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Scenarios and strategies for future-proofing ecosystem management under climatic novelty

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Abstract

Climate change is driving unprecedented declines in dominant, habitat-forming foundation species across marine and terrestrial ecosystems globally. As climatic novelty becomes the norm, ecosystem reassembly will become increasingly common. Predicting and understanding these transitions, and their implications for future ecosystem functioning, is essential for designing effective forward-looking management strategies. We explored 3 scenarios that describe a range of ecosystem reassembly trajectories following declines in previously dominant habitat-forming taxa: compensation, in which functionally similar subdominant or immigrating taxa maintain ecosystem structure and function; decline, in which no compensation occurs leading to loss of ecosystem structure and function; and transformation, in which the ecosystem present historically can no longer persist and shifts into a fundamentally different ecosystem type with distinct structure and function. This range of potential outcomes highlights the urgent need to assess the ecological feasibility and functional implications of potential management actions. Scientists and managers can work together to quantify local-scale climatic novelty and ecosystem resilience to better predict the most likely reassembly trajectories and identify management interventions that will optimize ecosystem function. This approach would allow for more proactive planning to support persistence of ecosystem structure and function, helping to future-proof ecosystem management in a rapidly changing world.

KEYWORDS
climate change, ecosystem management, ecosystem transformation, ecosystem transitions, foundation species, novel climates

INTRODUCTION

Climate-driven mass mortality events are becoming increasingly pervasive across the world's marine, terrestrial, and freshwater ecosystems (Grimm et al., 2013; Hoegh-Guldberg & Bruno, 2010; Parmesan & Yohe, 2003). Some of the largest impacts are occurring in ecosystems characterized by "foundation species" (Ellison et al., 2005; Wernberg et al., 2024): the numerically or structurally dominant, habitat-forming taxa that define ecosystem structure and function (Dayton, 1972; Ellison, 2019). For example, the increasing frequency and intensity of marine heatwaves over the last several decades have contributed to >50% declines in coral populations (Eddy et al., 2021), ~19% declines in seagrass habitat (Dunic et al., 2021), and the loss of nearly 40% of kelp forests globally (Krumhansl et al., 2016). Mass mortality events may be less ubiquitous on land, but heat- and drought-related mortality are nonetheless becoming increasingly common in forests worldwide (Allen et al., 2015; Anderegg et al., 2013; Hammond et al., 2022; Phillips et al., 2024; Seidl et al., 2017). Although climate is not always the dominant driver of ecosystem change (Jaureguiberry et al., 2022), the potential for ecosystem persistence in the face of climate change will largely depend on how far and how fast climate diverges from the historical baselines that gave rise to contemporary species assemblages (Loarie et al., 2009; Williams & Jackson, 2007).

Climate change is predicted to expose many of the world's ecosystems to combinations of climate-related stressors that are without precedent in recent ecological history (i.e., recent decades to centuries; Williams & Jackson, 2007; Williams et al., 2007). This "climatic novelty" can be defined globally, when abiotic conditions fall outside of the range of climates experienced historically anywhere on Earth (Lotterhos et al., 2021; Ordonez et al., 2024; Williams et al., 2007), or locally, when environmental conditions in a particular location or ecosystem diverge from its recent climate history (Mahony et al., 2017; Radeloff et al., 2015; Williams et al., 2007). Although global-scale climatic novelty is rare at present, at least ~50% of the world's marine and terrestrial ecosystems are predicted to experience climates without any historical analog by 2100 (Lotterhos et al., 2021; Ordonez et al., 2024). At local, management-relevant scales, the degree of climatic novelty will likely be even higher (Radeloff et al., 2015; Trew et al., 2024; Williams et al., 2007). As local-scale climatic novelty increases, transitions of once-stable ecosystems to altered states will become increasingly common (Graham et al., 2014; Hobbs et al., 2009; Ordonez et al., 2024; Williams & Jackson, 2007). For foundation species that already exist near the extremes of their physiological tolerances, ecosystem reassembly, and associated transitions in ecosystem structure and function, may be inevitable (Conradi et al., 2024; Osland et al., 2025; Williams & Jackson, 2007).

As increasing climatic novelty continues to reframe the challenge of ecosystem reassembly from a question of what if to where and when, managers are faced with the daunting challenge of how to confront what comes next. Despite efforts to develop more future-proof ecosystem management frameworks that acknowledge, rather than resist, ecosystem transitions (Darling et al., 2019; Hobbs et al., 2009; Lynch et al., 2021, 2022; Schläppy & Hobbs, 2019; Schuurman et al., 2022), more conventional management approaches still dominate the literature (McLaughlin et al., 2022), particularly for marine ecosystems (Oestreich et al., 2020; Rist et al., 2013). As a result, ecosystem managers too often find themselves reacting to, rather than preparing for, impacts of climatic novelty (Seastedt et al., 2008). One reason for this disconnect is that the best-available science is often not designed to directly address management objectives and is not often effectively communicated to ecosystem managers. This leaves managers without the information needed to predict the most likely trajectories of change at management-relevant scales.

