Applying cumulative effects to strategically advance large-scale ecosystem restoration

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International efforts to restore degraded ecosystems will continue to expand over the coming decades, yet the factors contributing to the effectiveness of long-term restoration across large areas remain largely unexplored. At large scales, outcomes are more complex and synergistic than the additive impacts of individual restoration projects. Here, we propose a cumulative-effects conceptual framework to inform restoration design and implementation and to comprehensively measure ecological outcomes. To evaluate and illustrate this approach, we reviewed long-term restoration in several large coastal and riverine areas across the US: the greater Florida Everglades; Gulf of Mexico coast; lower Columbia River and estuary; Puget Sound; San Francisco Bay and Sacramento–San Joaquin Delta; Missouri River; and northeastern coastal states. Evidence supported eight modes of cumulative effects of interacting restoration projects, which improved outcomes for species and ecosystems at landscape and regional scales. We conclude that cumulative effects, usually measured for ecosystem degradation, are also measurable for ecosystem restoration. The consideration of evidence-based cumulative effects will help managers of large-scale restoration capitalize on positive feedback and reduce countervailing effects.

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Although the common foundations of site-scale ecosystem restoration are well understood, the spatial scale and duration of restoration are rapidly expanding, raising theoretical questions and practical concerns. For instance, the primary goal of the Bonn Challenge, issued jointly in 2011 by the International Union for Conservation of Nature and the Government of Germany, is to restore 350 million ha of degraded land by 2030, while the UN General Assembly recently proclaimed 2021–2030 to be the Decade on Ecosystem Restoration. Such coordinated restoration across large spatial and temporal scales is a response to widespread environmental degradation, human welfare needs, and increased understanding of how species are sustained by distributed habitats and ecosystems (Lotze *et al.* 2006; Hall *et al.* 2018). In view of these trends, the Society for Ecological Restoration (SER) recently formed a Large-Scale Ecosystem Restoration section (Daoust *et al.* 2014).

In a nutshell:

- Cumulative effects of human activities, typically found in ecosystem degradation, also occur in large-scale ecosystem restoration
- Definitions for eight modes of cumulative effects are adapted for use in ecological restoration, ecosystem management, and conservation science
- A conceptual framework incorporating spatial, temporal, and systemic cumulative effects will aid multidisciplinary restoration science teams
- Tools for managing cumulative effects enable interconnected restoration sites to achieve benefits and avoid negative effects at landscape and regional scales

What does ecological restoration science offer to those working toward such ambitious goals? Restoration ecology provides information about the study of individual sites, ecosystems, and vulnerable species developed over the past half century (Roman and Burdick 2012; Clewell and Aronson 2013), yet for the most part it has not addressed large-scale restoration that includes multiple ecosystems and restoration projects across landscapes. Large-scale restoration is usually more cost-effective than local site-specific planning (Neeson *et al.* 2015); however, little formal research on achieving successful program-level outcomes has been reported. Useful principles to support the enormous projected expansion of restoration and ensure that large investments produce planned ecosystem functions are urgently needed.

In practice, large-scale restoration is typically overseen by multidisciplinary teams and based on an ecosystem approach developed at the site scale, as can be seen in the programs we reviewed (Figure 1). Geomorphic conditions and hydrological

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Figure 1. The study areas represent four of the five major updated Köppen-Geiger climate classes: equatorial; arid; warm temperate; and snow, but not polar (Kottek *et al.* 2006). A wide range of ecosystems and species are considered, although the restoration areas are all within the continental US.

processes are regarded as ecosystem controlling factors that largely determine ecological structure and function (Brinson 1993). Ecosystem conceptual models are used to inform decisions about altering controlling factors and reducing stressors to achieve ecological objectives (Gentile *et al.* 2001). Sites with less-disturbed conditions are incorporated as reference sites or targets for the trajectories of restored sites (Raposa *et al.* 2018).

In this review, we propose that a complementary approach – that of cumulative effects – be employed for comprehensive understanding of the ecosystem change associated with large-scale restoration. This approach, originally developed to assess stressor effects, signals both a shift in management perspective and the need for a conceptual framework to accommodate ecological processes over a large range of spatiotemporal scales. Studies of cumulative effects in conservation science traditionally focus on the impacts of human-caused stressors, whereas here we examine the cumulative effects of restorative actions. "Cumulative effects" are defined as the collective impacts of past, present, and future human activities on the environment (Spaling and Smit 1993). Numerous assessments convincingly demonstrate the associations between multiple interacting stressors and declining functions of aquatic and terrestrial ecosystems (Luoma *et al.* 2001; Darling and Côté 2008). As noted by the US National Research Council, "when many individual areas in a region are repeatedly altered…the result can be dramatic changes in the mix, arrangement, and internal characteristics of the habitats of species" (NRC 1986). Several studies have described similar landscape-scale effects of restorative actions at multiple sites (eg Diefenderfer *et al.* 2016; Beck *et al.* 2019) and interactions between species facilitating restoration (Halpern *et al.* 2007).

