

REVIEW

Trait-based approaches to restoration ecology: Synthesizing insights from diverse systems

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Abstract

Under accelerating global change, trait-based approaches are emerging as essential tools in the ecological restoration toolbox. Where restoration has traditionally focused on the recovery of focal species in isolated systems, trait-based methods can provide a common language that extends beyond

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species- or system-specific contexts, allowing scientists and practitioners to translate insights across organisms and ecosystems and predict functional variation critical to resilience in the face of rapidly changing environmental conditions. Trait-based insights can thus help achieve restoration that is both adaptable and scalable as future climate scenarios unfold. To date, trait-based approaches to restoration have developed and proceeded independently across habitats and ecosystems, limiting information sharing and innovation. Here, we synthesize diverse perspectives and research on trait-informed restoration across ecosystems, distilling our findings into three key insights. First, variable contexts and trade-offs in trait-function linkages shape restoration outcomes at distinct ecological scales and project stages. For example, individual-level traits that underpin stress tolerance may play a critical role in initial survival and establishment during early project stages, while traits that influence species interactions and modify energy transformation may play a larger role as communities reassemble and ecosystem function becomes a priority at later stages. Second, coordinating trait-informed restoration across ecosystems can advance multi-trophic and multi-system restoration by closing the divide between “top down” approaches that target individual organisms or populations typically in large, mobile animal reintroductions and “bottom-up” approaches that target community-level organization in the restoration of foundation species. Finally, enhanced interdisciplinary communication and knowledge-sharing can help develop solutions to major challenges hindering the progress of trait-informed restoration (e.g., accounting for intraspecific variation). As novel environmental conditions continue to arise, an integrative approach to trait-informed restoration that spans ecological scales, promotes knowledge-sharing across diverse ecosystems, and fosters management-science collaboration can help unify and advance restoration efforts under current and future disturbance scenarios.

KEYWORDS

community reassembly, cross-system, ecological restoration, ecosystem function, functional traits, global change, knowledge-sharing, management, multi-trophic, variation

INTRODUCTION

The field of restoration ecology is rapidly evolving to meet challenges created by climate change and other anthropogenic disturbances. Where ecosystems have been irreversibly altered by global change, managers and practitioners are now re-evaluating traditional restoration goals and approaches (Hobbs, 2007). Traditionally, restoration has focused on recovering degraded ecosystems to a historical reference taxonomic composition (Shackelford et al., 2013) or re-establishing historically dominant taxa (Branton & Richardson, 2011, 2014) of high ecological, cultural, and economic value, via release, planting, breeding, or seeding (Luong et al., 2023). However, as the gaps

between current and historical conditions widen, contemporary restoration increasingly prioritizes recovering ecosystem function and promoting resilience to future climate conditions (Benayas et al., 2009; van Oppen et al., 2017). As restoration today takes place in ecosystems that are experiencing unprecedented environmental conditions (Radeloff et al., 2015), adapting to such change requires an understanding of the processes and interactions underlying reassembly and function, information on which is often limited when considering taxonomic identity alone. Thus, whether attempting to return to a historic composition or recover ecological functioning, it is becoming increasingly critical to consider mechanistic sources of information and approaches to restoration.

To reach desired restoration outcomes, a growing body of literature has explored the application of species' functional traits to restoration design (e.g., Carlucci et al., 2020; Madin et al., 2023; Ostertag et al., 2015). Traits are any measurable morphological, phenological, behavioral, or physiological characteristics that affect the fitness or performance of an individual and provide key insights into the interactions between organisms and their environments, one another, and ecosystem functioning (McGill et al., 2006; Violle et al., 2007). Traits therefore provide a way to compare between individuals, populations, and species and generalize across ecosystems by focusing on organisms' essential component functions rather than taxonomic identity. By shifting focus towards transferable characteristics rather than focal taxa, trait-based approaches can thus aid in selecting target species that are likely to succeed (Table 1). For example, selecting species that tolerate changing or novel environmental conditions (Cadotte et al., 2011; Laughlin et al., 2018), limit competition with invasive species (Funk & Wolf, 2016), counter the biotic homogenization of communities (Holl et al., 2022), or assist the recovery of species that support essential functions (e.g., pollination, nutrient cycling; De Groot et al., 2002; Jones et al., 2023) can help align the trajectory of restored communities with project objectives. Even in efforts centered on restoring specific taxa, overall biodiversity or reference conditions, traits can serve as a complementary tool to uncover additional interactions that may otherwise go undetected and limit recovery (Karimi et al., 2022; Watts & Mason, 2015).

How traits can inform restoration design, implementation, and evaluation varies depending on the goals and stage of the restoration initiative (Figure 1). In the early stages of restoration, when a species' ability to establish, grow, and reproduce is key and environmental conditions are harsh due to a lack of suitable resources and habitat, understanding how traits influence organismal function and tolerance may be critical to identifying project goals (Kimball et al., 2016). For instance, in the initial phase of a plant restoration project, stress-tolerance traits such as deep roots or small size might contribute to higher plant fitness in exposed areas (Funk et al., 2024). However, the importance of specific traits may shift in response to evolving stressors as the system develops (Funk, 2021; Kempel et al., 2013). Later in the restoration process, traits associated with rapid growth, like high specific leaf area (SLA) or low root mass fraction, may become advantageous when competition emerges following the colonization and establishment of species (Simpson et al., 2021). It may therefore be necessary to consider organismal traits at multiple steps within the ecosystem restoration process.

Trait-based approaches can also be implemented at different biological levels of organization, informing the selection of individuals and populations based on performance or fitness (Laughlin et al., 2020; Violle et al., 2007), as well as combinations of species that will result in desired facilitative interspecific interactions that aid in community recovery (e.g., "nurse plants"; Fiedler et al., 2018). The applicability of certain traits may therefore change depending on the ecological scale targeted by a restoration project's goals. For example, if restoration aims to enhance coexistence within a community, practitioners may focus on traits that can capture species niche differences (Cadotte, 2017; Hallett et al., 2023; Kraft et al., 2015). Trait-informed restoration can thus be the reverse engineering of a biological system (see Csete & Doyle, 2002), whereby traits linked to key functions can be manipulated across project phases and ecological scales to promote any process supporting the self-organization of organisms, populations, communities, and ecosystems.

In theory, traits hold the key to recovering and sustaining essential ecosystems in the face of changing environmental conditions, providing information on desired functions and capacity to scale knowledge beyond local contexts. However, variation in the application of trait-based ecological theory to restoration can produce mixed outcomes and present barriers to use across diverse systems (Loureiro et al., 2023; Suding, 2011). Recent work reviewing the use of traits in restoration suggests that researchers and practitioners in different fields are often highly siloed, such that most ideas progress unevenly and independently across ecosystems and taxa (Carlucci et al., 2020). Specifically, the use of functional traits in restoration tends to be heavily weighted towards plants and terrestrial ecosystems in temperate climates (Green et al., 2022). These discrepancies across ecosystems reflect a broader divergence in restoration, where varying approaches to applying traits have led to inconsistent success, highlighting the challenges in achieving more standardized practices that produce effective outcomes (Suding, 2011). To help close this gap, we reviewed the relevant literature and knowledge on the application of trait-based approaches to restoration ecology through a cross-systems lens, highlighting key insights and priorities for future research and practice. Our review aims to strengthen restoration ecology research by contributing (1) our vision of how trait-based approaches can be used to set and achieve restoration goals across project phases and ecological scales, (2) insights that can be gleaned from comparing approaches to trait-informed restoration across systems

TABLE 1 Examples E1–E5 of how trait-informed restoration strategies have been adopted to achieve different goals across systems within the proposed framework (Figure 1a).