By merging insights from ecological theory and empirical observations across the world's marine and terrestrial ecosystems, we considered 3 scenarios of ecosystem transitions that are likely to arise from the disproportionate impacts of climate change on historically dominant foundation species and their implications for ecosystem function (i.e., ecosystem properties, goods, and services [sensu Christensen et al., 1996]). We used that conceptual model to provide guidance on how scientists and ecosystem managers can coproduce research to better predict the most likely trajectories of ecosystem change under climatic novelty at management-relevant scales. We also explored how that information can be used to navigate existing ecosystem management frameworks to optimize functional outcomes of future management actions (Harris et al., 2006; Jackson & Hobbs, 2009).

RESISTANCE OF FOUNDATION SPECIES TO CLIMATIC NOVELTY

Foundation species are, by definition, abundant, with a few taxa often dominating the habitat-forming assemblages of ecosystems (Ellison, 2019) (blue-shaded bars in Figure 1a). This

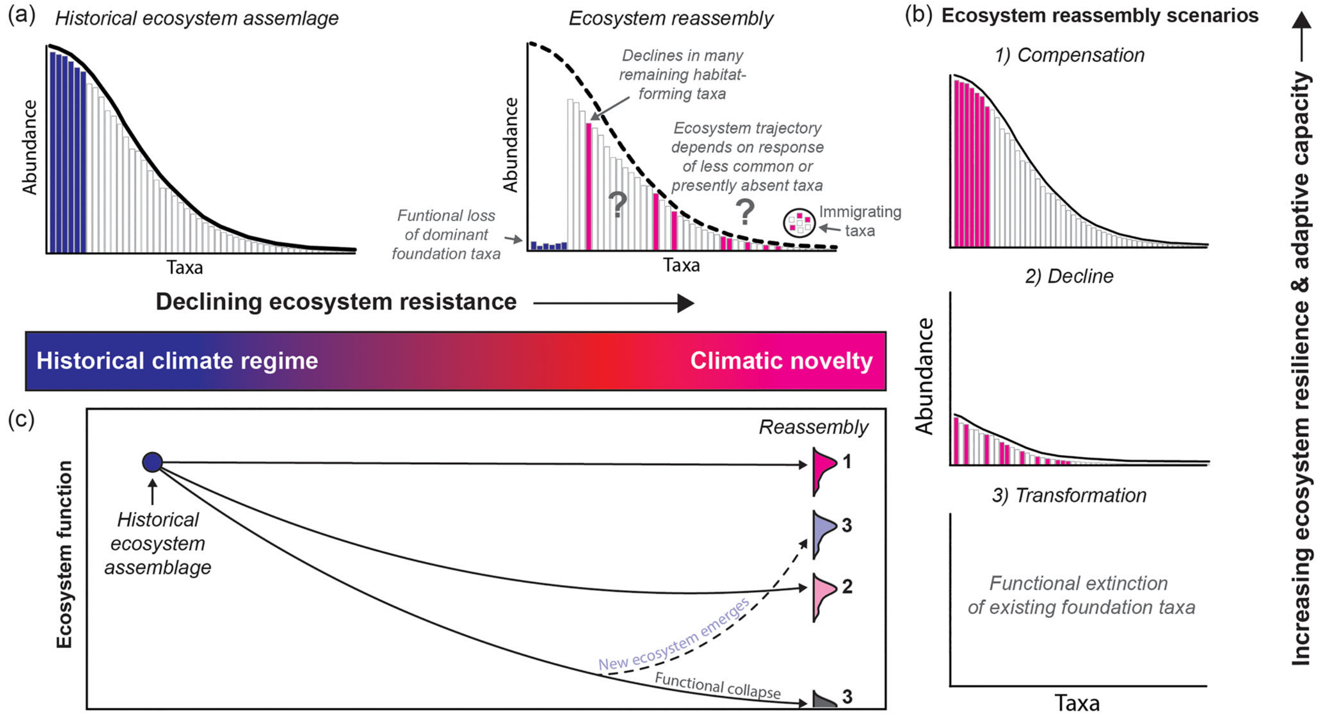

FIGURE 1 (a) Declines in habitat-forming foundation species (blue bars) that dominated ecosystems under historic climate regimes may drive different scenarios of (b) ecosystem reassembly and (c) functional outcomes based on the resilience and adaptive capacity of subdominant or immigrating taxa left behind (change in pink bars relative to [a]) (1, functionally similar taxa fill the niche opened by formerly dominant taxa, providing a similar level of ecosystem structure and function [compensation]; 2, compensation does not occur, other habitat-forming taxa persist at similar or lower abundances as historically and ecosystem function is reduced [decline]; 3, impacts on existing taxa are so extreme that the ecosystem is severely degraded and key ecosystem functions are lost [gray shading, functional collapse] or a different type of ecosystem emerges and some level of function is maintained [purple shading] [both types of transformation]; a range of functional outcomes [dashed line] are possible under the latter scenario depending on the composition of the emerging ecosystem). Functional trajectories in (c) are visualized as smooth curves for simplicity, but real-world changes in ecosystem function will likely be more variable across the transition into climatic novelty.

