# Increasing the resilience of ecological restoration to extreme climatic events

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**Extreme climatic events (ECEs) are increasing in frequency and magnitude as part of global climate change, with severe consequences for both nature and human societies. While many restoration projects account for gradual climate change, ECEs are rarely considered. Through a literature search and the use of expert opinion, we reviewed the impacts of ECEs on habitat restoration projects, and the degree to which they were resilient. ECEs had overwhelmingly negative impacts on habitat restoration, although some projects also reported positive outcomes. The severity of impact varied among and within projects. Nearly all projects that included more than one focal species, life stage or genotype, restoration method, site, habitat type, or microhabitat reported better outcomes for at least one of these project aspects. We suggest that practitioners may be able to reduce risk from future ECEs through a portfolio approach, incorporating heterogeneity into project design, including in site selection and propagule choices.**

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Extreme climatic events (ECEs) – statistically rare climate events such as severe storms and tornados, heat waves, and extended drought, which can result in extreme ecological impacts (Smith 2011; IPCC 2012) – are increasing in frequency and severity with global climate change (Easterling *et al*. 2000; Herring *et al*. 2014). ECEs can decimate the built environment, disrupt human economies, and impact human health (Meehl *et al*. 2000; IPCC 2012; Babcock *et al*. 2019). ECEs can also shape ecological processes over time (Reich and Lake 2015; Ummenhofer and Meehl 2017; Chang *et al*. 2018).

## In a nutshell:

- Extreme climatic events (ECEs), such as severe storms, heat waves, and droughts, are increasing in frequency and magnitude due to global climate change
- Despite overwhelmingly negative impacts on restoration efforts, ECEs are rarely considered in planning for habitat restoration
- Approaches such as using multiple propagule sources, or restoring over multiple sites or seasons, may reduce overall risk from ECEs via the portfolio effect
- Planning for the uncertainty of ECEs also means having funds and developing protocols to detect ECEs and respond with adaptive management

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Ecological restoration, intentionally or unintentionally, has helped buffer some of the impacts of ECEs by reinstating conditions that enable greater resilience to large disturbances. For example, improved river–floodplain connectivity can mitigate flood impacts (Hey and Philippi 1995; Opperman *et al*. 2010) and restoring coastal foundation species can protect shorelines from hydrodynamic disturbances (Gedan *et al*. 2011; Narayan *et al*. 2016). However, restoration projects themselves will likely be increasingly impacted by ECEs.

Most restoration projects that plan for climate change focus on incremental changes in air and water temperature, salinity, sea-level rise, and so forth (Justice *et al*. 2017; Kane *et al*. 2017). Such gradual shifts are important and may exacerbate the effects of other stressors like habitat loss and fragmentation, invasive species, and nutrification (Reich and Lake 2015; Aplet and McKinley 2017). Restoration science has responded to incremental climate change by revising assumptions and objectives for restoration (Harris *et al*. 2006; Higgs *et al*. 2014), including considerations of resilience in design (Keane *et al*. 2016; Falk 2017; Justice *et al*. 2017), and recognizing the need for ongoing human management of restored ecosystems (Keane *et al*. 2016; Aplet and McKinley 2017).

However, ECEs – the most proximate and dramatic effects of climate change – are addressed relatively infrequently in restoration planning, with a few notable exceptions (Renton *et al*. 2014; Reich and Lake 2015). As a practical matter, ECEs can create major setbacks to restoration projects by destroying or damaging restoration structures and threatening restored species (Turpin and Bortone 2002; Shaish *et al*. 2010a), but this is seldom acknowledged or incorporated a priori in adaptive management strategies.

Here, we review the impacts of ECEs on restoration projects and the degree to which they were resilient to ECEs, and why, using examples from the literature and expert opinion. Drawing from the larger conservation literature, we discuss approaches to restoration design that may enhance resistance and resilience to ECEs. In particular, we build on the recommendations of Schindler *et al.* (2015) to reduce risk through the adoption of a portfolio approach.