Restoration goal(s)	System(s) and species	Initial restoration strategy and outcome	Trait-informed restoration strategy or applications	Position within framework	References
Re-establish breeding populations; recover ecosystem processes	Islands, nesting seabirds	Following the removal of invasive predators from islands, resident seabird populations have shown limited passive recovery due to life histories that limit their rate of natural recolonization.	Following invader eradication, selecting seabirds for active translocations based on traits underlying life history and behavior led to an increased population recovery rate.	E1	Kappes and Jones (2014)
Recover reference community composition	Fishless alpine lakes, zooplankton	Restoration relied on the passive recovery of zooplankton communities following fish predator removal.	Considering traits helped elucidate the trajectory of functional versus taxonomic recovery and recovery rate, which varied across contexts (see Box 1).	E2	Stuparyk and Vinebrooke (2024); Box 1
Recover ecosystem processes; suppress invasion	Hawaiian lowland wet forest	Invasive species removal was followed by native species planting. Although native seedling recruitment increased, the influx of undesired, non-native species altered abiotic conditions and promoted continued invasion.	Learning from the outcomes of traditional approaches, native and introduced species with traits that support conditions and feedbacks unfavorable to invasion were planted through the Liko Nā Pilina experiment (see Box 2).	E3	Cordell et al. (2009), DiManno et al. (2023), Ostertag et al. (2009); Box 2
Suppress invasion; limit loss of native endemics	Caribbean coral reefs, invasive lionfish	Local efforts to extirpate an invasive predator across the region were unsuccessful due to rapid recolonization following removal, leading to declines in native fauna.	Considering traits of native species most vulnerable to predation by the invader alongside range size allowed managers to identify potential impact hotspots to prioritize for ongoing invader suppression.	E4	Linardich et al. (2021)

TABLE 1 (Continued)

Restoration goal(s)	System(s) and species	Initial restoration strategy and outcome	Trait-informed restoration strategy or applications	Position within framework	References
Re-establish associate populations; recover key interactions and trophic dynamics	Brazilian Atlantic forest, agoutis	Forest flora and fauna were restored first through reforestation using native and non-native species, and subsequently through faunal reintroductions of agoutis and monkeys a century later.	The traits of an endemic tree species were matched with those of the agouti to recover and extend seed dispersal and germination processes. Harnessing these relationships better facilitated the synergistic recovery of interacting flora and fauna.	E5	Fernandez et al. (2017), Mittelman et al. (2020)

to advance multi-trophic and multi-system restoration, and (3) potential solutions to barriers and challenges in trait-informed restoration through the translation and integration of ideas produced in siloed fields.

RESTORATION GOALS ACROSS ECOLOGICAL SCALES

Setting project goals

Goals and objectives defined at the outset of a restoration project set expectations, dictate on-the-ground actions, and guide subsequent monitoring (Ehrenfeld, 2000) in specific, quantifiable, and actionable ways (Gann et al., 2019). Goals vary greatly depending on the primary mandate for the project, the priorities of managers and communities, and the feasibility of different goals at a site (see *Individuals and populations* and *Communities and ecosystems* below). Trait-based approaches can help achieve a variety of restoration goals, as traits often drive mechanisms that underlie processes key to restoring functions across different ecological scales, such as environmental filtering at the individual or population level, or reassembly and trophic interactions at the community or ecosystem level (Table 1). The application of traits to restoration may therefore vary depending on the primary goals, stage, and/or scale of a restoration project (Figure 1a). While the framework we outline below provides one conceptualization of these dynamics, we recognize that the relationships among traits, mediating processes, and restoration outcomes or goals are inherently more complex than can be visualized in a two-dimensional figure.

Individuals and populations

Restoration projects may benefit from understanding variation in trait expression at multiple biological levels: interspecific variation, intraspecific variation (which comprises both individual- and population-level variation), and changes in trait expression within an individual's lifetime. Within populations, variation in trait expression between individuals or genotypes can help inform the selection of genetic mixes tolerant to current and future climate and environmental limitations (Silliman et al., 2024; Urban et al., 2024). Intraspecific trait variation is often considered through the selection of local or resilient genotypes for restoration, which are often sourced based on the assumption that these genotypes are locally adapted, allowing them to better establish and improve community function (Havens et al., 2015; Westerland et al., 2021). There may also be a desire to conserve unique, local genetic diversity or specific populations within a species (Shackelford et al., 2013). For example, in coral reef restoration, coral genotypes are highly controlled through fragmentation or sexual reproduction using locally-sourced wild colonies, after which different clusters of local genets are often replanted on reefs to promote local diversity and the formation of full colonies (Baums et al., 2022).

Decision-making based primarily on heritable traits during restoration may not sufficiently capture dynamic organism–environment interactions, as traits can also be plastic, changing within an organism's lifetime as a result of local conditions or previous experience (Boutin & Lane, 2014; Dingemanse et al., 2010; Henn et al., 2018). When considering the effects of local conditions,

knowledge on how environmental matching and filtering interact to restructure populations can help identify interventions that leverage trait–environment relationships (e.g., burning or shading) to optimize outcomes (Ernst

et al., 2012; Funk, 2021; Luong & Loik, 2022). To buffer against potential organism–environment mismatches, a “safety net” can be created by bolstering functional and genetic diversity within a restored population and