Here, we examine whether large-scale ecological restoration could benefit from an increased focus on cumulative effects as a restorative mechanism. To do so, we first adapted the stressors-based definitions of eight modes of cumulative effects (CEQ 1997) for alternative applications in ecological restoration, ecosystem management, and conservation science (Table 1). We then collected and assessed evidence from large-scale coastal and riverine restoration projects (Figure 1) to explore how insights regarding cumulative effects inform restoration in practice (WebTable 1). Our primary goal was to evaluate whether any modes of the accumulation of effects were evident after stressors were reduced (Figure 2).

In every study area we considered, more than one mode of cumulative effects accounted for interactions and ecological consequences of restoration actions. Multiple restoration and species recovery objectives were identified for each study area (WebTable 2), and governance models ranged from centralized programs to subregional organization or separately managed projects. For simplicity, we illustrate how each mode of cumulative effects contributed to restoration in just one or two study areas. On balance, our findings indicated that using available tools to incorporate cumulative effects mechanisms into the existing ecosystem approach (WebTable 3) is a suitable strategy for improving the effectiveness of restoration and adaptive management at large scales.

Systemic cumulative effects

The systems approach to cumulative effects consists of three modes of accumulation of ecological benefits: (1) compounding effects, previously termed multiple stressors or cascading effects (Darling and Côté 2008; Lefcheck *et al.* 2018); (2) triggers and thresholds (Groffman *et al.* 2006); and (3) indirect effects, originally known as secondary effects (NRC 1986) (Table 1).

Compounding effects: restoring Tampa Bay and the greater Florida Everglades

Positive effects arising from multiple pathways have been observed in Tampa Bay, Florida, where watershed-scale nutrient management and local habitat protection and enhancement projects aided seagrass recovery (Beck *et al.* 2019). Advanced wastewater and stormwater treatment since the 1970s reduced total nitrogen (N) inputs into the Bay by 90%. After system-wide improvements in numerical water transparency, chlorophyll-*a* concentration, and total N loading rates, seagrass acreage in 2014 exceeded recovery goals established in 1996 based on 1950s benchmark levels (WebTable 1; Greening *et al.* 2016). Similarly, in the Florida Everglades, multiple lines of evidence collected over three decades indicate that the effects of water management and

Table 1. Main characteristics of systemic and spatiotemporal cumulative effects

		Cumulative effects of large-scale ecosystem restoration and management	Cumulative impacts of environmental stressors and degradation*
Systemic	Compounding	In ecosystems altered by restoration, multiple internal or external drivers produce linear or non-linear, antagonistic or synergistic effects and feedback	Effects arising from multiple sources or pathways (eg synergism among pesticides; synergisms†)
	Triggers and thresholds	Thresholds are points in restoration response functions at which small changes in drivers or sudden changes in state variables yield abrupt shifts between alternate ecosystem states; triggers are environmental drivers that produce non-linear system-state responses	Fundamental changes in system behavior or structure (eg global climate change)
	Indirect	Restoring physical processes has biological effects, often including linkages between primary and secondary production	Secondary effects (eg commercial development following highway construction)
Spatial	Landscape pattern	Reduced fragmentation, increased patch size, and restored connectivity and configuration influence ecosystem processes and population dynamics	Change in landscape pattern (eg fragmentation of historic district; nibbling†, fragmentation‡)
	Cross boundary	Restoration influences system states or processes outside of restored sites, including interactions between restoration sites	Effects occur away from the source (eg acidic precipitation; space lags†)
	Space crowding	Multiple restoration projects are implemented within the same geographic domain, with overlapping areas of influence and interaction	High spatial density of effects (eg non-point-source pollution discharges to streams)
Temporal	Time lags	Important interactions and biota appear long after restoration alters drivers or components as the system adapts and develops	Delayed effects (eg exposure to carcinogens)
	Time crowding	The frequency or duration of restoration actions affects the ecosystem, or restoration alters the timing of stressors	Frequent and repetitive effects (eg forest harvest rate exceeds regrowth)

Notes: definitions are adapted for the effects of restoration versus National Environmental Policy Act (NEPA)-related environmental impacts. *Definitions and examples in CEQ (1997); †the name given in NRC (1986); ‡the name given in CEQ (1997).

restoration projects on food availability during the nesting season are key contributors to nesting success and the sustainability of wading bird populations (WebTable 1; Beerens *et al.* 2015). The compounding effects of managing environmental factors, including the hydropattern, water quality, and spatial extent of contiguous habitat, control the production and concentration of prey in high-quality habitat patches (Figure 3).