dominance is the legacy of the close alignment of foundation species' physiological trait distributions with historical climate regimes, combined with other functional and life-history traits that historically conferred a competitive advantage over other taxa able to occupy the same fundamental niche (Ellison, 2019; Hillebrand et al., 2008; Hutchinson, 1957; McNaughton & Wolf, 1970; Wiens et al., 2009). With climatic novelty, foundation species that rose to dominance under historical climate regimes are often being subjected to unprecedented levels of physiological stress as climate deviates from historical baselines (Flory et al., 2022; Hoegh-Guldberg & Bruno, 2010; Jaureguiberry et al., 2022; Wernberg et al., 2024).

In this context, the functional and life-history trait distributions that gave rise to the dominance of foundation species are now becoming irrelevant or even maladaptive (Jump et al., 2017; Renema et al., 2016; Zhu et al., 2024). For example, favorable historical climate regimes can allow abundant growth of long-lived, historically dominant trees, but this "structural overshoot" leaves them especially vulnerable to dieback under novel drought extremes (Jump et al., 2017). Similarly, the relative stability of tropical climates, combined with the sea-level fluctuations that characterized the last ∼2 million years, has allowed rapidly growing but thermally sensitive *Acropora* spp. corals to dominate coral-reef ecosystems worldwide (Renema et al., 2016; van Woesik et al., 2012). The fact that acroporids are so well adapted to relatively stable historical climate regimes is also why they are among the most sensitive to increasing climatic novelty (van Woesik et al., 2012). As Renema et al. (2016) put it, these ecosystems are "victims of their own past success."

Increased climate-related mortality events have already begun to erode the dominance of many foundation species worldwide (Allen et al., 2015; Ellison et al., 2005; Hammond et al., 2022; Hughes, Anderson, et al., 2018; Waycott et al., 2009; Wernberg et al., 2024), and with increasing climatic novelty, foundation species will likely continue to be disproportionately disadvantaged in the future (Ellison, 2019; Wernberg et al., 2024). There has been growing recognition that traditional management approaches aimed at maintaining or restoring a historical baseline of species composition may prove increasingly ineffective, cost-prohibitive, or even counterproductive for sustaining ecosystem functions under climatic novelty (Bayraktarov et al., 2016; Harris et al., 2006; Jackson & Hobbs, 2009; Lynch et al., 2021; McLaughlin et al., 2022; Seastedt et al., 2008). Put another way, for many of these ecosystems, and the people who manage them, resistance to climate change may be futile (Figure 1a).

SCENARIOS OF ECOSYSTEM REASSEMBLY

In ecosystems where historically important foundation species can no longer maintain their dominance under climatic novelty, scientists and ecosystem managers face the daunting challenge of confronting what comes next (Hobbs et al., 2009; Lynch et al., 2021; Schläppy & Hobbs, 2019). Although the unprecedented rate, scale, and magnitude of climate change will inevitably produce some “ecological surprises” (Williams & Jackson, 2007), we drew from ecological theory and empirical observations of ongoing transitions in ecosystems dominated by foundation species to explore 3 potential scenarios of ecosystem reassembly under climatic novelty (Figure 1b,c), which we termed compensation, decline, and transformation. We used this conceptual framework to make predictions about when and where each may occur and discuss implications for future ecosystem function.

Compensation by functionally similar taxa

The first possibility is that increases in functionally similar subdominant or immigrating taxa (pink bars in Figure 1a,b) compensate for the loss of formerly dominant foundation species to maintain similar levels of ecosystem function (compensation) (Figure 1b,c). This scenario may be more likely if the life-history traits of foundation species conferred a strong competitive advantage over other functionally similar habitat-forming taxa (Ellison, 2019; Hillebrand et al., 2008; Hutchinson, 1957; McNaughton & Wolf, 1970). Although competitive exclusion would have historically moderated the abundance of nondominant taxa, recent climate-driven declines of foundation species would result in competitive release and resilience of ecosystems with high functional redundancy (Biggs et al., 2020; Hooper et al., 2005; Nash Suding & Goldberg, 2001).