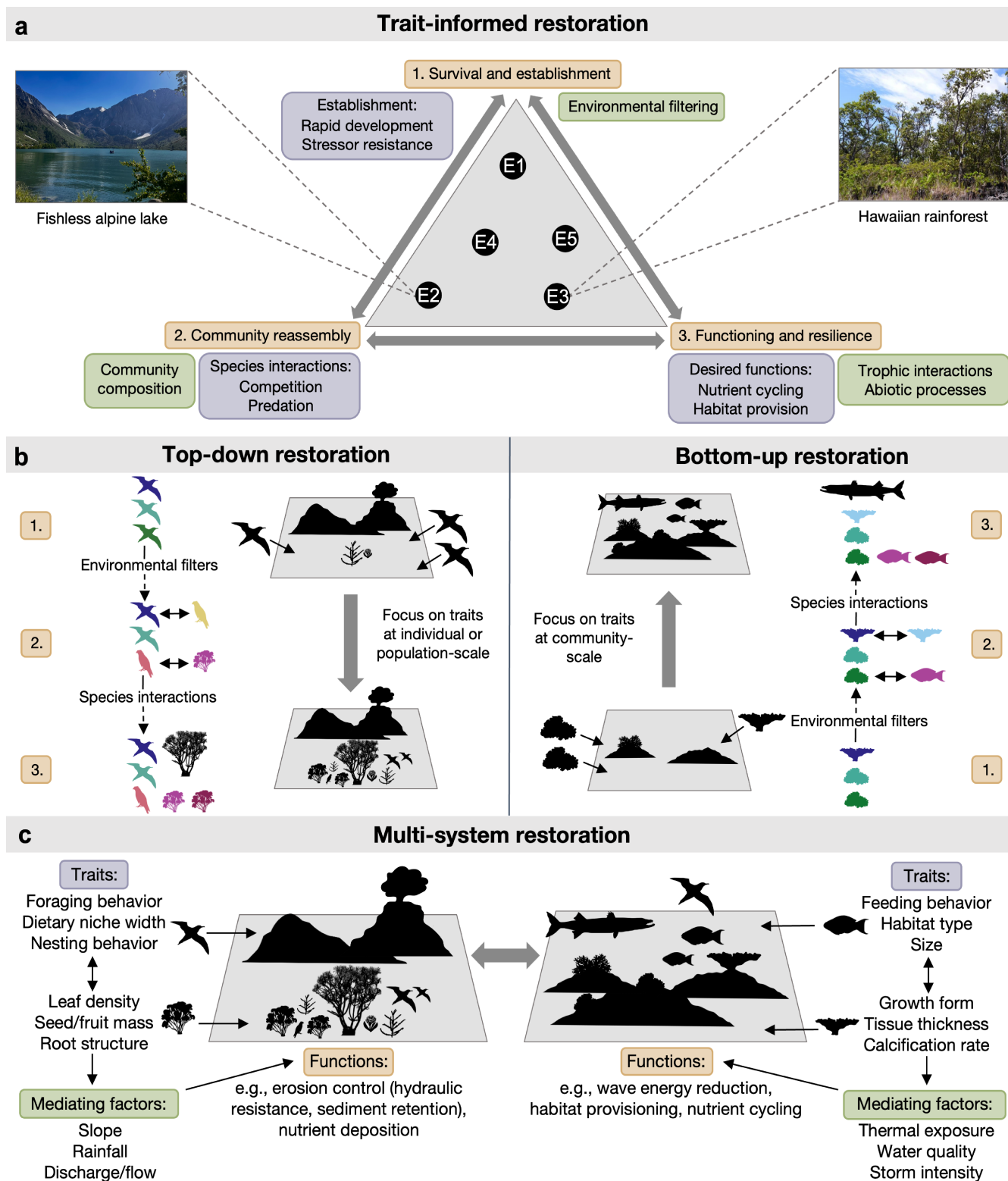


FIGURE 1 Legend on next page.

carefully considering sources of intraspecific variation, especially during the early stages of restoration when survival and establishment are critical (Cadotte et al., 2011; Kettenring et al., 2014; Reynolds et al., 2012).

Communities and ecosystems

Quantifying interspecific variation in functional traits at the community or ecosystem level can aid in identifying combinations of species for restoration by considering how traits affect community reassembly and invasibility post-disturbance (Funk et al., 2008; Laughlin, 2014). These key community functions are often driven by species interactions, which are governed by multiple traits (i.e., trait syndromes). For example, positively correlated traits may amplify or dampen the intensity of a species interaction. In alpine lakes, the coupling of conspicuously large body size and bright pigmentation heightens the susceptibility of zooplankton to predation by invasive sportfish (Box 1; Loewen & Vinebrooke, 2016). Conversely, the positive correlation between small body size and rapid motility enables pale species to evade detection by these visual predators (Stuparyk & Vinebrooke, 2024).

Trait syndromes and functional structures that support recovery can also shift over time with species turnover and changing interactions during the process of ecological restoration (Figure 2). During the early stages of recovery, mutualisms or facilitative interactions between species can ameliorate stress in a degraded environment (Padilla & Pugnaire, 2006). For instance, mutualistic interactions between soil microbial organisms and host plants have the potential to increase drought tolerance (Petipas et al., 2017; Staudinger et al., 2016) or herbivore resistance (Thamer et al., 2011). As the community reassembles, trait trade-offs may confound

which species should be reintroduced to help achieve restoration targets since strong abiotic tolerance is often negatively correlated with growth potential and competitiveness (Grime, 1977). Selection for competitive traits may be particularly important in certain cases where persistent tolerant species have become so abundant during ecosystem degradation that they later suppress recolonization by extirpated species via competition or predation, resulting in reintroduction resistance (Tielke et al., 2020). The applicability of certain traits to restoration can therefore change with evolving restoration goals and as reassembly progresses, ultimately supporting higher level goals that often focus on ecosystem functioning and processes.

Trait-based approaches provide a framework to maximize particular ecosystem functions when relevant to restoration goals (Table 1). Selecting species with traits that support ecological processes and are connected and complementary to the traits of species in adjacent trophic levels can be essential to restoring resilience (Schmitz et al., 2015; Silliman et al., 2024). The importance of such traits often becomes apparent as restoration or reassembly progresses and multi-trophic interactions (e.g., predator-mediated competition or selective predation) arise once higher trophic levels have recolonized or been restored (Ng'weno et al., 2019). Complementarity can be used to select traits that promote desired multi-trophic interactions and functions (e.g., both competitive ability and predation evasion) (Eisenhauer et al., 2019). For example, restoring mixtures of plant species often leads to higher productivity than expected (overyielding) because re-establishing functionally diverse assemblages can dilute the impacts of pathogens that suppress productivity and induce resource partitioning (Eisenhauer, 2012; Maron et al., 2011; van Ruijven et al., 2020; Wang et al., 2023). Alternatively, sourcing functionally redundant species (i.e., species with similar

FIGURE 1 The utility of trait-informed restoration when considered across ecosystems and ecological scales: (a) a multidimensional conceptual framework for identifying the types of traits (purple) most useful for informing restoration strategies based on the ecological processes at play (green) and functional targets or desired outcomes given the stage of the restoration project (orange). Each point represents an example numbered E1–E5 of trait-informed restoration as described in Table 1 and Boxes 1 and 2. (b) A comparison of “top-down” and “bottom-up” approaches to trait-informed restoration as mediated by successive filtering processes. In “top-down” restoration (left), population-level variation in intraspecific traits (icon color) underlying environmental matching is emphasized in the restoration of mobile animals. In “bottom-up” restoration (right), community-level variation in interspecific traits (icon type) underlying environmental matching is emphasized in the restoration of foundation organisms. (c) An example of multi-system and multi-trophic restoration, showing how the traits (purple) of restored species interact across trophic levels (arrows; e.g., fish traits linked to herbivory reduce algal competition and support coral growth, which in turn provides habitat for small-bodied fishes) and with mediating factors (green; e.g., coastal rainfall can influence plant growth, which in turn affects seabird nesting and soil retention) to support key functions or outcomes (orange; e.g., coral growth reduces wave energy, while plant growth controls erosion) linked through inter-system feedback loops (Benkwitt et al., 2022, 2023; Delevaux et al., 2018; Ferrario et al., 2014). Panel (a) photo credits: Celia C. Symons (left) and Rebecca Ostertag (right). In panels (b) and (c), silhouette icons of reef substrate, volcanic mountains, and *Montipora* were drawn by Julia K. Briand, while remaining icons (incl. *Sphyraena*, *Falco*, *Carpobrotus*, *Puffinus*, *Pandanus*, *Eucalyptus*, *Pocillopora*, and *Scarus*) were obtained from PhyloPic (<https://www.phylopic.org/>) under the CC0 1.0 Universal Public Domain Dedication license.

BOX 1 Restoration of fishless mountain lake ecosystems

Trait-based approaches can be essential to predicting and understanding the dynamics of ecosystem recovery following the elimination of a perturbation (e.g., through community assembly and regime shift models; Bannar-Martin et al., 2018; Weisberg et al., 2024), as species composition and trait structure may not recover simultaneously (Figure 2). Indeed, the application of trait-based approaches can elucidate the complexities of aided versus natural species recovery and its impacts on ecosystem functioning, as exemplified by the recovery of zooplankton communities following the removal of non-native sportfish from mountain lakes (Stuparyk & Vinebrooke, 2024). The introduction of fish into naturally fishless systems profoundly impacts native organisms like zooplankton (Knapp et al., 2001, 2007; Knapp & Matthews, 2000; Loewen & Vinebrooke, 2016; Symons & Shurin, 2016), often shifting community composition away from larger bodied herbivores integral to promoting trophic cascades (Parker & Schindler, 2006) towards smaller bodied, less pigmented, faster moving zooplankton. While fish removals have succeeded in restoring native zooplankton taxa (Knapp et al., 2001), less is known about the recovery of the functional structure of zooplankton communities (Stuparyk & Vinebrooke, 2024). Traits may be key to tracking and supporting functional recovery, as post-removal shifts towards larger body sizes can stimulate secondary production by the extant native communities, regenerating natural feedback loops.

