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# *Restoration of marine ecosystems: understanding possible futures for optimal outcomes that minimise risk*

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## Abstract

*Accelerating declines in the extent, quality and functioning of the world's marine ecosystems have generated an upsurge in focus on practical solutions, with ecosystem restoration an increasingly attractive mitigation strategy for systems as diverse as coral reefs, mangroves and tidal flats. While restoration is popular because it promises positive outcomes and a return to something approaching unimpacted condition and functioning, it involves substantial public and private investment, both for the initial restoration activity and for on-going maintenance of the restored asset. This investment often affords one big chance to get things right before irretrievable damage is done. As a result, precise, well considered and accountable decision-making is needed to determine the specific focus for restoration, the scale of restoration, the location for deploying restoration activities, and indeed whether or not restoration is necessary or even possible. We explore the environmental/ecological considerations and constraints governing optimal decisions about the nature, location and prioritisation of restoration activities in marine ecosystems, and in particular the constraints on achieving understanding of possible futures and the likelihood of achieving them*. We conclude that action must be informed by a context-specific under- standing of the historical situation, the current situation, the constraints on change, the range of potential out- come scenarios, and the potential futures envisioned.

## Introduction

Accelerating declines in the extent, quality and functioning of the world's marine ecosystems have generated an upsurge in public awareness, media scrutiny, and ultimately political attention, promoting increased interest in practical solutions (Lubchenco & Petes 2010; Waltham *et al.* 2020). Ecosystem restoration (defined as; the process of restoring one or more valued processes or attributes of a landscape (Davis and Slobodkin, 2004)) is an increasingly attractive mitigation strategy for systems as diverse as coral reefs, mangroves and tidal flats, because it promises positive outcomes through return to something approaching unimpacted condition and functioning (Geist and Hawkins, 2016; Weinstein et al., 2019; Pazzaglia et al., 2021) or at least to a hybrid ecosystem status that provides useful ecological functioning (Hobbs et al., 2009).

Intense public, media and political attention means that, not only is there an imperative to act, but that large amounts of public and private (insurance companies, philanthropic donor) money are increasing directed to restoration (Bayraktarov *et al.* 2019; Leo *et al.* 2019; Lewis et al., 2019).

Consequently, it is imperative that the sum of direct and indirect economic benefits, and the incremental social and ecological values, outweigh costs (Bullock *et al.* 2011). The project lifecycle costs involved in restoration, and the opportunity-costs of prioritising restoration, mean it is imperative that restoration action is strongly knowledge-based and takes account of all the factors contributing to a successful outcome (Lee *et al.* 2019). This will only become more critical for managers as they push for government or private funding for ocean science and the restoration of coastal ecosystems under initiatives such as the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) (Waltham *et al.* 2020).

Any ecosystem restoration activity needs to be optimised across environmental, social/cultural, commercial, developmental, political, re- source security, livelihood and disaster mitigation values (Lewis et al., 2019). This optimisation cannot take a static view but needs to account for temporal factors such as future human needs, climate variability and sea level rise (Waltham et al., 2021). It also needs to be carefully posi- tioned with respect to legislative frameworks and requirements, jurisdictional issues and legal expectations (Stewart-Sinclair et al., 2020). These considerations can be complex, interactive and/or cumulative, as highlighted by the current situation in Small Island Developing States (SIDS). For instance, Tongatapu, the main island of Tonga, is experiencing substantial and consistent sea level rise (>6 mm per year since 1993), declining rainfall and increasing air and ocean temperatures (ABM and CSIRO, 2011). Tongatapu's residents rely almost entirely on diminishing ground water supplies for potable and agricultural needs, and these supplies are at risk from climate variability. Ground water also supports the freshwater reaches of coastal wetlands. The future of the island's wetlands is further jeopardised by the armouring of much of the island's low-level coasts for protection from sea level rise and storm surges. This armoring has disrupted freshwater-marine connectivity and left many mangroves areas disconnected from either freshwater or marine environments. This tension between the needs of the people and those of the environment is a global problem in achieving meaningful conservation outcomes (Liberati et al., 2019), with decisions on the development or restoration of ecosystems needing to satisfy an array of often competing environmental, social, commercial, develop- mental, and political imperatives. For example, the effective management of Florida's Everglades is still elusive despite many years of restoration and management activities, with conflict between simultaneously supporting human needs such as flood protection and water supply, and ecosystem needs such as environmental flows, and habitat provision for a variety of flora and fauna (Gibble et al., 2020; Mitsch, 2016).

The success of restoration activities is also variable. For instance, mangrove restoration has only been successful for about 20% of the area in Sri Lanka where it was attempted, with levels of survival ranging from 0 to 78% (Kodikara et al., 2017). This is largely the result of selection of sites that were inappropriate because of topography, hydrology or potential for disturbance. In another example, seagrass restoration, that has initially favoured the use of local genetic material, often results in low genetic diversity (Jordan et al., 2019), suggesting that mixed seed sourcing may be required to increase diversity and long-term restoration success (Tan et al., 2020). A similar story is repeated for freshwater and coastal wetland restoration projects around the world, underlining the importance of not initiating restoration projects when aims of resto- ration and on-ground realities are misaligned, or when understanding of the components and processes of the target systems is incomplete (Geist and Hawkins, 2016; Pander et al., 2018; Lee et al., 2019; Sheaves et al., 2020).

The difficulties that stem from competing anthropogenic aspirations and the restoration actions needed to support optimal functioning of restored marine ecosystems are complicated further because the natures of systems, and the influences on them, vary over complex spatial and temporal scales (Green and Sadedin, 2005). This places limits on the applicability of existing knowledge and indeed to what can in fact be known (Harris and Heathwaite, 2012). While satisfying these complex data needs can be challenging, ensuring key data are available is vital because the quality of decisions depends on the accuracy of the information available to decision-makers (Sheaves et al., 2012; Thompson et al., 2016). Getting restoration decisions wrong be- cause of misinformed decision-making means that meaningful out- comes may not be achieved, and efforts and resources (funds, effort, public opinion) are likely to be misdirected. This can lead to perverse outcomes (e.g., restoring one component while a potentially more important component is left to degrade) or improvements that are not sustained beyond the short term (Lee et al., 2019).

Many factors need to be considered when planning restoration activities. Some of these relate to the conduct of the restoration itself. For example, it is important to understand the anthropogenic pressures that led to past/present impacts, as well as the landscape and socio- economic changes that resulted from those impacts. This allows the his- tory of land use change to be respected form both cultural and ecological standpoints when selecting restoration sites, and allows understanding the history of habitat rehabilitation failures, so that unsuccessful tech- niques are not used in future restoration activities (Geist, 2015; Lewis et al., 2019). It is also important to clearly define goals and measures of success when developing monitoring programs, and to ensure that restoration activities are able to respond adaptively to new information and advances in technology (Lewis et al., 2019). Perhaps more impor- tant than decisions on the nature of the restoration activities to be implemented, are decisions on (i) whether or not to restore at all, and (ii) what the focus for restoration should be. Such decisions need to be based on clearly defined functional outcomes and rooted in outcome- specific knowledge. For instance, before mangrove revegetation is attempted, it is important to determine whether this is indeed the ap- propriate corrective action (or indeed the only action required) to achieve the desired functional outcome (e.g. supporting nursery value (Litvin et al., 2018)), whether the specific action will have long-term benefits (e.g. the value of extensive monogenetic planting of mangroves using ‘convenient’ species (Lee et al., 2019)) or indeed whether the solution and technology to achieve it are available (Waltham et al., 2020).

