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Research Letters

Enhancing climate change resilience of ecological restoration — A framework for action

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HIGHLIGHTS

- Climate change needs considering in seven areas of restoration design/implementation.
- These range from objective setting through to monitoring and adaptive management.
- Evidence is scant for climate change resilient restoration in practice.
- Our framework can help structure a more climate change resilient restoration approach.

GRAPHICAL ABSTRACT

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ABSTRACT

Ecological restoration is a tool for climate change mitigation and adaptation, and yet its outcomes are susceptible themselves to climate change impacts. Drawing on the literature documenting this in theory and practice, we present a comprehensive overview of climate change risks and considerations across the whole life cycle of a restoration initiative. The resulting framework identified seven areas of restoration design and implementation in which climate change is important to address: setting restoration objectives, selecting sites and managing connectivity, choosing target species and ecosystems, managing key ecosystem interactions and micro-climates, identifying and mitigating site-level climate change risks, aligning the project with long-term policies, and designing a monitoring framework that enables adaptive management. A scan of restoration projects focussing on two regions – Brazil and countries of the Association of Southeast Asian Nations, ASEAN – revealed limited inclusion of these considerations in practice, with less than 5% of the projects evidently addressing at least one of the seven areas. We discuss two projects showing good practice in climate resilient restoration: restoration of Atlantic forest in Brazil that plans for climate change in connectivity and hydrological management, species selection, and policy alignment, and crayweed underwater forest restoration in Sydney, Australia, whose careful attention to species provenance, genotype measurement and monitoring provided a "future-proofing" approach to restoration success in the long term. Building on such examples, our framework can be used as a tool to support global restoration targets and the UN Decade on Ecosystem Restoration 2021–2030 through more climate resilient restoration.

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Introduction

Degraded land and seascapes cover over 2 billion hectares, threaten the welfare of 3.2 billion people and cost one tenth of the global gross product due to the loss of biodiversity and ecosystem services (IPBES, 2018). Ecological restoration ('the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed'; SER 2004), can help halt and reverse degradation, stimulate economic growth and contribute to the 2030 Agenda for Sustainable Development, namely poverty alleviation, biodiversity conservation and climate action (UN, 2015). The demonstrable environmental and societal benefits of ecological restoration have galvanized governments worldwide to restore degraded land and seascapes (FAO and UNEP, 2020). This includes the formation of national, regional and international goals and commitments, notably the Bonn Challenge, Initiative 20 × 20, and African Forest Landscape Restoration Initiative. These initiatives will be reinforced by the forthcoming UN Decade on Ecosystem Restoration (2021–2030), by developing political momentum, broadening the coalition of partners, and building capacity through communications, tools and knowledge exchange (www.decadeonrestoration.org).

Attention on the potential of ecosystem restoration as a nature-based solution to tackle climate change has grown considerably in recent years (Bustamante, 2019). Conservation, restoration and improved land management have enormous potential in many countries to cost-effectively mitigate climate change whilst also bringing other social and environmental benefits, including climate resilience (Griscom et al., 2020, 2017). Such opportunities have been mapped in relation to the world's tropical forests (Brancalion et al., 2019).

However, the course and success of restoration can itself be impacted by climate change (Harris et al., 2006; Pramova et al., 2019; Suding et al., 2015). For example, whilst restoration is an important tool for capturing excess carbon in the atmosphere, modelling shows that its overall potential for this purpose will be affected by how climate change alters the area that can support forest regrowth (Bastin et al., 2019). Increases in temperature, drought, fire, and pest outbreaks can negatively impact photosynthesis and carbon storage (Anderegg et al., 2020; Griscom et al., 2020, 2017). Furthermore, mal-adapted restoration initiatives have the potential to cause more harm than good. For example, reforestation of formerly forested land can bring great benefits for climate adaptation and biodiversity, however, tree planting in other places can have adverse outcomes and even exacerbate climate change impacts (Morecroft et al., 2019).

The importance of climate change adaptation in biodiversity conservation planning has long been recognised (Heller and Zavaleta, 2009; Oliver et al., 2012; Stein et al., 2013). Ecological restoration design and implementation similarly needs to be adapted to climate change and other long-term environmental and social factors (Aronson et al., 2020), in order to be effective in the long term (Chazdon and Brancalion, 2019). This has been described in relation to different aspects of ecological restoration. For example, promoting landscape heterogeneity and biological diversity safeguards species evolutionary potential and capacity to adapt to a changing environment (Brancalion and Chazdon 2017). Target species for a restoration site should reflect suitable climate conditions both now and into the future (Butterfield et al., 2017), with a diversity of species and genotypes used to increase the likelihood that species can respond to climate change (Wilsey, 2020). Furthermore, novel ecosystems are a necessary consideration in restoration planning. Environmental change means historic species assemblages may no longer be viable (Perring et al., 2013) and novel ecosystems will play a key role in maintaining future global biodiversity. The focus needs to be the management of change rather than targeted restoration of a former state that may no longer be possible with climate change, and as a result the use of the term "renovation" is sometimes used instead of "restoration" (Morecroft et al., 2019). Hobbs et al. (2009) propose criteria for judging whether a novel ecosystem is a suitable target of restoration, including whether the system is maturing, or capable of maturing, is along a stable trajectory, resistant and resilient, and thermodynamically efficient.