The geologic record provides several analogs for this process over evolutionary timescales, including shifts in the dominance of various reef-building taxa following regional- to global-scale extinction events (Budd, 2000; Kiessling, 2009). Recent examples of functional replacement of long-lived foundation species like corals and trees exist (Curry et al., 2007; Davis, 1969; Dolanc et al., 2013) but are rare, particularly in the context of climate change. Ecological-scale functional replacement may be more common for foundation species with rapid turnover rates, such as high-diversity grasslands and coastal marshes, where increases in subdominant taxa following environmental perturbations have sometimes maintained ecosystem functioning (Forbes & Dunton, 2006; Walker et al., 1999; Zhu et al., 2024). Often, however, shifts in species dominance will have functional trade-offs, such as in coastal ecosystems in the northeast United States, where climate-driven changes in dominant dune grasses have altered dune geomorphology and inland ecosystem processes (Goldstein et al., 2018; Harris et al., 2017). Likewise, in high-alpine forests, climate-driven declines in whitebark pine (*Pinus albicaulis*) (Dudney et al., 2023) may allow upward migration by other conifer species that could eventually provide similar structural and ecohydrologic functions but not the same critical food source for a diversity of associated taxa, from birds to bears (Logan et al., 2010). Nonetheless, even if the functional roles of new ecosystem assemblages are not identical to those of the foundation species they replaced, transitions to functionally similar taxa may maintain similar levels of overall ecosystem structure and function (Figure 1c).

Decline in ecosystem structure and function

In the second scenario, subdominant or immigrating taxa have limited resilience to climate-related disturbances and therefore cannot fully compensate for the loss of foundation species, resulting in a net loss of ecosystem structure and function (decline) (Figure 1b,c). Moreover, because of the central role of foundation species in facilitating ecosystem diversity and modulating resource availability, their loss alone can lower the fitness of the habitat-forming taxa left behind (Ellison, 2019). The combined impacts of climate-related disturbances, altered ecological interactions, and biological limitations (e.g., maximum size) prevent remaining taxa in this scenario from balancing the net loss of ecosystem structure and function.

In coral-reef ecosystems, shifts toward stress-tolerant assemblages characterized by smaller, less structurally complex, and slower-growing (so-called weedy) corals are becoming increasingly common following disturbances (Courtney et al., 2020, 2024; Darling et al., 2012; Graham et al., 2014; Hughes, Kerry, et al., 2018; Perry et al., 2015). The relative increases in these taxa have done little to prevent the ongoing shift toward net reef erosion (Perry et al., 2013, 2015, 2018, 2025; Toth et al., 2022) and the loss of essential habitat-forming and wave-breaking functions that structure supports (Perry & Alvarez-Filip, 2019). Similarly, more frequent disturbances are replacing some mature forests with younger and lower-density stands of trees, with novel species composition (McDowell et al., 2020; Steel et al., 2023). In semiarid riparian habitats, for example, decreases in streamflow have allowed invasive saltcedars (*Tamarix* spp.) to replace native willows (*Salix* spp.), transforming floodplain geomorphic processes and habitats (Birken & Cooper, 2006; Sogge et al., 2008). Although these remnant taxa may allow ecosystem persistence under climatic novelty, ecosystem function will be substantially reduced (Figure 1c).

Ecosystem transformation

The third possibility is that the impacts of climatic novelty are so extreme that the functional group of habitat-forming taxa that defined the ecosystem historically cannot persist, and a conversion to an entirely different ecosystem type (e.g., transitions from forest to grassland) or a severely degraded state occurs (transformation) (Figure 1b). These types of complete ecosystem transformations will likely be most common for ecosystems that already exist near critical environmental thresholds (Harrison, 2020; Osland et al., 2025) or when the climatic niche of subdominant habitat-forming taxa is relatively narrow (Ohlemüller et al., 2008; Vincent et al., 2020). Additionally, because foundation species are ecosystem engineers that alter their abiotic environment (e.g., creating microclimates for associated taxa), their loss may increase the vulnerability of remaining habitat-forming taxa to climate-related disturbances (Ellison, 2019; Jones et al., 1994). This scenario could also occur when the dominant sources of mortality are not directly climate related (e.g., insect outbreaks, eutrophication) (Jaureguiberry et al., 2022; Logan et al., 2010; Smith, 2003).

In the most extreme cases, transformations will result in long-term functional collapse of ecosystems (gray distribution in Figure 1c). For example, climate warming and declining precipitation are predicted to drive increases in desertification in many alpine, arid, and semiarid grasslands (Le Houérou, 1996; Sun et al., 2019) and would result in near-total loss of habitat and ecosystem productivity (Asner & Heidebrecht, 2005). In other cases, transformations will allow a different ecosystem to emerge, for example, through drought- and fire-related conversions of forests to shrublands or grasslands that have higher adaptive capacity to shifting climatic conditions (Batllori et al., 2020; Coop et al., 2022; Donato et al., 2016; Phillips et al., 2024; Zhu et al., 2024). These types of transformations may result in a shift, rather than a complete loss, of ecosystem function (purple box in Figure 1c). For example, warming winter temperatures have enabled poleward range expansion of freeze-sensitive mangroves, which replace existing salt marsh habitats (Cavanaugh et al., 2019; Osland et al., 2017). Both foundation species are functionally important for providing coastal habitat, stabilizing shorelines, and buffering impacts of storms and sea-level rise, but they do so in different ways (Kelleway et al., 2017; Osland, Chivoiu, et al., 2022). In these same coastal ecosystems, however, conversion of coastal wetlands to open water due to accelerating sea-level rise (Saintilan et al., 2023; Smith et al., 2025; Törnqvist et al., 2021) can drive substantial declines in shoreline stabilization, wave-energy dissipation, and tidal wetland habitat (Costanza et al., 1997; Friess et al., 2020), but could result in increases in functionally distinct subtidal habitats like seagrasses (Capistrant-Fossa & Dunton, 2024; Costanza et al., 1997; Nordlund et al., 2018). Although examples of complete, irreversible losses of ecosystem structure and function have been rare historically, such transformations are likely to be increasingly common under climatic novelty (Williams & Jackson, 2007).