## Impacts of ECEs on restoration projects

A literature search for examples of restoration projects impacted by ECEs (see WebPanel 1 for more details) returned 1601 titles, of which we read 960 abstracts and 52 papers. We found 22 papers describing 17 restoration projects (Table 1). The projects spanned multiple target taxa and habitat types, and included both active (eg replanting trees, transplanting coral fragments, establishing structures to recreate coastal dunes) and passive (eg management actions to improve estuarine water quality) restoration methods (WebTable 1). The effects of a single ECE were described for seven of the projects; five dealt with multiple similar events (eg two hurricanes), and five with multiple types of ECEs (eg a hurricane followed by a heat wave). Twelve projects reported negative impacts only, one reported positive impacts only, three reported both negative and positive impacts, and one reported neutral changes.

We expect that many impacts remain unreported in the literature because restoration practitioners typically focus on project construction, often lacking resources for long-term monitoring and publication beyond reporting to funders and stakeholders. Therefore, in addition to the literature review, we contacted practitioners in regions where ECEs have occurred recently (eg the US Gulf Coast) and with organizations involved in large-scale restoration (eg The Nature Conservancy) to collate unreported observations and anecdotes. From these discussions, we identified seven additional restoration projects that met the same criteria as described above for the literature search (Table 2; WebTable 2). Most of these projects were in estuaries or riparian areas and varied in age and approach; of these, five projects reported negative impacts only, one reported both negative and positive impacts, and one reported no damage.

Hurricanes and severe storms were the most commonly reported ECEs in the literature we reviewed and in interviews with experts, impacting 76% of projects via wind, floods, and/or waves. For example, hurricane-generated waves moved large artificial reefs that had been sunk for fish habitat, transporting some of them over several kilometers (Turpin and Bortone 2002), and broke transplanted coral fragments (eg Wells *et al.* 2010). Higher turbidity and lower salinity levels damaged coral tissue and reduced survivorship (Shaish *et al.* 2008, 2010a,b). Waves and wind destroyed restored sand dunes and vegetation (Gallego-Fernandez *et al.* 2011). Lowered salinity in an estuary reduced target species, disrupted recruitment cycles, and shifted ecological communities (Verdelhos *et al.* 2014). Heavy floods killed seedlings outright or reduced growth in a marsh restoration project (Doherty and Zedler 2015). For some projects, hurricane impacts were both immediate and long term. Winds knocked down trees, broke branches, and stripped leaves in rainforest restoration projects, and new gaps in canopy cover resulted in an increase of nonnative invasive plants, creating a new management concern (Kanowski *et al.* 2008). Hurricanes defoliated and otherwise directly damaged restored mangroves (*Rhizophora mucronata*), but also negatively affected long-term recovery by transforming soil conditions (Salmo *et al.* 2014). Extreme flooding drowned and washed away plants in a cordgrass (*Spartina alterniflora*) marsh and lowered the soil profile to such an extent that soil additions will be needed before replanting can begin (WebTable 2).

Not all impacts from storms and hurricanes were negative. A hurricane resulted in increases in woody debris, a historically present habitat type often missing in rainforest restoration sites (Kanowski *et al.* 2008). Artificial reefs that were "lost" after having been moved by waves became de facto sanctuaries for fish, resulting in greater fish abundance and sizes before being rediscovered by fishermen (Turpin and Bortone 2002). Sediment deposited on oyster restoration structures increased oyster mortality, but greater sedimentation between the oyster structures and a mangrove stand assisted with a secondary goal of shoreline protection (WebTable 2). Other changes were neutral, such as shifts in dominance among desirable native species (Chapple *et al.* 2017).

Similarly, droughts, the next most common ECE (28% of projects), had both negative and positive impacts, and acted in ways that were simple at some times and complex at other times. Droughts increased the cover of target submerged aquatic vegetation (SAV) in estuaries on account of improved water clarity, reduced water level, and increased water residence time (Beklioglu and Tan 2008), but also reduced seedling survival and negatively impacted marsh plant growth and health (Doherty and Zedler 2015) and, when coupled with a heat wave, reduced the extent and biomass of SAV and associated estuarine fauna (Verdelhos *et al.* 2014). Drought combined with an intense fire season hindered a riparian project when fires prevented crews from accessing their site to water newly planted vegetation (WebTable 2). An extended drought led to increased coyote (*Canis latrans*) predation on a target species, the desert tortoise (*Gopherus agassizii*), as populations of the coyote's preferred prey declined (Esque *et al.* 2010).