For the first time, we bring together these and other important questions into a framework comprehensively outlining seven areas where ecological restoration needs to be adapted to climate change to build the resilience of the restoration initiative and its outcomes, from objective setting and design through to implementation, monitoring and evaluation. From a review of international restoration experience, we find practical examples of adapting restoration to climate change and highlight two cases of best practice. However, in general we identify a critical gap between the urgency for, and practice of, climate resilient restoration. We discuss how closing this gap is essential in order to achieve successful and durable outcomes for people and nature.

Framework and literature review

We identify seven areas where climate change needs to be considered in restoration design and implementation to increase resilience against anticipated impacts (Fig. 1). These are derived from a survey of peer-reviewed literature on restoration in a climate change context and in-house expert knowledge in climate change vulnerability of species and ecosystems. The framework is discussed in detail in the Section "Framework for building climate change resilience in the design and implementation of ecological restoration projects".

A targeted search was undertaken in September 2019 (completed 13/09/19) of restoration initiatives in Brazil and countries belonging to the Association of Southeast Asian Nations (ASEAN), target geographies of the Restore + initiative (www.restoreplus.com), using the terms for "restoration" and the country name in Google and Google Scholar searches. References to "climate change" in respect to the restoration objectives, potential impacts, design and/or implementation were sought from websites, and publicly-accessible grey and published peer-review literature relating to identified projects. Projects referencing climate change were then scrutinised for evidence that any of the seven areas in our framework had or were being addressed by the project.

In total, 118 projects were identified and investigated: 86 in ASEAN countries and 32 in Brazil. Documents of approximately one third of all projects (27 ASEAN and 13 Brazil) referred to climate change (Supplementary materials 1). Of these 33 included this term within the restoration project name and/or goal, of which 19 included discussion of climate change in the documentation viewed. Only five evidently addressed some aspect of our seven-point framework (Table 1), equating to <5% of the projects screened, and we use these in the description of the framework below. Examples of good practice are to be found in other regions such as Australia, from where we document further examples illustrative of different points in the framework (Section "Framework for building climate change resilience in the design and implementation of ecological restoration projects" and Table 1).

Framework for building climate change resilience in the design and implementation of ecological restoration projects

Described below are seven areas where climate change needs to be considered in restoration design and implementation (Fig. 1).