Triggers and thresholds: coastal restoration in the northeastern coastal states

Positive feedback can be triggered to induce abrupt shifts in system state. Much of Hog Island Bay on the Virginia coast lies within a depth range where vegetated seagrass meadows with relatively clear water or unvegetated seabeds with turbid water are alternative stable states (Carr *et al.* 2010). Thresholds are examples of non-linear behavior and vary spatially. Large-scale restoration of eelgrass (*Zostera marina*) in the Virginia Coast Reserve's lower bays improved water clarity, crossing a threshold that led to rapid eelgrass meadow expansion (Orth *et al.* 2012). After 40 years of nutrient enrichment on a Long Island Sound embayment in Connecticut, removal of a nutrient source induced a shift from an algae-dominated ecosystem to an eelgrass-dominated ecosystem within 15 years (Vaudrey *et al.* 2010). In these instances, positive feedback occurred as seagrasses modified the underwater light environment (Figure 4, a and b). Seagrasses increase the deposition of sediments suspended in water, limit the resuspension of bottom sediments, and capture nutrients that would otherwise promote algal growth. Although thresholds are often difficult to measure or predict (Groffman *et al.* 2006), understanding the thresholds that determine alternative states is necessary to drive management decisions (WebTable 1). Simply removing or reversing stressors may be insufficient to restore the system state if the magnitude of thresholds on the return path differs (a phenomenon called hysteresis; Beisner *et al.* 2003). For effective large-scale restoration to be triggered by smaller actions, the system state must be moved past conditions such as the critical light availability thresholds separating seagrass and algal systems.

Indirect effects: floodplain wetlands on the lower Columbia River and estuary

Where human development isolates ecosystems from natural physical processes, restoration causes an interim period of disruptive hydrologic and sedimentary change (Day *et al.* 2009). On the tidal river and estuarine floodplain of the Columbia River on the Oregon–Washington border, for example, the wetland restoration program reconnects formerly diked lands to riverine hydrology (Ebberts *et al.* 2017). The direct effects of reconnection on hydrology and sedimentation in turn produce indirect effects on native plants and the aquatic food web (Thom *et al.* 2018). Initially, remnant plants

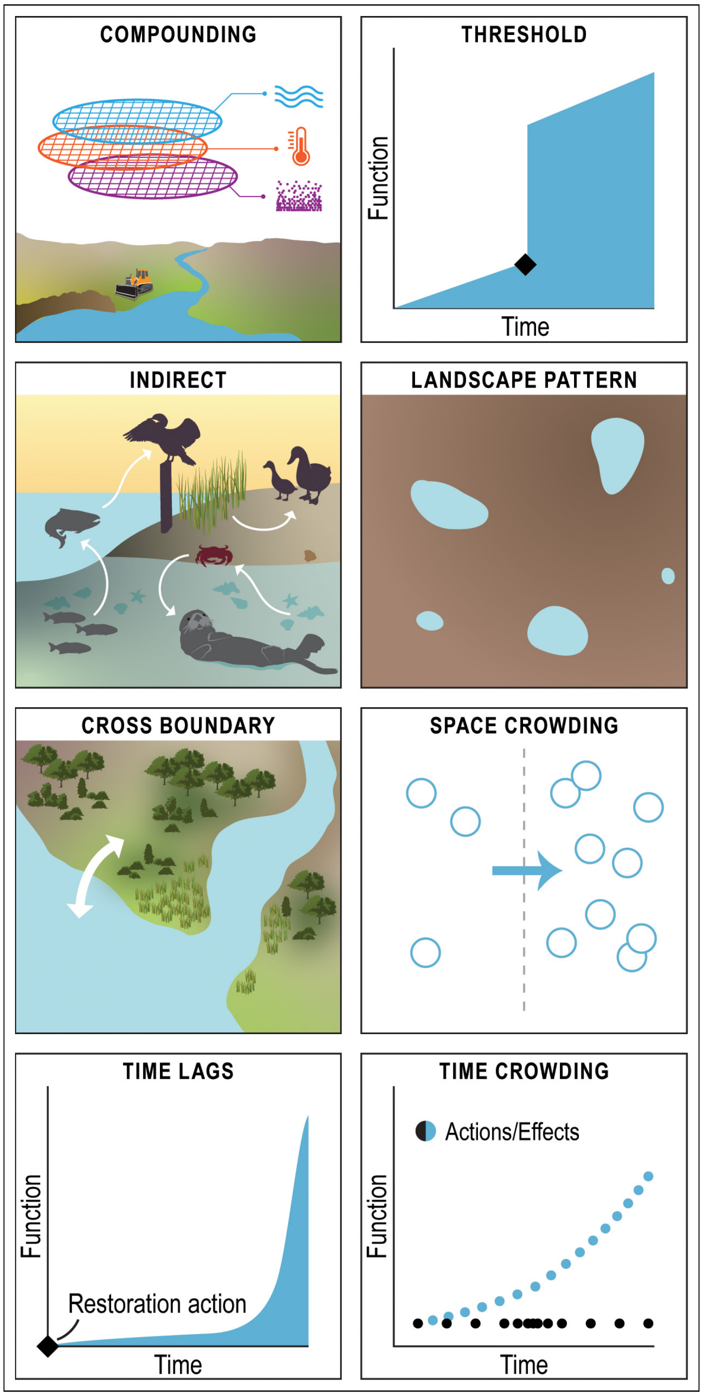

Figure 2. Depiction of the eight modes of cumulative effects. For more details, see Table 1.