The severity of impacts varied substantially by project. For example, the effects of a hurricane depended on whether restoration projects were located near the hurricane's landfall, where strong winds resulted in minor impacts to projects, or, in one case, where the hurricane stalled for 4 days, resulting in extreme flooding and damage to projects (WebTable 2). Although some coral restoration projects recorded minor or moderate negative effects of hurricanes (Wells *et al.* 2010; Shaish *et al.* 2008) or extreme heat (Shaish *et al.* 2010a,b), others reported mass mortality and loss of all transplanted corals (Fadli *et al.* 2012). In an eelgrass and oyster restoration project, heavy rains lowered salinity to such

**Table 1. Impacts of ECEs on restoration projects: literature review**

| Habitat | Location | Species/taxa | Study years | # of ECEs | ECE type(s) | Impact | Impact types | Ref |
|---|---|---|---|---|---|---|---|---|
| Coastal dunes | Spain | Multiple dune plants | 2001–2008 | 1 | Storms | – | Mortality, habitat (dunes) destroyed | 1 |
| Coral reef | Philippines | Multiple coral species | 2005–2008 | 4 | Hurricanes, heavy rain/low salinity, heat | – | Mortality, damage, reduced growth | 2–4 |
| Coral reef | Fiji | Multiple coral species | 2005–2006 | 1 | Heat | – | Mortality | 5 |
| Coral reef | Indonesia | Multiple coral species | 2006–2009 | 1 | Heat | – | Mortality | 6 |
| Coral reef | British Virgin Islands | Elkhorn coral (*Acropora palmata*) | 2005–2011 | 2 | Storms | – | Mortality | 7 |
| Coral reef | Turks and Caicos | Multiple coral species | 2006–2008 | 2 | Hurricanes | – | Mortality | 8 |
| Coral reef | US | Fish assemblages | 1995–1997 | 2 | Hurricanes | –, + | Lost recreational opportunities, increased fish abundance and size | 9 |
| Desert | US | Desert tortoise (*Gopherus agassizii*) | 2008 | 1 | Drought | – | Mortality | 10 |
| Estuary | US | Submerged aquatic vegetation | 1996–2003 | 2 | Heavy rain/tropical storms, drought | +, – | Increased dispersal, increased cover of focal species, decreased other taxa | 11 |
| Estuary | Portugal | Eelgrass (*Zostera noltii*), associated invertebrates | 1993–2009 | 9 | Heavy rain/floods, low salinity, drought, heat | – | Reduced cover, biomass, reproduction | 12–15 |
| Tidal marsh | US | Multiple marsh plant species | 1990–2005 | 2 | Heavy rain/floods, low salinity | Neutral | Community composition shift | 16 |
| Freshwater marsh | US | Tussock sedge (*Carex stricta*) | 2012–2013 | 2 | Drought, heavy rain | – | Mortality, reduced growth, reproduction | 17 |
| Lake | Turkey | Submerged aquatic vegetation | 1998–2003 | 1 | Drought | + | Increased cover | 18 |
| Mangrove | Philippines | Red mangrove (*Rhizophora mucronata*) | 2009–2010 | 1 | Hurricane | – | Defoliation, mortality, decreased seedlings, multiple water and soil quality parameters | 19 |
| Temperate forest | France | Maritime pine (*Pinus pinaster*) | 1949–2006 | 3 | Extreme frosts | – | Tree mortality | 20 |
| Tropical rainforest | Australia | Multiple trees and shrubs | 2006 | 1 | Hurricane | – | Damaged vegetation | 21 |
| Tropical rainforest | Australia | Multiple trees and shrubs | 2006 | 1 | Hurricane | –, + | Damaged vegetation, high numbers of invasive species, deposition of woody debris | 22 |

**Notes:** impacts are described as negative (–), positive (+), or neutral. Ref: references; numbers correspond to the references listed in WebPanel 1.

