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Ecological scenarios: Embracing ecological uncertainty in an era of global change

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Abstract

Scenarios, or plausible characterizations of the future, can help natural resource stewards plan and act under uncertainty. Current methods for developing scenarios for climate change adaptation planning are often focused on exploring uncertainties in future climate, but new approaches are needed to better represent uncertainties in ecological responses. Scenarios that characterize how ecological changes may unfold in response to climate and describe divergent and surprising

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ecological outcomes can help natural resource stewards recognize signs of nascent ecological transformation and identify opportunities to intervene. Here, we offer principles and approaches for more fully integrating ecological uncertainties into the development of future scenarios. We provide examples of how specific qualitative and quantitative methods can be used to explore variation in ecological responses to a given climate future. We further highlight opportunities for ecological researchers to generate actionable projections that capture uncertainty in both climatic and ecological change in meaningful and manageable ways to support climate change adaptation decision making.

KEYWORDS
climate change adaptation, ecological methods, natural resource management, uncertainty

INTRODUCTION

Climate change adaptation is a critical mechanism for coping with the effects of climate change on ecosystems and society (Wasley et al., 2023). Adaptation planning for natural resource management relies on science that evaluates climate change implications for ecosystems and the services they provide (Stein et al., 2013), which is subject to substantial uncertainties. Projecting future ecological responses to climate change is inherently challenging because of uncertainty not only in future climate but also due to abiotic and biotic novelties and the complexity of ecological dynamics that create multiple potential ecological outcomes under a given set of future climate conditions (Crausbay et al., 2022; Rangwala et al., 2021). Yet, evaluating and exploring uncertainty in ecological responses to climate change is needed to support meaningful action in preparing for the future (Coreau et al., 2009; Crausbay et al., 2022).

Climate change adaptation scientists and practitioners (hereafter "adaptation practitioners") are increasingly planning under uncertainty by considering multiple scenarios of future climate and ecological change, rather than relying on a single or a narrow set of projections (NPS, 2013; NPS, 2021; Terando et al., 2020). Current approaches often focus on evaluating uncertainty across climate projections to generate future scenarios for adaptation planning (Lawrence et al., 2021; Miller et al., 2022), but similar approaches for systematically envisaging and integrating ecological uncertainty have received less attention and remain a major challenge. At the same time, ecological researchers often seek to develop projections of future change using predictive models to support management decision making (Dietze, 2017; Hendry, 2023; Mouquet et al., 2015). Although such models are often assessed based on their predictive accuracy, they can also be adapted to explore a broad range of plausible ecological conditions and dynamics that can emerge over time frames relevant to adaptation planning (e.g., decades; Maier et al., 2016). Thus, the growing fields of climate change adaptation science and predictive ecology have great potential to enhance one another.

Here, we discuss principles and approaches for integrating ecological uncertainty into climate change adaptation planning through the development of ecological scenarios, defined as coherent descriptions of plausible ecological responses given assumptions about changes in key drivers (e.g., climate, disturbance) and ecological dynamics. First, we outline the current state of practice in scenario-based climate change adaptation planning, and then identify opportunities for building on current applications through the integration of three critical elements. We argue that scenarios will be most informative for planning if they (1) span a range of uncertainty in ecological responses under each of several climate futures, (2) characterize trajectories through which ecological changes could unfold temporally, and (3) explore extreme or unexpected outcomes. In a final section, we discuss methodological approaches and examples of quantitative and qualitative tools that can contribute to ecological scenario development. Ultimately, integrating both climatic and ecological uncertainties into scenarios supports adaptation planning by more comprehensively accounting for impacts, risks, and opportunities.

BACKGROUND: SCENARIOS IN CLIMATE CHANGE ADAPTATION PLANNING

Scenarios are not forecasts or predictions but are instead plausible characterizations of the future, which

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have been used across a variety of fields and applications to support decision making in situations characterized by irreducible uncertainties (Peterson et al., 2003; van der Heijden, 2005). Here, we focus on the use of scenarios in climate change adaptation planning for natural resource stewardship (detailed in Miller et al., 2022). In adaptation planning, a manageable set (~2–5) of scenarios that describe critical uncertainties in future climate and their effects on focal resources are used to help decision makers plan for unfamiliar circumstances. This often involves evaluating resource stewardship goals and actions under each scenario to identify adaptation approaches that are robust to uncertainty (i.e., effective under most or all plausible future conditions). For example, the U.S. National Park Service (NPS) has used scenarios to guide decisions about actions such as protecting cultural sites and managing hydrological structures and a variety of natural resources (Miller et al., 2022; Schuurman, Miller, et al., 2022). Following NPS guidance (NPS, 2013), a set of scenarios should be:

1. relevant to the decision(s) at hand and the social-ecological context in which they are embedded;
2. challenging enough to stimulate creative thinking about how actions and goals will need to adapt;
3. divergent enough to encourage thorough exploration of potential implications and responses; yet
4. plausible, in that they adhere to first principles and are internally consistent.

Although the current state of practice includes rigorous methods for representing climate uncertainty (drawing on variation among emissions pathways and model projections to capture divergent climate futures; Lawrence et al., 2021), and qualitative and quantitative methods for characterizing climate impacts on resources (Symstad et al., 2017), it generally does not examine variation in ecological responses under each climate future (Figure 1). Focusing primarily on future climate uncertainty may be appropriate for situations in which the effects of climate on management foci are relatively straightforward (e.g., infrastructure, water resources; Lawrence & Runyon, 2019). Yet, natural resource management objectives often pertain to ecological conditions (e.g., community composition), and variation in ecological responses can be more consequential than the range of climate futures themselves (e.g., Felton et al., 2022; Renwick et al., 2018). Therefore, a needed extension of scenario development is the integration of uncertainty in ecological responses alongside uncertainties in climate to capture a wider range of potential outcomes.