intolerant of restored environmental conditions are eliminated (Burdick *et al.* 1997), in some cases producing surfaces with few vascular plants analogous to mine reclamation, the origin of restoration ecology (Bradshaw 1987). Wetland primary production is re-established through interactions of soil microbes, minerals, and nutrients with the evolving plant community, whether planted or derived from natural sources in the ecosystem. On the Columbia River floodplain, reconnection restores the primary production and export of marsh plants that die back annually, producing detritus that subsidizes organic matter in channels nearby and the food web that supports juvenile salmon, among other species (Figure 4, c and d; WebTable 1; Diefenderfer *et al.* 2016).

Spatial cumulative effects

Coordinating the management of restoration projects linked by ecological processes and evaluating their collective effectiveness requires understanding how populations and ecosystems are affected by changing spatial patterns, cross-boundary effects, and space crowding across the landscape (Table 1).

Change in landscape pattern: San Francisco Bay and the Sacramento–San Joaquin Delta

In San Francisco Bay and the Sacramento–San Joaquin Delta, the loss of 90–95% of wetlands within the estuary, extensive habitat loss in the Central Valley, habitat fragmentation, and loss of connectivity severely impact numerous wetland species, including the California Ridgway's rail (*Rallus obsoletus obsoletus*) and salt marsh harvest mouse (*Reithrodontomys raviventris*; Callaway *et al.* 2012). Commercial salt pond restoration creates a pattern of habitat patches with interacting water quality, primary production, and sediment dynamics (Valoppi 2018). The focus of recovery planning for highly mobile and/or migratory species like the anadromous longfin smelt (*Spirinchus thaleichthys*) and Chinook salmon (*Oncorhynchus tshawytscha*) differs from that for solely wetland-dependent species (Hobbs *et al.* 2017). For species such as smelt and salmon, survival across a mix of habitats in multiple parts of the estuary, tidal river, and watershed must be considered in conjunction with flow management. For instance, habitat restoration in a Puget Sound watershed measurably increased habitat complexity, which in turn was positively associated with Chinook salmon productivity (Hall *et al.* 2018), and reconnection of estuarine habitat on the Oregon coast resulted in greater life-history diversity for a population of coho salmon (*Oncorhynchus kisutch*; Jones *et al.* 2014). Relationships between life histories and habitat connectivity add complex dimensions to restoration planning, monitoring, and evaluation (WebTable 1; Herbold *et al.* 2018).

Cross-boundary effects: nesting birds on Missouri River sandbars

Cross-boundary effects include the movement and fate of water, sediments, detritus, dissolved organic matter, nutrients, other chemical constituents, organisms, and propagules between spatial domains (NRC 1986). Rivers present cross-boundary effects when management actions alter reservoir releases or channel configuration. On the Missouri River, newly created sandbar or reservoir shoreline habitats attract breeding pairs of piping plover (*Charadrius melodus*) and least tern (*Sternula antillarum*) (Figure 5, a and b). Sandbars are managed to improve nesting conditions, (eg by removing vegetation). Managing Missouri River reservoir releases to reduce the threat of inundation of nests on the riverine sandbars downstream conversely increases the threat of inundation of nests on the shorelines of reservoirs upstream (WebTable 1). Too little habitat restoration, or restoration of high-risk habitats that attract birds from other locations, may reduce the reproductive output of piping plovers competing for territory (Hunt *et al.* 2018). Habitat conditions also influence bird dispersal between segments of the Missouri River and other nesting habitats in tributaries and prairie pothole wetlands, thereby affecting the distribution of birds over a broad geographic area (Roche *et al.* 2016).

