (figure 1). Such planning can increase preparedness

Box 1. What influences which conditions a stakeholder desires?

The following factors often influence stakeholder and manager preferences about desired future conditions. Upstream, deliberative engagement can create space to explore these factors more explicitly and incorporate them into decisions about which management pathways to pursue.

Values

Values are moral beliefs about what is good to do in the world. They are formed early in life, are relatively stable, and inform attributes such as attitudes and behaviors (Manfredo et al. 2003, 2018, Schwartz 2006).

Knowledge

Knowledge includes both local or traditional ecological knowledge and scientific understanding, reflecting researchers' understanding that someone's knowledge is a hybrid of informal and formal ways of knowing (Goldman et al. 2011, Watson 2013, Oakes et al. 2016).

Livelihoods and economic incentives

Livelihoods and economic incentives are the work someone does, their livelihood, the economic value they get from land or water and its use, and their related future desires (e.g., a desire to pass land or a fishing location down to their children; Reimer et al. 2014, Sorice and Donlan 2015, Dayer et al. 2018).

Nonmarket use of land or resources

Nonmarket use of land or resources includes the ways that someone interacts with or uses land and natural resources that do not have economic value in the market, but are often very important to quality of life in material or immaterial ways (Allen and Moore 2016, National Ecosystem Services Partnership 2016).

Sense of place

Sense of place describes the importance of a particular place for providing features and conditions that support desired activities or the symbolic importance of a place for its connection to certain emotions and relationships (Williams et al. 1992, Williams and Vaske 2003, Ardoin 2006, Chapin and Knapp 2015). Histories and legacies of a place also have important influences on peoples' relationship to place and the meaning they attribute to it (Finney 2014).

Spiritual and cultural significance

Spiritual and cultural significance includes resources that have important meaning, symbolism, or other intangible associations and benefits. This may include resources that act as important historical records of human activities and cultures (Fatorić and Seekamp 2017) as well as resources that are culturally important to indigenous communities because of spiritual meaning, use in ceremonies or customs, and links to creation stories, oral histories, or other parts of their culture (Zellmer 2002).

RAD decisions do not necessarily need to account for all of the above, but can explicitly frame the discussion and validate how these types of social factors contribute to perceptions of ecological trajectories, desired conditions, and pathway implementation. Managers may choose to revisit conversations about the above social factors more frequently than in the past to understand how they are changing as the ecosystems and resources themselves change (Gorddard et al. 2016). Scenario planning efforts may help to identify both ecological and social indicators that can signal a need to reconvene stakeholders to reassess plans in light of new information.

decision process can generate creative ideas. Deliberative engagement methods can also be incorporated into formal decision processes (CEQ 2007). Using deliberative engagement methods upstream can encourage managers and scientists to step out of authority roles and actively question their own assumptions (Felt and Fochler 2008). Deliberative methods also create opportunities to consider other forms of knowledge and the full range of social, political, and economic factors that may influence future ecological trajectories and management pathways (box 1; Pidgeon and Rogers-Hayden 2007). A variety of upstream, deliberative engagement methods can be used across a variety of political and cultural contexts (see Rowe and Frewer 2005, Stirling 2005, Victorian Government Department of Sustainability and Environment 2014). As was discussed in foundation 1, scenario planning promotes deliberation and can be a particularly effective method for engaging stakeholders in joint discovery and mutual learning upstream of a decision (Yung et al. 2013, Crausbay et al. 2021).

Upstream engagement and the use of deliberative methods are not a panacea. Transformation would likely exacerbate conflicts over use of natural resources, as past uses become infeasible, ecologically imprudent, or incompatible with stakeholder expectations and preferences. Managers and stakeholders may well experience a range of emotions including fear, anger, and sadness when confronted with ecosystem transformation. Upstream engagement does not avoid or circumvent conflict and it may not result in agreement about which ecological trajectories are acceptable or which management pathways to pursue (Stirling 2005). Ultimately, managers may make hard decisions that may not please everyone. Furthermore, managers may still consider who to engage and when, and upstream engagement may not replace the need for other, more traditional forms of involvement such as public meetings or comment periods.

What upstream, deliberative engagement does offer is a more proactive and transparent means of addressing conflict by identifying management triggers, accounting for contingencies, and evaluating opportunities to change course (Haasnoot et al. 2013, Wise et al. 2014, Colloff et al. 2017). Spatial variability is pervasive in ecological systems, providing diversity that can support ecological changes in species composition, structure, and processes. Given this raw material, contingencies can be leveraged to shape social–ecological trajectories. Climatic conditions, which are not readily managed, account for some of this variability. Other sources of variability include disturbance regimes, pollution inputs, landscape fragmentation (including population sinks and sources), and biotic composition and interactions. These factors are often targets of management and have a large influence on ecosystems. In addition, past history, such as introductions (deliberate or otherwise) of exotic species or grazing or fisheries practices, modify ecosystem structure, function, and vulnerability to change (Thomas 2020). These historical factors can provide insights into management interventions that can influence future change (foundation 1).