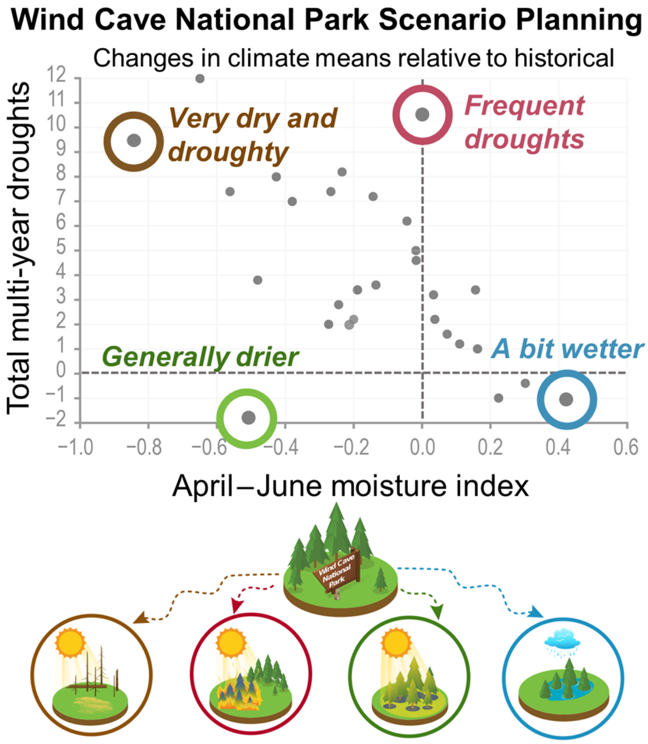

FIGURE 1 Example of climate futures (top) and scenarios (bottom) for Wind Cave National Park, adapted from Knapp et al. (2023) and Runyon et al. (2021). Each dot on the graph represents a climate projection for mid-century, with four selected to capture a set of divergent climate futures: (1) very dry and droughty, (2) frequent droughts, (3) generally drier, and (4) a bit wetter. Collectively, these projections represent a range of plausible changes in climate metrics that are relevant for park resources, including multi-year droughts and spring moisture availability. Through a participatory process, park staff and subject-matter experts developed four scenarios describing natural resource outcomes under these climate futures, each with their own challenging management implications (e.g., scenarios encompassed outcomes ranging from expansion to decline of forest extent and persistence to extirpation of some plant species; Runyon et al., 2021). Here, we emphasize that ecological scenario development can be advanced through approaches that explore the potential for multiple ecological trajectories and outcomes under each climate future. Illustrations: National Park Service Climate Change Response Program.

CRITICAL ELEMENTS OF ECOLOGICAL SCENARIOS

Ecological uncertainty

Uncertainty in ecological responses to a changing climate derives from multiple sources, encompassing difficult-to-predict climatic, geophysical, biological, and socioeconomic factors (Maris et al., 2018). Ecological dynamics in response to climate change may be difficult

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to predict as a result of environmental and demographic stochasticity and path dependency (i.e., the system response depends on its past state; Blonder et al., 2017). The potential for non-stationarity, or variation in the relationship between environmental drivers and ecological processes over time and space, particularly under novel biotic or abiotic conditions, further challenges our ability to extrapolate into the future (Wolkovich et al., 2014). Incomplete understanding of complex ecological dynamics (e.g., feedbacks, biotic interactions; Holt & McPeek, 1996) and challenges in modeling such complexity further add to uncertainty (Littell et al., 2011; Rangwala et al., 2021). As such, multiple ecological outcomes could result from a given change in climate (Crausbay et al., 2022). For example, in boreal forests of southern Alaska, the plausibility of future vegetation states—including spruce forest, deciduous forest, and grassland—depends not only on climate but also on specific events and ecological conditions (e.g., fire severity, seed availability; Magness, Wagener, et al., 2022). Ecological scenarios can be used to explore the potential for multiple ecological responses under each of multiple climate futures to avoid underestimating the range of plausible outcomes. Furthermore, exploring uncertainty in ecological responses focuses attention on the mechanisms, spatiotemporal patterns, and rates of ecological change (Williams et al., 2021), which may improve the utility of scenarios for informing management decisions.

Trajectories

Projections of ecological characteristics in response to climate change often emphasize shifts in species distributions, community composition, or even biomes, implying a transition to a new state. However, it is valuable to characterize not only these end states but also how such shifts could play out (Magness, Hoang, et al., 2022). An ecological trajectory is a description of the temporal dynamics of ecological properties (e.g., community composition). Embedding "trajectory thinking" into scenario development requires (1) considering climate futures that capture consequential events (e.g., extreme drought; Moss et al., 2024; Reyer et al., 2013), (2) characterizing mechanisms that drive ecological change (e.g., demographic and community assembly processes; ecological and evolutionary feedbacks governing transitions among alternate states; Dakos et al., 2019), and (3) understanding that changing climate, atmospheric composition, and land use are expanding the bounds within which naturally dynamic ecosystems fluctuate.

Scenarios that include descriptions of ecological trajectories improve both the plausibility and actionability of scenarios. For instance, future climates could support a range of ecosystem types within Nebraska's Sandhills ecoregion, including mixed-grass prairie, woodlands, or de-vegetated dunes (Box 1; Figure 2). Under climate conditions that would facilitate the expansion of woody vegetation, a trajectory involving increased fire frequency prior to woodland establishment could shift the direction of change toward grassland (Fogarty et al., 2020; Twidwell et al., 2021). Understanding the mechanisms underlying this trajectory helps identify prescribed fire as a potential management lever for guiding the ecosystem along certain pathways. More generally, discrete events like severe fires or other disturbances can create windows of opportunity during which trajectories are especially sensitive to stochastic physical or biotic processes and management intervention (Seidl & Turner, 2022). For instance, post-fire planting is a tool that could be used to shape successional trajectories toward species assemblages better suited to future climate and disturbance regimes (Coop, 2023; North et al., 2019). Understanding such contingencies facilitates planning about when, where, and how to intervene, and helps resource stewards recognize nascent signs of ecological changes (Bradford et al., 2018; Magness, Hoang, et al., 2022).

Surprises

Surprises, or substantial ecological changes that contradict expectations (including those that are not anticipated by existing ecological knowledge or models; Doak et al., 2008; Thompson & Smith, 2019), have the potential to create outsized impacts. Extreme and compounding events, novel biotic and climatic conditions, and poorly understood ecological feedbacks or tipping points can give rise to surprises (e.g., Dakos et al., 2019; Lenton et al., 2008). Additionally, ecological responses that exceed the range of recent historical variability may often be perceived as surprising, whether or not they could have been anticipated (Glantz et al., 1998). Scenario-based exploration that stretches thinking to identify outcomes and interactions at the bounds of plausibility (i.e., extreme or novel but not fanciful; Shearer, 2005), including those absent from past experience, can help managers anticipate and prepare for impactful events. For example, scenario planning at Sequoia and Kings Canyon National Parks in 2013 examined the possibility that climate change could amplify the impacts of natural disturbances (i.e., wildfire, insects, disease, floods) on giant sequoia groves and produce unprecedented outcomes—almost all of which played out in the following years (K. Nydick, National Park Service, personal communication 2024). In this case, "out of the box" thinking fostered by scenario planning engaged managers in discussing high-consequence possibilities, such as mortality

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BOX 1 Case study: Identifying ecological scenarios and trajectories for the Nebraska Sandhills

The Nebraska Sandhills are one of the largest intact grasslands in the world (Scholtz & Twidwell, 2022), composed of sand dunes stabilized by mixed-grass prairie. Here, we identify several plausible trajectories for this ecoregion to illustrate how multiple lines of evidence can be integrated to develop ecological scenarios. We assessed potential ecological responses under a set of divergent climate projections based on historical and paleoecological records, climate analogs, and workshops with refuge staff and other experts (Figure 2). Current trends include eastern redcedar (*Juniperus virginiana*) encroachment, highlighting a plausible transition to woodland that could be redirected through managed fire and tree removal (Fogarty et al., 2022; Garmestani et al., 2020). Ecoregional climate analogs additionally support the plausibility of remaining in a grassland state (Stralberg, 2018). Paleoecological records support another, extreme possibility: de-vegetation of the dunes triggered by extended (>10 years) severe drought (Mangan et al., 2004).