**Table 2. Impacts of ECEs on restoration projects: interviews with experts**

| Habitat | Location | Species/taxa | Study years | # of ECEs | ECE type(s) | Impact(s) | Impact types | Source |
|---|---|---|---|---|---|---|---|---|
| Estuary | California | Olympia oyster (*Ostrea lurida*), eelgrass (*Zostera marina*) | 2011–2017 | 1 | Heavy rain | – | Mortality, reduced recruitment | Authors' unpublished data |
| Estuary | Florida | Eastern oyster (*Crassostrea virginica*) | 2014–2019 | 1 | Hurricane | –, + | Mortality, shoreline protection | L Geselbracht, (The Nature Conservancy [TNC]); Geselbracht *et al.* (2017) |
| Estuary | Texas | Eastern oyster | 2014–2018 | 1 | Hurricane | None | NA | J Pollack (Texas A&M Corpus Christi) |
| Estuary | Texas | Multiple bird species, eastern oyster, seagrass | 2005–2020 | 1 | Hurricane | – | Mortality, erosion, damaged structures | J Sullivan (TNC) |
| Tidal marsh | Texas | Cordgrass (*Spartina alterniflora*) | 2016–2019 | 1 | Hurricane | – | Mortality, erosion | J Culbertson (Texas Parks & Wildlife Department) |
| Riparian | California | Multiple tree, shrubs, and herb species | 2014 | 3 | Drought, heavy rains | – | Mortality, damaged structures and habitat, increased project costs | A Hebshi; M Bates (TetraTech) |
| Riparian | California | Multiple tree, shrubs, and herb species | 2014 | 1 | Drought, wildfires | – | Mortality, increased project costs | A Hebshi; M Bates (TetraTech) |

**Notes:** impacts are described as negative (–), positive (+), or none. NA = not applicable.

an extent that all target species died off (Figure 1; WebTable 2); other sites within the estuary were not as heavily impacted, allowing oysters (*Ostrea lurida*) to recruit back naturally and eelgrass (*Zostera marina*) to be re-transplanted from other sites within the same estuary. Across multiple mangrove restoration projects hit by a single hurricane, researchers found impacts varied by project age, with older projects hit hardest (Salmo *et al.* 2014).

Fourteen of the 22 papers and two of the seven experts interviewed noted that effects of ECEs were not uniform across the restoration site, across all restoration methods, or across species, life stages, or strains/genotypes. For example, surface heterogeneity played a large role in the impacts of extreme weather on a sedge in a project that intentionally added hummocks, depressions, and varied surface materials across a large area with natural variation in moisture retention (Doherty and Zedler 2015). Within the project, plants in wetter sub-locations in depressions fared poorly in flood years, while plants in drier sub-locations on hummocks fared poorly during droughts. For an estuarine bivalve, a series of storms, heat waves, and droughts negatively impacted recruitment, population biomass, and individual lengths and weights, but all impacts were greater in sandflats than in seagrass beds, likely due to less stressful conditions within the seagrass (Verdelhos *et al.* 2014). After brief instances of extreme cold, maritime pine (*Pinus pinaster*) trees belonging to a southern strain died while trees originating from the northern portion of the species range were unaffected (Benito-Garzón *et al.* 2013). Multiple coral species in a nursery grow-out and transplant project subjected to hurricanes and heat waves experienced impacts varying from minimal to devastating depending on species, site, and species–site interactions (Shaish *et al.* 2010a,b). Researchers also noted differences in response to hurricanes by species and genotype in the nursery phase of this project (Shaish *et al.* 2008). An area planted with cordgrass just 2 months before a hurricane hit fared far worse than portions of the marsh with more established plants, whose roots were better able to retain soils (WebTable 2).

## A potential strategy for restoration in preparation for ECEs

The projects reviewed above illustrate that the impacts of ECEs on restoration projects are diverse and complex, with responses dependent on the type(s) and severity of the ECE, restoration method, habitat, target species, and genotypes. Many papers noted differences in impacts even within a project, suggesting that heterogeneity within (or across) restoration projects is an important factor. This complexity presents a challenge to restoration practitioners who wish to predict the effects of future ECEs on restoration projects, but it also suggests a possible avenue for promoting resilience: through the incorporation of a portfolio approach (Schindler *et al.* 2015; Aplet and McKinley 2017) into restoration efforts.