Moments with potential for ecological change often have been points at which action is taken to maintain historical conditions, such as seeding after disturbance. The RAD framework, however, also seeks opportunities to direct change, and relies on understanding how novel ecosystem drivers (e.g., arctic tundra colonization by beavers; Tape et al. 2018) and deviations from historical disturbance regimes can shape potential system states (foundation 1). Regularly assessing ecosystem services can help maintain harvestable resources, desired disturbance regimes, and cultural services. In this way, it may be possible to sustain ecosystem services and other broad goals desired by managers and other stakeholders, despite changes in specific attributes of ecosystems. For example, grasslands might be maintained despite changes in the relative abundance and composition of species (e.g., Zamin et al. 2018).

In addition to describing plausible future states, it is useful to identify potential transitions and triggers when ecological change cannot be prevented. For example, changes in climate, climate-sensitive disturbance regimes, sea level rise, and urbanization are not readily controlled by local managers and dictate new boundary conditions under which they must operate. Conceptual mapping can be developed among managers, researchers, and stakeholders, including identification of events that underlie transitions among states (Levin and Möllmann 2015, Tekwa et al. 2019). Conceptual state-and-transition models are already used in some systems (Briske et al. 2005), and can be extended to include novel states and transitions. Alternative system states that are self-sustaining and retain desirable attributes (e.g., community composition, disturbance regime) may reduce the need for ongoing intensive management and therefore be preferred to the historical state (Schuurman et al. 2021).

It is important to be aware of feedbacks (e.g., grass-fire cycles) that maintain a system in a desired or undesired state or that might push the system to a different state (foundation 1; Crausbay et al. 2021). Pathways that account for tipping points are more likely to be successful than those that do not (Kelly et al. 2015, Selkoe et al. 2015). Information on tipping points and feedbacks can be gained from long-term data or from spatial analogs with different climatic, land use, or management history (Foley et al. 2015). Ideally, these would have different historical uses that intersect with key abiotic gradients to understand land use–environment interactions. Some events and feedbacks that underlie change may be more controllable (e.g., invasive plant cover, prescribed fire) than others (e.g., extreme weather events). When controllable, these can be used to direct the system state ("Actively create contingencies" in table 1). When not controllable, they may identify management triggers that can be used to prepare to intervene or to reassess management objectives (Kwadijk et al. 2010).

When directional changes in key control variables are highly likely and difficult to prevent, managers can consider interventions that might reduce the impact of those changes or direct change to preferred outcomes (Thompson et al. 2021). Addressing feasibility, implementation barriers, and constraints well before the management trigger occurs allows for timely discussion and implementation (Lynch et al. 2021a). However, given the inevitable uncertainty of future changes in ecological drivers and ecosystem responses, pilot studies, monitoring, and frequent reassessment of management goals and strategies can enable the most robust adaptation strategies (Lynch et al. 2021b).

Management pathway planning can increase the management decision space to act in the face of uncertainty (Haasnoot et al. 2013, Wise et al. 2014). Preparedness is key because of the short time windows for action following an event that could trigger transformation (when in reactive mode). Preparedness is also key for building the institutional and social license to take action when in a proactive role. The feasibility of any pathway includes social, technical, economic, legal, policy, and other agency considerations, which may preclude some potential paths (foundation 2; Tekwa et al. 2019, van Kerkhoff et al. 2019, Lynch et al. 2021a). Pathway planning can be used to address the governance issues that can create inertia for and barriers to implementation of novel adaptation that directs change to novel future conditions (Wise et al. 2014). Pathway planning can also be used to explicitly consider if interventions taken today could limit or increase future decision space in order to maintain future options and opportunities. For example, invasive plant control can be part of passively or actively allowing other species to establish (Crausbay et al. 2021), and therefore part of a strategy to resist or to direct change. Evaluating trade-offs between pathways can clarify short- versus longer-term costs and benefits (Bosomworth et al. 2015, Colloff et al. 2017)

Foundation 4: Portfolio design

Foundation 4 highlights coordination of local-scale choices into portfolios to manage risk and account for multiple preferences and variable conditions across space and time. Spatial conservation and management portfolios provide a framework for coordinated planning within and among management units (figure 1; Magness et al. 2011, Magness and Morton 2017). Overarching goals could include maintaining representation and redundancy of priority biotic elements (Margules and Pressey 2000) and managing in the face of uncertainty by avoiding overinvestment in any one action that may fail (Aplet and McKinley 2017). Historically, management objectives were developed using information from within management boundaries, and a unit's contributions to a broader conservation network were treated as fixed (Belote et al. 2016). Climatic suitability for species, communities, and biomes was treated as temporally stable in reserve design efforts (Jenkins et al. 2015, Lawler et al. 2020). Incorporating climate change into portfolio planning can clarify potential future contributions of management areas. This comes by recognizing the ongoing shifts in species' viability and ranges, the dynamic nature of ecological communities, and the potential for changes in biome types, ecological processes, and socioeconomic benefits and threats (Hamann and Wang 2006, Rehfeldt et al. 2012, Holsinger et al. 2019). The RAD framework involves assigning the decision to resist, accept, or direct change to different locations within and across units. Ecological and social contexts vary over space and underlie allocation decisions at both regional and local scales. Climate change exposure, sensitivity, adaptive capacity, human use, and legal options to respond are not uniform across the landscape (Foden et al. 2019). An understanding of these patterns and their associated uncertainty and opportunities can contextualize choices about how to respond to local change (Magness et al. 2011, Belote et al. 2017, Belote et al. 2018). For example, managing the leading edge of a range shift may be different than managing the trailing edge (Gilbert et al. 2020). In multijurisdictional landscapes, some decision-makers may be more likely to select or avoid a specific response to change (resist, accept, or direct) given differences in agency missions, landowner objectives, and community priorities. Differences in agency mission and culture can help to diversify response (Magness and Morton 2017), and coordination across managers can disperse risk in achieving a desired set of conditions. For example, in a landscape in which vulnerability to ecological transformation is high over a large percentage of the area for a given resource, managers from differing jurisdictions could disperse RAD application so that no one agency would incur all the risk of uncertainties (Belote et al. 2018). On the other hand, it would be important to not conflate a portfolio approach with weak decision-making in which an ad hoc shotgun approach is used to placate constituents.