Because the goal of restoration must be to provide optimal functional outcomes (Cairns Jr, 2000; Litvin et al., 2018) while minimising the risk of unexpected detrimental outcomes (Pastorok et al., 1997), the matrix of complexity, the limits of knowledge, and the limits of models connecting understanding to outcomes (Scheffer, 2004) need to be taken into account before action is taken. As a result, in deciding whether or not to restore and in determining the focus for restoration actions, it is necessary to understand the range of possible futures resulting from restoration, the likelihood of achieving them, and the on-going maintenance costs (including who pays for maintenance into the very distant future, well beyond any grant scheme or tenure of the responsible political entity). We extend on the principles expounded in standards for ecological restoration (e.g. McDonald et al., 2016) to explore the environmental/ecological considerations and constraints governing optimal decisions about the nature, location and prioritisation of restoration activities in coastal wetlands, and in particular the constraints on achieving understanding of possible futures and the likelihood of achieving them.

# Why is prediction so difficult?

## *Understanding the limits on expectations*

Restoration and rehabilitation are undertaken in an attempt to remediate degraded function and, consequently, the quality of ecosystem services (Lubchenco and Petes, 2010). However, there are limits to what can be achieved in a degraded system, and indeed there is often no guarantee that the expected outcome will be achieved. Take for example the extreme endmember of temporal variability where changes in key ecological parameters pass a threshold, resulting in regime shift. As a result, changes to the underlying nature of the system may be so substantial that return to anything close to pristine condition may not be possible (Beisner et al., 2003). Pathways of recovery may lead to different or hybrid end-points (Hobbs et al., 2009) due to hysteresis (i.e. dependence on history) (Fig. 1), the size/cost of restoration may be too great to be feasible and, even if reinstatement of original system functioning is achieved, the path and timing of recovery may be difficult to predict (Mitsch, 2016; Dakos et al., 2018). Indeed, all that may be possible to achieve is a hybrid ecosystem, in a state somewhere between pristine and degraded (Hobbs et al., 2009). Not only do the natures of the systems and the changes that have occurred limit the likelihood of achieving the expected outcomes, but the very nature of the drivers of perturbations may also be poorly defined and understood, further limiting the predictability of outcomes (Powell et al., 2011).

Even beyond the potential impacts of hysteresis and poorly defined drivers of change, there is the underlying problem that natural systems are inherently complex (Harris and Heathwaite, 2012), with outcomes almost invariably complicated by causal thickets (interaction causes acting in overlapping scales of space and time) (Harris and Heathwaite, 2005; Wimsatt, 2007), aliased causation (multiple causes producing indistinguishable outcomes) (Scheffer, 2004), non-linearity (Green and Sadedin, 2005), cross-scale effects (Paschalis et al., 2015), connectivity across multiple scales (Sheaves, 2009; Harris and Heathwaite, 2012), unexpected consequences of small-scale effects, and by the adaptive responses of ecosystems in the face of change (Harris and Heathwaite, 2005). Consequently, unpredictable outcomes should be expected, so decision-makers need to be cognisant of the extent and nature of the uncertainty (Pastorok et al., 1997; Hilderbrand et al., 2005; Ascough Ii et al., 2008) and employ restoration strategies that minimise unexpected deleterious outcomes (Harris and Heathwaite, 2012; Sheaves et al., 2016b). Importantly, pervasive uncer- tainty means that it is vital to carefully manage expectations of the proponents and proposed beneficiaries of restoration actions (Cairns Jr, 2000).

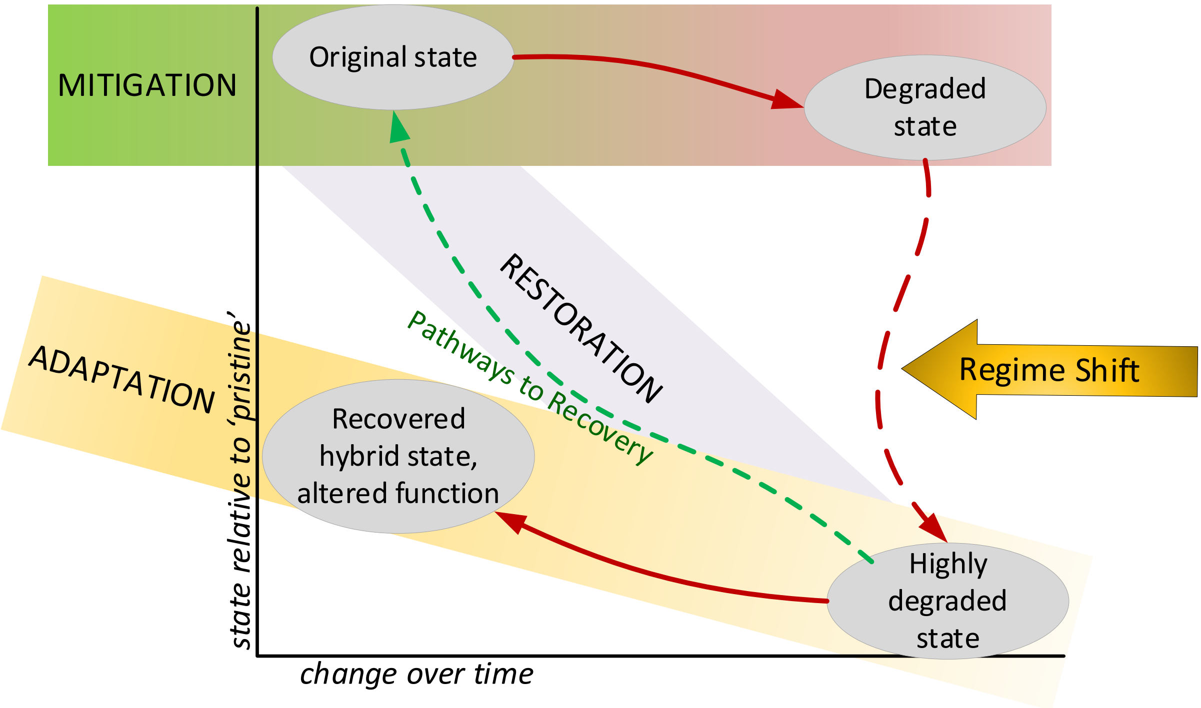


*Figure 1: Diagrammatic representation of the options and pathways to recovery for a degraded ecosystem. Solid red arrow = declines to a degraded state (where mitigation could be successful); dashed red arrows = declines to a highly degraded state; solid green arrow = successful recovery under restoration; dashed green arrows = pathways to recovery under restoration or adaptation. Under mild degradation, mitigation actions may induce recovery to a 'near-original' state. More extensive degradation may result in key ecological parameters exceeding a threshold resulting in 'regime shift'. Restoration actions may be undertaken to regain something similar to the original state and functioning. However, in many cases changes to the underlying nature of the system and its functioning may be so substantial that return to anything close to original condition may not be possible and the system may need to adapt (either passively or through targeted actions) to a new hybrid state with altered function. This may result in reduced or altered ecosystem services (e.g., the ecosystem supports fish but they are of poor edible quality). There is also a possibility that a highly degraded ecosystem may never recover, leaving a poorly functioning, low value ecosystem.*

## *The tenuous track between action and outcome*

With pervasive uncertainty meaning unplanned outcomes are likely, balancing risks versus planned outcomes is critical. As a result, the focus should be on robust, responsive and adaptable strategies that manage the risks engendered by uncertainty (Lempert and Collins, 2007; Harris and Heathwaite, 2012; Sheaves et al., 2016b). It is vital to understand the consequences of uncertainty, and learn how to manage, minimise and account for it. As a result, understanding what constrains our ability to reliably predict outcomes becomes a critical issue. To this end, restoration efforts have sometimes been seen as experiments, each with associated assumptions and caveats,and resulting in successes or sometimes failure (which is also important to report) (Waltham et al., 2021).