In the debate over whether to reintroduce zooplankton species or allow them to naturally recolonize mountain lakes, proponents of species reintroductions have argued that such efforts are necessary based on traits that severely limit the ability to disperse back into these ecosystems and re-establish viable populations (e.g., McNaught et al., 1999), whereas others have highlighted traits, such as the production of sedimentary resting eggs, which enable species to re-emerge from sediments (Parker & Schindler, 2006). In the latter case, species with trophic traits that allow them to evade size-selective predation can limit recovery by preying on the early life stages of extirpated species as they re-emerge (Stuparyk & Vinebrooke, 2024). Due to the plasticity of traits, functional redundancy among species, and potential for dispersal limitation, zooplankton communities in mountain lakes may recover functionally, via plasticity and the recovery of some species from the egg bank, before a complete taxonomic recovery occurs (Figure 2).

traits) can also increase resilience (Devoto et al., 2012; Rayome et al., 2019; Tsujii et al., 2020; Yachi & Loreau, 1999). Restoration goals that are more directly associated with physiological processes such as nutrient uptake by algae (Bracken & Stachowicz, 2006; Cardinale, 2011) or ecosystem stability (Cadotte et al., 2012) can also benefit from the consideration of how traits link to multi-trophic and abiotic mechanisms.

CROSS-SYSTEMS COMPARISONS AND INSIGHTS

Previous work has found that overarching restoration goals (e.g., rebuilding resilience against disturbance, re-establishing a self-sustaining population, and suppressing the spread of an invader) are often similar across systems and organisms, but the approaches taken to achieve such goals differ (Table 1; McAlpine et al., 2016), including the application of trait-derived information (Carlucci et al., 2020; Green et al., 2022). While work in some systems, like grassland restoration, has developed

methods that directly apply trait-derived knowledge to restoration planning and evaluation (Carlucci et al., 2020; Funk, 2021), restoration of other ecosystems often involves traits less directly. Lack of communication across fields, systems, and taxa (e.g., ecology and conservation, terrestrial and aquatic, and plant and animal) has likely stifled global advancements in trait-informed restoration. Thus, cross-system comparisons could yield general insights and identify potential synergies among knowledge and practice areas (McAlpine et al., 2016). By bridging gaps in knowledge, we can develop global collaborative, integrative, and innovative approaches to trait-informed restoration.

Bottom-up restoration

The restoration of foundational, biogenic habitat-forming organisms tends to prioritize traits based on theories of “bottom-up” community assembly and succession (e.g., E1; Figure 1a,b). For example, in plant restoration, traits are often considered within the context of larger

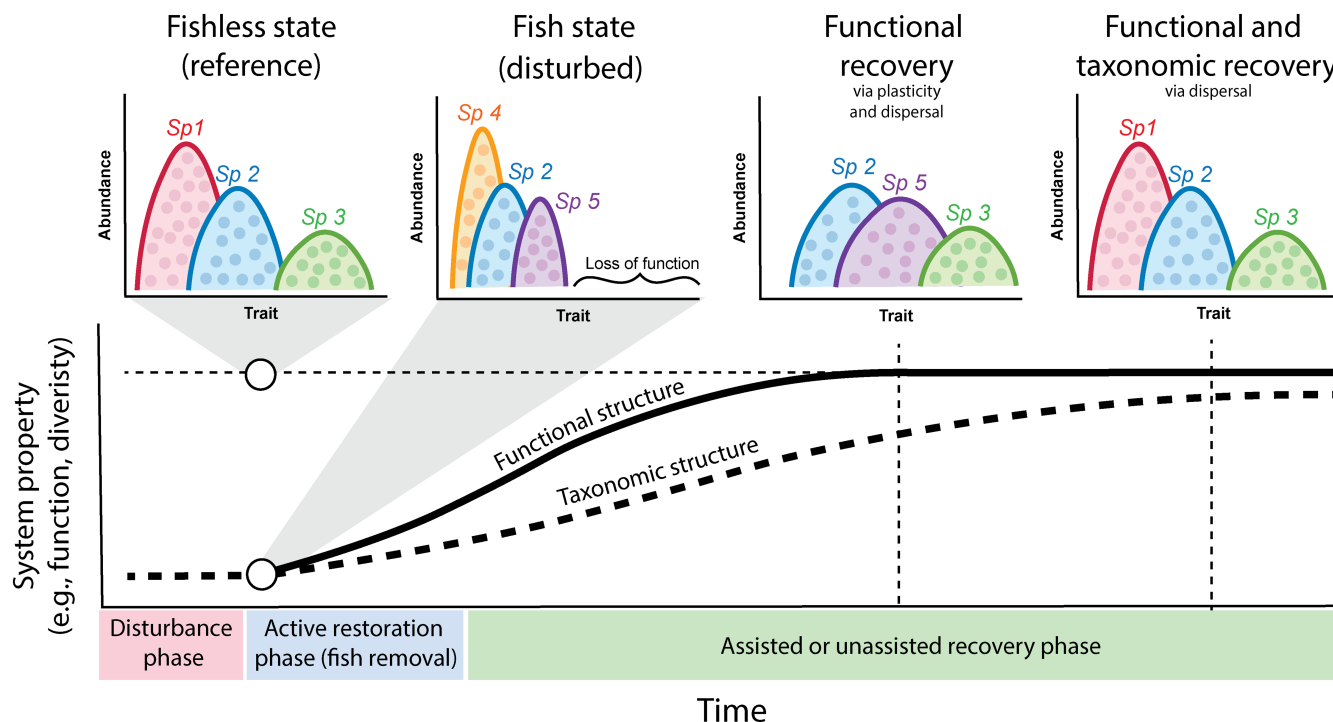


FIGURE 2 Community trajectories towards a restoration target (increase in zooplankton community diversity and abundance to regain ecosystem function, facilitated by invasive fish removal), where functional and taxonomic composition recover at different rates: In the disturbance phase, non-native fish introductions reduce the functional diversity of zooplankton communities; during active restoration, fish are removed from lakes, allowing communities to recover functions associated with naturally fishless systems; the assisted or unassisted recovery phase is characterized by the initial reassembly of functional structure via plasticity and dispersal followed by taxonomic recovery through additional dispersal. Traits are shown as univariate for illustrative purposes but can encompass multiple traits in practice.

community recovery and restructuring (Wainwright et al., 2018). In fact, multiple conceptual frameworks have been developed to select suites of plant traits that promote community reassembly and ecosystem function according to desired outcomes (Laughlin, 2014; Lavorel & Garnier, 2002; Wang et al., 2021). Approaching restoration from a community perspective also allows for the selection of complementary traits across different species to support an overall goal, such as establishing fire tolerance or invasion resistance (e.g., Box 2; Ostertag et al., 2015). Yet, the efficacy of this strategy may vary across (a)biotic contexts, and anthropogenic use may render some environments fully altered or local genetic pools too limited, making the re-establishment of habitat-building species insufficient to support the recolonization of associate species at higher trophic levels altogether (Palmer et al., 2016; Violle et al., 2007). For example, while the “Field of Dreams” paradigm suggests that habitat restoration will lead to ecological recovery, recent work shows that other trait-driven factors (e.g., species interactions, dispersal limitations) and management also play significant roles in reassembly (Guiden et al., 2021; Luong et al., 2019). Reassembly can also occur over disparate timescales within and across systems as mediated

by trait–environment interactions. Nevertheless, community assembly theory can be a powerful tool in trait-informed restoration that can often be readily tested in terrestrial plant systems (McGill et al., 2006).