Existing social–ecological conditions can provide a basis for RAD decisions in complex landscapes, particularly when ecological trajectories and responses to treatments are well understood (Hobbs et al. 2017). For example, resistance-based strategies can be applied to maintain vulnerable attributes, such as populations of endangered or culturally significant species or key ecological process. Resistance strategies may be continued for legal, ethical, or cultural reasons even when resistance is unlikely to be effective in the long run. Such cases can be paired with a strategy to direct another location to accommodate the focal resource (Richardson et al. 2009). Acceptance of change may be applied to lower-priority locations, when an ecosystem has been degraded beyond some ecological threshold into a new self-reinforcing state or when it is contributing novel functions or services (Hobbs et al. 2014). Other degraded areas in which restoration is deemed infeasible may have potential for directed change toward a novel condition that achieves a valued ecosystem function, even one that was not historically present (Acreman et al. 2014). Grass invasions and fire have transformed sagebrush ecosystems of the United States, and postfire responses may include resistance via methods such as seeding native species, acceptance where invasive grasses already dominate, and directing to nonnative perennial grass communities where native species restoration is infeasible and risk of conversion to invasive annual grass dominance is high (Davies et al. 2021). The design of portfolios can account for the increasing costs of resistance over time, and the decreasing costs of directing change toward a more self-sustaining ecological system (Magness and Morton 2017).

Management decisions proceed despite uncertainties, and spatial planning can reduce and mitigate some of this inevitable uncertainty. Pilot projects can reduce uncertainty surrounding the effectiveness of management treatments, and can be applied within the context of variability in ecological conditions, legal authority, and plausible social–ecological futures (Lynch et al. 2021b). Management treatments could be applied as pilot projects before larger investments are made. Replicates of treatments can reflect different methods to resist or direct change, whereas acceptance treatments provide a baseline for comparison (Larson et al. 2013). Experimental designs can be limited to within a certain ecological condition for which management outcomes are uncertain or can be assigned in a multiscale stratified manner across locations with different ecosystem types, vulnerabilities, or stakeholder interest. Experimental treatments provide an opportunity for learning and can serve to represent different stakeholder interests with different treatment types (Larson et al. 2013). However, it is important to recognize the difference between adaptive management approaches based on learning and portfolio approaches that minimize overall risk by holding poorly performing assets within a diversified set. The timescale for performance assessment is typically shorter in an experimental adaptive management approach, where learning about treatment efficacy allows useful approaches to then be applied to other locations (Lynch et al. 2021b). In contrast, a portfolio approach assumes that some assets will perform poorly, and seeks to minimize risk for a given level of performance (Ando and Mallory 2012). Overall performance is assessed at the scale of the portfolio, rather than at the project scale,