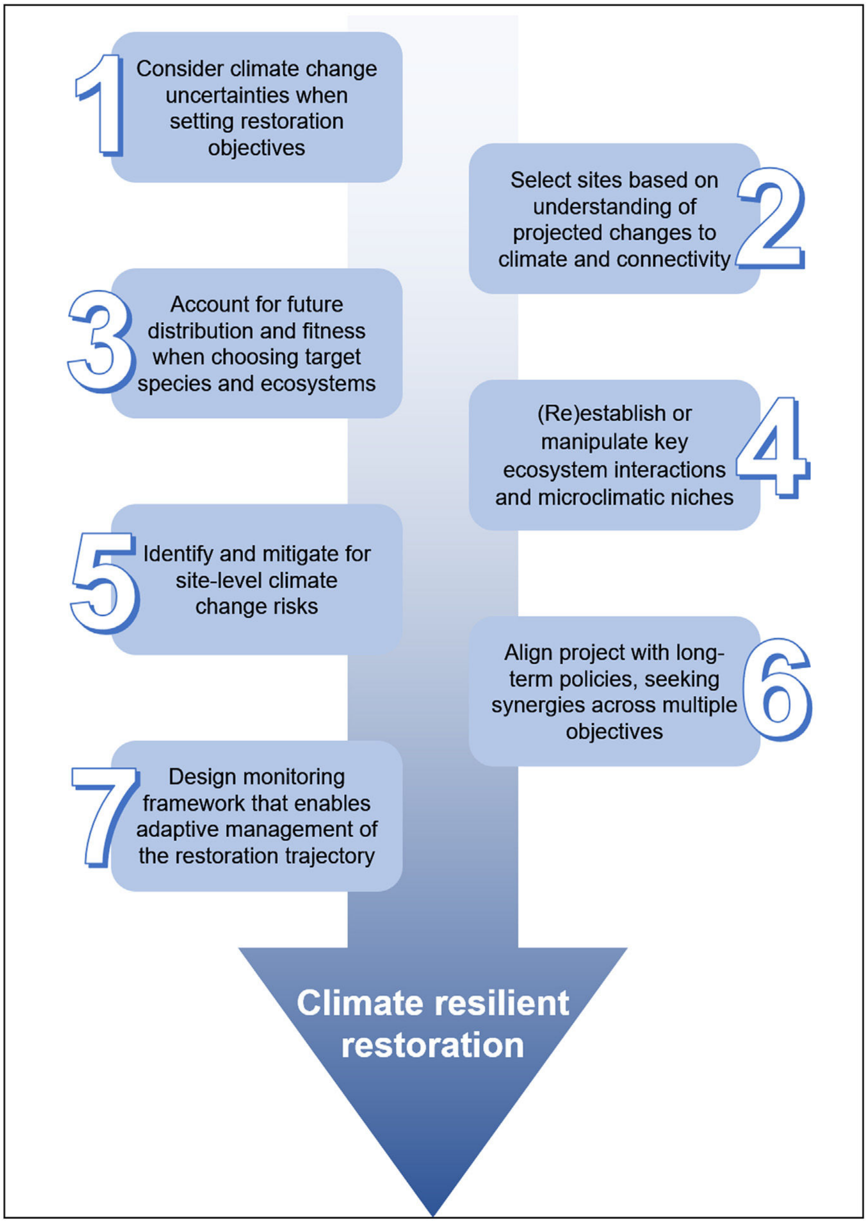

Fig. 1. Seven areas that practitioners should consider when designing and implementing an ecological restoration project in order to build its climate change resilience.

(1) Consider climate change uncertainties when setting restoration objectives

Certain restoration objectives and targets will be more sensitive to climate change than others. For example, whilst recreational benefits can be achieved by a range of different landscape configurations, the recovery of a threatened species may be dependent on a narrow range of habitat conditions. This is illustrated at the Mayesbrook Climate Change Park, where 45 hectares were restored with the objective of helping a community adapt to flooding risk, exemplifying how urban greenspace could provide key ecosystem services (Restoring Europe's Rivers, 2019). As the location centred around a large urban park, the ecosystem service and recreational benefits could be realised without specifying a target habitat type or targeted species reintroductions.

Restoration approaches often use historic conditions to set objectives and measure success. However, uncertainties in the characteristics of future, novel ecosystems (Corlett, 2016; Nolan et al., 2018) mean objectives may instead need to be adaptive and focussed on the rehabilitation and resilience of specific ecosystem functions (i.e. 'ecological renovation'; Prober et al., 2019). Lessons can be learned from rewilding, which typically focuses on functionality rather than prescribed structural/compositional outcomes. There is also a need to consider novel ecosystem configurations as possible restoration targets. In relation to coral reefs, some sites are becoming non-coral systems, whilst coral species range shifts are creating new species configurations, interactions and functionality at other, sometimes previously non-coral sites (Graham et al. 2014).

(2) Select sites based on understanding of projected changes to climate and connectivity

The suitability of sites for restoration action will change as environmental conditions alter, species distributions shift and the intensity and footprint of pressures change. When identifying potential sites, it is important to consider the anticipated climatic changes in that area. This includes the response of

Table 1
Restoration projects in Brazil, the ASEAN region and Australia incorporating climate change into their design and implementation.

Project Name	Project purpose and short description	Climate change considered in:						
		1 Restoration objectives	2 Sites & their connectivity	3 Target species & ecosystems	4 Ecosystem-level interactions	5 Mitigation of impacts	6 Alignment with policies	7 Adaptive management
Atlantic Forest Restoration Pact, Brazil	Aims to restore 15 million hectares of Atlantic Forest by 2050. There are over 200 partners and stakeholders operating under the pact across eight Brazilian states.		√				√	
Reforestation in Pontal do Paranapanema, Brazil (Box 1)	Aims to reforest the region between two national parks to conserve biodiversity, build livelihoods and promote economic development.		√	√		√	√	√
Berau Forest Carbon Program, Indonesia	Aims to preserve and restore the natural native forest cover in the region by implementing a REDD + scheme and coordinating spatial planning and community empowerment.						√	√
World Bank Coral Reef Targeted Research Program, Philippines	Primarily a research program with the aim of investigating coral reef gardening as a novel, cheaper strategy for restoring damaged coral reefs.	√	√	√	√	√		
Coastal Wetlands Protection and Development Project (CWPDP), Viet Nam	Involved engaging with communities to restore mangrove forests in southern Viet Nam. The project was purposefully multi-functional, with a key aim of alleviating poverty and diversifying livelihoods as well as mangrove forest restoration.			√	√		√	
Crayweed Restoration, Australia (Box 2)	Aims to carry out large scale restoration of crayweed underwater forests in Sydney, increase community engagement, and improve awareness about the importance of seaweed forests to marine ecosystems.	√	√	√		√		√
Gondwana Link, Australia	Aims to provide 1,000 km of continuous habitat, from the dry woodlands of the Australian interior at the Nullarbor Plain to the tall wet forests of the far south-west corner of Western Australia. Also aims to build livelihoods and support traditional owners to manage the land.		√	√			√	
Great Eastern Ranges (GER), Australia	Aims to protect, link and restore habitats across 3,600 km, from western Victoria through NSW and the ACT to far north Queensland, through long-term industry, government and civil society support.	√	√	√		√		√

species and ecosystem components (see Section "Account for future distribution and fitness when choosing target species and ecosystems"), the vulnerability and exposure to threats, and the space available for the system to expand or move. Furthermore, in order to increase the probability of achieving positive outcomes, reducing the drivers of habitat degradation and loss first and foremost is imperative before commencing restoration actions.