Many comparisons can be drawn and lessons shared between the trait-based restoration of terrestrial plant systems and that of other foundation, habitat-forming taxa (e.g., corals, sponges, oysters). For example, restoration in marine systems may benefit from selecting suites of traits that will drive desired community reassembly, nutrient cycling, and resilience as done in the Hawaiian lowland wet forest system (Ostertag et al., 2015; Box 2; Figure 3). In coral reef restoration, much of the initial work focused on restoring populations of specific, high-profile species known to add complexity and color to a reef, but more recent approaches have moved towards rebuilding community structure to support the re-establishment of ecosystem function (Ladd et al., 2019; Smith et al., 2010). The restoration of oyster beds, another vital biogenic component of coastal estuarine and marine environments, has also begun to incorporate trait-based methods in the use of specific genetic stocks that influence bed establishment and health (e.g., Hanley et al., 2023). The vital habitat-forming role of these

BOX 2 How traits can inform restoration design in Hawaiian rainforest

To directly integrate trait-based approaches into restoration objectives, projects like the Liko Nā Pilina hybrid restoration project in Hilo, Hawai'i have explicitly involved traits at the outset. The lowland wet forest habitat of Hawai'i Island has been heavily altered by invasive plant and animal species that have outcompeted many native species and altered ecosystem functioning (Hughes & Denslow, 2005; Ostertag et al., 2009). With more non-native than native flora (Brock & Daehler, 2020) and only one extant frugivore species, there exist many barriers to restoring Hawaiian lowland forests.

To combat the effects of invasive plants with traits on the acquisitive end of the plant economics spectrum (i.e., associated with resource acquisition and fast growth; Reich, 2014) (Figure 3), the Liko Nā Pilina experiment restored native and non-native, non-invasive (introduced) species based on resource-conservative traits (i.e., associated with resource conservation, efficiency, and long-term survival). Species with traits such as high wood density, high maximum height, and low foliar N were selected to slow down the rate of nutrient cycling and increase carbon storage, the main functional target of this restoration project (DiManno et al., 2023). In addition to these species, smaller trees and shrubs were selected based on trait complementarity (maximum distance from the centroid) or redundancy (minimum distance from the centroid, Figure 3) to provide resistance to invasion, allowing for native plant regeneration and an opening of the understory, leading to low required levels of weeding and other management. Through this targeted and intentional trait selection, experimental treatments have greatly reduced rates of nutrient cycling, enhanced native seedling regeneration, and decreased weed invasion (DiManno et al., 2023).

species creates strong parallels between the restoration of their communities and approaches used in terrestrial plant restoration, suggesting that much of the emerging research and efforts in aquatic restoration can draw from advances made in terrestrial systems and vice versa.

Top-down restoration

For restoration initiatives that aim to reintroduce large, mobile animal species following decline or extirpation, a greater focus lies on variation in physiological and life history traits within and among populations of focal species rather than community structure (Wainwright et al., 2018), leading to a more “top-down” approach (e.g., E3; Figure 1a,b). With this focus on population- and individual-level differences, genetic and phenotypic information that characterizes intraspecific variation in key traits of focal species can be used alongside knowledge on local context at reintroduction sites to enhance restoration outcomes. For example, recent work on the reintroduction of threespine stickleback fish used genetic and phenotypic information to identify benthic versus limnetic ecotypes, differentiated by foraging traits and therefore prey preferences (Hendry et al., 2024). These fish were then matched to lakes based on conditions for their foraging methods and preferred prey. Through such investigations, it is apparent that traits can play a large role in animal restoration alongside genetic theory. More

direct and intentional use of traits to understand the target population and larger community can therefore ensure habitat suitability and support the recovery of essential functions.

Emphasis on the reintroduction of specific taxa has resulted in the active restoration of functionally distinct species (e.g., keystone species), which play valuable ecological roles but alone cannot guarantee the re-establishment of key ecosystem functions and processes. For example, in Europe, previous work has shown that most actively reintroduced mammals were functionally distinct but did not completely fill the functional niches endemic to the region (Thévenin et al., 2022). However, a recent increased interest in the restoration of large herbivores through trophic rewilding has produced implicitly trait-focused approaches that consider both intra- and interspecific variation to achieve functional outcomes (with body size and muzzle width being key functional traits; Atkinson et al., 2024; Fløjgaard et al., 2022; Lundgren et al., 2020, 2024).

Traits relevant to bottom-up versus top-down restoration

Just as the ecological scales (e.g., individual vs. community) prioritized in the restoration of habitat-forming or sessile species differ from large, mobile animal species, so do many of the relevant traits. For foundation organisms,

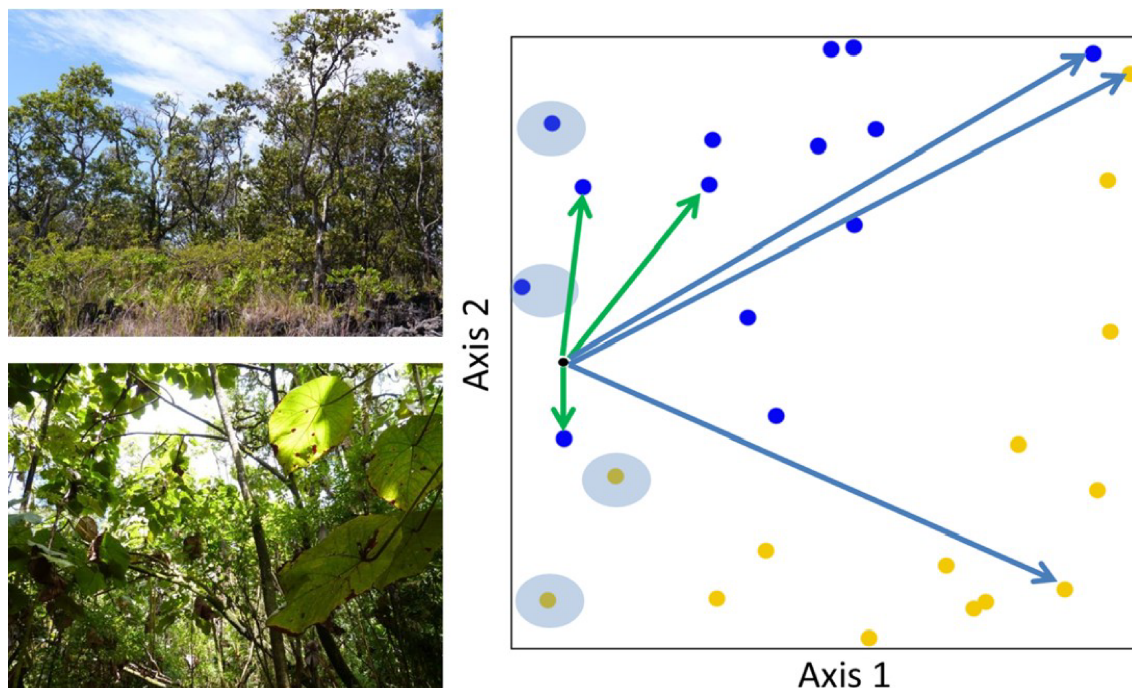


FIGURE 3 Invasive species have completely transformed vegetation structure (Zimmerman et al., 2007), seedling regeneration (Cordell et al., 2009), and nutrient cycling (Ostertag et al., 2009) in lowland wet forests of Hawai'i Island. Native plant species with conservative traits related to slow growth on young nutrient-poor lava substrates and relatively open canopy (top left) have been replaced by highly invasive plant species with large, nutrient-rich leaves that grow quickly and produce dense shade (bottom left). To develop experimental hybrid restoration communities (Ostertag et al., 2015), candidate native (blue) and introduced species (yellow) were oriented in trait space. Core species (enclosed by blue circles) with traits such as high wood density and maximum height were identified along with additional species selected based on redundancy (those near the centroid, green arrows) or complementarity (those far away from the centroid, blue arrows) with the core species. The separation of native and introduced species in trait space provides support for the hypothesis that these species, when grown collectively, could outcompete invasive species, based on the principle of limiting similarity (Funk et al., 2008; Hess et al., 2019). Photo credits: Rebecca Ostertag.