MANAGING BEYOND HISTORICAL BASELINES

The historical baselines of species composition that have often been used to guide management actions are, in many cases, a guidepost from a bygone era (Harris et al., 2006; Jackson & Hobbs, 2009). Climate change has already diminished the resilience of many of the world's ecosystems to a point at which traditional management actions, such as establishing protected areas, are increasingly failing to facilitate recovery of foundation species (Bruno et al., 2019; Forzieri et al., 2022; Seastedt et al., 2008). It may likewise become both infeasible and cost-prohibitive to actively restore foundation species to historical baselines under increasing climatic novelty (Bayraktarov et al., 2016; Jackson & Hobbs, 2009; Peterson St-Laurent et al., 2021; Schläppy & Hobbs, 2019). On some western Atlantic coral reefs, for example, the vast majority of outplanted *Acropora* spp. corals, sometimes representing more than a decade of restoration efforts, were killed by a single, catastrophic coral-bleaching event in 2023 (Birkart & Alvarez-Filip, 2025; Manzello et al., 2025; Toth et al., 2025). Under climatic novelty, these types of setbacks are likely to continue, with models suggesting, for example, that reversing historic coral-reef declines could take a century or more of continuous outplanting of thermally resistant corals (DeFlippio et al., 2022). Even more proactive management actions that have been successful in the short term, such as assisted migration of the whitebark pine (*Pinus albicaulis*) to more climatically favorable locations beyond its current range (McLane & Aitken, 2012), could take centuries to fully restore historical baselines of ecosystem structure and function. Although there is inherent value in preserving biodiversity and preventing species extinctions (Justus et al., 2009), management that focuses limited time and resources on restoring historical baselines of ecosystem composition may be increasingly impractical and could impede progress toward identifying and facilitating transitions to new states that are more resilient to climatic novelty (Harris et al., 2006; Jackson & Hobbs, 2009; Lynch et al., 2021; Seastedt et al., 2008). A more flexible approach that embraces the likelihood of ecosystem disassembly and reassembly under climate change (Antão et al., 2022) could provide an opportunity to future-proof management by optimizing functional outcomes (Figure 2).

Several existing management frameworks explicitly incorporate the likelihood of future ecosystem transitions, including adaptive management strategies (Rist et al., 2013; Williams, 2011; Williams & Brown, 2016), the Resist–Accept–Direct (RAD) framework (Lynch et al., 2021, 2022; Schuurman et al., 2022), the resistance–resilience–transformation typology (Peterson St-Laurent et al., 2021), and triage approaches (Schläppy & Hobbs, 2019). We sought to provide new insights into how scientists and managers could work together to identify and address key research gaps to more effectively navigate those existing frameworks in the context of climatic and ecological novelty (Meadow et al., 2015). For example, the RAD framework suggests that managers can decide whether to resist, accept, or direct change by assessing the ecological, societal, and financial feasibility of each option and applying an adaptive management approach (Lynch et al., 2021, 2022; Schuurman et al., 2022). More intentional coproduction of management-relevant science (Meadow et al., 2015) could improve predictions about the likelihood and functional consequences of ecosystem transitions. This would allow managers to better assess the ecological feasibility and functional implications of accepting or directing change (or of resilience- vs. transformation-based management strategies [Peterson Sant-Laurent et al., 2021]) for ecosystems in which resisting transitions has become futile. Although any management decisions will ultimately also be weighed against societal (or ethical) considerations, coproduction of a portfolio of informed management actions aimed at maximizing functional outcomes under climatic novelty can also help optimize financial feasibility. The process of developing this sort of forward-looking management strategy that explicitly addresses