Using models of climate, vegetation, land use and biodiversity it is possible to refine areas suitable for restoration. For example, in the humid tropics, candidate areas for restoration have been identified by combining models that describe how plant functional types reorganise under climate change with spatial predictions of deforestation (Asner et al., 2010). This helped identify areas where high deforestation coincided with climatically more suitable conditions and climate refugia. In the Brazilian Atlantic Forest, candidate restoration sites were selected based on modelling that not only accounted for climate change and land use change but also considered socio-economic factors and management approaches such as protected areas (Zwiener et al., 2017). In selecting candidate sites it is also important to think about the wider land-/seascape, to facilitate and aid restoration by connecting patches (Tarabelli et al., 2005). However, in a climate change context, connectivity also needs to be managed in relation to potential negative impacts, for example where landscape corridors can aid the spread of invasive species (Resasco et al, 2014).

(3) Account for future distribution and fitness when choosing target species and ecosystems

When determining which ecosystem components to restore, projected changes in environmental conditions and species fitness and distributions must be accounted for. Species distribution modelling (SDM) based on climate envelopes can help shortlist possible species to use in restoration projects. In identifying semiarid shrubland species of potential use for restoration in Central Mexico, Gelviz-Gelvez et al. (2015) analysed 46 species to select those with the most desired characteristics of sociability, cover, abundance, and micorrhization, and subsequently used SDM to further refine the list.

The projected impacts of climate change will influence whether natural regeneration (e.g. passive restoration involving locally adapted species) is preferential to active restoration using species within or outside their native ranges. In the latter case, taxon substitution may be necessary to replace a native species vulnerable to climate change with a non-native species able to fulfil the same or similar ecosystem function (Corlett, 2016). Experience in the latter option derives from the practice of assisted migration in response to climate change (Williams and Kasten Dumroese, 2013), where species at lower latitudes are predicted to fare better under non-analogous future climate conditions at higher latitudes, or indeed altitudes. However, this option is fraught with uncertainties because of cryptic maladaptation, underestimation of climate variability differences, and many unforeseen issues from introduced and/or invasive species (Benito-Garzón et al., 2013).

Local material is often the preferred choice in order to ensure good adaption to the local environment, maintain the genetic integrity of the site and prevent potential pollution of the gene pool (Harris et al., 2006). However, in the context of a rapidly changing environment this should be challenged as local provenance may be poorly adapted to future climates and disturbance regimes (Prober et al., 2015). Instead, material may be sourced from areas currently experiencing conditions similar to the predicted climatic conditions for the restoration site (Booth, 2016). At the same time, resilience and adaptability can be enhanced by genetic diversity within and among species, capitalising on the capacity of species to adapt to environmental change through plasticity, selection, or gene flow. In this way, space for evolutionary development can and indeed should be encouraged by restoration projects (Rice et al., 2003).

Prober et al (2015) call for a "climate-adjusted" provenance strategy, combining genetic diversity and adaptability, targeting the direction of projected climate change, whilst also allowing for uncertainties in those projections and in the possibility of unforeseen selective agents. In the case of coral reefs, climate change adapted coral material can be identified from colonies that have survived high temperature events and/or mass coral bleaching, representing promising genetic/epigenetic variants for reef restoration initiatives (Morikawa and Palumbi, 2019; Rinkevich, 2015). This was the case for the World Bank Coral Reef Targeted Research Program, which investigated coral reef gardening as a novel, cheaper strategy for restoring damaged coral reefs. Species selection was made climate resilient, since coral species that showed resilience to increasing sea surface temperature were selected for propagation (Shaish et al., 2008).

(4) (Re)establish or manipulate key ecosystem interactions and micro-climatic niches

The biophysical environment may need modification to maintain or create favourable conditions for the ecosystem components and their desired outcomes. Recovery may suffer if ecosystem components are vulnerable to climate change, for example, if key micro-climatic niches or vital ecological functions are lost. Understanding how climate change will impact ecosystem interactions and climatic niches can lead to the development of efficient and targeted physical modifications to the ecosystem as part of the restoration project.

Restoration can involve physically changing the environment, such as installing dams to alter water levels and recreate the conditions suited to the restoration target. Climate change may add a new level of necessity to such environmental manipulation. For example, human-built structures may be needed to limit climate change impacts (e.g. sea water inundation) or give natural systems more space or time to adapt, by creating small-scale climate refugia. In south-western Australia, dense replanting along rivers has been proposed to keep water temperatures within the thermal tolerance of temperature-sensitive aquatic fauna (Davies, 2010), with a 10% increase in riparian cover generally leading to a reduction of water temperature by 1 °C. In the case of river floodplains, restoring connectivity can be important to reverse the effects of past river and floodplain engineering such as levees, ditches and channelization, and counter future reduction of flow levels and flood events (Perry et al., 2015).