focus may lie on traits related to productivity, structural complexity, and/or reproductive mode, which support energy transfer and reassembly. Conversely, for mobile animals, traits associated with prey selection, habitat selection, movement, or behavior are more relevant to maintaining trophic dynamics (Villéger et al., 2017). Behavioral traits, such as boldness, can affect survival during introductions and are highly relevant for restoration (McDougall et al., 2006; Merrick & Koprowski, 2017), but these traits can vary through space and time (Bremner-Harrison et al., 2004; Sinn et al., 2014), and be difficult to measure and compare in free-roaming populations. Consequently, many animal-based studies focus on categorical traits (Kohli & Rowe, 2019) and body size as a “soft trait,” which is indirectly linked and correlated to functions of interest (Cooke et al., 2019; de Bello et al., 2010), but disproportionate attention to such traits can make extracting key mechanisms and predicting community dynamics difficult (Wootton et al., 2022). This is also seen in plant restoration, where “soft traits” (e.g., SLA) are more readily measured than “hard traits”

(e.g., photosynthetic rate), which are typically more consistent and directly linked to mechanisms underlying function. Nevertheless, both the “bottom-up,” community-based approaches to plant restoration, and “top-down,” population-focused approaches to animal restoration, can benefit from the integration of knowledge on their respective approaches to the application of traits.

Multi-trophic restoration

At the community level, multi-trophic interactions like pollination and predation are increasingly considered in restoration. However, many trait-based theories and studies examining interactions occur in “horizontal” communities, where inter- or intraspecific competition is the primary force determining species diversity (Kraft et al., 2015; Kunstler et al., 2016). As traits often define how species assemblages at different trophic levels interact to affect ecosystem functions, “vertical” assemblages

that include interactions across life forms or trophic levels are critical to consider in restoration, but have received relatively little explicit attention until recently (Green, 2025). In marine systems, fish and coral traits have been shown to covary across local contexts (Anderson et al., 2023), synergizing to support ecosystem functions (e.g., carbonate-cycling and energy transfer; Figure 1c), but effects on habitat restoration outcomes have not been thoroughly explored. Generating information on suites of traits that confer vulnerability to predation by invasive predators has proven useful for prioritizing locations for invader population control in places with communities likely to face the most severe impacts (Table 1; Linardich et al., 2021). Accounting for traits driving “vertical” nutrient and energy transfer in restoration is likely to be challenging given that knowledge on sets of traits characterizing different interacting taxa is required. Given that taxonomically based food web and trophic network relationships can also be difficult to track and quantify (Berlow et al., 2004), trait-based approaches show promise for predicting interaction strength as species composition and contexts change (Gleiber et al., 2024). Understanding how traits that confer information about food web interaction strength and traits governing organisms’ ecological functions (e.g., nutrient transfer) co-occur can help to link “bottom-up” and “top-down” approaches to restoration, and promote effective re-establishment of multi-trophic processes (Figure 1b).

Developing knowledge on trait interactions across trophic levels can not only inform restoration within one ecosystem but also help support larger scale projects that span multiple systems. As all ecosystems are connected, expanding to multi-system or “ecoscape” restoration (Wedding et al., 2025, 2026) can ensure that key inter-ecosystem processes recover (e.g., Sterba et al., 1997). For example, recent work has demonstrated that, through trait-driven processes, the restoration of tropical forests and seabirds with attributes linked to healthy nutrient deposition can stabilize sediment to prevent harmful runoff and support healthy nutrient delivery to reefs via guano, while, reciprocally, the restoration of corals and reef fish can reduce wave energy to further prevent coastal erosion and sustain seabird populations that prey on fish inhabiting the reef (Figure 1c; Benkwitt et al., 2022, 2023; Delevaux et al., 2018; Ferrario et al., 2014; Kappes & Jones, 2014). In these systems, traits of restored species can facilitate erosion control and wave energy reduction to advance coastal storm resilience, promoting the growth and persistence of organisms in both connected ecosystems and generating a positive feedback loop.

GLOBAL CHALLENGES AND RECOMMENDATIONS

Combating climate change and supporting human well-being requires the restoration of degraded lands and waters (UNEP, 2021); yet, as climate change and land-use push ecosystems farther from their historical conditions, traditional methods of restoration ecology become less and less effective (Hobbs et al., 2009; Radeloff et al., 2015). Trait-informed approaches hold significant promise for enhancing restoration efficacy in the face of changing conditions (Loureiro et al., 2023). Yet, the application of functional traits to restoration varies greatly across ecosystems, and researchers who observe the promise of this approach in experiments lament its lack of application in practice (Merchant et al., 2023). Below, we outline common limitations faced in trait-informed restoration that persist across systems, highlight successes in focal systems that could be replicated elsewhere, and provide recommendations for advancing the application of traits within the field of restoration ecology.

Knowledge gaps

Intraspecific variation

As discussed in *Individuals and populations*, trait-based ecology often focuses on differences at the species level, but within-species variation in functional trait values can be substantial. Intraspecific variation can arise from contextual differences that occur across space and time and have important ecological effects (Des Roches et al., 2018; Stahlhut et al., 2023). Such differences may stem from adaptation or response to local conditions, genetic variation, or developmental stage, and contribute to variation within populations (Cleasby et al., 2024; del Mar Delgado et al., 2018) and site-specific responses, as well as to ecological and evolutionary processes (Forsman & Wennersten, 2016; Violle et al., 2012), including reintroduction success (Homberger et al., 2021). Consequently, the aggregation of trait values measured at the individual level into estimates at higher level units like species or functional groups can sometimes oversimplify existing variation, making restoration outcomes difficult to predict (Briand et al., 2023; Brudvig et al., 2017; Yeager & Hughes, 2025). Rigorous methods are thus needed to determine when intraspecific variation in traits is relevant for restoration outcomes and when species-level differences provide enough information to make robust decisions (Gallagher et al., 2021). However, we often lack information on how genotypes translate to certain phenotypic traits and associated functions, making it

difficult to achieve restoration goals by leveraging within-species variation. Within-population trait measurements and genotype–phenotype linkages can help enhance our understanding of intraspecific differences in restoration planning that would otherwise go unnoticed. For example, understanding the importance of local adaptation versus resilience to a changing environment could inform which traits should be prioritized when selecting source populations for restoration in climate-impacted ecosystems (Baer et al., 2019; Jochems et al., 2022).

Trait syndromes and trade-offs

As single traits may not reliably predict functions, we are faced with the challenge of understanding the collective effects of trait syndromes in restoration. Scaling these connections at the ecosystem level to conduct restoration can be challenging, because ecosystem functions tend to vary not just with trait combinations, but with confounding conditions and contexts as well (Eviner & Hawkes, 2008). Thus, managers may need to prioritize different traits as restoration progresses and local conditions change. There may also be trade-offs between trait syndromes that confer different ecosystem-level functions, further complicating restoration management. In coastal restoration, practitioners often struggle to restore species that both increase fish habitat provisioning and nutrient uptake because traits associated with habitat building (e.g., structural complexity, branching order, and maximum length) may trade-off with traits associated with nutrient uptake (e.g., surface area-to-volume ratio; Mauffrey et al., 2020). When selecting species to restore, the identification of trade-offs between trait syndromes can ensure desired functions and outcomes are realized at each stage of restoration, but more research is needed on how trait syndromes affect functions and trade-offs across different scales.