A set of scenarios summarizes these divergent possibilities and the drivers, triggers, and ecological sensitivities that could bring about each trajectory (Figure 2). These are illustrative in nature, intended to demonstrate several features of ecological trajectories. First, shifts in trajectories may be triggered by management intervention, climate extremes, or disturbances. Trajectories may differ in the rate of change while ultimately converging to a similar state. Additionally, similar trajectories may occur under different climate futures, or different trajectories may occur under the same climate future, depending on ecological uncertainties. Laying out these alternate futures can help managers think about which are acceptable or preferred and recognize early signals of each trajectory, such as accelerated cedar encroachment under a wetter climate future. They may also be useful for identifying adaptation strategies (e.g., increased use of prescribed fire) or needs for contingency planning (e.g., in case of extended drought) that could help direct trajectories away from less preferred outcomes.

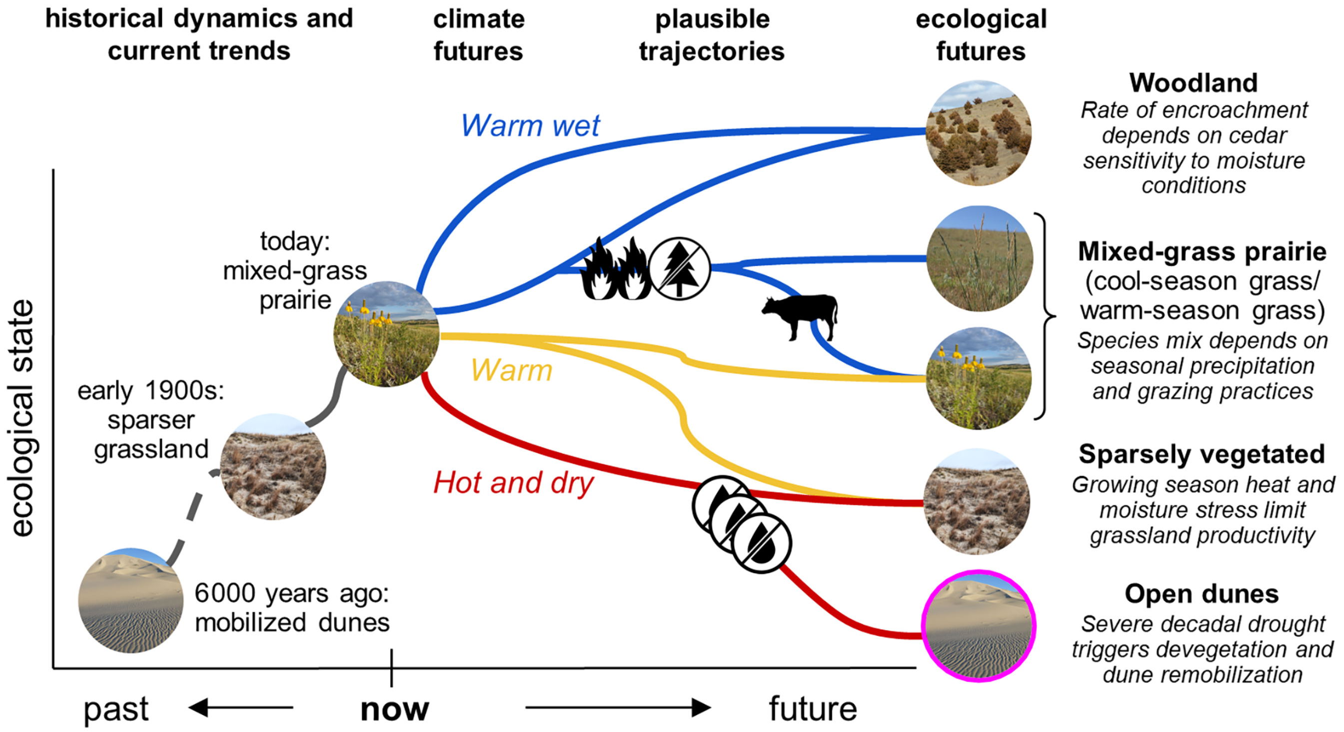

FIGURE 2 Qualitative example describing past trends and plausible future ecological trajectories for the Nebraska Sandhills ecoregion. The magenta border on the open dune future indicates that it is an extreme or potentially surprising possibility. The trajectories depicted here represent dominant landscape- or ecoregion-level trends; trajectories at individual points on the landscape may be less smooth, and multiple trajectories could coexist in different locations (e.g., prairie refugia in moist low-lying areas under an open dune future). Additional scenarios or trajectories could be identified by considering other drivers such as land conversion. See Box 1 for additional details. Photo credits (top to bottom): T. Walz; M. Lavin; C. Helzer; O. Richmond; National Park Service.

of giant sequoia from previously innocuous bark beetles under severe drought. When these climate-amplified extreme events unfolded sooner than expected, managers were able to mobilize quickly to study and react to the unprecedented effects of multiple mortality agents (Pearman et al., 2022). Managers recognized that actions to address the consequences of a 20th-century fire deficit by thinning sequoia groves could not only reduce extreme fire impacts on adult trees (Shive et al., 2022), but could also reduce drought impacts and, potentially, bark beetle infestations (van Mantgem et al., 2021). Although there will always be "unknown unknowns" that cannot be anticipated (Kopp et al., 2017), such efforts to explicitly capture extreme or surprising outcomes improve preparedness and support institutional norms that enable nimble management responses (Walker & Salt, 2012).

APPROACHES FOR DEVELOPING ECOLOGICAL SCENARIOS

Here we offer a set of principles and tools to inform the development of ecological scenarios that build on previously developed scenario-based adaptation methods (Miller et al., 2022, 2023) to more systematically integrate ecological uncertainties, explicitly characterize trajectories, and explore impactful surprises (Figures 3 and 4). These are intended for a diverse audience, including ecologists and adaptation practitioners. Adaptation practitioners use scenarios to support a particular decision or plan, in which the initial framing of the decision context, risk tolerance, focal resources, and relevant scales guide the development of scenarios that describe a range of future climates and their ecological and resource implications (Miller et al., 2023). A co-production approach involving both practitioners and ecologists can be effective for integrating ecological understanding and analyses into scenarios, for example, by clearly framing the problem to guide ecological modeling efforts that support scenario development (e.g., Miller et al., 2017). However, not all adaptation planning is done in close partnership with ecologists, nor are all ecological projections developed for a specific management application. Regardless of the context in which ecological projections are developed, we argue that ecological researchers can expand on current efforts to generate actionable future projections by drawing on scenario-based approaches in predictive modeling to represent uncertainties about ecological responses in transparent, manageable ways (Coreau et al., 2009; Maris et al., 2018). Such "scenario-friendly" ecological projections may be