Climatic changes have the potential to significantly impact the functioning of ecosystems. For example, phenological changes may limit the spatiotemporal availability of food sources, as already documented for some bird species (Carey, 2009; Mastrantonis et al., 2019). Hence, restoration initiatives may need to consider when and where the loss of critical species interactions and ecosystem functions may occur in the future. Conceivably, ecosystem engineering approaches, including species introductions, may be required to fill the roles of keystone species extirpated by climate change impacts, including extreme events such as floods and wildfires. The Vietnamese Coastal Wetlands Protection and Development Project (CWPDP) utilised both physical manipulation and species selection when restoring mangrove forests in southern Vietnam: plantations were specifically designed to be species-rich to provide genetic variety, following the lack of success with monoculture plantations in the north of Vietnam (Powel et al., 2011). Building dykes and bamboo fences also allowed for the natural rehabilitation of mangroves, whilst acknowledging that climate change and past land use had resulted in differing abiotic conditions that hindered natural regeneration (World Bank, 2008).

(5) Identify and mitigate for site-level climate change risks

Many threats to natural environments are directly related to climate change, such as more intense and frequent extreme weather events and increasing sea surface temperatures. Other threats are the result of tangible human actions such as increased nutrient input leading to eutrophication, and some are the result of directed actions which are then exacerbated further by climate change, such as invasive species and the spread of disease.

These global change hazards can have local, site specific impacts and must be considered in order to enhance the resilience of restoration projects. Whilst certain risks may be minimised using the approaches outlined elsewhere in this framework, some might be difficult to abate. Potential impacts should be anticipated and mitigated within the design and implementation of the restoration activity. Climate change related risks are summarised in Fig. 2 and discussed in more detail below.

Biological disturbances

Invasive alien species (IAS) are one of the biggest causes of biodiversity loss and species extinctions. Climate change can facilitate the spread and invasiveness of species, and create new opportunities for alien species to become invasive (IUCN, 2017). This may result in IAS outcompeting specialist native flora and fauna. The

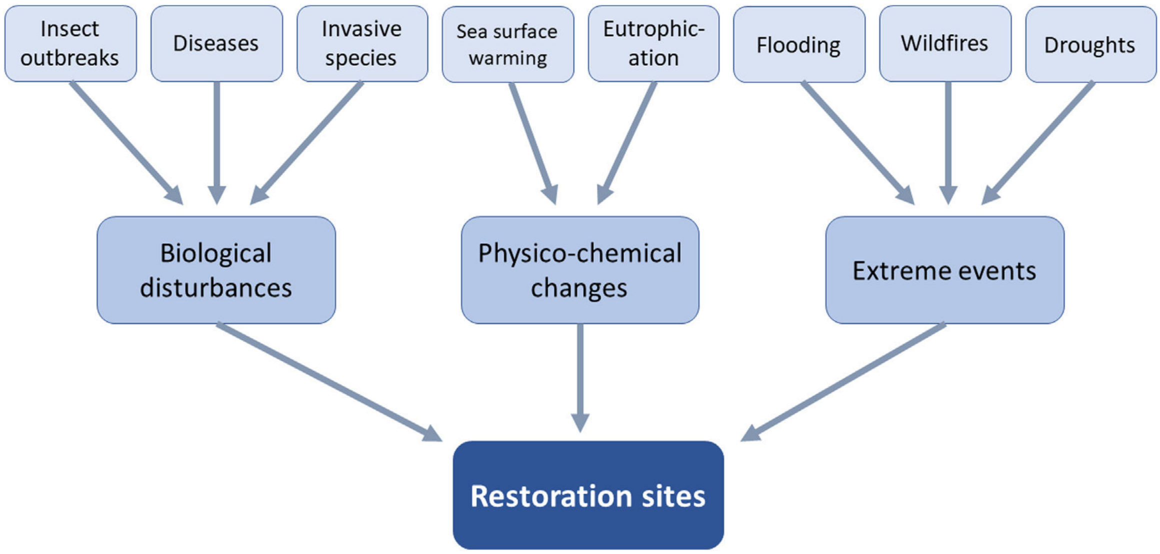

Fig. 2. Hazards that have the potential to impact local restoration projects can be grouped into distinct themes. The ones shown here are not exhaustive.

poleward expansion of the sea urchin *Centrostephanus rodgersii*, for instance, is linked to increased sea surface temperatures, resulting in catastrophic shifts from seaweed dominated reefs to sea urchin dominated barrens in Tasmania, Australia (Ling et al., 2015).

Restoration initiatives may also need to take into account future invasive species ('sleepers') currently existing within a project site, and include eradication or control measures in management plans (IUCN, 2017). Some IAS could conceivably play a recognised role in a restoration plan in cases when it would be impractical to control them and, moreover, they could serve a useful function within an emerging novel ecosystem (Corlett, 2016).

Climate change will also affect the distribution and extent of damage caused by pests and diseases (Lehmann et al., 2020; Nazir et al., 2018) and this requires consideration in restoration planning and design (Pawson et al., 2013). The potential link between climate change and pest damage is demonstrated in Whitebark pine forest restoration in western North America. Whitebark pine forests have suffered major declines as a result of outbreaks of mountain pine beetle (*Dendroctonus ponderosae*) and the exotic disease white pine blister rust (Keane et al., 2017). Projected future warming and drying may increase the distribution of the mountain pine beetle and white pine blister rust, further exacerbating Whitebark pine decline and compromising the success of restoration. Planting rust-resistant Whitebark pine seedlings is one recommended mitigation measure being investigated to combat this trend.