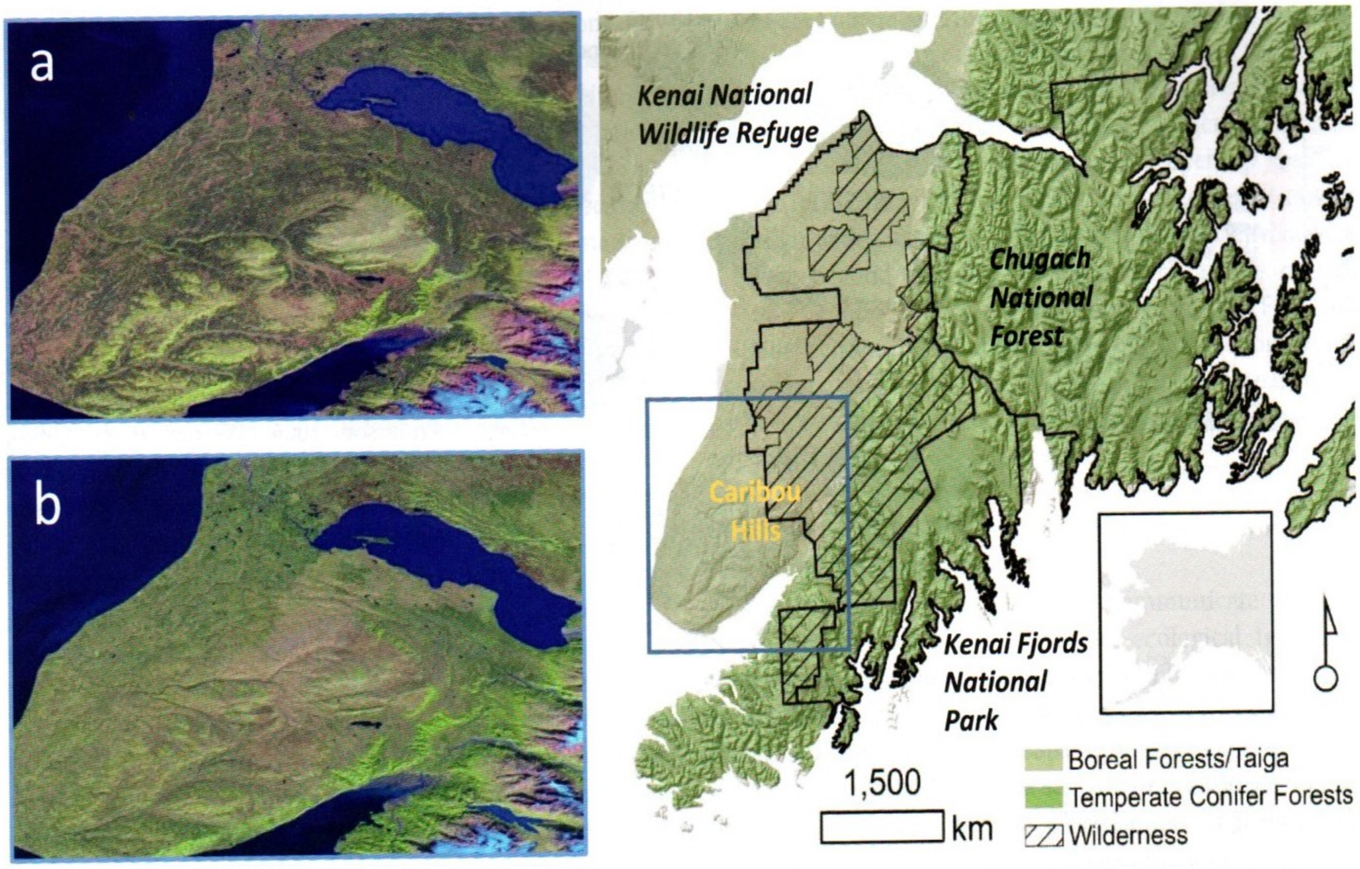

Figure 2. In 1980, the US Congress established the Kenai National Wildlife Refuge (NWR) and Kenai Fjords National Park, which along with the Chugach National Forest increased the area managed by the Federal government to approximately 75% of the 6-million acre Kenai Peninsula, Southcentral Alaska. The Caribou Hills in the southwestern peninsula is on the trailing edge of the boreal forest and the leading edge of temperate forest biomes. Approximately 40,000 acre of grassland occupy what was mature Lutz spruce just three decades ago. Deforestation occurred between (a) Landsat imagery from September 1986 and (b) September 2014 in the aftermath of a 15-year spruce beetle outbreak and a human-caused wildfire. Images from USGS LandLook (https://landlook.usgs.gov/landlook). This work was partially supported by the National Park Service through funding FedNET facilitators Jonathan Bartsch and Melissa Rary.

which would represent a shift in how managers and stakeholders assess success.

Kenai National Wildlife Refuge

This case study presents each foundation through the lens of almost two decades of addressing transformation on the ground by Kenai National Wildlife Refuge (hereafter, Kenai Refuge) staff, two of whom are coauthors on this article. The Kenai Refuge is 805,000 hectares of mostly intact but rapidly changing boreal ecosystems managed for natural diversity, wilderness values, and recreational opportunities on the Kenai Peninsula in Southcentral Alaska (figure 2). Surrounded by an urbanizing landscape composed of more than 50,000 residents and tribal and other public lands managed sometimes for conflicting purposes, the Kenai Refuge is visited by more than 1 million tourists annually. Early outreach focused on addressing climate change denial among residents and visitors, certainly not transformative adaptation. Intra-agency agreement about climate change did not always align because of early failures by biologists and managers to recognize that ecological trajectories were much less dramatic on the eastern than on the western peninsula because of orographic effects of the Kenai Mountains. Therefore, communities or other agencies did not necessarily embrace early attempts to address climate change impacts or envision actions beyond real-time monitoring (Beach 2015). We used insights gained about the information and practices needed to implement transformative adaptation on the Kenai Refuge, including building the knowledge and forums to discuss future-oriented management, to develop the four foundations.