There are three key questions: '*What are the possible outcomes*?','*Which outcomes are likely to eventuate*?', '*Will the outcomes live up to expectations*?' (ii) knowledge of known and estimable uncertainty; and (iii) Knightian uncertainty (unknown uncertainty). While Knightian uncertainty will always remain, the quality of knowledge, data and models will deter- mine the value of the prediction, the extent of understanding of know- able uncertainty and, hence, the reliability of predictions. In the face of uncertainty, knowledge will never be perfect and even the best science will rely on a number of assumptions. For example, policy measures to address environmental decline can introduce uncertainty in environ- mental outcomes (Dovers and Hussey, 2013). As a result, it is crucial that (a) all the assumptions made are documented explicitly, (b) the consequences of their violation understood, (c) that they are validated as far as possible, and (d) that mechanisms exist so that knowledge is updated as additional information becomes available, and then flows on to decision makers.

A final consideration is, of course, the acceptability of the eventual outcome if it diverges from that intended, with both the consequences of not achieving the desired outcome and the consequences of obtaining particular alternative outcomes requiring consideration (Fig. 2: far right bottom components). On top of all this come financial cost-benefit considerations 'What will the outcome cost?', 'What cost are we prepared to pay?', and community acceptability ('What outcome are we collectively willing to accept, and how will this change over time as the impacts of restoration decisions become apparent or societal values evolve?') (Baker and Eckerberg, 2016).

## A Solution Framework

One general pathway to optimising restoration decisions involves(a) understanding the historical situation (scientific, cultural and economic) (Geist, 2015), (b) understanding the current situation,(c) understanding the constraints on change, (d) scoping possible out- come scenarios, (e) envisioning potential futures and, finally,(f) making knowledge-informed decisions on actions to manage risk versus reward (Fig. 3). These ideas define a simple, but necessary, set of information on which to build a framework for decision support.

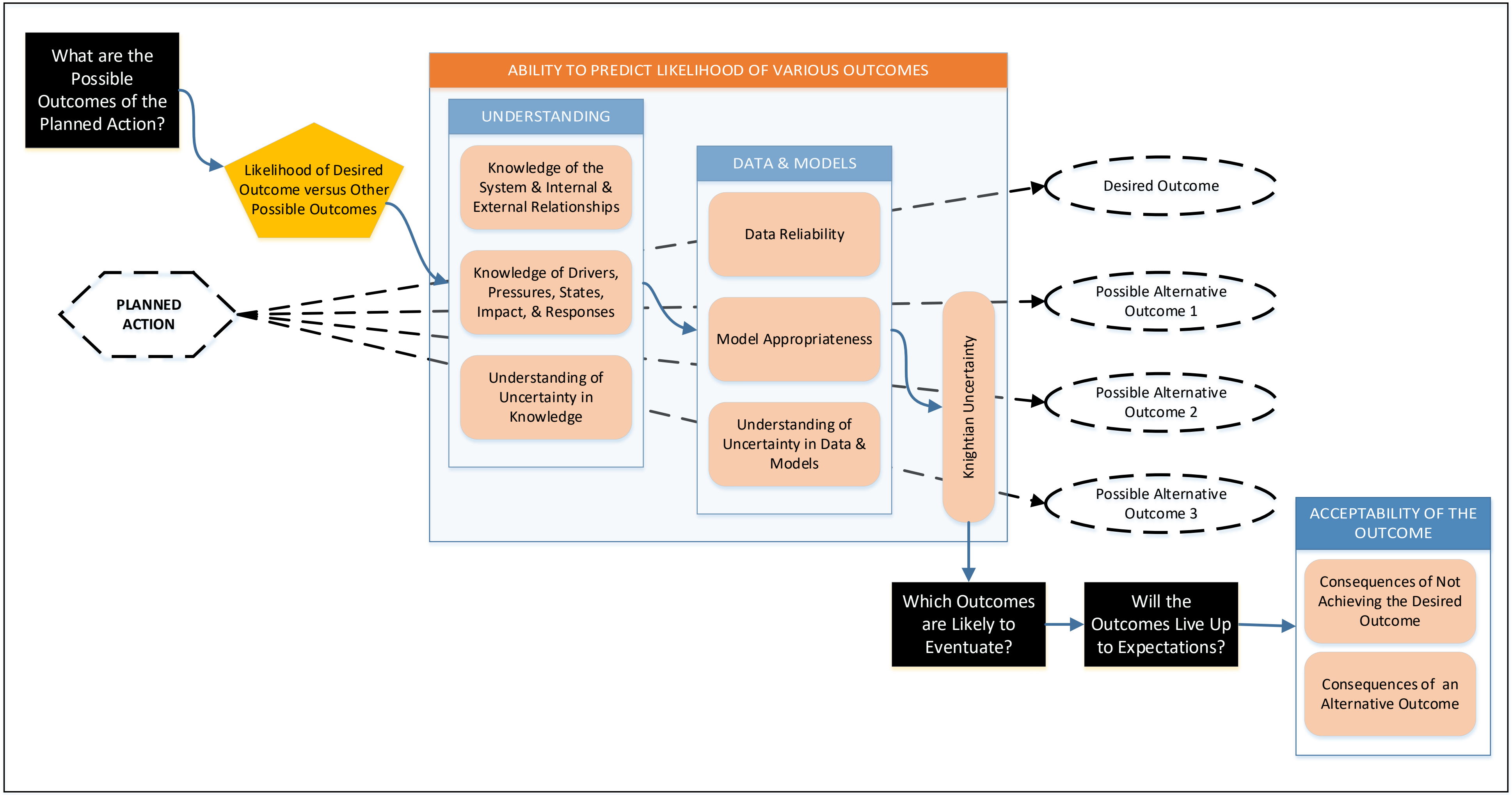


*Figure 2: The link between planned action and outcomes. Because of pervasive uncertainty, planned actionswill not always produce the desired outcomes (dashed outlines and lines). This uncertainty leads to three key questions (filled square boxes), with the likelihood of the desired versus alternative outcomes (filled pentagon) a critical consideration in deciding on whether to proceed with the proposed restoration action. Various factors influence the ability to predict the likelihood of various outcomes (central components), and the acceptability of the outcome that is achieved depending on the consequences of that outcome (far right bottom components).*