Space crowding: green infrastructure in Puget Sound watersheds

There are theoretical limits on the maximum restoration benefit for a given geographic area, and the density of restoration projects can produce space-crowding effects through ecosystem processes (eg water flow; Diefenderfer *et al.* 2012). When stormwater systems are designed to maximize efficient transport, event-driven spikes in land-use-related contaminants limit the potential for downstream ecosystem restoration and species recovery. Low-impact development such as stormwater green infrastructure provides opportunities for the management of rivers, stormwater, and treated-sewage runoff to support ecosystem restoration (Greening *et al.* 2016). Rain gardens, bioretention, and vegetated roofs moderate runoff events and associated nutrient loads (Pennino *et al.* 2016). Managers are encouraging such infrastructure in Puget Sound watersheds to reduce the impacts of contaminants on a network of river delta and tidal marsh restoration projects, as well as four deep aquatic basins. Higher densities of stormwater treatment areas implemented in watersheds are correlated with watershed-scale reductions in annual peak runoff, high-flow event frequency, coefficient of variation in runoff, and N loads (Pennino *et al.* 2016). Increased implementation of stormwater treatment projects combined with the phase-out of the stormwater-borne contaminant polybrominated diphenyl ethers (PBDEs) led to the reduction of PBDEs in Puget Sound harbor seals (*Phoca vitulina*; Ross *et al.* 2013). Infrastructure in urbanized or otherwise highly engineered basins influences basin-scale processes and flow dynamics, and consequently the trajectories of functional development at restored sites (Simenstad and Thom 1996).

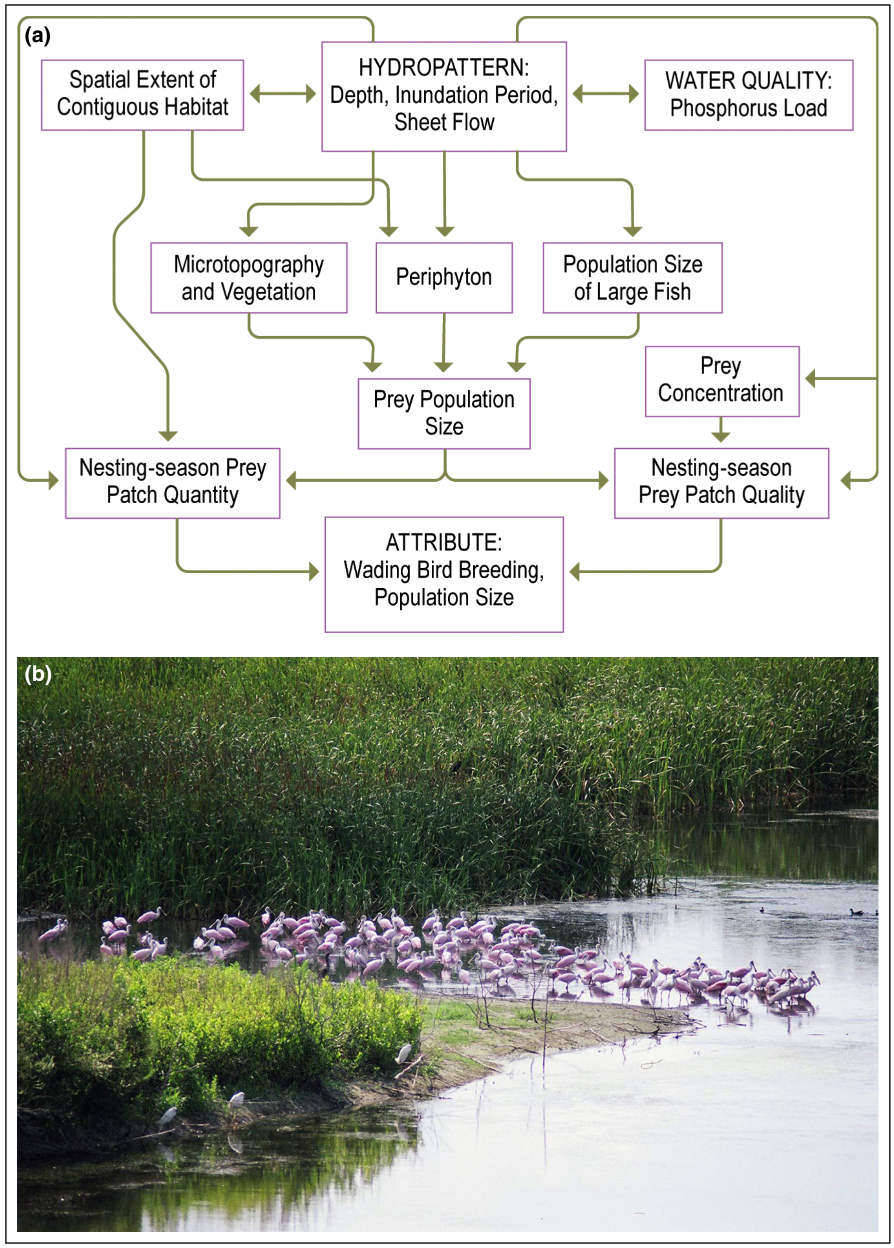

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Figure 3. (a) Compounding effects of restoration activities produce high-quality prey patches throughout the nesting cycle, a key to successful Everglades restoration for wading birds. (b) Roseate spoonbills (*Platalea ajaja*) occupy the mangrove ecotone where freshwater meets saltwater, which affects water depth and prey availability. Conceptual model in (a) adapted from Trexler and Goss (2009) and Beerens *et al.* (2015).