Species interactions

Species interactions play pivotal roles in driving key community functions (McGill et al., 2006), but a major hurdle in trait-informed restoration is forecasting the collective contributions of species to interactions and subsequent community functionality. Biotic interactions are complex, and we lack knowledge about how traits of species relate to their interactions while also recognizing that species' effects can vary depending on diversity-mediated species interactions (Cassidy et al., 2020) and that the cumulative impact of species interactions on community functionality is often not additive. Even where there are studies of

how traits relate to species interactions (Schmitz et al., 2015), these are rarely a priori tests that allow us to determine whether targeting certain traits or trait syndromes within communities actually results in desired interactions and functions. Conducting a priori tests of trait–interaction connections can be particularly important in a changing environment, when shifts in some traits (e.g., phenology) can lead to a decoupling of species interactions (Kharouba et al., 2018; Winder & Schindler, 2004). Considering multiple traits of different organisms interacting across trophic levels can improve the likelihood of restoring key interactions (e.g., predation and plant–microbiome interactions; Trivedi et al., 2020) that are essential for recovering ecosystem dynamics. Advancements in this area will likely come from studies and projects that link suites of traits to specific functions at multiple trophic levels and monitor these interactions over time (Abdala-Roberts et al., 2025; Eisenhauer et al., 2019). For example, both traits and functions may be measured in situ (Nelson et al., 2020), traits may be grouped by functions they are anticipated to mediate (Waldén et al., 2023), or trait values may be used to model functions when direct measurement of functions is difficult (Raffard et al., 2017).

Environmental interactions and changing global conditions

Studies examining links between traits and organismal performance have highlighted another source of variation that can be difficult to account for in restoration: trait–fitness relationships that change across species and environmental conditions (e.g., Balazs et al., 2020). For instance, Zirbel and Brudvig (2020) found that environmental factors such as soil moisture and light availability influenced how traits predicted seedling establishment, with lower specific leaf area plants displaying higher seedling establishment than high-SLA species under conditions of low light availability versus high light availability. These interactions also occur in animal systems. Reintroduced bettongs (rabbit-sized jumping marsupials; *Bettongia lesueur*) with larger hind feet had higher survival due to more successful burrowing, but only when feral cat densities were low (Bannister et al., 2021). Site conditions can also modify the ecosystem effect of a given trait, as it can interact with environmental conditions (such as soil type) to provide a distinct outcome, even if the species' trait does not vary across sites (Eviner & Hawkes, 2008).

Environmental conditions are also rapidly changing. Successful restoration will therefore no longer be primarily judged based on recovery to a previous ecosystem state

(Choi, 2004), but rather rely on understanding and overcoming factors presently limiting natural recovery and on building ecosystems to maximize resilience and “future-proof” ecosystem services. Yet, this ecosystem novelty still presents two main avenues of uncertainty for those implementing restoration projects. First, there is uncertainty about what future conditions a site will experience as conditions continue to change. For instance, a site may have increasingly frequent or emerging disturbances such as fire and drought or face annual increases to average temperature. Second, given that we expect to see combinations of abiotic and biotic conditions that do not currently exist, it remains unclear whether trait relationships characterized under current conditions will translate to these scenarios (Ahrens et al., 2020). To help predict variation critical to restoration in the face of rapidly changing and heterogeneous environmental conditions, more extensive and advanced monitoring, targeted experiments, and application of traits that have well-documented links to function are needed (Brudvig & Catano, 2024). While new, cost-effective technologies like remote sensing and functional genomics tools can be applied towards post-restoration monitoring, replicated experiments like the International Drought Experiment (Smith et al., 2024) can be used to consistently manipulate abiotic and biotic variables, unraveling some of the context dependencies in trait–function relationships that will be key to building future resilience.

Data gaps and limitations

Despite the potential applicability of traits to restoration, limited trait data, knowledge on the context dependency of traits and knowledge on trade-offs among traits present challenges to the uptake of trait-based approaches and development of trait-informed restoration projects, as well as the scientific evaluation of restoration (Merchant et al., 2023; Sandel et al., 2015). The future adoption of trait-informed restoration relies on accurate and informative organismal trait data, which vary in quantity and quality across systems. While species-level trait information is increasingly accessible in open-source databases (e.g., TRY, Encyclopedia of Life, GIFT, Marine Traits Portal of the World Register of Marine Species, AusTraits, Fishbase; Froese & Pauly, 2024; Falster et al., 2021; Kattge et al., 2020; Weigelt et al., 2019; WoRMS Editorial Board, 2025), these databases are limited in geographic, taxonomic, and trait coverage. Indeed, data gaps are non-randomly distributed among taxa and across regions (Cornwell et al., 2019; Etard et al., 2020; Schrodtt et al., 2015). For example, many species are underrepresented in the Southern Hemisphere (Cornwell et al., 2019)

and in more remote habitats or systems, including the deep sea (Boschen-Rose & Colaço, 2021; Chapman et al., 2019), along with species that are functionally rare but important (Leitão et al., 2016) or threatened and could benefit from functional restoration approaches (Gallagher et al., 2021). Coverage of functional trait information is higher in temperate species, in particular birds and trees, and in terrestrial habitats, especially those in North America and Europe (Carlucci et al., 2020; Prober et al., 2019). There are also biases impacting which traits are measured, with an overrepresentation of traits that are more easily measured or qualitative traits that are less expensive to produce (Hébert et al., 2016), even if those traits are irrelevant for functional restoration targets.

Moreover, while trait databases have enabled macro-scale research, these resources usually only report species’ mean or maximum trait values without information about the variability of traits across or within individuals and populations. More complex or temporally explicit measures may be needed to infer recovery or change if intraspecific trait variation is greater than differences between species (Des Roches et al., 2018). When choosing trait-based restoration targets, it is therefore important to know the likely trait values in the given location, at the given time, with the given population history. Intraspecific variation has not traditionally been captured in existing trait databases, although this is beginning to change (Kattge et al., 2011, 2020). One potential way to incorporate intraspecific trait variability into models could be the use of what we refer to as a “meta-trait,” or traits that describe traits. Meta-traits encompass but expand beyond traditional measures of trait variation (e.g., mean or range of trait values, functional diversity), and could be applied at different biological levels (*sensu* Cleasby et al., 2015). Specifically, we emphasize the potential of including meta-traits that quantify the distribution of expressed trait values (e.g., bimodal or skewed distributions will not be represented accurately by a mean), the consistency in the expression of traits by describing within-group variance (e.g., within a population or individual), and tracking the plastic nature of trait distributions due to reaction norms and trait–environment interactions, which can reveal otherwise undetected patterns in trait expression. Cumulatively, meta-traits could be collated into a “trait profile” for a species using existing studies or databases, which could then be used to inform and predict restoration outcomes.

Problems arising from the lack of trait coverage for practitioners are compounded by the fact that measuring traits requires significant time investment, technical expertise, and specialized equipment, limiting the feasibility of measuring traits *in situ*. We therefore support incentivizing research on less commonly measured

species with a greater focus on trait measurements across large ecological networks, including remote systems to reduce disparities in the availability of trait data. In addition to bolstering databases, standardized, clear approaches or procedures for trait measurement, while often well established for plant traits, should be expanded to other systems (Pérez-Harguindeguy et al., 2016). The formation of regional networks or collaborations, such as the National Ecological Observatory Network (NEON) or the Long-Term Ecological Research Network (LTER), could be key to supporting trait measurement and documentation across systems (Brancalion et al., 2018; Luong et al., 2023). Yet, solutions to incomplete trait information are unlikely to be entirely resolved by collecting more data and may rely on improving “gap-filling” analytical methods (Schrodt et al., 2015), which must be used with care to avoid inaccurate estimates of missing values (Sandel et al., 2015). Nevertheless, enhancing trait information through databases, syntheses, and networks can help predict responses in situ, as only 12% of studies have tested trait-based *a priori* predictions through restoration according to a recent meta-analysis (Carlucci et al., 2020).