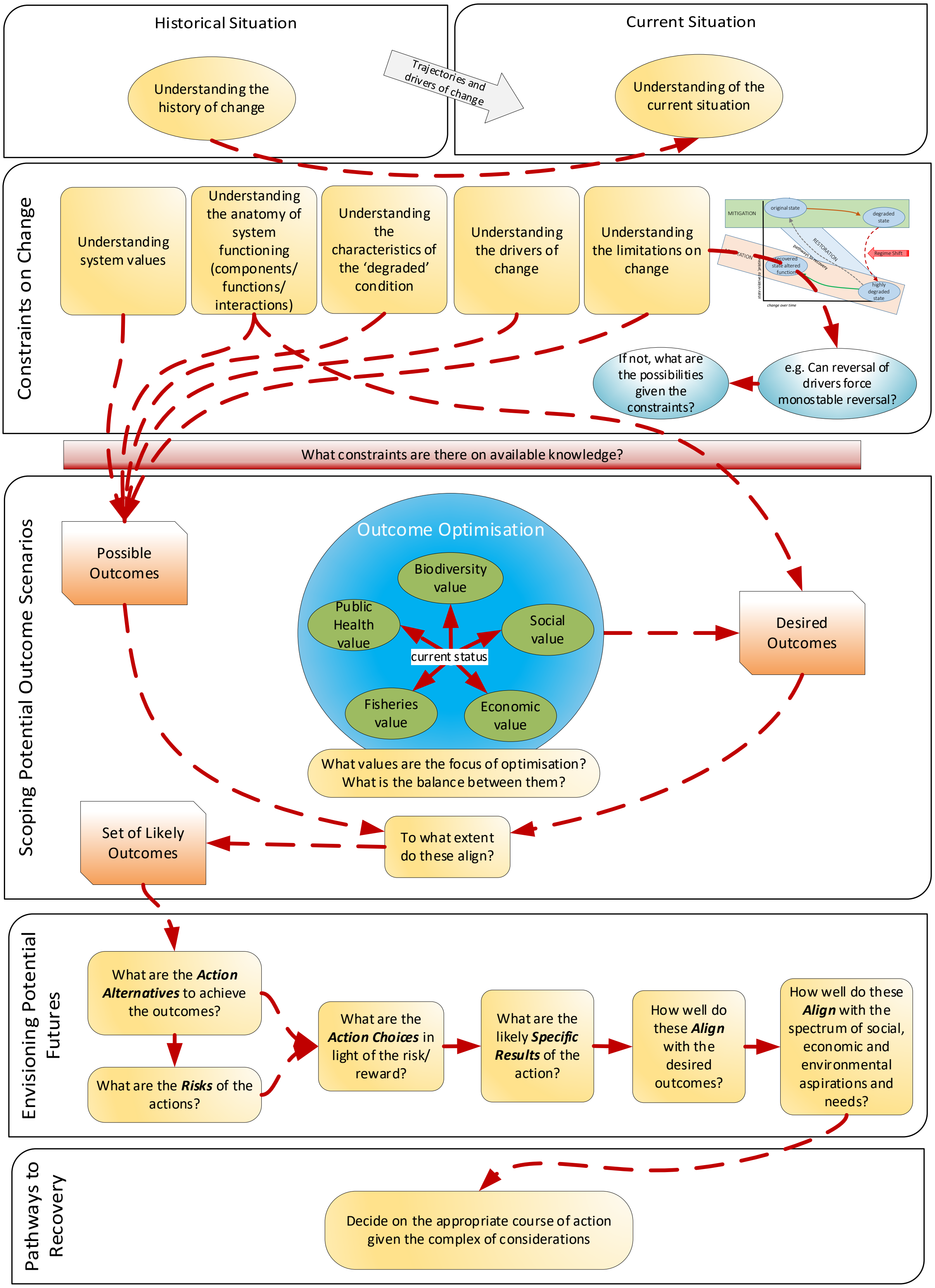

Historical Situation
Understanding the history of change
Trajectories and drivers of change
Current Situation
Understanding of the current situation
Constraints on Change
Understanding system values
Understanding the anatomy of system functioning (components/ functions/ interactions)
Understanding the characteristics of the 'degraded' condition
Understanding the drivers of change
Understanding the limitations on change
MITIGATION
original state
degraded state
RESTORATION
pathways to recovery
Regime Shift
recovered state altered function
highly degraded state
state relative to 'pristine'
change over time
e.g. Can reversal of drivers force monostable reversal?
If not, what are the possibilities given the constraints?
What constraints are there on available knowledge?
Scoping Potential Outcome Scenarios
Possible Outcomes
Outcome Optimisation
Biodiversity value
Public Health value
Social value
current status
Fisheries value
Economic value
What values are the focus of optimisation? What is the balance between them?
Desired Outcomes
Set of Likely Outcomes
To what extent do these align?
Envisioning Potential Futures
What are the Action Alternatives to achieve the outcomes?
What are the Risks of the actions?
What are the Action Choices in light of the risk/ reward?
What are the likely Specific Results of the action?
How well do these Align with the desired outcomes?
How well do these Align with the spectrum of social, economic and environmental aspirations and needs?
Pathways to Recovery
Decide on the appropriate course of action given the complex of considerations

*Figure 3: A general pathway to optimized restoration decisions that involves; understanding: the historical and current situations, understanding the matrix of factors that constraint change, from there scoping possible future scenarios, and based on those deliberations making knowledge-informed decisions on actions that minimise risk while maximising rewards.*

## Historical situation

Complex dependencies in time and space mean that understanding the history of the issues and of the location in question is a logical point of entry to the process of prioritisation (Fig. 3a). There aremany specificissues that can only be resolved by understanding history. A long-term palaeoecological view is needed to enable visualisation of the prior nature and condition of the restoration site (Willard and Cronin, 2007; Saunders and Taffs, 2009), as well as the series of events that have led to the current condition, including the more recent history. This historical view needs to go beyond environmental change to include the social, cultural and economic context in which change has occurred (Alleway and Connell, 2015). In addition to providing an understanding of the unimpacted state that might allow definition of initial restoration goals, a historical understanding can highlight location- or situation specific issues that might limit, complicate or direct decisions; for instance, if there is a known problem with acid sulphate-forming soils, or what competing interests need to be taken into account when setting restoration objectives. However, most importantly, understanding history can provide insight into trajectories and drivers of past change. Although providing a vital baseline for decision-making, appropriate historical detail is often difficult to amass; a problem that is being addressed in some situations through improvements in quantitative assessment of change enabled by recent advances in palaeoecological methods (Saunders and Taffs, 2009).

## Current situation

Understanding the current situation requires that the full range of issues that need to be identified and optimised (environmental, social/cultural, commercial, resource security etc.), are taken into account (Fig. 3b). There is often considerable relevant information available to assist in building this understanding. However, caution is required for three reasons. Firstly, the sources and nature of information sources need to be considered. For instance, information that might be suitable for report-cardingmay not be specific or detailed enough to provide the level of understanding needed for decision-making. Secondly, the quality of available information is often unreliable, with quoted ‘facts’ often poorly supported by evidence (Sheaves et al., 2020). As a result, each item of information on which decisions are based should be verified by tracing back to the original study on which it is based - a time consuming but necessary process. Thirdly, even when verified, it is important to ensure that the information used reflects current, rather than dated, understanding (Sheaves et al., 2020). Finally, the transferability of information needs to be considered because there are limits on the relevance of theoretical or empirical understanding developed in one location when applied to different parts of the world, different latitudes, different regions, different locations within regions, different types of systems (e.g. estuarine vs coastal vs island mangroves) (Sheaves, 2016; Bradley et al., 2020), and even different parts of a single system (Sheaves et al., 2007). For instance, not only does the dominant mangrove flora vary greatly in response to geography, availability of freshwater and so on (Bunt et al., 1982; Duke, 1992), but the frequency, duration and depth of flooding varies substantially due to differences in tidal range and tidal pattern (Baker et al., 2015), all of which define the role of mangrove habitat within an ecosystem. There is strong evidence this is also the case for other common targets of restoration including inland freshwater (Cantonati et al., 2020), floodplain (Pander et al., 2018) and seagrass and saltmarsh habitats (Bradley et al., 2020). As a result, when developing an understanding of the current situation, and of the likely outcomes of restoration actions, it is vital to assess the source, quality and transferability of available information. In many cases additional situation-specific data may need to be collected, with these needs defined in a careful gap analysis. In data-poor regions, local knowledge can be a particularly important source of information on environmental state and historical trends, but this needs to be captured in ways that are sensitive to local contexts and community needs (Beaudreau and Levin, 2014; Lyver et al., 2015).