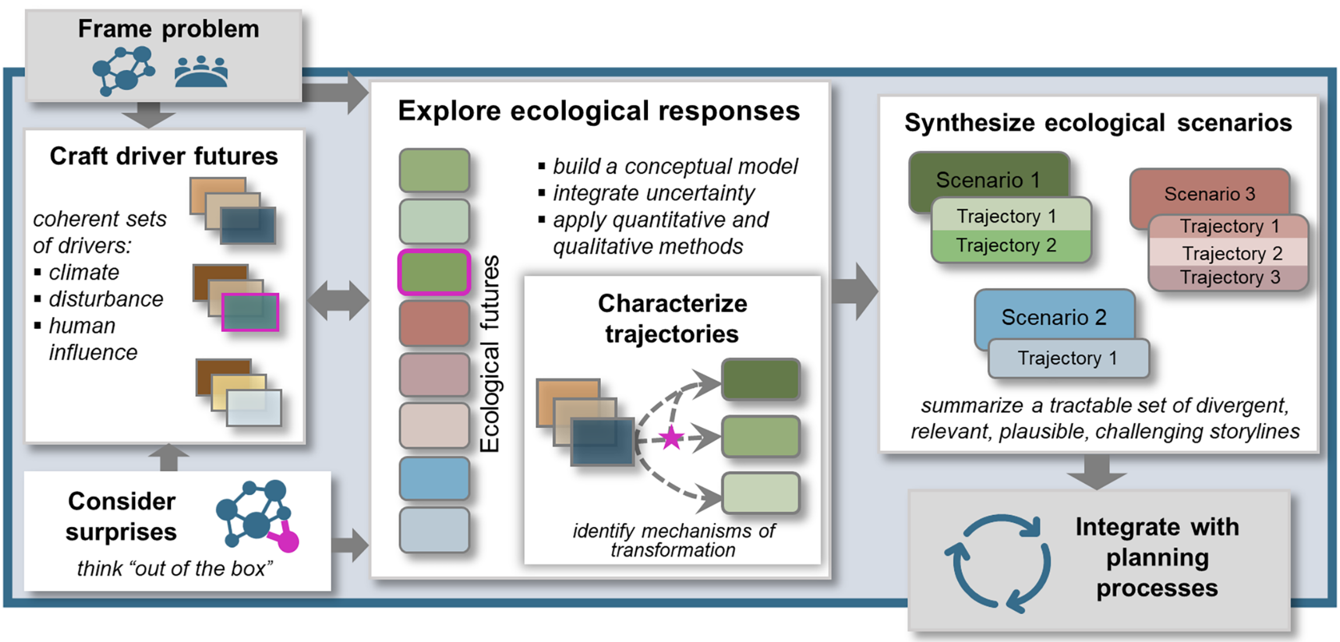

FIGURE 3 A generalized workflow for developing ecological scenarios, which involves initial problem framing to define the appropriate scope and scale, selecting driver futures representing divergent conditions in key factors affecting ecological outcomes, exploring a range of ecological outcomes under each driver future, considering extreme driver futures and ecological responses to capture potential surprises, and synthesizing this information into a set of alternative futures that may encompass multiple trajectories and can be used to inform management choices. The core components discussed in detail in this paper (white boxes) represent a module that can fit within and support comprehensive adaptation planning processes that involve additional steps, from defining management goals to implementing adaptation strategies and monitoring effectiveness; refer to fig. 2 in NPS, 2021 for an example of a generalized planning cycle. Specifically, scenario development supports the assessment of climate impacts and vulnerabilities in the context of climate change adaptation planning.

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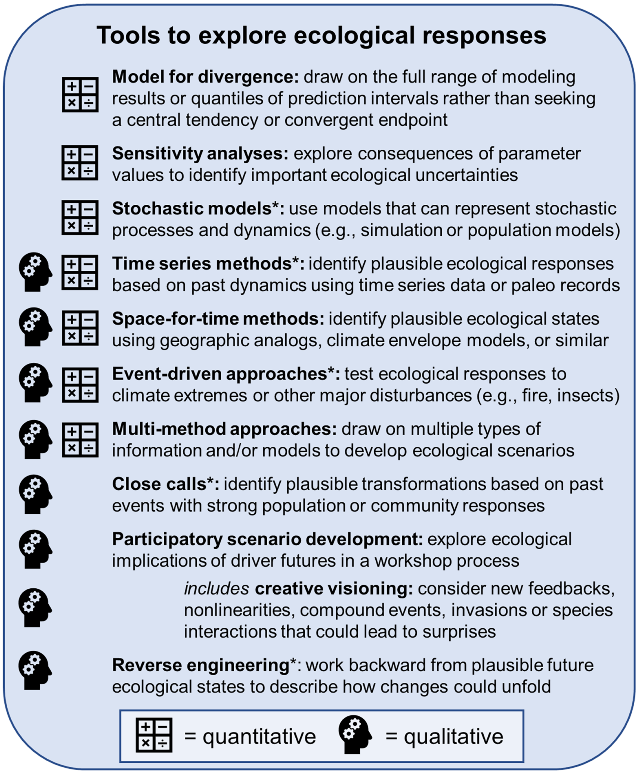

FIGURE 4 "Toolbox" of quantitative and qualitative approaches for working with ecological uncertainties in developing ecological scenarios for climate adaptation planning. Those with an asterisk are likely to be particularly useful for characterizing trajectories. See Table 1 for additional detail and applied examples from prior research.

particularly valuable for practitioners when planning is constrained by time, funding, or capacity, and must rely on available (e.g., published) information. Below, we describe four general steps to inform the development of ecological scenarios (Figure 3), oriented toward adaptation planning but with broader applicability for predictive ecological modeling. We focus specifically on opportunities for exploring ecological uncertainty through scenarios (Figure 4), recognizing that adaptation decisions involve additional processes not discussed in detail here.

Craft "driver futures"

Developing plausible, divergent, challenging, and relevant ecological scenarios involves characterizing sets of future conditions in factors that shape ecological responses of interest, focusing on those drivers that are most uncertain and influential (Peterson et al., 2003; van der Heijden, 2005). Although scenario-based adaptation planning predominantly focuses on relevant climate metrics, other driving factors such as land-use change, climate-related disturbance (e.g., wildfire; Box 2), and species introductions may also warrant exploration. As with the development of climate futures (Lawrence et al., 2021), considering multiple levels of a particular driving factor is key for scenario development when future changes in that driver are uncertain and could strongly influence ecological outcomes. Once a subset of key drivers is identified, their plausible future conditions are combined in coherent ways to produce "driver futures" (Figure 3). For example, the ecological scenarios explored in Box 2 are based on combinations of future climate and fire severity that determine the potential for transitioning from forest to non-forest (Figure 5). These driver futures must be internally consistent to maintain plausibility; for instance, an arid climate future may be inconsistent with increasing land conversion of rangeland to unirrigated row-crop agriculture (Rashford et al., 2016). It may also be appropriate to develop driver futures iteratively with ecological responses to consider possible feedbacks, such as vegetation changes that modify disturbance regimes (two-way arrow in Figure 3; Archibald et al., 2018). Resulting driver futures focus attention on the most important sources of uncertainty and clarify the assumptions about future conditions that underlie ecological scenarios (e.g., Coop, 2023; Janousek et al., 2023). Although some assumptions about management may be necessary for systems in which the ecological conditions are strongly shaped by current management (e.g., King et al., 2013; Miller et al., 2017), driver futures generally do not include management alternatives; rather, potential adaptation strategies and actions are considered in a later step of planning (Figure 3).