Physio-chemical changes

Restoration projects in coastal and marine environments are limited in the extent to which they can tolerate the impacts of changes in sea surface temperature and sea level rise. The most important design measures will relate to site and species selection (2-3), the provenance of material (3), and the manipulation of the environment and ecosystem (4). For example, experiments in the Florida Keys National Marine Sanctuary are attempting to help corals adapt to increasing sea surface temperature by growing heat-resistant corals in laboratories before transplanting them to the wild (Brock, 2015). However, this is labour intensive and upscaling these practices is limited by accurate predictions of sea surface temperature changes at local scales. Reduction of non-climate change stressors (e.g. invasive alien species, nutrient levels) is also important to increase the resilience to sea surface temperature rise, sea level rise, and other climate change related impacts (Brock, 2015).

Climate change will impact nutrient levels and acidity in water systems as well as altering the metabolisms of microbes through increased dissolved CO_2 and water temperatures (Jeppesen et al., 2017). More intense storms, altered precipitation patterns and melting glaciers are just some of the ways that nutrient loading in freshwater and coastal systems will be affected by climate change. Furthermore, certain cyanobacteria thrive under increased CO_2 concentrations, leading to enhanced and more frequent eutrophication events (O'Neil et al., 2012).

One possible solution to combating increased eutrophication risk is through biomanipulation, which purposefully attempts to lower nutrient loading by altering existing food webs. In Denmark, 17 lakes that had undergone biomanipulation by fish removal were analysed over two decades and showed success in returning to pre-disturbance low nutrient levels (Özkan et al., 2016). Biomanipulation efforts may have to be intensified or applied more regularly to prevent lakes reverting to turbid states. Another key way of ensuring long-term success is to remove any artificial causes of high nutrient inflow (Jeppesen et al., 2017), such as reducing fertiliser use on adjacent farms.

Extreme events

The impacts of extreme events such as drought, storms and heavy rain will be felt across many restoration projects and should be mitigated for. For example, as parts of the world become drier and hotter there will be a build-up of dead plant matter and an increased risk of more intense and destructive wildfires. Vegetation that is not adapted to frequent fires will be particularly vulnerable. Even fire-adapted forests will be at high risk of destructive wildfires under climate change, as was recently observed in the 2019–2020 bushfires in Australia (Piper, 2020). The absence of effective fire management policies is likely to exacerbate the impact (Fulé, 2008). Therefore, future fire risk needs to be considered in objective setting (1), site selection prioritisation (2) and definition of target ecosystems (3), as well as being mitigated within restoration plans. Such mitigation measures may include creating or maintaining firebreaks, prescribed burns and indigenous burns to reduce fire fuel loads. Prescribed burns, however, can be limited by the availability of firefighting services and a reduction in the available timeframe for safe fire-setting conditions. Taking a long-term view on fire reference conditions, including from sites with currently drier conditions, can be helpful for understanding fire risk under future climate change (Fulé, 2008) and draw relevant lessons for restoration design.

Water availability and seasonality is critically important to species establishment, growth, and survival. For example, the success of restoration projects that utilise passive or assisted vegetation recovery is highly dependent on water availability. Drought can interact with other stressors to negatively affect restoration outcomes. In the rangelands of western North America, dry and warm weather can alter forage quantity/quality and the life cycles of insects (Finch et al., 2016), exacerbating the impact of pest species on vegetation. The risk of drought to restoration projects can be considered through site selection (2) and/or determining the ecosystem components to be restored (3).

Conversely, extreme rainfall events, cyclones and storm surges can bring about flooding of inland regions and coastal zones. Restoration projects may need to incorporate actions that adapt to this threat, such as by working with natural flood regulating ecosystems, whether provided by a river system, mangroves or an intertidal coastal marshland. In some cases, "Nature-based Solutions" alone may prove insufficient and engineered or hybrid solutions may be required, as is done when supplementing marshlands with river channel dredging or the construction of levees.

(6) Align project with long-term policies, seeking synergies across multiple objectives

Policies, land management options and stakeholder dynamics may be affected by climate change in ways which influence the feasibility and direction of restoration. This is exemplified in the Berau Forest Carbon Program, which aims to preserve and restore the natural native forest cover in Indonesia by implementing a REDD+ scheme and coordinating spatial planning and community empowerment. By aligning the project with Indonesia's Low Carbon Growth Strategy scheme and becoming a recognised REDD+ activity, the program was able to benefit from guidance and cooperation from these policies (IGES Forest Conservation Team, 2013). In addition, the program attracted support from The Nature Conservancy, who aided in the remediation of tenure conflicts (Anandi et al., 2014).