## Constraints on Change

Understanding of potential futures needs to be framed in relation to the historical and current situations because these provide the location specific context and detail needed to build a cogent future vision, and because the extent and direction of response is at least in part determined by what has gone before (e.g., Fig. 1). However, knowledge of the past and current situations only provides the basis for recognising and defining the range of possible futures and the likelihood of achieving them. In addition, predicting possible futures requires a deep understanding of the values and functioning of the system, of social and economic contexts, and of the drivers and processes of change, both in general and at a local level. It also requires a clear understanding of likely future environmental conditions over multiple time horizons. This is particularly important given the changes expected as a result of ongoing human development and climate change, that different factors may drive change in the future, and that future conditions may be exceed tolerance limits of current flora and fauna. These factors place constraints on the change that is possible (Fig. 3c). This understanding also needs to be supported by appropriate and sufficient data to enable useful assessment of uncertainty across all components, aspects and functions

## Understanding system values:

Initial expectations are often based on popular, paradigm-based beliefs of likely outcomes. However, these beliefs are often poorly aligned with current scientific understanding (Thompson et al., 2016; Sheaves, 2017; Sheaves et al., 2020). This mismatch often happens when the focus is on restoring a particular habitat or ecosystem type (e.g., riparian vegetation, mangroves or seagrass) rather than on restoration of specific functions or values (such as intrinsic ecosystem values or services for particular interest groups (e.g., fisheries value)). Restoration based on the generic understanding that an ecosystem type is ‘valuable’ can lead to poorly focused restoration aimed at achieving potentially trivial outcomes (e.g., increasing the area of the ecosystem or habitat type without a broader consideration of functioning), and can result in restoration failure (Lee et al., 2019) or even a loss of functionality despite an increase in habitat area (Peng et al., 2016; He et al., 2018). Consequently, the first constraint on achieving beneficial outcome relates to the soundness and robustness of expectations. These need to be founded on knowledge of the outcomes that are achievable given as accurate and complete an understanding of the system's values as is possible. This step aligns expectations with reality by ensuring that all involved have an informed vision of what can be expected. If ‘presumed’ values and ‘real’ values don't align, ‘desired’ outcomes are likely to be ill-defined, leading to the egregious situation where the ‘desired’ outcome is not possible or does not fulfil expectations. In addition, a detailed understanding of systemvalues is key to understanding appropriate targets for optimisation, key information when making decisions about specific restoration goals. This system-values understanding can be achieved, for example, through community or stakeholder meetings or deliberative visioning to identify and manage uncertainty, and capture, and agree on, desires and expectations to be used as the basis of restoration goals (Pernaa, 2017). Consequently, precise understanding is needed to shape a well-focussed vision of expected outcomes. Up to date knowledge-based understanding of system values is best achieved before developing initial expectations, although this will rarely be the case because initial expectations are often the main motivation for restoration. Unless initial expectations are referenced against detailed understanding, and realigned as necessary, there is considerable potential for the focus of restoration to be locked onto misconceived objectives from the start. As is the case when developing an understanding of the current situation, it is vital to assess the source, quality and transferability of available information. In many cases, specific additional data may need to be collected, with these needs defined in a careful gap analysis. Collecting detailed, comprehensive data for all components of an ecosystem is likely to be prohibitively expensive and time consuming, making it crucial that research is tightly focussed on understanding the factors that constrain the accomplishment of the desired outcomes (Sheaves et al., in review), and on known obstacles to restoration (e.g. knowledge, legislation, technology (Stewart-Sinclair et al., 2020)).

## Understanding the anatomy of system functioning

A natural system is a complex entity, with system components (organisms, habitats, physical environment) interacting and combining in diverse ways and across many scales, to confer the range of life supporting functions and ecological and ecosystem services that the System provides. The way this network of organisms, habitats and physical environments interacts to provide system function can be thought of as the anatomy of system functioning (Fig. 4). To add to the complexity, the anatomy of system functioning is also influenced by situational modifiers, such as anthropogenic factors (e.g., building a seawall for continued port navigation, which changes local hydrodynamics and potential erosion elsewhere (O'Shaughnessy et al., 2019)), or sea-level rise (Grilli et al., 2017). As a result, the habitats and resources used by a particular organism, and consequently the anatomy of functioning, are context-dependent, with the specifics of the anatomy contingent on the particular function (and indeed scale) of specific interest. This alters the reason organisms use particular habitats, their mode and extent of utilisation, and the specifics of animal-habitat and animal-resource relationships from place-to-lace and over time (Ley et al., 1999; Bradley et al., 2019). At the same time as this complicates the spatial transferability of knowledge, awareness of context-dependence affords insight into the limits of the spatial transferability of understanding (Bradley et al., 2020). Because of context-dependence, understanding of the anatomy of system functioning is also intimately dependent on clear knowledge of the particular values that restoration is intended to improve, and on the outcomes that are desired. Understanding the anatomy of system functioning requires detailed knowledge of the mechanisms through which system values are conferred, information that is critical to develop a vision of the outcomes that are likely or possible, and to predicting responses of the system to change. Consequently, understanding the anatomy of system functioning is central to determining where and how restoration effort should be directed. This understanding needs to take an integrated, holistic view at a scale, and with a scope, appropriate to the function that is the objective of restoration. For instance, the nursery values of mangrove systems are conferred by the interaction of many habitat components (e.g., seagrass, subtidal structures, mangrove forests), each catering for different needs (e.g., food, refuge, hydrodynamic advantage). Consequently, mangrove restoration intended to improve fisheries values is likely to fail despite achieving mangrove regrowth, if it focusses solely on mangrove reforestation and neglects other interlinked systems components. The need for a holistic understanding of the anatomy of system functioning is often a major stumbling block to restoration success because integrated information at the scale and scope of functional units is usually less available and harder to collect than information on particular components. Again, the amount of data required to underpin this understanding can be optimised by focussing on the factors that constrain desirable outcomes (Sheaves et al., in review).