Explore ecological responses

A diversity of approaches can facilitate exploration of plausible and divergent ecological responses to a given set of future conditions in climate and other drivers (Figure 4). In practice, the user has a great deal of leeway in selecting a subset of methods appropriate to a particular system and decision context. Here we discuss general principles for working with ecological uncertainty through a scenario-based lens, while remaining non-prescriptive to accommodate a wide range of variation among ecological systems and applications. We call on existing examples that make use of some of these principles (Table 1), and we further underscore opportunities for ecological researchers and adaptation practitioners to expand their use of scenario-based approaches for representing uncertainty in ecological responses under future climate change.

Models developed and run according to distinct sets of assumptions about drivers and ecological processes

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BOX 2 Case study: Leveraging empirical data to develop ecological scenarios for US southwestern forests

US southwestern dry forests are vulnerable to ecological transformations catalyzed by wildfires in a changing climate (Coop et al., 2020). Previous research has investigated the drivers and ecological outcomes of transformation by characterizing postfire changes in plant communities (e.g., Coop, 2023; Davis et al., 2023; Rodman et al., 2020). Here, we call on a specific example in southwestern ponderosa pine (*Pinus ponderosa*) forests (Coop, 2023) to illustrate how an empirical study including elements of the workflow in Figure 3 could be leveraged to support scenario-based climate change adaptation planning.

In the original study, observational data were used to characterize distinct postfire trajectories of vegetation change (Figure 5). Field-collected plant community composition data in previously burned areas were analyzed using non-metric multidimensional scaling to identify postfire community types indicative of either forest recovery (ponderosa pine reestablishment), transition in forest type (mixed conifer, aspen), or transition to non-forest (bunchgrass, oak scrub, mixed shrub, ruderal grass). A statistical model was developed to understand how environmental factors and fire severity influenced the likelihood of each of these trajectories. This model was run under a set of driver futures, representing wet and dry mid-century climate projections combined with three fire severity scenarios in order to characterize plausible ecological outcomes. Model outputs were used to assess the range of future ecological responses under each of those fire and climate futures, distinguishing between forest and non-forest trajectories. These published, empirical results could be summarized into ecological scenarios and used to identify climate change adaptation strategies that are robust across a range of futures (Figure 5).

The scenarios are relevant for informing both pre-fire and postfire management. Observed community types identified in the study represent a range of fire-catalyzed vegetation transitions plausible at a localized scale, with each trajectory differing in prevalence across the landscape under alternative future scenarios (Figure 5). Proactive actions to reduce fuel loads could reduce the overall risk of transformation associated with scenarios involving high-severity wildfire (Davis et al., 2023, 2024). Additionally, under a given scenario, different postfire community transitions at individual locations could motivate targeted adaptation actions, such as planting drought-adapted tree species or lower-elevation genotypes in areas dominated by non-native grasses after fire to promote resilient forests (Coop, 2023).

While this example illustrates how quantitative research can be informative for exploring a range of plausible ecological futures, these scenarios could be expanded upon through other qualitative or quantitative approaches to account for potential surprises. For example, scenarios could additionally consider the effects of new non-native or range-shifting native species, sequences of events such as climate extremes or multiple severe fires in succession, and feedbacks between vegetation transitions and fire characteristics (e.g., frequency and severity).

can provide scenario-based, rather than "best guess," projections (refer to fig. 1 in Maier et al., 2016). Integrating ecological uncertainty may involve exploring the consequences of parameter uncertainties (e.g., physiological thresholds of dominant species), structural uncertainties (e.g., competing model formulations), and stochastic factors shaping ecological responses (e.g., different sequences of climate extremes or demographic events like recruitment or masting) (Dietze, 2017). For example, process-based models that integrate stochastic processes such as wildfire can generate a range of plausible future ecological states and trajectories under a given climate projection (Turner et al., 2022; Table 1), which could be synthesized into a manageable set of distinct scenarios for adaptation planning. Such scenario-based modeling approaches may often involve a conceptual shift in how models are applied and their outputs communicated. Certain applications of methods that seek convergence in model outputs, such as ensemble averaging, have the potential to collapse and conceal meaningful variation in future projections (Lawrence et al., 2021), whereas modeling to inform scenario development actively seeks divergent outcomes and transparently represents assumptions.

Furthermore, because models are inherently simplified representations of complex systems, integration of multiple sources of information—including qualitative reasoning—helps to account for processes or dynamics