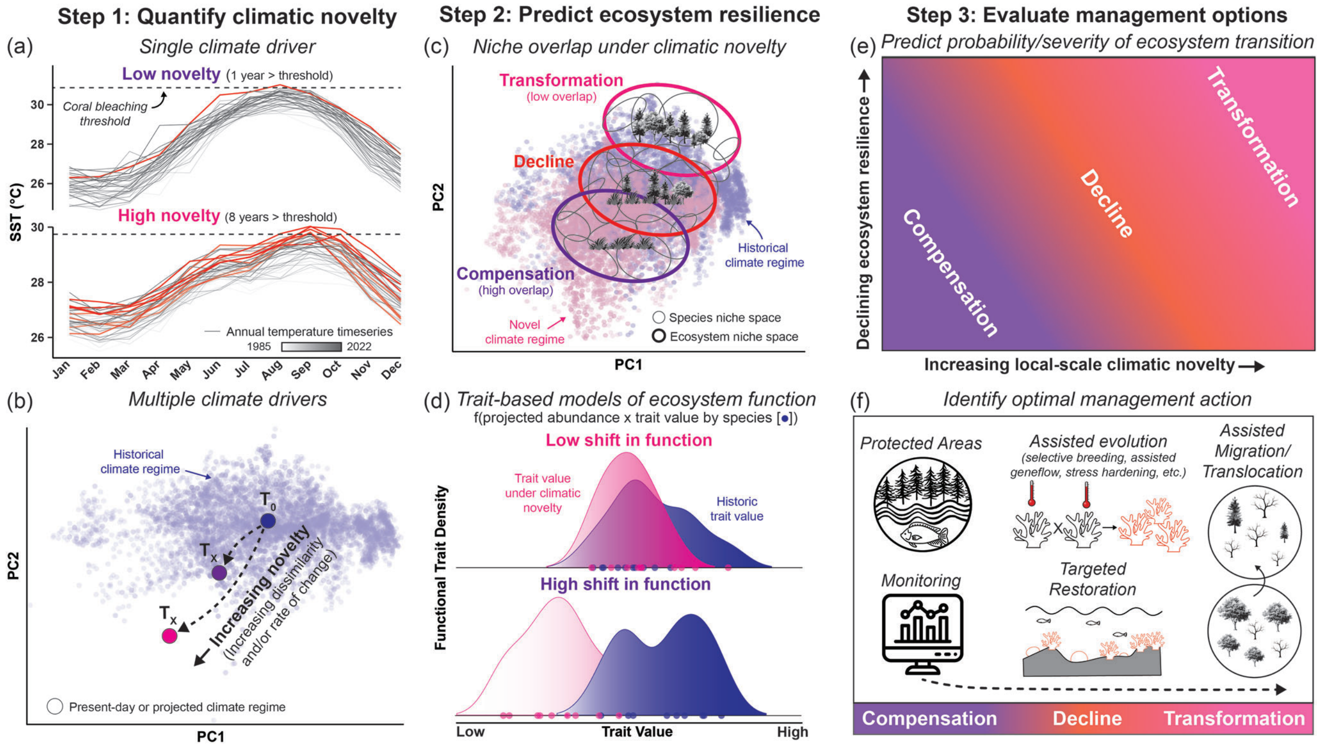

FIGURE 2 Steps for managing ecosystems under climatic and ecological novelty: Step 1, quantify local, ecosystem-scale climatic novelty based on (a) one climate driver (here number of years sea-surface temperatures [SSTs] exceed local coral bleaching thresholds [Skirving et al., 2020; https://coralreefwatch.noaa.gov/]; top, Cuba; bottom, Belize or (b) multiple climate drivers (vectors of change from the centroid [T0, time zero] of a baseline, historical climate regime [here, 1960–1980 CE] defined based on principal component [PC] ordination [blue points] of the means and standard deviations of temperature and precipitation for New England [USA] Acadian forests [https://research.fs.usda.gov/programs/fia]; climate data from WorldClim [https://www.worldclim.org/]); Step 2, predict ecosystem resilience to climatic novelty based on (c) niche modeling (relative overlap of theoretical species [thin ellipses] and ecosystem [thick ellipses] niches with the emerging novel climate regime [2000–2020 CE, pink points] in New England [USA] Acadian forests [historical climate as in b] is used to predict the most likely ecosystem transition, as described in Figure 1) and based on (d) trait-based modeling (theoretical density plot shows low [top] and high [bottom] shifts in trait values under climatic novelty [pink] relative to historic climates [blue]); Step 3, how the results of Steps 1 and 2 could be applied to (e) predict the most likely type of ecosystem transition (Figure 1) and (f) how the predictions could be used to optimize management actions. All images were produced using copyright-free graphics from Canva (www.canva.com).

the reality and consequences of climate novelty can be summarized in 3 steps: quantify climatic novelty, predict ecosystem resilience, and evaluate management options.

Quantify climatic novelty (Step 1)

A critical first step, sometimes overlooked in ecosystem management, is direct evaluation of the current and future climatological context of the system (Groves et al., 2012; Hannah et al., 2002) (Figure 2a,b). Identifying where an ecosystem currently is, or will likely be, on the spectrum of climatic novelty could provide valuable insight into the immediacy and magnitude of the threat of ecosystem transitions (Hansen et al., 2022; Mahony et al., 2017; Williams & Jackson, 2007) (Figure 2e). We hypothesized that, although a range of potential outcomes may be possible under small or moderate deviations from historical climate regimes (i.e., compensation or decline [Figure 1]; gray lines in Figure 2a and purple point in Figure 2b), more complete ecosystem transformations are increasingly likely under climatic novelty (red lines in Figure 2a and pink point in Figure 2b). Global-scale models of climatic novelty (Lotterhos et al., 2021; Ordonez et al., 2024; Williams et al., 2007) could be used to identify regional hotspots of rapid environmental change; however, climate projections are most informative when they are better aligned with the smaller spatial scales of management units (Rummukainen, 2016; Wiens & Bachelet, 2010), highlighting the importance of close collaborations between scientists and managers to coproduce actionable climate projections at management-relevant scales (McLaughlin et al., 2022; Meadow et al., 2015; Seastedt et al., 2008).