Southcentral Alaska experiences high climate-change exposure (Markon et al. 2018). On the western Kenai Peninsula, warming accelerated in 1968 and annual water availability decreased by 55%, which has caused receding glaciers, rising tree and shrub lines, drying peatlands, and warming nonglacial streams (Klein et al. 2005, Berg 2006, Dial et al. 2007, Berg et al. 2009, Mauger et al. 2017). These ecological changes, although they foreshadow a very different future landscape, are slow enough that Kenai Refuge managers, who have a legislative mandate to conserve natural diversity, have continued to link them to stationarity and historical benchmarks (Fischman 2003, Magness et al. 2012). However, deforestation over large areas of the Caribou Hills on the southwestern peninsula has challenged that paradigm. In this section, we illustrate how the four

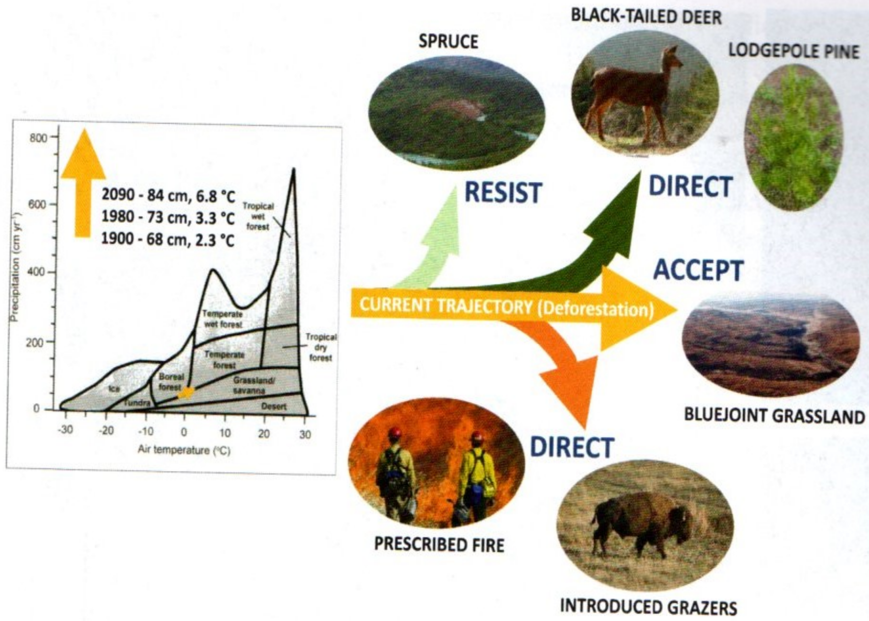

Figure 3. Broad ecological types delineated by annual precipitation and temperature biomes plot from Staudinger et al. 2012. On the basis of directionally changing precipitation and temperature for Caribou Hills on the Kenai Peninsula, Alaska, the historical trajectory is moving away from boreal forest along the boundary between temperate forest and grassland biome states (yellow arrow on biome plot). Without intervention, this developing bluejoint grassland in the Caribou Hills is likely to persist and expand as frequently occurring human- and lightning-caused wildfire hinders recolonization by native spruce and deciduous trees (accept). Other management pathways (resist and direct) are possible. The resist pathway via replanting native spruce is unlikely to succeed because spruce beetle and wildfires will likely continue to be significant drivers in this warming and drying landscape. However, land managers could choose a direct pathway to forested landscape by reforesting with nonnative trees that are more drought resistant, such as lodgepole pine, and allowing or even encouraging introduced Sitka blacktail deer from southeast Alaska to replace native moose on the landscape. Alternatively, the system could be directed toward a more age- and species-diverse grassland by introducing grazers such as bison and using prescribed fire to create both heterogeneity and fuel breaks to protect property and human communities in this area.

management foundations facilitated implementation of the RAD framework to navigate this transformation (figure 2).

Foundation 1: Plausible social–ecological trajectories on the Kenai National Wildlife Refuge

The Caribou Hills is located at the climatic nexus of three biomes: grassland, temperate forest, and boreal forest (see "State factors" in table 1, figure 3). Each represents a plausible trajectory that may unfold on the landscape, likely by unintentional anthropogenic drivers such as human-caused fires and introduced nonnative species, as well as by continued climate warming and its cascading ecological effects (Magness and Morton 2018). Although much of what was previously white (*Picea glauca*) and Lutz (*Picea* X *lutzii*) spruce is regenerating as both conifer and deciduous forest, the northwestern slopes appears to be tipping toward an ecosystem of approximately 8100 ha of grasslands. This transformation is ultimately driven by a warming and drying climate, but proximately by spruce beetles, a native disturbance agent, and novel spring grassland fires ("Ecological contingencies" in table 1; Bowser et al. 2017, Hess et al. 2019, Baughman et al. 2020).