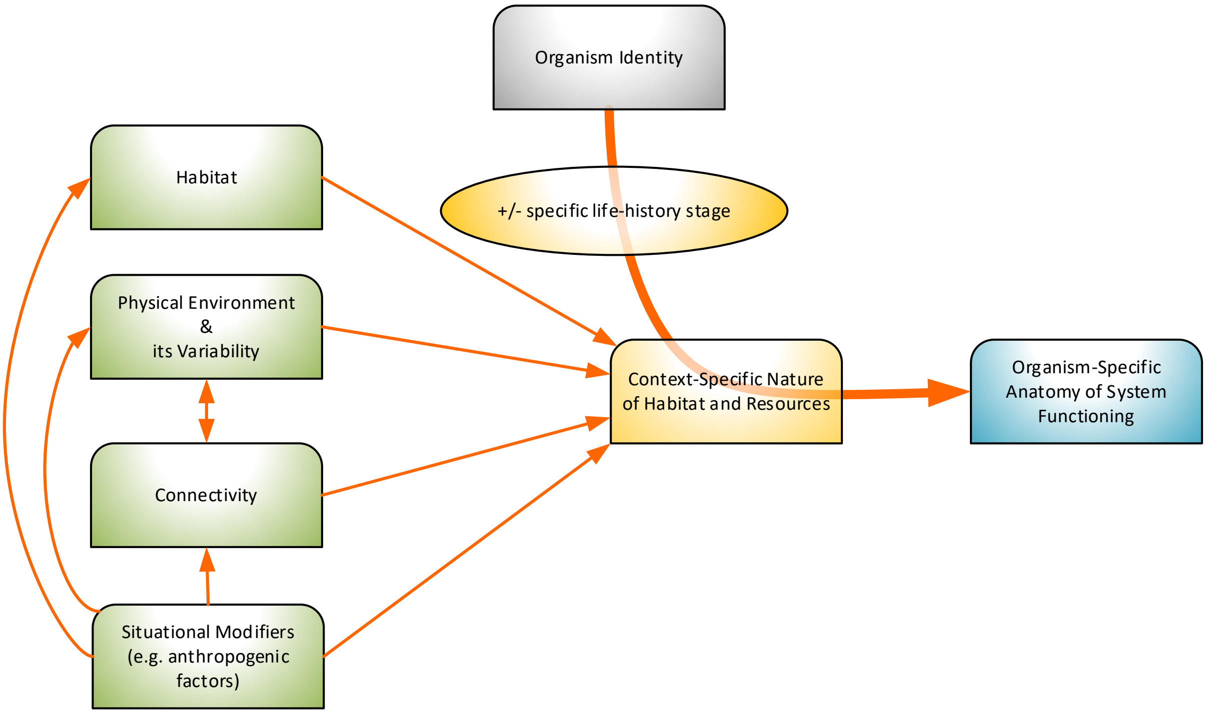


*Figure 4: Anatomy of system functioning. Summary of the complex interaction of organisms, habitats and the physical environment that combine in diverse ways and across diverse scales, to confer a diversity of life-supporting functions, and ecological and ecosystem services.*

## Understanding the characteristics of the ‘degraded’ condition

Detailed knowledge of the ‘degraded’ condition, its biota, physical properties, connectivity and human activities, provides information crucial to understanding what is possible and exactly how restoration should be conducted. Indeed, because the ‘degraded’ condition, and not the ‘natural’ state will be the starting point for restoration, the specific characteristics of the ‘degraded’ condition has a substantial bearing on what is possible, and even what is relevant or sensible. For example, changes made to the ‘degraded’ area may have promoted alternative values - although a bund wall may impede the connectivity needed for marine species to move between a coastal wetland and the ocean (Sheaves et al., 2014), the bund may have produced large areas of habitats used by freshwater species or migratory birds (Abbott et al., 2020). As a result, decisions regarding whether or not to remove the bund will require consideration of the trade-off between fisheries/nursery values and the needs of migratory birds that often come to rely on these manmade habitats to replace functionality that is lost as natural areas degrade (Vuosalo-Tavakoli et al., 2018).

## Understanding the drivers of change

Regardless of the original cause of degradation, there will be a network of factors operating on the systemthat influence on-going and future change. These include natural variability, large scale systematic factors (e.g., climate change, sea level change), local geological events (e.g., earthquakes), anthropogenic influences, etc. As with the drivers of system functioning, drivers of change interact in complex ways and will often be context dependent. Additionally, the state of the system will usually be substantially altered from its original state, likely modifying the influence of the different regulating factors. For instance, the physical nature of the components and connections may have changed, altering the potential impact of various factors, meaning that a once dominantly influential driver of change may in the future be replaced by another. Importantly, because a network of influences is operating on the system, meaning the state of the system will usually be very different to its original condition, it would be naïve to suppose that the different influencing factors will have the same relative influences in the future. Again, it is important to understand drivers of change in detail, and to align that understanding to the specific context in question.

## Understanding the limitations on change

Clear understanding of the constraints and limitations on change is crucial when scoping potential outcome scenarios. Many factors can limit the nature of possible responses and the outcomes that are achievable. These interact and are often not mutually exclusive, but their outcomes are important determinants of the likelihood of restoration success, and consequently in how restoration should proceed and, indeed, if restoration is even the best option (Fig. 5). Changes to the system may be limited, with only the value of variables changed while the parameters determining functioning remain unchanged (Beisner et al., 2003), providing the potential for return to the original state (Fig. 5a). On the other hand, the changes to the underlying parameters governing the nature of the system may have been so profound that the original state is no longer possible (Fig. 5b). However, even if return to the original state is theoretically possible, there are at least two complicating scenarios. Firstly, although the original state could exist the pathway to recovery (e.g. alternative green lines, Fig. 5c) may be quite different to the pathway to degradation (red line, Fig. 5c), so it is likely that a restored state and its functioning might be different to the original. This is often likely because ecological outcomes stem from interactions between individuals, populations species and communities leading to non-linear dynamics and complex feed-back loops that can depend on both the spatial and temporal contexts (Green and Sadedin, 2005). Secondly, even though the path to recover the original state and function may be possible, the changes needed and/or on going maintenance may be too extensive and/or expensive (grey dotted line, Fig. 5d).

## Scoping Potential Outcome Scenarios

Understanding the current and historical situations, and the constraints on change is a key input to a knowledge-based understanding of the possible outcomes, given the anatomy and functioning of a system. This information provides key inputs to allow scoping of potential outcome scenarios (Fig.

3d). Outcomes will usually be contextdependent, and the values achieved will often vary depending on the aspect or organism involved (e.g. Table 1). As a result, desired outcomes need to be informed by the values that are the focus of enhancement, potentially requiring optimisation across such considerations as biodiversity, public health, fisheries, social, economic values, etc. In reality, in the face of complex or incomplete knowledge, decision makers will find optimisation too hard a problem so, instead of exploring the full range of outcomes and attempting to optimise, will satisfice (Schwartz et al., 2011; Dewulf et al., 2020), looking for solutions with consequences that are ‘good enough’ relative to their aspirations (Simon, 1956). This limits the desired vs possible outcomes equation and emphasises the need for meaningful interaction between producers and users of knowledge (Dewulf et al., 2020). The ‘desired’ outcomes are only one part of the equation; they need to balance against the outcomes that are possible. Determining the extent to which the desired and possible outcomes align enables the definition of a set of likely outcomes that are acceptable in the context of expectations. Both desired and possible outcomes are informed by the matrix of constraints on change. However, almost invariably, precise knowledge of likely outcomes will be limited by the quality of available information and the underlying uncertainty (Harris and Heathwaite, 2005; Harris and Heathwaite, 2012). The unpredictability engendered by interactions between patterns, processes and biotic responses in complex ecological systems (Lempert and Collins, 2007), such as mangrove, estuarine and coastal wetlands, means that there will invariably be a level of unpredictability about the outcomes of management actions (Harris and Heathwaite, 2012). This uncertainty needs to be kept in mind and included in thinking throughout the prioritisation process. Indeed, ensuring that all those involved have a clear understanding of uncertainty in general, and the uncertainty associated with the specific decisions (Lempert and Collins, 2007) in particular, is key to informed decision-making that manages both risks and expectations.