For ecosystems where transitions are primarily driven by a single climate variable (e.g., maximum temperature, minimum rainfall), predictions could be made about where and when critical thresholds may be exceeded by evaluating climatological data (Osland et al., 2025; Skirving et al., 2020) or climate models (Trisos et al., 2020). For example, it is well established that coral bleaching and bleaching-related mortality become increasingly likely when sea-surface temperatures exceed 1°C above the historic (1985–1990 and 1993 CE) maximum monthly mean at a given location (Skirving et al., 2020) (bleaching threshold in Figure 2a). The frequency at which a given reef has experienced temperatures beyond that threshold thus provides a useful metric of relative climatic novelty for coral-reef ecosystems (Figure 2a). Downscaled climate projections of sea-surface temperatures have also been used to predict when coral bleaching is likely to become an annual phenomenon: a scenario under which significant ecosystem transitions are inevitable (Donner et al., 2005; van Hooidonk et al., 2015, 2016).

Where ecosystem transitions are associated with interactions between multiple climatic drivers, for example, shifting temperature and precipitation regimes in forest ecosystems (Batllori et al., 2020; Coop et al., 2022; Donato et al., 2016; Hammond et al., 2022; Triepke et al., 2019), assessing local-scale climatic novelty is less straightforward. One possibility in such cases would be to apply the approaches used in global-scale assessments of climatic novelty to identify hotspots of ecosystem vulnerability at smaller, management-relevant scales (Fitzpatrick et al., 2018; Mahony et al., 2017; Triepke et al., 2019; Williams et al., 2007). Ordination of multiple climate variables (e.g., mean and variability in temperature and precipitation of forests in Arizona, USA, in Figure 2b) could be used to assess the dissimilarity between the historical and present-day (or projected future) climate regimes of an ecosystem (Kling et al., 2020; Mahony et al., 2017; Radeloff et al., 2015) (colored circles in Figure 2b). Comparisons of those dissimilarities (vectors of change; dashed lines in Figure 2b) across space and time could provide a relative measure of climatic novelty based on how far and how fast the local climate is diverging from the historical baseline.

Predict ecosystem resilience (Step 2)

The other essential part of predicting the most likely trajectories of reassembly is determining the relative sensitivity, adaptive capacity, and functionality of the full assemblage of habitat-forming taxa (Figures 1b & 2c,d). Although ecosystems with higher response diversity and functional redundancy or both are generally predicted to have higher resilience (Biggs et al., 2020; Elmqvist et al., 2003; Hooper et al., 2005), the relationship between the most commonly measured diversity metrics (e.g., species richness) and functional diversity is not straightforward (Elmqvist et al., 2003; Hooper et al., 2005). Indeed, the difference in the functional outcomes of an ecosystem experiencing compensation versus decline (Figure 1) underscores why managing for diversity alone (i.e., relying on the portfolio or insurance effects) may not always be effective and why diversity–stability relationships often break down, particularly in systems with high dominance (Biggs et al., 2020; Elmqvist et al., 2003; Hillebrand et al., 2008; Hooper et al., 2005; McCann, 2000). The capacity to retain ecosystem function under climatic novelty will likely depend not on biodiversity per se but rather on the variability in responses and adaptive capacity within an ecosystem's species assemblage (Frietsch et al., 2023). In many systems, the physiological tolerances and functional roles of rare species are poorly constrained compared with more dominant taxa (Leitão et al., 2016). This highlights the importance of experimental and observational studies to quantify the most likely trajectories of the full suite of existing, and potential, habitat-forming taxa for a given ecosystem under both historical climate regimes and projected climatic novelty (Hansen & Turner, 2019; Harris et al., 2006; Hooper et al., 2005; Lynch et al., 2021).

Where climatic novelty is most extreme, the impending threat of ecosystem transformation may be too urgent for a wait-and-see approach that promotes reactionary rather than proactive management action (Seastedt et al., 2008). A more proactive option is niche modeling, in which researchers use the distribution of individual species (regionally or globally) (thin ellipses in Figure 2c) to identify the range of environmental conditions that can support them (Anderson, 2013; Wiens et al., 2009; Zhu et al., 2024). Species niche models could be compared with recent (or projected) climate regimes to determine which taxa exist near or past their physiological tolerance (small ellipses) and the degree of ecosystem (large ellipses) niche overlap (e.g., Kling et al., 2020; Thuiller et al., 2005; Wiens et al., 2009) (Figure 2c). Where the ecosystem niche space largely overlaps with the novel climate regime (e.g., some high-diversity grasslands [Zhu et al., 2024]), compensation may be possible. However, when niche overlap is low (e.g., a low-diversity, old-growth forest), transformation may be inevitable. Evaluation of present-day species ranges compared with rates and directions of climate trends (e.g., Figure 2b) could provide a similar metric of vulnerability (e.g., Loarie et al., 2009). Trait-based models that incorporate projected species abundances with information underpinning key ecosystem functions, such as species growth rates or productivity (Brockerhoff et al., 2017; Darling et al., 2019; Osland, Hughes, et al., 2022; Perry & Alvarez-Filip, 2019), could then be used to quantify the potential trajectories of ecosystem function based on which and at what level taxa are most likely to persist (Figure 2d). A key uncertainty in this approach is how functional trait distributions may shift under climatic novelty, underscoring the importance of continued experimental and observational studies.