Similar to the economic investment principle, diversifying where, when, and how restoration is performed may be rewarded simply because of variability within the portfolio (van Katwijk *et al.* 2009; Schindler *et al.* 2015). This idea has rarely been applied to restoration projects, which tend to have a narrow set of goals and geographic focus.

As opposed to approaches to address gradual, long-term, unidirectional climate change, planning for ECEs means taking into account the effects of rapid, often short-term, multidirectional changes (eg floods followed by droughts). Given the unpredictable nature of these events, we suggest that bet-hedging through the use of the portfolio effect is the best way forward for restoration in the face of ECEs. For example, given the patchiness and variation in the scale of future ECEs, having a network of restoration sites is likely to increase the chances of robustness against any single ECE (van Katwijk *et al*. 2009; Gallego-Fernandez *et al*. 2011; Reich and Lake 2015). A portfolio effect could be achieved by undertaking restoration at different geographic scales (eg multiple versus single estuaries or in a single estuary at different tidal heights) and different temporal scales (eg multiple years, but also multiple seasons), or by using multiple target species and/or genotypes (Figure 2).

For any restoration project, key decisions include site selection and within-site design; for projects involving planting/transplanting, there is another key decision: selection of appropriate propagules or target species (Figure 3). These choices would be guided by prior knowledge of the extent and severity of future ECEs, and how target taxa may respond, where such data exist. Even in the absence of these data, resilience to ECEs may be improved if design decisions are based on risk reduction (eg through the incorporation of heterogeneity at multiple scales) and preparedness (eg having a post-ECE response plan in place). Monitoring data gathered following an ECE, as part of the response plan, could then be used to inform future restoration projects (Figure 3).