Temporal cumulative effects

Restoration actions are often intended to catalyze ecological processes to act on the landscape and create the desired system state (Clewell and Aronson 2013). Managing the timing of ecosystem stressors and drivers while depending on natural processes to complete recovery results in time-lag and time-crowding effects (Table 1; Carpenter and Turner 2001). As changes occur, continuing ecosystem management may be more or less active and adaptive according to the decision framework and depending on the results of

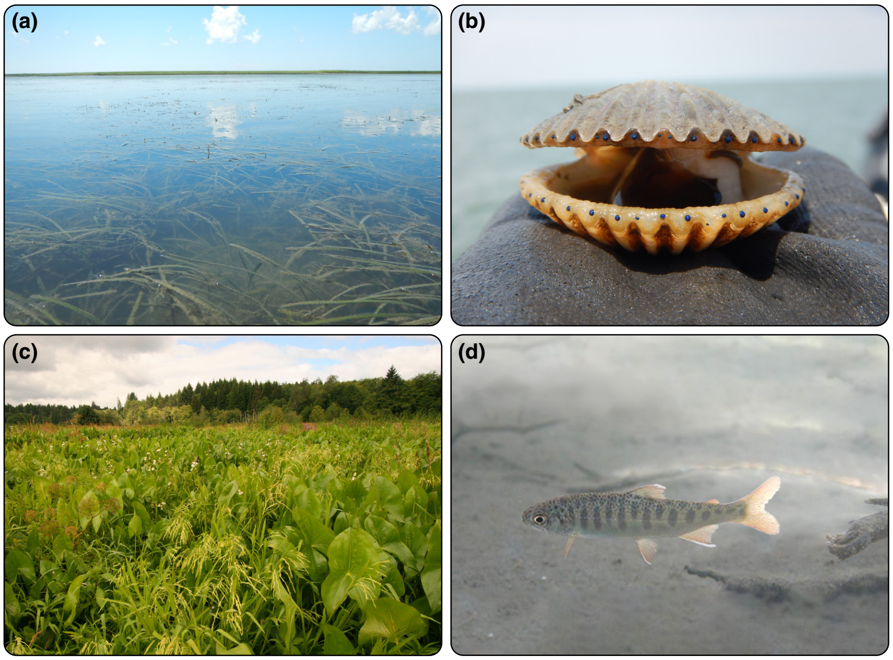

Figure 4. (a) In Virginia coastal bays where eelgrass (*Zostera marina*) beds have recovered, (b) efforts to re-establish bay scallop (*Argopecten irradians*) populations using scallops collected in North Carolina began in 2009. (c) Tidal freshwater wetlands, such as this wapato (*Sagittaria latifolia*) marsh, are being restored on the lower Columbia River and estuary, and provide habitat for numerous species like (d) salmon (*Oncorhynchus* spp), which use coastal wetland habitat during juvenile life stages.

monitoring (WebTable 3; Neckles *et al*. 2015; Ebberts *et al*. 2017).

Time lags: marshes and seagrass in the Gulf of Maine

Compelling examples of time lags are found throughout the restoration literature. For instance, many coastal restoration programs modify landforms, thereby altering water depths. Despite short hydrodynamic forcing time scales (eg tidal), the restoration of geomorphology through ecosystem responses associated with erosion and deposition is usually gradual. Numerous examples demonstrate the response of coastal marshes to tidal flow restoration (Roman and Burdick 2012). In salt marsh reconnections in Maine and New Hampshire, some conditions and components (eg salinity) returned to previous levels immediately, whereas others required up to 50 years (Burdick *et al*. 1997). Vegetation and soils take more time to develop a variety of functions, such as biodiversity, carbon storage, resistance to erosion, control of invasive species, microbial activity, and organic matter export. After eelgrass was planted at two locations in the Gulf of Maine, the development of the eelgrass bed canopy height and biomass over 8 years was followed by increased fish species richness (Evans and Short 2005). Time lags may impose limits on management control of the system, which need to be addressed by long-term monitoring within adaptive management or structured decision-making frameworks (WebTable 3; Neckles *et al*. 2015; Ebberts *et al*. 2017). In some types of restoration, the rates of physical and biological responses are predictably sequential while others are more uncertain (Burdick *et al*. 1997; Carpenter and Turner 2001; Bellmore *et al*. 2019).