*Table 1: Example of possible impacts on key physical parameters and some of the resulting outcomes for biodiversity, fisheries and public health, under two scenarios (i) before bund wall removal from the intertidal zone of a dry tropical coastal system and (ii) following from the bund wall removal. The specific outcomes will vary with context, depending on considerations such as the level in the intertidal that the bund wall is situated and complicating factors such as the presence of pollutants. The examples outcomes align with (Knight et al. 2013; Abbott et al. 2020; Mattone et al. in review).*

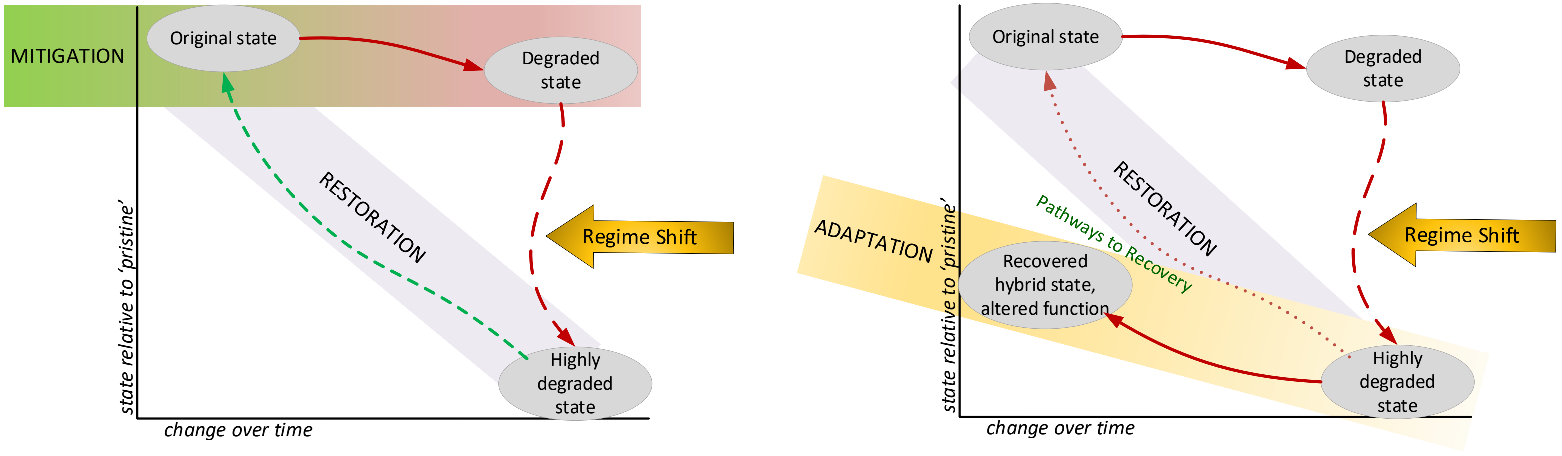
| | Scenario 1: bund in place | | Scenario 2: outcome after bund removal | |
|---|---|---|---|---|
| Physical Parameter | Condition | Values | Condition | Values |
| Tidal exchange | Only on extreme high tides (<10 times per year) | Biodiversity (e.g. waterbirds)<br>• High because of large areas of permanent shallow water low salinity water<br>Fisheries (e.g. juvenile nursery)<br>• Low because juveniles excluded from potential nursery and unfavourable physical conditions<br>Public Health (e.g. *Aedes vigilax* mosquitoes)<br>• Poor because high temperatures and low oxygen are tolerated by mosquito larvae and predatory fish are excluded<br>Carbon additionality and Greenhouse Gas emissions<br>• Generally advantageous but may depending on the specific situation | On most high tides | Biodiversity (e.g. waterbirds)<br>• Reduced because water levels more variable and salinity increased<br>Fisheries (e.g. juvenile nursery)<br>• High because juveniles have access to potential nursery habitat with suitable physical conditions<br>Public Health (e.g. *Aedes vigilax* mosquitoes)<br>• Improved because physical conditions unfavourable to mosquitoes and favourable to predatory fish<br>Carbon additionality and Greenhouse Gas emissions<br>• Generally reduced values but may depending on the specific situation |
| Dissolved Oxygen | Low because of long periods without tidal influence | | High because of regular tidal influence | |
| Hydrological Connectivity | Low because of long periods without tidal influence | | High because of regular tidal influence | |
| Biological Connectivity | Low because of low hydrological connectivity | | High because of high hydrological connectivity | |
| Temperature | High because of long periods without tidal influence | | Remains close to seawater ambient because of regular tidal connection | |
| Salinity | Low because freshwater trapped and low tidal connection limits salinity increase | | Variability increase with changes due to interaction of seasonal freshwater input and regular tidal connection | |

## Envisioning Potential Futures

Once there is clear understanding of set of likely outcomes that are acceptable in the context of expectations, it is possible to envision potential futures (Fig. 3e), with a focus on robust decision-making (Lempert and Collins, 2007). A robust decision-making framework will generally require the trade-off to some degree of optimal performance against less sensitivity to uncertain assumptions (Lempert and Collins, 2007), with alternative possible actions balanced against the risks of those actions to provide a set of action choices that take into account the risks, uncertainty and rewards over the lifetime of potential consequences (Sheaves et al., 2016b). Key questions here for decisionmakers are: 'What are the probable results of the actions?', 'How well do these align with the desired outcomes?' and 'How do these outcomes align with the spectrum of social, economic and environmental needs and aspirations, both present and emerging?' It is vital to remember that restoration is only one of a range of potential actions to respond to environmental/ecological concerns that include both active and passive responses (e.g. Sheaves et al., 2016b). Consequently, whether to take a restoration pathway as opposed to another option is a key consideration in light of the situation-specific risk/reward evaluation.