Communication and discipline siloing

Although the incorporation of trait-based tools may help advance restoration, multiple factors limit adoption (Merchant et al., 2023). A main limiting factor to implementing trait-informed restoration is the perceived lack of increased project success compared to the resources required to implement trait-informed restoration (Barak et al., 2022; Bayraktarov et al., 2019; Merchant et al., 2023). Restoration practitioners are often limited in resources and mandated to reach specific goals, so they commonly choose species and methods that are perceived to be most cost-effective and reduce the risk of noncompliance (Lesage et al., 2020; Luong et al., 2023). Further, funding often limits project implementation to 1–5 years, which leads to rapid project planning and implementation not conducive to strategic trait-based planning (Luong et al., 2023). Additionally, practitioners often lack accessible trait-based tools and indices. There are some trait-based tools tailored for restoration (Rayome et al., 2019), but they are inherently geared towards larger agencies that have more resources, infrastructure, and access to local ecological knowledge (Gornish et al., 2023). The co-development of accessible tools through focused partnerships could help overcome current barriers to implementing trait-informed restoration in practice and may also enhance access to funding and resources that would otherwise be unavailable to either party alone (e.g., CORDAP funding awards). By

addressing challenges and leveraging opportunities, enhanced collaboration can reduce perceived risk and accelerate the pace at which successful restoration occurs across ecosystems.

Restoration practitioners indicate that the current goals and spatiotemporal scales of ecological research often mismatch with their on-the-ground needs (Matzek et al., 2015). For example, studies often occur at single sites over a single year and focus on a single species, whereas needs for implementation span larger spatial, temporal, and biodiversity scales. Enhanced bidirectional information-sharing between scientists and restoration practitioners could ensure that trait-focused research agendas serve the needs of real-world restoration programs (Gornish et al., 2023; Jellinek et al., 2021; Kurle et al., 2022) and that research discoveries are vetted at the spatial and temporal scales at which restoration occurs. Recent success in other fields of applied ecological management using collaborative adaptive management (e.g., through translational ecology or knowledge co-production; Clark et al., 2019; Norström et al., 2020) and “loop learning” models has shown the feasibility of providing near-term scientific updates to inform decision-making (Hunt et al., 2016; Wilmer et al., 2018). The expertise and experience that managers and many communities have (e.g., traditional or local ecological knowledge) is highly valuable and should be used alongside co-produced data to develop integrated systems models that drive decision-support tools to aid in scenario planning and recommending best management practices.

Trait-informed restoration may also be limited by disconnected groups working in the growing fields of trait-based ecology and restoration ecology without knowledge-sharing through standardized resources. Such rapid development in organizational silos leads to radical discrepancies in how seemingly straightforward traits like growth rate are measured (Boström-Einarsson et al., 2020). It is thus imperative to enhance communication between restoration practitioners and researchers working in different ecosystems. The standardization of approaches across systems can occur through restoration programs (e.g., market-based programs and public-private partnerships) established in concert with existing standards and certification bodies that present useful frameworks for standardizing trait selection, metrics, and monitoring protocols. For example, countries under the Paris Agreement often include blue-carbon sequestration in national emissions reductions through carbon trading mechanisms like REDD+ (Taillardat et al., 2018; UNEP-WCMC, UNEP, & IUCN, 2020). Mangrove traits that enhance carbon sequestration (Alongi, 2012) could be published alongside these standards to promote the

adoption of trait-based approaches across systems, especially as blue carbon expands to seagrass, kelp, and other taxa (Greiner et al., 2013). To further achieve broadly applicable strategies, metrics like trait richness, divergence, and uniqueness can be linked to restoration objectives of interest across contexts (Mouillot et al., 2021).

Limitations

Trait-based approaches can enhance restoration outcomes, but their limitations should also be carefully considered. As discussed in *Knowledge gaps*, neglecting to account for trade-offs can result in unanticipated long-term outcomes. Instances like oyster bed restoration failures underscore the importance of considering long-term survival, where focusing solely on traits that enhance fast growth in juvenile stages may compromise resilience to heat events, reducing oyster bed formation in the long term (McAfee et al., 2017). Additionally, local adaptation may be difficult to track through commonly measured, species-level traits, making trait–environment matching difficult. In European freshwater systems, even slight differences in substratum cohesiveness between donor and recipient rivers have prevented successful mayfly reintroductions (Tittizer et al., 2008). Similarly, the application of traits to restoration under the assumptions of hypotheses (e.g., the limiting similarity hypothesis) without practical evidence may overlook the influence of interacting abiotic factors and local context-dependencies (e.g., nutrient context and resource availability) in driving outcomes (Holden & Cahill, 2024; Silliman et al., 2024). Achieving collaborative, large-scale trait-informed restoration thus requires a nuanced understanding of these limitations to avoid potential pitfalls and associated ecological consequences. Nevertheless, as the mechanisms underlying these limitations become better understood, trait-based approaches play increasingly essential roles in guiding restoration towards success.

CONCLUSION

The ideas presented here synthesize and direct future knowledge-sharing and collaborative development in trait-informed restoration that transcends system-specific boundaries in research and practice. Interdisciplinary frameworks can be developed from lessons learned across systems to guide and inform the application of trait-based approaches in restoration, advancing the field in response to rapidly changing global conditions. These frameworks can help us better understand and provide approaches for all levels of ecological organization to adapt to

changing conditions (e.g., seed archives) and recognize the multiple pathways through which species and communities can cope with environmental stress. To facilitate the development of applicable frameworks, a large-scale information-sharing and cooperation network could help identify and co-develop trait-informed restoration approaches. For example, the United Nations Decade on Ecosystem Restoration web platform provides a hub for both managers and researchers interested in restoration to find projects, partners, funding and the knowledge they need to make their restoration efforts a success.

Although our recommendations can help move the field of trait-based restoration ecology forward, we recognize that practitioners are often already using traits implicitly in their work. Thus, implementing and building on these ideas in collaboration with practitioners is key to fully realizing the potential of functional traits in restoration. Further co-creation of interdisciplinary, multi-system recommendations and frameworks will be essential to overcoming barriers and developing innovative solutions in trait-informed restoration.

The application of trait-based approaches to restoration is an emerging field of research and practice, but three opportunities for further advancement become clear when integrating multi-system perspectives. (1) Context dependency and trade-offs in trait–function linkages impact outcomes at various ecological scales and stages of restoration critical to achieving project goals. Filling in data and knowledge gaps can help account for this in trait-informed restoration, particularly as novel conditions arise. (2) Knowledge on how traits mediate processes at each ecological scale has been applied to restoration differently across ecosystems with focus often limited to either individual- or community-level organization. A more integrative approach can help inform restoration that promotes trait-mediated processes across ecological scales and systems. (3) Organizational siloing in the application of traits to restoration with limited cross-system and cross-discipline (i.e., practitioner–researcher and researcher–researcher) communication has resulted in isolated advancements in the field. Knowledge-sharing, along with standardization and management-science collaboration will ensure that trait-based methods are advancing in practice and across ecosystems.

Effective restoration practices, for which trait-based approaches provide insight, will be critical in preventing ecosystem collapse under quickening global change. Traits can be used to design ecosystems that provide desired functions as future climate scenarios push us away from historical reference systems, but more predictive work that considers our recommendations under shifting baselines and future climate scenarios is required to inform restoration. By formalizing cross-systems

knowledge-sharing and bringing diverse perspectives together, ideas presented in this paper have the potential to break innovation-stifling silos and contribute to advances in trait-based restoration ecology imperative to combating the effects of global change.

AUTHOR CONTRIBUTIONS

Julia K. Briand conceived the study with Stephanie J. Green. All authors contributed to developing the first draft with guidance from Julia K. Briand, Stephanie J. Green, Sheryl C. Hosler, and Thomas K. Merchant. Boxes were developed by Celia C. Symons, Rolf D. Vinebrooke, and Rebecca Ostertag. Restructuring and revisions were conducted by Julia K. Briand, Sheryl C. Hosler, and Thomas K. Merchant.

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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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