Climate change policies, and other policies that can be affected by climate change, may influence the viability, design, implementation and ultimate success of restoration projects. Restoration may be incentivised by climate change policies and mechanisms (e.g. REDD+), but in some cases discouraged as when increased demand for biofuels raises competition for land (Brodie et al., 2012). Policy impacts may be direct, for example when a hydropower plant as part of a low carbon energy plan causes direct loss of a landscape undergoing restoration. They may also be indirect, for example when changes in agricultural suitability can create but also close opportunities for restoration (Bradley et al., 2012). Stakeholder and land management is therefore key to restoration success in locations other than officially protected areas. Adoption of secure conservation measures, such as conservation covenants with private landholders, purchase of strategically critical properties and expansion of the public protected area estate are being utilised in the Gondwana Link project in Australia, to reduce the predicted impact of increased land use competition under future climate change. The Gondwana Link project aims to provide 1,000 km of continuous habitat, from dry woodlands in the interior to tall wet forests in the south-west corner of Western Australia. This project also aims to build livelihoods and support traditional owners to manage the land (Bradby et al., 2016; Figgis et al., 2012; Jonson, 2010). Restoration projects such as this, designed around the 'triple wins' of joint mitigation, adaptation and development goals may be most resilient to policy influences (Favretto et al., 2018).

Fig. I. Restored wildlife corridor in Pontal do Paranapanema. (WeForest).

Fig. I. Juvenile crayweed being measured (John Turnbull).

Policies and land management options can also be enacted at local levels within countries. The Atlantic Forest Restoration Pact is a collection of the efforts of many smaller organisations to restore parts of the Atlantic Forest in Brazil. The Pact has a covenant in which signatories define their priorities including sharing knowledge on forest restoration, providing advice to align restoration actions with the Forest Code (a law requiring landowners to maintain part of their property as native vegetation), and contributing to public policy formation to enhance outcomes. Through this Pact, smaller local restoration projects create greater impact by aligning their actions. Project proponents also benefit from knowledge and technology sharing, training opportunities and expansion of job opportunities that participation in the Pact brings (Pacto Mata Atlantica, 2016).

(7) Design a monitoring framework that enables adaptive management of the restoration trajectory

In a rapidly changing climate, restoration management decisions may be valid for only short time periods. For this reason, monitoring and adaptive management of restoration projects is key to ensuring their success (Jandl et al., 2019). This requires clearly stated and attainable objectives supported by appropriate indicators, sufficient monitoring resources and implementation plans. At the Stewart Lake Waterfowl Management Area in north-eastern Utah, restoration work aimed to reduce hazardous selenium contamination by careful water inflow/outflow control. This was sensitive to decreased river flow and increased risk of drought as predicted by climate change models (Farag et al., 2017). The management was designed to be adaptive. Data collected from monitoring water, sediment, plankton and fish selenium levels were used at regular stakeholder meetings to evaluate and refine the restoration strategy, informing water management and other measures going forward.

Adaptive management that allows for changes to restoration actions throughout the project is also important in aiding their resilience. For example, the Great Eastern Ranges (GER) project in Australia aims to work with communities to restore healthy, biodiverse forests, woodlands, soils and wetlands to restore carbon stocks (Dunn et al., 2012; Mackey et al., 2010a, 2010b). The project is working to link habitats across 3,600 km, from western Victoria through NSW and the ACT to far north Queensland. Research was conducted to identify and characterise the integrity of landscapes within the GER corridor. This information was used to understand patterns of land disturbance and the likely influence of climate change on future weed outbreaks. As a result, emergent outbreaks could be prioritised for immediate treatment before they take hold in a landscape, thus prioritising actions within an organised and proactive management framework.

Discussion and conclusions

Climate change poses a significant challenge to the long-term efficacy of ecological restoration initiatives. For this reason, the assessment of climate change risks is of vital importance in the design and implementation of ecological restoration. We have described examples of good practice in this respect. However, our review highlights the paucity of projects that demonstrate climate change resilience, certainly in terms of rigorously addressing climate change considerations through the life cycle of a restoration initiative, from design and inception through to full implementation, adaptative management and monitoring. Our research relied heavily on online material and in English language; a more in-depth literature review and interviews would likely uncover further evidence of climate change being considered in planning and practice, even if the absence of information in the public realm is indicative of the low priority being given to this issue.

Some deeply embedded tenets of restoration practice break down in the face of widespread climate change impacts on ecosystems: for example, that local populations provide the best regeneration material, that natural regeneration and succession is the most desirable approach, and that management decisions are valid for decades to centuries. Upscaling climate change resilient restoration demands challenging these tenets and replacing them with scientifically underpinned approaches that are fit to meet future change and uncertainty. To this end, we have presented a comprehensive seven-point framework for addressing climate change in ecological restoration. The seven areas can be used as

Box 1: Reforestation in Pontal do Paranapanema.

Overview

The Brazilian Atlantic Forest is a world biodiversity hotspot (dos Santos et al., 2019). Since 2002, the Institute of Ecological Research (IPE), Sao Paulo University and WeForest have worked to reforest Pontal do Paranapanema and create an ecological corridor to Morro do Diabo State Park. The original 10-year 'Atlantic Corridors Project' (AFCP) restored 890 hectares (WeForest, 2019), conserving biodiversity, promoting economic development, and building livelihood resilience. Following this success, WeForest joined the Atlantic Forest Restoration Pact, which intends to restore 15 million hectares of Atlantic Forest in Brazil by 2050 (Pinto et al., 2014). WeForest shares research findings to prioritise future areas for restoration (Scarano and Ceotto, 2015).