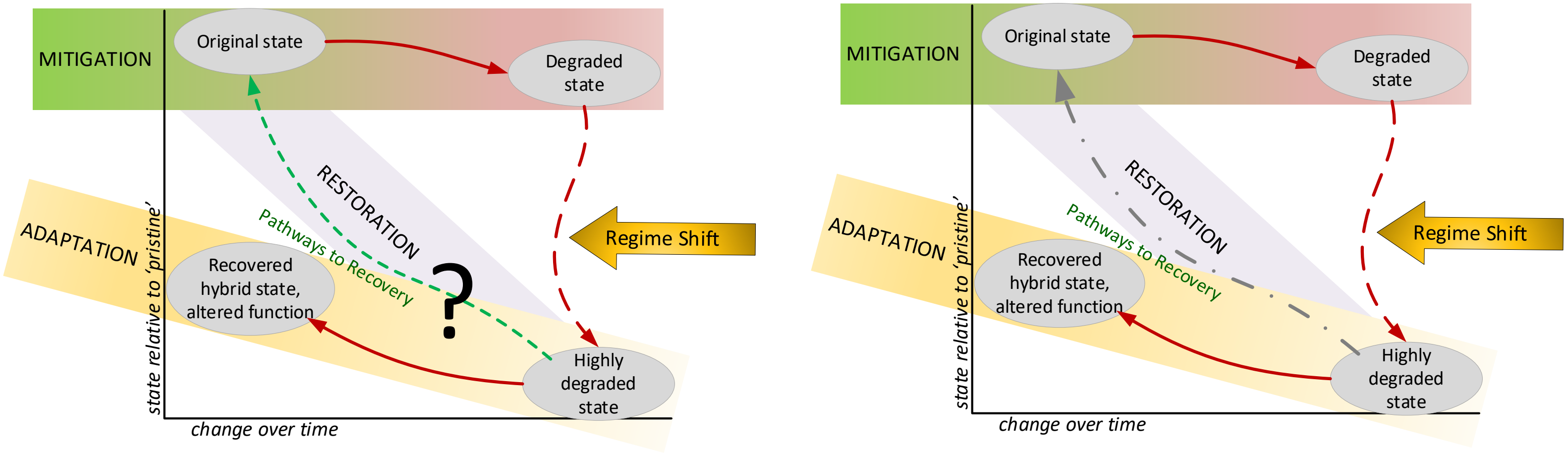
## Pathways to Recovery

The final step to recovery involves deciding on the appropriate course of action to take given the matrix of considerations. The complexity of ecological systems means that restoration decisions need to be nuanced, necessitating case-by-case assessment. However, at the most fundamental level, informed by consideration of (i) the historical situation, (ii) the current situation, (iii) the constraints on change, (iv) the potential outcome scenarios, and (v) the potential futures envisioned, there are three general courses of action that can be taken: mitigation, adaptation, and restoration, referring to the limitations on change scenarios introduced in Fig. 5. Mitigation (Fig. 5a) is suitable when the extent of change has been limited enough that simple actions, such as removing or reducing the frequency or duration of stressors, provide a real possibility that the system can readjust towards something close to its original state over the short to medium term. Restoration may be feasible in more severely degraded situations, where more serious intervention is needed, and detailed assessment indicates that return to something close to the original state is possible. At the other extreme, the nature of change might be so profound that the original state can no longer exist. As a result, return to the original state is not possible (Fig. 5b), meaning restoration isn't a feasible option and adaptation to allow recovery to the most beneficial altered state is a more reasonable option. In between these extremes are scenarios where (i) the pathway of recovery is uncertain (Fig. 5c), so even if restoration is attempted it may lead to an end point different from the original, meaning adaptation to the new altered state will be necessary; or (ii) recovery to original state would require extensive/expensive actions (Fig. 5d), rendering restoration infeasible, in which case adaptation may be the preferred option. Of course, when the situation is evaluated in detail, it may be that the likelihood of a positive outcome is so low that taking no action is the most pragmatic course of action. Uncertainty of outcomes and the natural adaptive responses of ecosystems under change (Harris and Heathwaite, 2012) mean that decisions on appropriate actions are best made in a robust strategic framework – involving multiple stakeholders representing community, government, industry, cultural and scientific sectors (Lempert and Collins, 2007; Lempert et al., 2010; Harris and Heathwaite, 2012). Robust strategies are based on the idea that robustness is a more appropriate decision criterion than optimality where uncertainty is substantial (Lempert et al., 2010; Sheaves et al., 2016b), and provides a rational way forward while avoiding some of the shortcomings of strict adherence to the precautionary principle (Sunstein, 2005; Lempert and Collins, 2007). Robust strategies encompass a diversity of goals, such as minimising collateral damage, enabling reversibility as insurance against unexpected inappropriate outcomes, maximising complimentary benefits and so on (see Sheaves et al. (2016b) for examples in the context of Climate Change). The diversity of robust strategies provides a suite of options with the flexibility needed to deal with the complex, situation-specific nature of restoration problems. Dealing with predictability isn't the end of the story. Once decisions are made other factors, such as the adequacy of monitoring programs (Ruiz-Jaen and Mitchell Aide, 2005; Sheaves et al., 2016a), the sufficiency of joined-up thinking, or a lack of stakeholder engagement, can still derail the achievement of optimal outcomes (Harris and Heathwaite, 2012). Of course, restoration will usually have multiple goals (e.g. carbon additionally and fisheries value), but poorly informed decision-making has the potential to prevent optimisation across the suite of benefits.



(a) Return to close-to-original state possible; restoration may be feasible

(b) Nature of change such that return to original state not possible; restoration infeasible; adaptation needed



(c) Pathway of recovery may lead to an end point different from original: restored state may not match original so adaptation might be needed

(d) Recovery to original state requires extensive/expensive restoration: restoration may be infeasible, adaptation may be the preferred option

*Figure 5: Alternate pathways to recovery.*

# Conclusion

Recognising and understanding the possible futures, and the likelihood of achieving them, is critical to the success of efforts to restore marine ecosystems. Although restoration might appear to present similar challenges in different situations, in reality, even within one ecosystem type, each situation is nuanced, with a range of unique considerations and potential responses. This means that prescriptive, one-size-fits-all advice is of limited value (Waltham et al., 2021). Consequently, rather than a rigid framework, we have developed a schema that provides a pathway through the network of factors that need to be taken into account in decision-making around marine ecosystem restoration activities. The importance of each will be situation-specific, as will the specific considerations and the resulting decisions. Indeed, from situation to situation, there will be critical considerations not included in the pathway thatwill require consideration and agreement among project partners. While the focus here has largely been on the environmental, ecological and biological considerations and constraints, as is the case for adaptation strategies more generally (Sheaves et al., 2016b), those perspectives need to be set in the broad landscape of considerations necessary to inform restoration actions that provide optimal and meaningful outcomes for all stakeholders across relevant timescales. Among many others, these include:

i) Whether to take restoration actions as opposed to alternative responses in light of the situation-specific risk/reward evaluation extended across the full spectrum of environmental, social and economic considerations, and considering the relative importance of different objectives to the various stakeholder groups (Dale et al., 2010).

ii) The sufficiency of the action – ensuring that restoration is in itself sufficient to produce a  eaningful impact, or if complimentary actions are required to producemeaningful and lasting outcomes at a worthwhile scale.

iii) The need for a focus on whole-of-system, long-term outcomes, will require a multiscale vision that considers the implications of local decisions taken at one time for outcomes at other locations and times.

iv) Considering the place the action has in the broader landscape of responses, and how it could add value to overall restoration efforts (while acknowledging potential detrimental outcomes) and perhaps be designed to interact with other actions to produce emergent outcomes.

v) Understanding the complex of governance structures, organisational arrangement etc. (Dutra et al., 2015), and complex links between science, policy and practice (Dale et al., 2019) that are likely to constrain outcomes and/or facilitate cooperation.

vi) Understanding the capacity (legislative, financial and technological) available to complete a restoration program.

vii) Understanding the societal values and priorities that constrain restoration options, including how these may change over time.

Despite the difficulties, impactful and meaningful marine restoration is possible and achievable. This is particularly important when considering the UN Decade Declaration on Ecosystem Restoration, under which managers will soon need to be evaluating which restoration sites/projects will be necessary and feasible to fund on the pathway back to a restored state (Waltham et al., 2020). However, restoration is an expensive venture and its success or failure can positively or negatively impact the lives and livelihoods of millions, as well as the future of ecosystems. Consequently, there is an imperative to make decisions about which restoration actions to fund and how those restoration actions are conducted that optimise the likelihood of success and minimise risk – that can only be achieved by in-depth collaboration among decision makers and knowledge providers, with the explicit aim of achieving decision superiority rather than decision expediency. Without that sharp focus, the outcome are likely be reduced or even impaired ecosystem services, reduced societal benefits and inefficient use of public money.

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