Linked insect and fire disturbance reinforces grassland conditions. Starting in the late 1980s, an unprecedented 15-year spruce beetle outbreak affected over 400,000 ha on the peninsula ("Ecological contingencies" in table 1; Berg and Anderson 2006, Werner et al. 2006). Triggered by consecutive summers of above-average temperatures, the beetle outbreak caused 100% mortality of the contiguous, mature white and Lutz spruce stands ("Ecological legacies" in table 1; Boucher and Mead 2006, Boggs et al. 2008) in Caribou Hills. As forest canopy disappeared, bluejoint (*Calamagrostis canadensis*), a native rhizomatous grass, thrived as a dense monoculture ("Ecological legacies" in table 1). To reduce perceived fire risk and provide economic opportunity, local government permitted road building and commercial salvage operations that led to new dwellings abutting the refuge boundary ("State factors" in table 1; Hansen and Naughton 2013). In 2005, a human-ignited grassland fire in spring was the first in modern times; in 2019, the first lightning-caused grassland fires in spring occurred. Fine-fuel fires in spring is a novel disturbance regime for the Kenai Peninsula ("Ecological contingencies" in table 1; Hess et al. 2019). Refuge biologists have fairly high certainty that this grassland ecosystem will expand in response to reduced annual water availability ("State factors" in table 1; Berg et al. 2009) once spring fires occur frequently enough to kill seedlings and reduce tree recruitment ("Alternative stable states" in table 1). In the absence of wildfires with short return intervals, the ecological trajectory could tip toward a deciduous forest, an outcome that has historically occurred when spruce forests have burned to mineral soil ("Ecological contingencies" in table 1; Magness and Morton 2018). Refuge staff worked with local gardening groups and foresters to inventory more than 60 nonnative tree species planted on the peninsula, which represents novel biota potentially available to exploit the opening climate niche ("Ecological legacies" in table 1; Thomas 2020).

Foundation 2: Upstream and deliberative engagement on the Kenai National Wildlife Refuge

Over two decades, deliberative engagement was necessary to construct a shared language and understanding around climate change, transformation, and the implications for management. In the early 2000s, stakeholders across the Kenai Peninsula did not necessarily think that climate change was human caused or that facilitated adaptation would be necessary (Beach 2015). Local ecologists did not anticipate a forest-to-grassland transformation because they expected the grass would only delay, not stop, forest succession as had happened in the past (Boucher and Mead 2006, Boggs et al. 2008). Although climate envelope and other models indicated the potential for ecological transformation (Magness and Morton 2018), this challenged the mental models of some managers (Clifford et al. 2021), resulting in disagreement about the validity of the ecological models.

Shared language and understanding of transformational change and related management problems began to emerge through several planning efforts, such as the Chugach National Forest and Kenai Peninsula Vulnerability Assessment (Hayward et al. 2017). These processes led to a management community that was more receptive to change. Refuge staff, who were early adopters of the need for adaptation, also used scientific conferences, agency workshops, newspaper articles, and presentations to community groups (e.g., League of Women's Voters, Rotary, Soldotna Historical Society, Alaska Sustainable Tourism Conference) to share information while learning about others' experiences with climate change impacts and their efforts to respond. Ironically, discussions about directing ecological transformation on the refuge were being fielded at venues outside of Alaska (e.g., National Adaptation Forum in 2015), but were not openly shared locally in public forums until 2019.

As local managers came to terms with the need to respond to change, refuge staff engaged in internal agency discussions about plausible future trajectories (foundation 1) and what discretion the agency might have within existing policies and mandates to involve stakeholders and manage nonstationary systems (foundation 3). For the past decade, refuge staff have created space to question assumptions and rethink how to interpret refuge purposes. Given that historical conditions may be impossible to maintain, staff explicitly chose to focus on enhancing biological diversity and minimizing species extinction (e.g., Bowser et al. 2017). They agreed that depauperate species assemblages were undesirable. Refuge policy gives managers flexibility when maintaining or restoring historical conditions is infeasible, meaning alternative management goals can be justified through a transparent record of decision (Schroeder et al. 2004, Meretsky et al. 2006).

To grapple with this new management paradigm, refuge staff worked with the US Fish and Wildlife Service Regional Office to establish the Anthropocene Working Group that was focused on having an internal dialogue among agency staff to reflect on their own assumptions, the state of the management problem, and possibilities for directing ecological transformation. These upstream deliberations within the agency informed options for and feasibility of management pathways (foundation 3). Although some conversations with stakeholders and the public have occurred in the context of planning processes, refuge managers are still in the process of engaging local stakeholders and bringing them into a deliberative process. Additional engagement outside the constraints of formal planning could open up space to discuss futures in which the current societal expectations do not align with plausible ecological trajectories. Envisioning a future beyond planning windows, such as the refuge's 15-year Comprehensive Conservation Plan (US Fish and Wildlife Service 2010), may open space for a more holistic exploration of preferred futures and the management pathways to get there, and may even generate innovative approaches not previously considered.

Foundation 3: Management pathways on the Kenai National Wildlife Refuge

Management pathways explicitly communicate how to resist, accept, and direct the social–ecological trajectory (foundation 1). Without intervention, the best-case scenario for accepting change is that a novel, depauperate, and mostly human-driven grassland system would persist because of a warming and drying climate (SNAP-EWHALE 2012), but without the benefit of large grazers that once populated the Pleistocene grassland (Klein and Reger 2015). The worst-case scenario for accepting change is that it would become populated by introduced, mostly undesirable species better adapted to frequently disturbed systems than native biota (Richardson and Gaertner 2013, Morton et al. 2019). These are significant findings from a societal perspective in that the no-action alternative (accept) is not a return to the recent historical state but a system continuously evolving in response to nonstationary drivers.