Evaluate management options (Step 3)

Comprehensive assessments of local-scale climatic novelty (Figure 2a,b) and the potential resilience of remaining habitat-forming taxa (Figure 2c,d) can help managers determine the most likely future ecosystem trajectories (Figure 2e) and evaluate functional trade-offs of different management actions (Figure 2f). Through codevelopment of management strategies, scientists can provide effective models to managers and help ensure the applicability of the information used to make decisions (Meadow et al., 2015; Seastedt et al., 2008). Although fundamental data are lacking for many subdominant habitat-forming taxa (Leitão et al., 2016), much of the data needed to build predictive models for evaluating management trade-offs exist for some ecosystems (e.g., plant and coral trait databases [https://www.try-db.org; www.coraltraits.org]) and could be synthesized. For example, taxon-specific coral-bleaching thresholds (Swain et al., 2016) and growth-rate data (Courtney et al., 2024; Perry & Lange, 2019) could be combined to model how reef growth could be maximized through selective restoration of fast-growing but thermally sensitive corals versus slower-growing, more tolerant corals under future climate scenarios

(Cornwall et al., 2021; Perry et al., 2025; Toth et al., 2022, 2023, 2025). This type of information would provide realistic estimates of what and how much ecosystem function can be maintained under climatic novelty, allowing managers to make more informed management decisions.

Where local-scale climatic novelty is low and there is sufficient functional redundancy, accepting transitions to a different suite of habitat-forming taxa (i.e., compensation) (Figure 2e) and employing traditional management strategies (e.g., establishing reserves or marine protected areas and continuing monitoring) (Figure 2f) may be sufficient. Where ecosystem transitions are likely to be more immediate or extreme, however, maintaining ecosystem function may require more direct and significant interventions (Jackson & Hobbs, 2009; Lynch et al., 2021, 2022; Peterson St-Laurent et al., 2021; Schuurman et al., 2022). Low niche overlap with emerging or near-term projections of climatic novelty (Figure 2c) would suggest a high likelihood of ecosystem decline or transformation (Figure 2e), favoring the application of proactive management actions, such as assisted migration or species translocation (Figure 2f; Aitken & Whitlock, 2013; Butt et al., 2021; Harris et al., 2006; McLane & Aitken, 2012; Palik et al., 2022), that direct transformation toward a novel ecosystem state (Lynch et al., 2021, 2022; Peterson St-Laurent et al., 2021; Schläppy & Hobbs, 2019; Schuurman et al., 2022).

Even in cases where many species may persist (decline), if traits or functions valued by managers are likely to be highly altered or even disappear as key foundation species are lost under climatic novelty (Figure 2d), managers might consider more proactive approaches to enhance the resilience of remaining populations or increase the efficacy of restoration through assisted evolution approaches such as selective breeding, assisted gene flow, or stress hardening (Aitken & Whitlock, 2013; Baker et al., 2025; van Oppen et al., 2017) (Figure 2f). Although there is significant controversy surrounding some of these proactive management solutions, either because of ethical concerns or because they are considered high risk (Harris et al., 2006; Schwartz et al., 2012; Volpe et al., 2024), the risk of inaction or of acting too late under climatic novelty may be even higher (Aitken & Whitlock, 2013; Baker et al., 2025; Lynch et al., 2021, 2022; Peterson St-Laurent et al., 2021; Schuurman et al., 2022). Any action taken to manage the impacts of climatic novelty can be considered an experiment and an opportunity to improve understanding, even when it fails to achieve desired outcomes, especially when combined with continued monitoring (Figure 2f) within adaptive management frameworks (Schuurman et al., 2022; Seastedt et al., 2008; Williams, 2011; Williams & Brown, 2016).

The ongoing global-scale pattern of rapid disassembly and reassembly of ecosystems is unprecedented in human history and may require equally novel ecosystem management strategies. Accepting that ecosystem transitions may be inevitable can be difficult, but letting go of unrealistic expectations based on obsolete historical baselines also presents an opportunity for managers to better prepare for what comes next. By exploring how habitat-forming terrestrial and marine assemblages may change as climate-sensitive foundation species are lost, we have demonstrated how managers and researchers can work together to parse the doom and gloom and optimize the functional outcomes of future management actions.

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