Areas where climate change was considered

Less than 7% of the original forest remains, and is highly fragmented (Tarabelli et al., 2005), so buffer regions that improve connectivity and facilitate climate-related distributional shifts are favoured. AFCP and IPE successfully lobby for the creation of buffer zones around forest fragments to facilitate species migration (2).

1,779,500 trees from community-based nurseries propagating 115 indigenous tree species were planted in designated land fragments (WeForest, 2019). Many have wide ranges and are fast-growing, acting as "pioneer" species in agroforestry practices and helping ensure the long-term resilience of the project (3).

The role of forests in regulating water supplies, and ability of restoration to re-establish ecosystem services, was explained in educational outreach. WeForest estimated that over 2,000 hectares of land are benefitting from improved water cycling and quality, helping to adapt to climate-related impacts of droughts and flooding (5).

The AFCP aimed to link land management and climate related policies by training landowners in sustainable agriculture and wider environmental education, with the aim of achieving longevity of the project even if the restored land comes under increasing pressure (6).

Conclusion

Additional strengths of the AFCP include the range of sites and techniques used, the range of partners, and the inclusion of socioeconomic criteria in monitoring protocols. There has been measurable success, including continuation of tree nurseries beyond project completion, and reports of fewer intentionally set fires. This is significant because fire can preferentially occur in regenerated secondary forest due to higher sun exposure; without adequate management, restoration success can be compromised (dos Santos et al., 2019) (Fig. I).

Box 2: Crayweed restoration in New South Wales

Project overview

In 2011 the Sydney Institute of Marine Science commenced crayweed forest restoration in Sydney. This macroalga once formed extensive underwater forests providing habitat for a diverse fauna including species important for wild caught fisheries. 'Operation Crayweed' aims to implement large-scale restoration, increase community engagement, and improve awareness about the importance of seaweed forests to marine ecosystems (Vergés et al., 2020).

Areas where climate change was considered

A principal objective was ecosystem service re-establishment and prevention of further declines due to climate change. A strong awareness and education programme highlights to the public the importance of underwater forests to ecosystem functioning, through a combination of art, narrative storytelling and science. Upscaling Operation Crayweed to the entire Sydney Metropolitan region will meet most success if awareness raising is continued (Vergés et al., 2020) (1).

Genetic testing of crayweed indicated that populations are distributed spatially across the NSW coastline and plants could be sourced from a 60 km radius for restoration. Restoration success was measured by genotyping the first generation of crayweed, which exhibited patterns of genetic diversity and structure similar to donor plants and natural populations (Wood et al., 2020). Ongoing research looks for potential warm-adapted genotypes in crayweed to 'future-proof' restoration (3).

A Before After Control Impact design was implemented to monitor survival, recruitment, range expansion and epifauna assemblage under changing environmental conditions (Campbell et al., 2014). Early monitoring demonstrates that crayweed survival was high (70%) and mobile epifauna assemblages on restored crayweed did not fully resemble those from reference crayweed populations (Marzinelli et al., 2015). This highlights that restoration of seaweed ecosystem assemblages is complex and a long-term process (7).

Conclusion

Over multiple generations, Crayweed range has expanded several hundred metres from original restoration sites and moved nearshore with minimal maintenance or additional plantings required (Vergés et al., 2020). The potential impact of rising sea surface temperature on herbivory is one area the project needs to address. Planning and management for novel herbivory under climate change will be crucial. This may include options such as determining optimum patch size and density for recruitment success, deterring herbivory (Westermeier et al., 2013) and restoring macrophytes when herbivory is lowest (typically in winter; Carney et al. 2005) (Fig. I).

a checklist for practitioners, including a route into the literature, some of which is reviewed here, that can help assess and build the resilience of their projects. Of particular importance within this framework is adaptative management: using indicators of restoration success, themselves needing to be defined in relation to changing environmental conditions, over long timescales to guide restoration management towards the ultimate restoration goals.

We recommend the use of the framework by the restoration community for the upscaling of climate change resilient restoration. The framework has utility for catalysing better knowledge exchange: the knowledge base for driving ecological restoration at scale is currently inadequate (Chazdon et al., 2017), and this appears particularly true in relation to adapting restoration to future climate change. Sharing good practice in climate resilient restoration, through the approaches and – importantly – results of existing initiatives, will be essential for moving forward, and our review provides a framework to support that. A useful further step will be to identify indicators for each of the seven areas we identify, to support the design of restoration activities and to monitor progress towards climate resilience. These should draw on ecological resilience studies that have identified biological, chemical, and physical attributes conferring resilience (Timpane-Padgham et al., 2017). Establishing a specific forum for knowledge exchange on climate resilient restoration would also be an important advance. We also recommend the development and dissemination of decision support tools that help practitioners understand the climate change risks and considerations across the seven component areas we describe. These tools need to point to the sources of best available scientific data, for example on climate change projections and the climate change vulnerability of species and ecosystems, and how to access and interpret them for any specified locality and restoration scheme.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.pecon.2021.05.002.

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