Pathway planning creatively explores outcomes beyond acceptance that are possible if managers choose to intervene to resist or direct change (figure 3). In the present article, conventional restoration by replanting native spruce is unlikely to succeed because spruce beetle and wildfires will likely continue to be significant drivers in this warming landscape. More drought resistant and fire tolerant nonnative trees such as lodgepole pine (*Pinus contorta*) could be planted and are already planted in neighboring nonfederal lands. Similarly, nonnative Sitka blacktail deer (*Odocoileus hemionus sitkensis*), which are now migrating onto the peninsula from populations introduced to the Prince William Sound area, could be allowed or even encouraged through translocation to proliferate in this novel forest assemblage in lieu of, or in addition to, native moose (*Alces alces*; Morton and Huettmann 2017). Alternatively, the system could be directed toward a grassland that is more diverse with respect to age and species by introducing grazers such as bison (*Bison bison*) and using prescribed fire to create both habitat heterogeneity and fuel breaks to protect infrastructure in this area. Parts of the Caribou Hills are clearly undergoing ecological transformation, and an opportunity exists to steward the outcome by manipulating drivers and the species available to create novel but functional assemblages.

Table 2. Management triggers on the Kenai Peninsula that identify points at which adaptation strategies can shape the ecological trajectory.

Management trigger	Tips toward	RAD options
Fire return interval drops below 30 years	Grassland trajectory	Resist—intensify fire suppression efforts and encourage boreal deciduous tree recruitment.
		Accept—anticipate a grassland community that is restricted to locally available seed sources and colonization events (native and nonnative).
		Direct—accelerate resorting of grassland species from other places; translocate plants and keystone species from climate analogs that match the emerging climate.
Seedling or sapling mortality event	Grassland or temperate forest trajectory	Resist—plant boreal tree variants that are adapted to the conditions causing the morality.
		Accept—anticipate herbaceous, grassland and other sun-loving plants to use open canopy.
		Direct—use prescribed fire to reinforce grassland fire regime and encourage grassland root mass development (grassland trajectory) OR accelerate the dispersal of trees that match the emerging climate by planting trees from climate analogs (temperate forest trajectory).
Sitka black-tail deer establish population	Temperate forest trajectory	Resist—eradicate deer population to reduce competition with moose.
		Accept—anticipate changes that come with deer– moose interactions (i.e., disease outbreaks, competition) and changes to vegetation.
		Direct—manipulate habitats to increase deer browse and translocate plants and other species from community assemblages that include deer.

Note: The RAD framework is used to create alterative options for each management trigger. The sequence of RAD options chosen in response to sequential management triggers constitute the management pathway.

Pathway planning is increasing preparedness by encouraging refuge staff to explore uncertainties and multiple intervention options. Refuge staff are beginning to define management triggers that may occur in the future and link them to management options within alternative pathways (table 2). Increasing fire frequency and intensity are key contingencies (Staver et al. 2011). Other potential triggers, such as widespread recruitment by a colonizing tree species, colonization by keystone species, or tree mortality events, could also be influential decision points in reconsidering RAD options. Feasibility assessment and learning is necessary to vet interventions against other management constraints prior to implementation. For example, the forest-to-grassland transition is occurring within federally designated wilderness; therefore, the Wilderness Act may be a policy barrier. Refuge staff explored how to balance untrammeled values with biodiversity concerns given rapid change and wilderness policy in working groups (i.e., wilderness evaluation framework: www.wilderness.net/restoration). The Alaska Department of Fish and Game is currently translocating wood bison (*B. bison athabascae*) within their historical range in Alaska, which excludes the Kenai Peninsula (Gardner and DeGange 2003). Upstream engagement with stakeholders (foundation 2) could include establishing relationships with North American bison conservation groups in order to pursue pathways that diversify the grassland using plains bison (*B. bison bison*). Finally, three common gardens across the latitudinal gradient of the refuge are ongoing pilot projects to explore tree species that could be considered for planting to steward a novel forest assemblage.

Foundation 4: Portfolio design on the Kenai National Wildlife Refuge

Kenai Refuge is still in the early phases of developing explicit management pathways (foundation 3) and therefore has not yet established spatial portfolios. Nonetheless, the refuge has been implicitly accepting many relatively low-velocity changes such as drying peatlands and rising treelines since they were documented 1–2 decades ago (Thompson et al. 2021). Similarly, the refuge has been implicitly resisting change via conventional management, such as by managing invasive species with herbicides, reintroducing extirpated caribou, maintaining landscape connectivity with highway underpasses and land acquisition, and restoring eroded stream banks. However, there are informal discussions underway about potentially managing beaver populations as a means to restore drying peatlands, an explicit decision to move from accept to resist. Deliberative engagement with adjacent landowners and nearby communities can help identify different perspectives on preferred future conditions while exploring a range of potential pathways and management portfolios. Across the Kenai Peninsula, land managers conceptualize climate-change risk differently, which influences whether and how ecological trajectories are used to inform management options (Beach 2015). Portfolio planning within the spatial domain of the refuge, as well as among adjacent public land management units on the peninsula, will almost certainly become more explicit in future planning cycles (Magness and Morton 2017). As Kenai Refuge staff become more explicit about resisting, accepting, and directing change, outcomes may include deliberate bet hedging, experimental validation of ecological outcomes from likely trajectories, and implementation of pilot studies to test novel adaptation approaches (Thompson et al. 2021)