Time crowding: pulses from watersheds to the Gulf of Mexico coast

The frequency, duration, timing, and magnitude of river flows altered by restoration and management affect sensitive systems and organisms (Allan 2004). Without new sediment, river deltas cannot maintain themselves against relative sea-level rise (Paola *et al*. 2011). In the Atchafalaya River Delta, Louisiana, a reference ecosystem on the Gulf of Mexico coast, hydrogeomorphic process domains occur across scales from the province to the basin and marsh (ie the combination of hydrological and geological factors controls ecosystem responses to environmental drivers; Twilley *et al*. 2019). The selection of appropriate restoration and management actions must therefore be scaled to the process domain. River diversions are a restoration approach often used in Louisiana to introduce freshwater, sediment, and nutrients into inactive delta lobes to combat saltwater intrusion, contribute to vertical accretion and land building, and stimulate marsh growth and production (Figure 5, c and d). Pulsing the inflow of diverted water represents an active use of time crowding. River stage and trend are key factors in timing pulses, because water diverted during rising or peak stages delivers at least twice as much sediment than it does during falling stages (WebTable 1; Day *et al*. 2009). Both basin and marsh restoration projects affect hydrodynamic regimes, sediment deposition, elevation deficits, salinity gradients, and land building at overlapping spatiotemporal scales. Pulsing could overcome some of the impacts of diversion-related salinity reduction on fisheries species, although the effects of suspended sediments on light, phytoplankton biomass, and filter feeders, such as Gulf menhaden (*Brevoortia patronus*), still require management (de Mutsert *et al*. 2017).

Advancing large-scale ecosystem restoration

For cumulative-effects strategies to advance beyond theory and move toward implementation, they must be shown to improve management outcomes in regard to large-scale restoration and recovery. As a practical matter, considering cumulative effects helps program managers make critical decisions about questions (WebTable 1) such as: given potential cumulative effects, how can the geographic scope of program planning be defined? How can projects be prioritized and budget requests justified when standard project-scale cost-effectiveness analyses fail to capture the full effects of the project? How can project benefits and/or unintended consequences that arise from multiple restoration elements in the landscape be accounted for? How can science information be translated into management triggers and thresholds for adaptive management decisions? To answer these types of questions, the Missouri River Recovery Program, for example, used suites of models to evaluate the potential for beneficial and countervailing effects of multiple restoration actions on focal species throughout the river system, fully account for benefits, and prioritize management activity (WebTable 3).

Figure 5. (a) On the Missouri River, sandbars are the location of (b) piping plover (*Charadrius melodus*) nests. (c) The Atchafalaya River Delta on the Gulf of Mexico coast. (d) White shrimp (*Litopenaeus setiferus*) use estuarine nursery habitats and spawn offshore in the Gulf of Mexico.

The evidence for cumulative effects theorized to occur in restoration programs is often deemed too expensive to fully develop and incorporate into restoration design and evaluation (Gilby *et al.* 2018). Sociocultural and institutional mechanisms can pose substantial barriers to planning, implementing, and evaluating large-scale ecosystem restoration even when the ecology is well understood (Daoust *et al.* 2014). Yet many research tools have been developed to assess the cumulative impacts of human-caused stressors, and some have the potential to be cost-effectively repurposed for ecosystem restoration. Useful tools for capturing interactions across landscapes include conceptual models, analytical frameworks, scenario planning, specialized indices (Nagel *et al.* 2018), spatial information, and quantitative hydrogeomorphic and ecological modeling methods (WebTable 3). Using spatial analysis and modeling to incorporate cumulative-effects mechanisms in forecasting may help to avoid unintended consequences and leverage system thresholds and positive feedback between projects to produce dramatic changes in system state (Groffman *et al.* 2006). These tools allow managers to move beyond prioritizing potential restoration actions or areas in an isolated manner and instead investigate the collective outcome of alternative suites of projects.

With the increasing scale of restoration planning in response to disasters, human population growth, and climate change (Figure 6), potential interactions encompass many ecosystem types, plant communities, and species affected by changing landscape patterns and ecological processes (WebTable 2; Nakano and Murakami 2001; LoSchiavo *et al.* 2013). The case studies discussed here demonstrated both threshold and compounding effects on seagrass recoveries; indirect and cross-boundary effects on bird and salmon populations; and indirect, space-crowding, and time-lag effects on tidal marsh restoration. Even study areas of the largest landscape scales interact with one another; for instance, the Mississippi River Delta receives only a fraction of the vast quantities of sediment historically transported via the Missouri River, but the two restoration areas are not jointly managed for collective objectives.

During restoration, ecosystems respond to disturbances and trends in climate, geological and hydrological processes, and land use, which complicates the job of distinguishing the effects of restoration activities from natural variability and other drivers (Luoma *et al.* 2001). Non-linear indirect effects are to be expected in watersheds and on coasts (Allan 2004). The detection of time- or space-crowding effects requires robust statistical modeling and experimental designs (Diefenderfer *et al.* 2012; Pennino *et al.* 2016). Resource limitations have sometimes prevented the hypothesis-driven experimentation and monitoring needed to distinguish restoration effects from background trends. Yet the history of impacts on an ecosystem helps point to likely modes of cumulative effects of restoration. For example, we observed compounding effects after multiple stressors were reduced and cross-boundary effects after man-made barriers were removed, and threshold effects occurred where phase shifts had previously degraded the system.