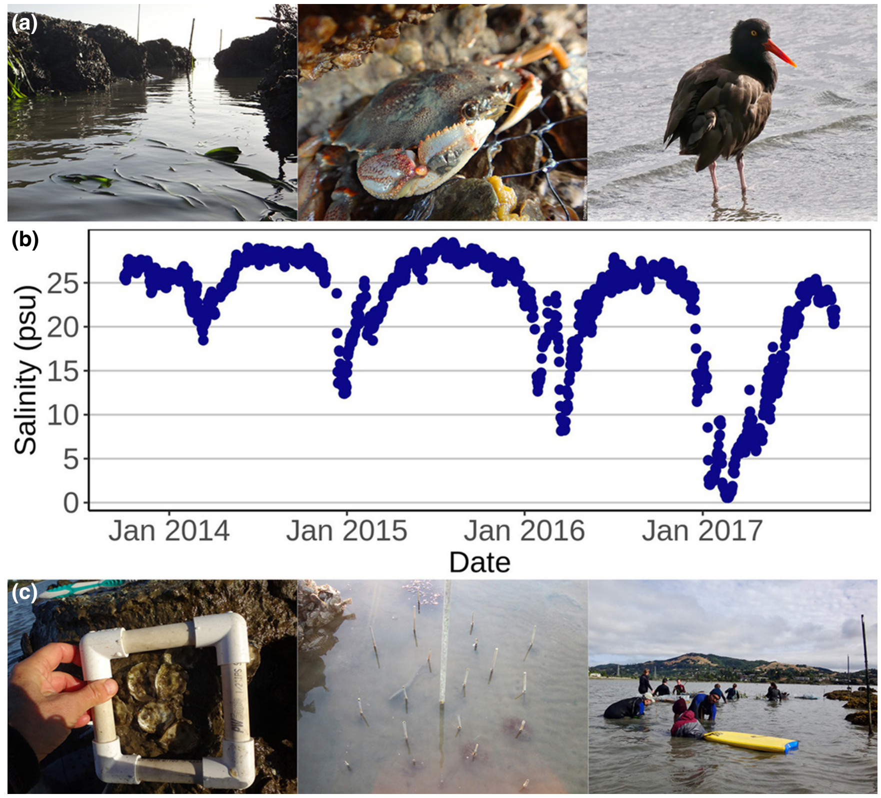


**Figure 1.** A "living shorelines" restoration project in California's San Francisco Bay (Table 2; WebTable 2) supported millions of oysters (*Ostrea lurida*) and a thriving eelgrass (*Zostera marina*) bed (a), which in turn provided habitat for a variety of invertebrates, fish, and birds (Boyer *et al*. 2017). (b) In 2017, a series of atmospheric rivers impacted the area, lowering salinity at the site to <10 practical salinity units (psu) for months, (c) resulting in mass mortality of oysters and eelgrass. Oysters recruited back to the site, but eelgrass required replanting. Water-quality data in (b) was obtained from nearby China Camp State Park (NOAA National Estuarine Research Reserve System [NERRS] System-wide Monitoring Program; data accessed from the NERRS Centralized Data Management Office: http://cdmo.baruch.sc.edu). Image credits for the crab and oystercatcher photos: S Kiriakopolos and W Chan (USGS), respectively.

## Spreading the risk through project design

Ideally, predictions of likely future ECE impacts and data on focal-species' traits could enable site selection to minimize risk (Figure 3). Many of the theoretical considerations from reserve design could then be applied to restoration siting (eg patch dynamics, population genetics, dispersal, exogenous stressors, broad-scale species declines; Allison *et al*. 1998). Key data for restoration siting include estimates of the scale and severity of likely ECEs, potential spatial and temporal refugia, and the ecology and life history of the restored species. Although long-term time-series of physical and biotic phenomena are rare and challenging to collect (Chang *et al*. 2018), filling these knowledge gaps is critical for optimizing site selection to enhance resilience.

For many target restoration species, little is known about life-history variation and physiological and biomechanical vulnerabilities across life stages (Kanowski *et al*. 2008; Martínez-Garza *et al*. 2013) in terms of stressors resulting from ECEs. Experiments can elucidate stage-specific physiological tolerances likely to be experienced in ECEs (eg to heat, cold, drought, and salinity) and biomechanical tolerances (eg to wind shear or wave impacts) to better predict performance in restoration projects. Recolonization probabilities based on reproductive life history, dispersal potential, and potential source populations are also important for predicting how quickly sites could recover.

Identifying spatial and temporal refugia and incorporating these into project design may reduce the impacts of ECEs (Figure 3). Key spatial information would ideally include the severity and duration of historical impacts by location and stress type. Information about shifts in risk due to non-ECE factors (eg land-use change, fire suppression, sea-level rise, habitat damage) should also be included. For instance, of particular importance in the context of ECEs is planning restoration activities so that species' most

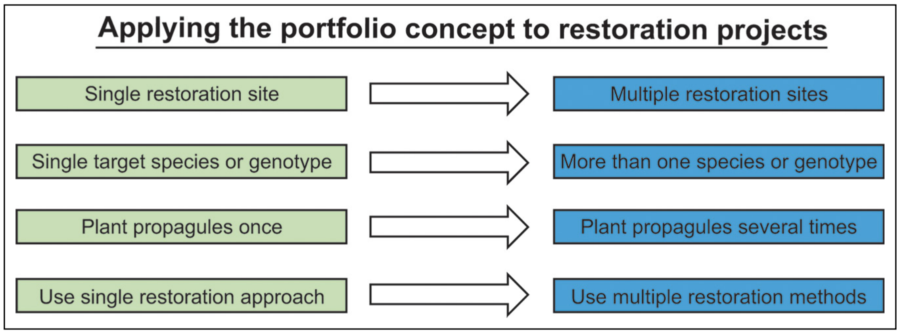


**Figure 2.** How a portfolio approach could be incorporated into restoration. Restoring over multiple sites, some of which may be connected via propagule dispersal, rather than a single site, increases the likelihood of positive outcomes within the portfolio of sites and increases the likelihood of recovery for impacted sites. Risk could be further reduced by spreading restoration effort over time, and through the inclusion of a suite of target species and/or a diversity of genotypes and restoration approaches.