Going forward: Enabling future-oriented management

Navigating ecological transformation is not a linear, decision-making process, but a dynamic adaptive response to changing conditions and expectations. In this process, management regimes may need to transform with the ecosystem, when the old governance systems become less responsive to the emerging reality (Wise et al. 2014, Colloff et al. 2017, van Kerkhoff et al. 2019). The Kenai Refuge case study describes a particularly convoluted process over two decades because as an early adopter of the need for facilitated adaptation to climate change, staff experienced resistance from its own agency, as well as other agency partners. Adaptively responding to change by adjusting the management regime, in terms of the knowledge, values, and rules that govern it, is now as important as efficiently managing established objectives (Colloff et al. 2017). To date, adaptation recommendations have tended to be very general, and novel solutions have not yet been widely sought or implemented (Gorddard et al. 2016, LeDee et al. 2021).

Management problem contexts are shifting quickly from discussions about the relevance of climate change to the implementation of novel adaptation approaches that assess how to resist, accept, or direct change (Lynch et al. 2021a, Thompson et al. 2021). Natural resource managers operate in a variety of situations and landscapes, so there cannot be a one-size-fits-all solution. Different people in different places with different problems will engage with these foundations in different ways. Climate change and transformation result in complex social–ecological dynamics that challenge natural resource agencies' ability to fulfill legislative mandates and foster public trust (GAO 2013, GAO 2014, GAO 2019). However, socially and ecologically desirable futures that are aligned with change are possible. Positive visioning can create more options and inspire novel alternative visions of a positive future world (Bennett et al. 2016).

RAD provides a powerful framework for expanding options beyond status quo approaches that were developed under assumptions of stationarity. Our four foundations (figure 1) support new management practices that can be used to implement RAD as part of a much broader and dynamic adaptive response because they include practices that increase capacity to transform the management regime in ways that may be necessary to accommodate novel conditions. These four foundations, combined with advancing science (Crausbay et al. 2021) and adaptive management (Lynch et al. 2021b), can provide the means to successfully sustain ecosystem services on rapidly transforming land and seascapes.

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References cited

Acreman M et al. 2014. Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. Frontiers in Ecology and the Environment 12: 466–473.

Allen KE, Moore R. 2016. Moving beyond the exchange value in the nonmarket valuation of ecosystem services. Ecosystem Services 18: 78–86.

Ando AW, Mallory ML. 2012. Optimal portfolio design to reduce climate-related conservation uncertainty in the prairie pothole region. Proceedings of the National Academy of Sciences 109: 6484–6489.

Aplet GH, McKinley PS. 2017. A portfolio approach to managing ecological risks of global change. Ecosystem Health and Sustainability 3: e01261.

Ardoin NM. 2006. Toward an interdisciplinary understanding of place: Lessons for environmental education. Canadian Journal of Environmental Education 11: 112–126.

Baughman CA, Loehman RA, Magness DR, Saperstein LB, Sherriff RL. 2020. Four decades of land-cover change on the Kenai Peninsula, Alaska: Detecting disturbance-influenced vegetation shifts using landsat legacy data. Land 9: 382.

Beach D. 2015. Reframing Climate Change Adaptation: Examining the Future of Landscape-Scale Climate Change Adaptation on the Kenai Peninsula in Response to Participant Identified Barriers to Implementation. US Fish and Wildlife Service. www.fws.gov/uploadedFiles/Beach_D_2015.pdf.

Beier P. Brost B. 2010. Use of land facets to plan for climate change: Conserving the arenas, not the actors. Conservation Biology 24: 701–710.

Beisner BE, Haydon DT, Cuddington K. 2003. Alternative stable states in ecology. Frontiers in Ecology and the Environment 1: 376–382.

Belote RT, Carroll C, Martinuzzi S, Michalak J, Williams JW, Williamson MA, Aplet GH. 2018. Assessing agreement among alternative climate change projections to inform conservation recommendations in the contiguous United States. Scientific Reports 8: 1–13.

Belote RT et al. 2016. Identifying corridors among large protected areas in the United States. PLOS ONE 11: e0154223.

Belote RT et al. 2017. Mapping conservation strategies under a changing climate. BioScience 67: 494–497.

Bennett EM et al. 2016. Bright spots: Seeds of a good Anthropocene. Frontiers in Ecology and the Environment. 14: 441–448.

Berg EE. 2006. Landscape drying, spruce bark beetles and fire regimes on the Kenai Peninsula, Alaska. Forest Ecology and Management 227: 219–232.

Berg EE, Anderson RS. 2006. Fire history of white and lutz spruce forests on the Kenai Peninsula, Alaska, over the last two millennia as determined from soil charcoal. Forest Ecology and Management 227: 275–283.

Berg EE, Hillman KM, Dial R, DeRuwe A. 2009. Recent woody invasion of wetlands on the Kenai Peninsula lowlands, south-central Alaska: A major regime shift after 18000 years of wet sphagnum–sedge peat recruitment. Canadian Journal of Forest Research 39: 2033–2046.

Boggs K, Sturdy M, Rinella DJ, Rinella MJ. 2008. White spruce regeneration following a major spruce beetle outbreak in forests on the