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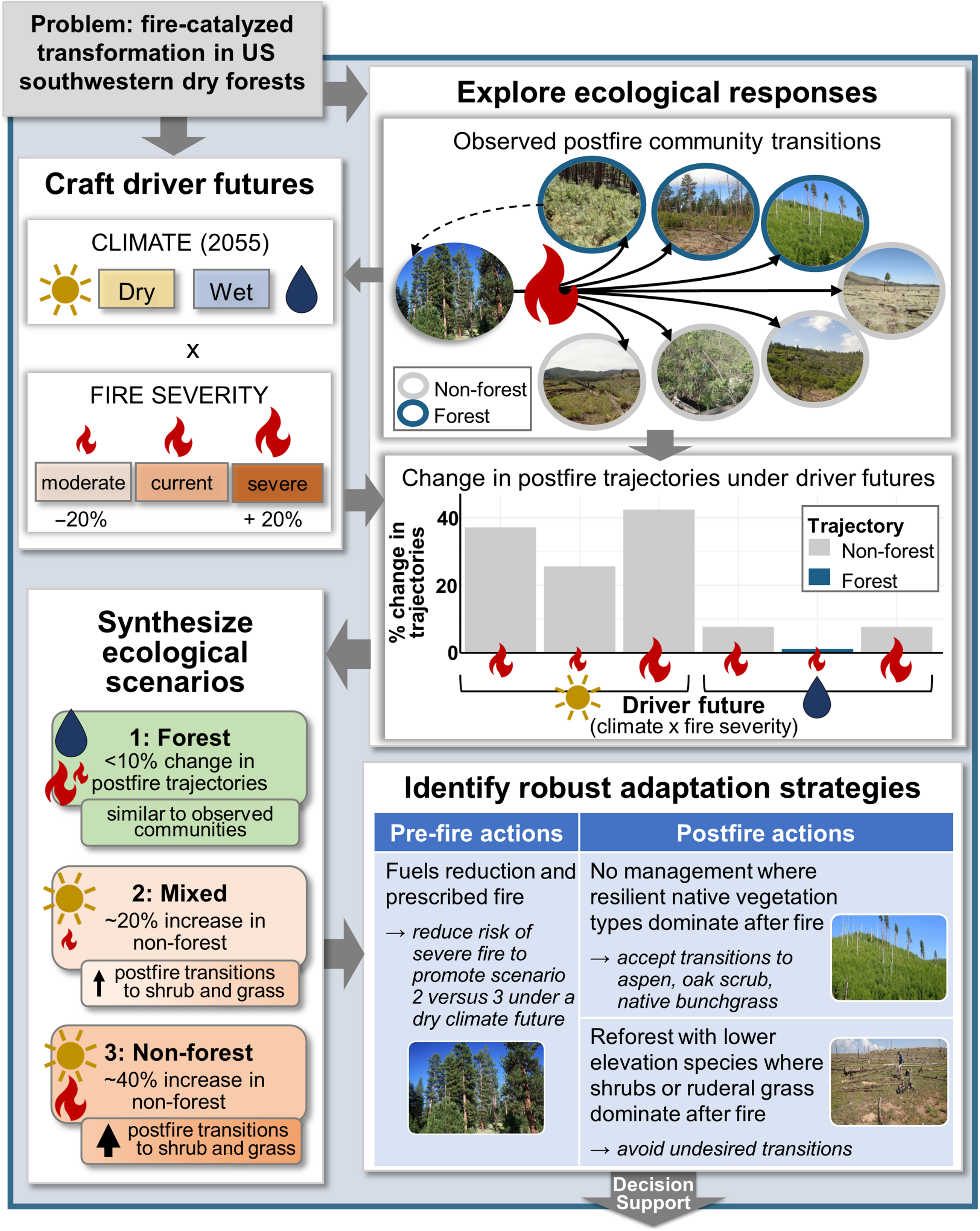

FIGURE 5 Ecological scenarios developed from data on postfire plant communities, adapted from Coop (2023). See Box 2 for additional details. Photo credits: United States Forest Service (ponderosa pine forest); J. Coop (all others).

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not well represented by models trained on data that may not adequately represent future conditions. Qualitative, participatory approaches are commonly used in scenario development (Table 1), especially in situations in which data, capacity, or resources constrain the use of quantitative models, or available quantitative tools are insufficient to capture nuanced ecological responses. Scenario planning excels at incorporating diverse viewpoints and information (Oteros-Rozas et al., 2015; Peterson et al., 2003), including through the use of guiding questions in a participatory process with adaptation practitioners. For instance, what native and non-native species may expand or migrate into an area? How might compound events or shifting disturbance regimes alter ecological dynamics? What amplifying or dampening mechanisms (feedbacks) could accelerate shifts between ecological states or confer resilience? Additionally, conceptual models can be powerful tools for synthesizing ecological understanding and guiding scenario development (Good et al., 2024). Although qualitative methods can be used alone, scenario development can also take advantage of existing approaches for integrating qualitative and quantitative methods (Alcamo, 2008; Miller & Morisette, 2014; Symstad et al., 2017), including expert elicitation to parameterize quantitative models in data-poor contexts (Jarnevich et al., 2019; Miller et al., 2017). For instance, conceptual state-and-transition models that describe plausible transitions among ecological states can also be quantified and spatialized through state-and-transition simulation modeling (Daniel et al., 2016).

Drawing on multiple methods facilitates the consideration of ecological change across a range of spatiotemporal scales relevant to planning (Magness, Wagener, et al., 2022). Climate strongly influences the distributions of biomes over long timescales, whereas particular realizations of ecosystem change (i.e., trajectories) are sensitive to the pace of climate change, discrete weather events, and biotic factors. Rigorous scenario development not only considers the range of plausible future states but also temporally explicit dynamics (trajectories) through which such futures could be realized. Although some types of methods may be well suited to characterizing change over time directly, many commonly used qualitative and quantitative approaches focus on anticipating future states, including those based on space-for-time substitutions (Figure 4). Pairing such methods with "reverse engineering" is a promising approach (Figure 4; Table 1). For example, one could start with a description of a plausible future state identified using climate analogs that implies a particular ecological transition (e.g., conversion of a forest to a grassland), and work backwards to infer the mechanisms leading to and stabilizing such a change (e.g., the fire regime and aridity that could drive tree regeneration failure) (Magness, Wagener, et al., 2022). The ability to identify a mechanistic trajectory through which a particular state could be reached can provide an important check for plausibility.

Additional work is needed to further develop and test methods for characterizing trajectories (Figure 4). For example, fisheries planning has used a participatory process that combines cards describing alternate future conditions in multiple factors to create divergent scenarios; a similar process could be adapted to explore ecological trajectories (Mid-Atlantic Fishery Management Council, 2023). Additionally, qualitative conceptual models could be used to identify causal biotic and abiotic factors involved in state shifts (Good et al., 2024). Applications of these approaches in scenario planning might result in descriptions of transitions involving specific sequences of climatic events under future conditions, and even potential transitions into new states not captured by observed system dynamics. Quantitative approaches that characterize community change through time, such as trajectory analysis (De Cáceres et al., 2019), could also be used to link potential drivers like extreme events or climate change to shifts in the directions of ecological trajectories. Long-term observational and experimental datasets are critical for building understanding of the drivers of ecological trajectories to better characterize them for scenario development. In particular, studies of post-disturbance trajectories provide empirical information on how interactions between climate events, disturbances, management interventions, and biotic interactions shape ecological dynamics (e.g., Coop, 2023). Areas of active research that can improve our ability to characterize trajectories include addressing the rates of key processes shaping ecological responses to environmental change (Smith et al., 2009; Williams et al., 2021) and exploring how community-level trajectories interact with landscape dynamics and trends relevant to management (Figure 5). Considering such cross-scale interactions could help structure thinking about the sources of ecological uncertainty shaping future trajectories and facilitate planning within and across management units.

Consider surprises

Deliberate effort to explore the bounds of plausibility throughout scenario development helps prepare practitioners for the range of situations they may face. Although every possibility cannot be anticipated, efforts to promote innovative thinking and creative applications of existing ecological methods or models can lead to the identification of challenging ecological scenarios or radical interventions (Pearman et al., 2022; Stein

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TABLE 1 Descriptions and examples of general approaches that can be used to explore ecological futures as part of scenario development.