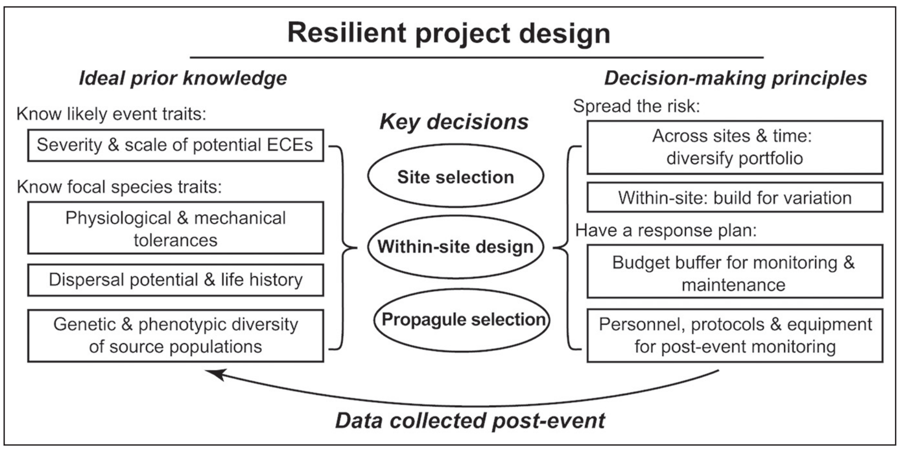


**Figure 3.** Key data, decisions, and decision-making principles for resilient project design for restoration. On the left, data types that can inform the key decisions of propagule (or target species) selection, project locations, and project design. On the right, approaches for risk reduction and response to extreme events. Data on impacts to projects from ECEs can be used to inform new projects and to guide adaptive management.

vulnerable life stages are less likely to be exposed to extreme conditions (Shaish *et al*. 2010a) and/or (where applicable) planting target species over several years to increase the likelihood of favorable conditions (Wilson 2015; Stuble *et al.* 2017; Mangueira *et al*. 2019).

Integrating these types of information can help guide site selection in cases where there are many options to choose from and multiple ECE types. Plotting impacts graphically may simplify site selection to minimize risk across a diversified site portfolio. For example, suppose an oyster source population has salinity tolerance such that only 10% of adults withstood dissolved salt concentrations of 5 parts per thousand for 5 days in experiments and that several potential sites exceeded these values during major storms; suppose too that there have also been oyster disease outbreaks associated with heat waves. We can plot the intensity of both impacts along an axis of site proximity, with some sites connected by dispersal (eg in the same embayment) to enable selection of sites with low impacts from both ECE types and increase the likelihood of recolonization after such events.

Restoration designs that address other stressors may also reduce the impacts of ECEs (Doherty and Zedler 2015; Falk 2017; Maccherini *et al*. 2018). In particular, restoration efforts can benefit from bet-hedging through the intentional incorporation of heterogeneity within a project site, including the use of sub-locations, microhabitats, restoration structures, and foundation species that create habitat and mitigate stress (Verdelhos *et al.* 2014; Shaish *et al*. 2010b; Martínez-Garza *et al.* 2013). Another potential approach is to select propagule sources to specifically enhance genetic diversity and adaptation potential to climate change (Prober *et al*. 2015); this may be especially important in instances where certain genotypes are more vulnerable to extreme conditions (Rice and Emery 2003; Harris *et al.* 2006; van Oppen *et al*. 2017). Many restoration practitioners use local genotypes to limit outbreeding depression and increase restoration success, but doing so may limit genetic variation and restrict a population's long-term evolutionary potential (Rice and Emery 2003; van Oppen *et al*. 2017).

For these reasons, it is important to consider that different populations and species may have different capacity to tolerate extreme stresses (Shaish *et al.* 2008, 2010b; Mangueira *et al.* 2019). Some coral species were more resilient to ECEs, including record rainfall and a heat-induced bleaching event (Shaish *et al*. 2010a,b). At the population level, Olympia oysters (*O lurida*) vary in their tolerance of low salinity (Bible and Sanford 2016). Variation in tolerance of extreme conditions would ideally be investigated before choosing broodstock or propagules for use in restoration (Shaish *et al.* 2008, 2010a; Benito-Garzón *et al.* 2013). Understanding trade-offs that may exist between resilience to ECEs and other desirable traits is critical to resilient project design (Figure 3).