Evaluating the effectiveness of restoration is at present primarily a project-scale endeavor. Many program reports offer simple, additive summaries of project outcomes. We suggest that restoration programs also routinely assess the five most commonly seen modes of cumulative effects at landscape or regional scales, consisting of compounding effects, indirect effects, changes in landscape pattern, cross-boundary effects, and time lags (Table 1; Figure 2). Although not as widely documented in large-scale restoration, we

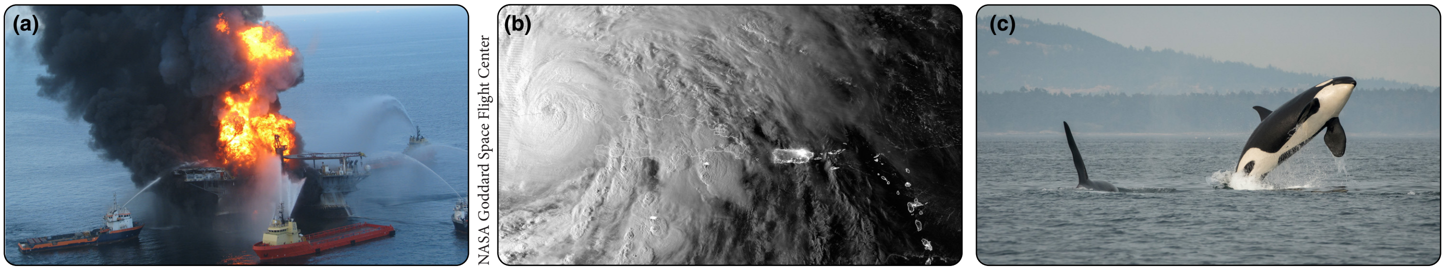

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Figure 6. A number of acute ecological and socioeconomic crises are increasing support for large-scale ecosystem restoration and underscoring the need for evidence-based cumulative effects strategies to increase effectiveness. (a) After the *Deepwater Horizon* oil spill, the RESTORE Act of 2012 directed billions of dollars to expand ecological restoration on the Gulf of Mexico coast, among five states and six federal agencies. (b) In 2012, after Hurricane Sandy, the US Department of the Interior invested hundreds of millions of dollars in coastal recovery, including wetland restoration on the East Coast. (c) After a Puget Sound orca whale (*Orcinus orca*) carried its deceased calf more than 1500 km in 2018, the governor of Washington State requested $1.1 billion for efforts – including coastal restoration – to recover the salmon food web, only about half of which was appropriated by the state legislature.

believe that valuable benefits, as shown here, would be achieved by incorporating thresholds, space crowding, and time crowding where ecological history suggests they are likely to occur.

Conclusions

This survey of restoration areas provides the first strong, collective evidence of beneficial cumulative effects within large-scale ecosystems. The site-scale outcomes of individual restoration projects are influenced by watershed- and landscape-scale processes, and by other restoration sites. We observed more than one mode of cumulative effect in each case study. These findings imply that collaborative understanding and management of cumulative effects are essential for the success of restoration at large scales. Accounting for cumulative effects is one basis for the advancement of large-scale, evidence-based programs to recover priority species and ecosystems on rivers and coasts worldwide.

Understanding the mechanisms of cumulative effects has the potential to unify the multidisciplinary teams of scientists that inevitably must address large-scale environmental restoration. A cumulative-effects framework helps to account for the non-linearity of the combined effects of restoration projects, particularly where the hydrological connectivity of ecosystems is high. Applying cumulative effects together with an ecosystem science foundation helps to address programmatic questions in large-scale restoration programs (WebTable 1). A cumulative-effects approach may be integrated into adaptive management and structured decision-making processes to bring more synthesis and evaluation of project-scale lessons to programs (WebTable 3). The development of effective regional restoration and management policies requires improved synthesis of interacting project effects across terrestrial and aquatic ecosystems aided by systems models.

We are nearing the beginning of the UN Decade on Ecosystem Restoration, in 2021. Currently in 2020, 57 entities (including countries, subnational governments, and private organizations) working with numerous international partnerships and SER have committed to restoring 170 million ha at considerable expense. The economic benefits deriving from improved food security, water supply, and biodiversity are estimated to be on the order of US$9 trillion, in addition to greater carbon sequestration. In this context, the utility of a cumulative-effects conceptual framework for large-scale ecosystem restoration is twofold: first, to plan to use ecological synergies beneficially and avoid countervailing effects of projects within interconnected ecosystems; and second, to design monitoring, synthesis, and evaluation strategies that fully account for and appropriately credit cumulative effects. The restoration of large-scale ecosystems, whether regional landscapes or whole bodies of water, will require the same vision and experimentation that was needed in 1972 to clean up lakes and rivers in the US after expansion of the Clean Water Act. Recognizing the individual and interacting ecosystem processes by which effects accumulate is necessary to harness their beneficial work to support the massive scale-up of restoration currently envisioned.

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