Tool for exploring ecological futures	Generalized approach	Examples from scenario planning or academic literature	Specific model(s) or method(s) used	Description
Trajectory-compatible forward-looking modeling	Develop ecological futures using models that represent stochastic processes and can provide outputs describing change over time (e.g., landscape, simulation, and demographic models). Outputs may require synthesis to improve their actionability for scenario-based applications.	Turner et al. (2022)	Landscape model (iLand)	Used a process-based forest landscape model (iLand) to explore future trajectories of ecosystem change in Greater Yellowstone landscapes, running stochastic simulations under multiple climate projections to explore the effects of climate and disturbance on ecological trajectories.
		Miller et al. (2017)	STSM	Co-produced a spatially explicit STSM to assess effects of climate futures & management alternatives on grassland productivity and composition in southwestern South Dakota; included sensitivity analysis and stochasticity (e.g., probability of encroachment, invasive spread and establishment, grazing and its effects).
		King et al. (2013)	Dynamic global vegetation model (MC1)	Ran a locally-parameterized version of MC1 for Wind Cave National Park under scenarios of future climate, grazing intensity, and natural and prescribed fire to assess potential vegetation changes, including shifts in the grass-forest ecotone over time.
Post hoc trajectory inference or "reverse engineering"	Infer plausible mechanisms or "what if" sequences of events that could lead to a particular future ecosystem state. The future state may be derived from another method, for example, climate analogs, which does not provide trajectory information directly.	Magness, Wagener, et al. (2022)	Qualitative (literature review of empirical research)	Assessed potential future biome shifts within Tetlin National Wildlife Refuge in Alaska based on climate analogs (multiple methods) and used literature synthesis to identify plausible ecological trajectories leading to those biome shifts. Descriptions of trajectories included the conditions and events that could either stabilize the current boreal forest or shift toward alternate future states of deciduous forest or grassland.
Multi-method approaches	Draw on multiple types of information and/or models to generate a range of ecological outcomes. Using multiple approaches can help explore the consequences of ecological uncertainties	Michalak et al. (2017)	Qualitative (trait-based sensitivities); correlative (climatic niche projections); dynamic global vegetation models (LPJ and MC1)	Three case studies of climate vulnerability assessments, each using multiple climate futures and ecological methods to assess plausible future vegetation changes. Ecological models with different formulations and assumptions provided divergent future projections.
		Renwick et al. (2018)	Correlative (using spatial data);	Used four different modeling approaches to assess vulnerability of big sagebrush to future climate change across the western United States. Found that the

(Continues)

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TABLE 1 (Continued)

Tool for exploring ecological futures	Generalized approach	Examples from scenario planning or academic literature	Specific model(s) or method(s) used	Description
	represented by differences in model structure and underlying assumptions.		correlative (using temporal data); mechanistic demographic model; dynamic global vegetation model (LPJ-GUESS)	choice of ecological model was a greater source of uncertainty in predicting the direction of future change in sagebrush than the choice of climate model or emissions scenario.
		Felton et al. (2022)	Correlative (using spatial data); correlative (using temporal data)	Developed correlative models relating rangeland productivity in the western United States. to climate using both a space-for-time approach (taking advantage of spatial climatic gradients) and a time-series approach (taking advantage of interannual climate variability) to estimate late-century productivity under multiple climate projections. A sensitivity analysis assessed the relative uncertainty associated with the climate model, emissions pathway, and ecological assumptions associated with each approach.
Space-for-time approaches	Large suite of methods relating the geographic distributions of species, communities, or biomes to spatial climatic variation to infer equilibrium responses under future climate conditions (e.g., climate analogs, species distribution models; Lovell et al., 2023). Can be combined with other methods to explore ecological uncertainties, or spatial variation could be exploited to identify a range of plausible ecological states under a given climate future.	Fisichelli et al. (2013)	Habitat suitability models	Used correlative models to compare current and future habitat suitability in Acadia National Park for 83 tree species. Evaluated species vulnerability to climate change and identified potential candidates for assisted or unassisted migration into the park, which could be used as the basis for scenarios of forest change.
		Magness and Morton (2018)	Climate envelope models	Used correlative models to relate vegetation cover types (identified from Landsat imagery) with environmental covariates and predict changes in vegetation cover on the Kenai Peninsula, Alaska under a range of future climate conditions and given certain assumptions about the resistance of current vegetation types to change.

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TABLE 1 (Continued)

Tool for exploring ecological futures	Generalized approach	Examples from scenario planning or academic literature	Specific model(s) or method(s) used	Description
Time-series approaches	Draw on empirical time-series data (e.g., long-term monitoring) or historical or paleoecological records to relate past ecological responses to climatic and other drivers. Note that future projections based on correlative relationships will often involve extrapolation. Can be combined with other methods to explore ecological uncertainties, or temporal data could be used to identify drivers of divergent trajectories.	Roy et al. (2001)	Statistical/ correlative models	Used time series data spanning 1976–1997 to develop models of annual abundance for United Kingdom butterfly species that incorporated weather and density-dependence as predictors. Predicted overall population trends for the past 200 years to compare against documented trends, and projected future trends under a range of climate scenarios.
Post-disturbance approaches	Use empirical data describing post-disturbance trajectories of reorganization or ecological transformation to identify plausible future trajectories, focusing on large-scale disturbances as catalysts for community change.	Coop (2023), Davis et al. (2023)	Statistical/ correlative models	Related post-wildfire observational vegetation data with environmental and fire-effects covariates, and used these statistical models to estimate potential forest versus non-forest recovery following future fires under different assumptions of climate and fire severity.
"Close calls"	Identify potential ecosystem transformations based on past events with strong population or community responses.	Mangan et al. (2004)	Historical records and process-based ecosystem model (CENTURY)	Identified a past event (Dust Bowl drought) that significantly impacted Nebraska Sandhills grasslands through plant mortality and species composition shifts, with recovery over several years. Ran simulations using an ecosystem model to test under what conditions a similar or more severe drought could cause widespread, lasting de-vegetation.

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TABLE 1 (Continued)

Tool for exploring ecological futures	Generalized approach	Examples from scenario planning or academic literature	Specific model(s) or method(s) used	Description
STM	Build a conceptual model describing relationships among ecosystem states, including the causal biotic, abiotic, and management drivers involved in transitions among states.	Good et al. (2024)	Qualitative (participatory workshop, expert elicitation)	A structured process for describing ecological states and identifying plausible transitions and their drivers was used to develop a multi-community STM for eucalypt woodlands in southern Australia, which informed the creation of conservation guides for managers. Demonstrates a process for identifying causal chains that could be extended to consider climate change.
Participatory scenario development	Explore consequences of driver futures in a workshop process with subject-matter experts and resource stewards	Schuurman et al. (2019), Runyon et al. (2021)	Qualitative (participatory workshop, expert elicitation)	Participatory scenario planning workshops with subject-matter experts and staff at Devils Tower National Monument and Wind Cave National Park to assess the climate vulnerabilities of priority resources. Participants identified major resource climate sensitivities (e.g., extreme precipitation, summer drought, freeze–thaw cycles, temperature maxima) that were used to select divergent climate projections. Participants developed comprehensive scenarios describing the plausible implications of climatic changes for natural and cultural resources, and identified management options.