Coping with ECEs may require both translocations of hardy individuals and other genetic enhancement techniques involved in assisted evolution, such as inducing acclimatization to stress and selective breeding (van Oppen *et al.* 2014). Assisted evolution – the process by which humans accelerate natural evolution to enhance certain traits – is controversial and relatively new for restoration practitioners (Jones and Monaco 2009; van Oppen *et al*. 2017). Evaluation is needed of assisted evolution techniques for coral reefs (van Oppen *et al.* 2014, 2017), which, along with many ecosystems around the world, are faced with multiple anthropogenic stressors and are experiencing rapid decline.

### Response plans

Planning for ECEs means planning to incorporate adaptive management, which may include ongoing maintenance, replanting, and minor or major repairs (WebTable 2; Reich and Lake 2015; Falk 2017). This requires setting aside funding in reserve or having a source of future funding to respond to ECEs (Figure 3).

A monitoring plan with sufficient duration to assess the establishment of species/ecosystem function – and that ideally includes control and reference sites – is critical to evaluating the success of restoration projects and advancing best practices (Miller and Hobbs 2007; Wortley *et al.* 2013). Monitoring plans must also have the capacity to respond rapidly to ECEs, both to detect the event and assess its effects (eg changes in water quality parameters following hurricanes) and to measure responses of the organisms (Verdelhos *et al.* 2014). To do this effectively, long-term partnerships should be established between local entities and/or community scientists and restoration practitioners to facilitate responses, given that ECEs may occur long after project completion. Best practices for measuring impacts include the delineation of the affected area and a control area, and, if relevant, across microhabitat or treatment types within the restoration project. Where possible, post-event monitoring should include quantification of key metrics such as mortality by age or size class, along with environmental parameters in both impact and control areas (Jurgens *et al.* 2015). Ideally, measurements would be made over a timescale sufficient to detect potential recovery, which may require reserve or emergency funding above what is allocated for regular monitoring.

Data generated from long-term and event-driven monitoring are necessary to guide adaptive management and inform future restoration designs that can be more resilient to ECEs (Figure 3). Frequently, restoration outcomes are reported to funding agencies and are unpublished, and thus are often more difficult to access than results published in peer-reviewed articles. To advance the science of restoration, we argue that lessons learned from projects impacted by ECEs should be reported and made readily accessible to the restoration community, perhaps through a public online portal.

## Critical shifts for restoration approaches in the face of ECEs

Effective adaptation to ECEs requires a reexamination of restoration objectives and approaches. Restoration ecology has begun to move away from the ideal of attaining a historical and static reference state (Harris *et al.* 2006; Higgs *et al.* 2014; Prober *et al.* 2019). Climate change, including ECEs, will in many places make such a return to former conditions impossible (Harris *et al.* 2006).

Adapting to ECEs will require that restoration projects shift away from traditional practices in several ways. Unlike approaches for adaptation to gradual climate change, restoration practice will need to include planning for greater uncertainty. Projects will need to explicitly include and secure adequate funding for monitoring and adaptive management in response to ECEs. Given added uncertainty, goals may not be achieved within predictable timeframes or by all sites in all years, and setbacks should be anticipated by restoration practitioners and funding agencies. Expectations should be set appropriately for the general public. Incorporating a portfolio approach (Schindler *et al.* 2015) may mean that longer timeframes, regional collaborations across more restoration sites, and a variety of approaches will be needed to meet success criteria.

With the increasing frequency and severity of ECEs, restoration science is now tasked with offering more guidance for practitioners working to restore threatened and damaged habitats amid the uncertainty of global change. Here, we provide a synthesis of current knowledge in the hope of inspiring more targeted research, and offer a way forward that we believe can improve the success of restoration despite a future of extreme events.

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## Data Availability Statement

No data were collected for this review.

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