Note: Some of the examples are from previous scenario development exercises that were part of specific adaptation planning processes. Others are from peer-reviewed academic studies in which some aspects of the methods or outputs include elements that could be extended for scenario-based applications. Not all of these examples meet every principle for development of ecological scenarios, nor is this list comprehensive, but they are intended to provide concrete examples of general approaches and tools described in Figures 3 and 4.

Abbreviations: STM, state and transition models; STSM, state-and-transition simulation model.

et al., 2024). Ecologists may benefit from techniques for stimulating thinking about complex, nonlinear dynamics from other fields, such as science-fiction prototyping (refer to Merrie et al., 2018 for an example application to fisheries scenarios). Another important way to consider surprises is to elicit views from diverse experts and knowledge holders. Indigenous perspectives, which may include knowledge of impactful historical surprises and dynamics, can provide critical insights in this regard (e.g., Ciocco et al., 2024; Herman-Mercer et al., 2020). Additionally, paleoecological records span a wider range of climatic and ecological variability than is represented in contemporary landscapes. By characterizing the range of past variation, they can be used to assess the potential for novel future conditions (Clark-Wolf et al., 2023; Higuera et al., 2021; Williams & Jackson, 2007) and identify plausible ecological transformations not evident from observed system dynamics (e.g., an open dune state in the Nebraska Sandhills; Figure 2; Nicholson & Swinehart, 2005).

Explicit consideration of extreme or compounding events can further assist in evaluating risks of abrupt ecological transformations (Turner et al., 2020). Albano et al. (2021) and Shepherd et al. (2018) offer qualitative and quantitative methods of using past climate events to explore the potential impacts of future extremes while maintaining plausibility. For example, a sequence of strong atmospheric river events in California was developed by simulating severe storms analogous to those experienced in 1861–1862; this simulation was then used to evaluate vulnerabilities and hazards including flooding, landslides, agricultural, environmental, and health impacts (Plumlee et al., 2016; Porter et al., 2011). More broadly, by drawing on approaches from military, intelligence, and computing fields, "red team" emulations could be used to elicit and prepare for surprising situations (Zenko, 2015).

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Synthesize ecological scenarios

The goal of ecological scenario development is to distill overwhelming possibilities in ecological responses into a tractable set of alternative future states and trajectories that capture major uncertainties (Figure 3). A large number of ecological projections may result when multiple quantitative approaches are considered, a wide range of drivers and uncertainties are explored, or the plausible ecological responses are highly varied. Methods for synthesizing numerous future projections include conducting multivariate analyses to cluster ecological responses into a smaller set of divergent and representative futures, or selecting individual projections to represent the range of possibilities (analogous to how climate futures are selected; Lawrence et al., 2021). For instance, one could synthesize across projections that result in similar vegetation states or those that have similar management implications to generate a set of divergent, relevant, plausible, and challenging scenarios. Without adequate synthesis to achieve a tractable set of ecological scenarios (e.g., 2–5), it can become too complicated and time-consuming to integrate them into a planning process.

Scenario synthesis and presentation will be most relevant for adaptation planning when guided by engagement with decision makers. Effective communication may involve synthesizing scenario information at relevant spatiotemporal scales and linking with practitioners' experiences of the system by, for example, drawing analogies to past events (Shepherd et al., 2018; Sheppard et al., 2011). Engagement with practitioners additionally refines scenarios to focus on actionable information for management and can help communicate scenarios in ways that are engaging and meaningful for decision makers. Once the scenarios have been created, they can be integrated into climate change adaptation planning processes to evaluate alternative management strategies in light of a range of plausible future conditions, with iteration as necessary to further refine the scenarios based on ecological responses to management (Figure 3).

CONCLUSIONS

Both the general principles and flexible set of tools presented here can be applied to develop ecological scenarios that integrate important uncertainties into a tractable set of futures against which potential goals, objectives, and strategies can be evaluated (NPS, 2021). Specifically, decision makers can use ecological scenarios to assess a suite of adaptation approaches based on their robustness under multiple climate futures (e.g., Runyon et al., 2020), to identify proactive actions to help reduce vulnerabilities under specific, impactful contingencies (e.g., extended drought; Box 1), and to develop monitoring strategies designed to detect early signals of emerging transitions. Explicitly integrating ecological uncertainties and exploring temporal dynamics and surprising or extreme outcomes improves the actionability of scenarios for informing management planning. For example, understanding the mechanisms and plausible trajectories of ecological change can help managers orient themselves as transitions begin to unfold, enabling more targeted monitoring, comprehensive contingency planning, and nimble responses.

The purpose of scenario planning is to explore the consequences of variation in factors that are uncertain, uncontrollable, and influential for the outcome(s) of interest in order to facilitate decision making under uncertainty (Peterson et al., 2003). Thus, explicit consideration of both climatic and ecological uncertainty through scenarios is warranted for situations where the ecological uncertainties are beyond control and are consequential for management, and the ecological outcomes cannot be reliably predicted based on future climate alone. For planning processes that would benefit from considering ecological uncertainties but are limited by time and capacity, we highlight tools and approaches spanning a range of effort levels that can be applied to develop ecological scenarios (Figure 4).

Scenarios do not themselves provide decision guidance, and in climate change adaptation planning, scenario development is one component of a larger process that involves both scientific and human dimensions. Existing frameworks (e.g., Schuurman, Cole, et al., 2022; Swanston et al., 2022), decision-support tools (e.g., Miller et al., 2023) and planning processes (e.g., Cross et al., 2012; NPS, 2021) can leverage ecological scenarios to inform strategy development and planning by helping to focus objectives, identify actions, and evaluate tradeoffs. For example, scenarios can inform decision making using the Resist-Accept-Direct framework by articulating the range of potential ecological outcomes and helping to determine whether transformation can be feasibly resisted, what ecological systems may emerge if change is accepted, and what new ecological conditions could be achieved through active management (Crausbay et al., 2022). For applications in which adaptation planning focuses on guiding the direction of ecological change toward preferred alternatives (Magness, Hoang, et al., 2022; Werners et al., 2021), characterizing ecological trajectories may be particularly useful to inform management decisions about when and how to intervene.

More broadly, insights and methods from ecology can improve scenario development. We have highlighted opportunities for ecological researchers to enhance the utility of

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ecological projections for informing adaptation planning by expanding the use of scenario-based approaches in predictive ecological modeling. Additionally, ongoing research to advance mechanistic understanding of ecological trajectories and transformations in a non-stationary world, including how lagged processes, feedbacks, and stochasticity shape ecological dynamics, will support the development of challenging and plausible scenarios (Crausbay et al., 2022; Yang, 2020). In an era of near-certain ecological change but of uncertain rates and outcomes, ecological researchers can frame uncertainties in the context of scenarios to provide actionable information for decision makers while advancing theory and methods to evaluate plausible ecological responses to climate change.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

No data were collected for this study.

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