Biological Conservation 292 (2024) 110516

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Perspective

Coupling marine ecosystem state with environmental management and conservation: A risk-based approach

Rebecca V. Gladstone-Gallagher[a,*], Judi E. Hewitt[a], Jasmine M.L. Low[a], Conrad A. Pilditch[b], Fabrice Stephenson[b,c], Simon F. Thrush[a], Joanne I. Ellis[b]

[a] University of Auckland, Auckland, New Zealand
[b] University of Waikato, Hamilton, New Zealand
[c] School of Natural and Environmental Sciences, Newcastle University, Newcastle, UK

ARTICLE INFO

Keywords:
Adaptive management
Restoration
Marine conservation
Risk assessment
Stressors
Cumulative effects

ABSTRACT

The sustainability of marine ecosystems demands a focus on ecological improvement, necessitating managers and conservationists to consider a range of actions from those that limit stressors to those that actively restore. Deciding the most appropriate action should be informed by environmental context, which includes assessing information on both degradation and recovery potential. Here, we provide an analysis of how the degree of ecological degradation coupled with the stressor regime can inform environmental management and conservation actions (e.g., stressor reductions, adaptive management, assisted recovery/restoration). With this analysis we design a risk framework combining principles that define ecosystem resilience and recovery times with those that characterize stressor regimes (i.e., the number, type, and impact). The combination of these principles defines where an ecosystem is placed along sliding scales of degradation and recovery and likely response to protective and restorative interventions. It is designed to facilitate place-based conversations regarding the risks of different management actions informed by the temporal dynamics of ecosystem degradation and recovery.

1. Introduction

The sustainability of the planet now requires a focus on rebuilding and restoring biodiversity and ecological function. A recent roadmap for rebuilding the ocean's biodiversity suggests substantial recovery of marine ecosystems is possible by 2050 if protective and restorative programs start now (Duarte et al., 2020). This will require humanity to employ a range of actions to match the degradation states that now exist in the ocean (Leadley et al., 2022). These actions should be informed by the intrinsic dynamics of marine ecosystems that determine the context specific responses to change. Alternate stable states, legacy effects, and the cumulative effects of stressors all represent factors we need to incorporate into pathways towards sustainable oceans.

Effective marine ecosystem management has been hindered by the multi-scaler social-ecological dynamics associated with overlapping usage (e.g., fishing, aquaculture, tourism, shipping) and the highly connected and complex nature of the biophysical ecosystem (Österblom et al., 2017). This inherent complexity means that the impacts of our activities occur through multiple direct and indirect effects (Selkoe et al., 2017) generating ecological responses that vary in time and space (Crain et al., 2008; Österblom et al., 2017). Characterizing empirically the ecological impacts of all stressor combinations (past, present and future) is impossible (Kanwischer et al., 2021) and when relevant data is limited (which is common for marine ecosystems) it can generate decision paralysis. However, an explicit focus on the elements that govern the rate of change in ecological status (both positive and negative) provide opportunities to assess the most appropriate management actions even when data quantity and quality is low. Importantly, a focus on elements that improve ecological status is now critical given the large scale degradation and shift in baseline conditions (Duarte et al., 2020; Worm et al., 2006).

Improvements to ecological status following management action can be slow and barriers to recovery are common (Diefenderfer et al., 2021; Lotze et al., 2011). Thus, understanding not only the recovery potential of a marine ecosystem, but also the timescales involved is paramount to informing the most appropriate action and managing societal expectations. These elements are rarely considered in environmental policy and assessments aimed at protecting marine ecosystems, but are essential in

* Corresponding author at: University of Auckland, Auckland 1010, New Zealand.
E-mail address: rebecca.gladstone-gallagher@auckland.ac.nz (R.V. Gladstone-Gallagher).

https://doi.org/10.1016/j.biocon.2024.110516
Received 12 June 2023; Received in revised form 23 January 2024; Accepted 18 February 2024
Available online 8 March 2024

transitioning to a rebuild of ocean biodiversity (Duarte et al., 2020). Recovery is influenced by combinations of reinforcing feedbacks that maintain ecosystems in alternate, degraded stable states (i.e., hysteresis) (Abram and Dyke, 2018; Maxwell et al., 2017; Nyström et al., 2012; van de Leemput et al., 2016), legacy effects of stressors (Commito et al., 2019; Johnston et al., 2020), and locational contexts that dictate the recovery trajectory (Hewitt et al., 2022; Thrush and Whitlatch, 2001). For ecosystems that have shifted to a new, but less desirable stable state, actions that do not explicitly manage for recovery may be ineffective. For example, stressor limit setting does not always lead to ecosystem recovery (Gladstone-Gallagher et al., 2022; Schiel and Howard-Williams, 2016), restoration efforts can fail (Reeves et al., 2020; Suding et al., 2004) and adaptive management can be too slow to respond to changes in ecosystem state (Andersen et al., 2017; Månsson et al., 2023). However, outcomes can be improved if management actions recognize both the ecological and stressor states and how these states dictate ecological responses to actions.

Here, we provide an analysis demonstrating how actions can be appropriately matched with both ecological and stressor states to assist ocean sustainability targets and ecosystem-based management (EBM). We do this through developing a principles-based risk assessment framework that links ecological status and likely trend to three potential management actions that are likely to be included in the EBM toolbox: stressor limit setting, adaptive management, and active assisted recovery. Although our framework is conceptual, it serves an important purpose highlighting how natural history and current ecological state can help identify the best practices for navigating towards the desired future. Critically it allows identification of actions that can be mismatched with ecological degradation state, and such recognition removes barriers to achieving sustainability goals.

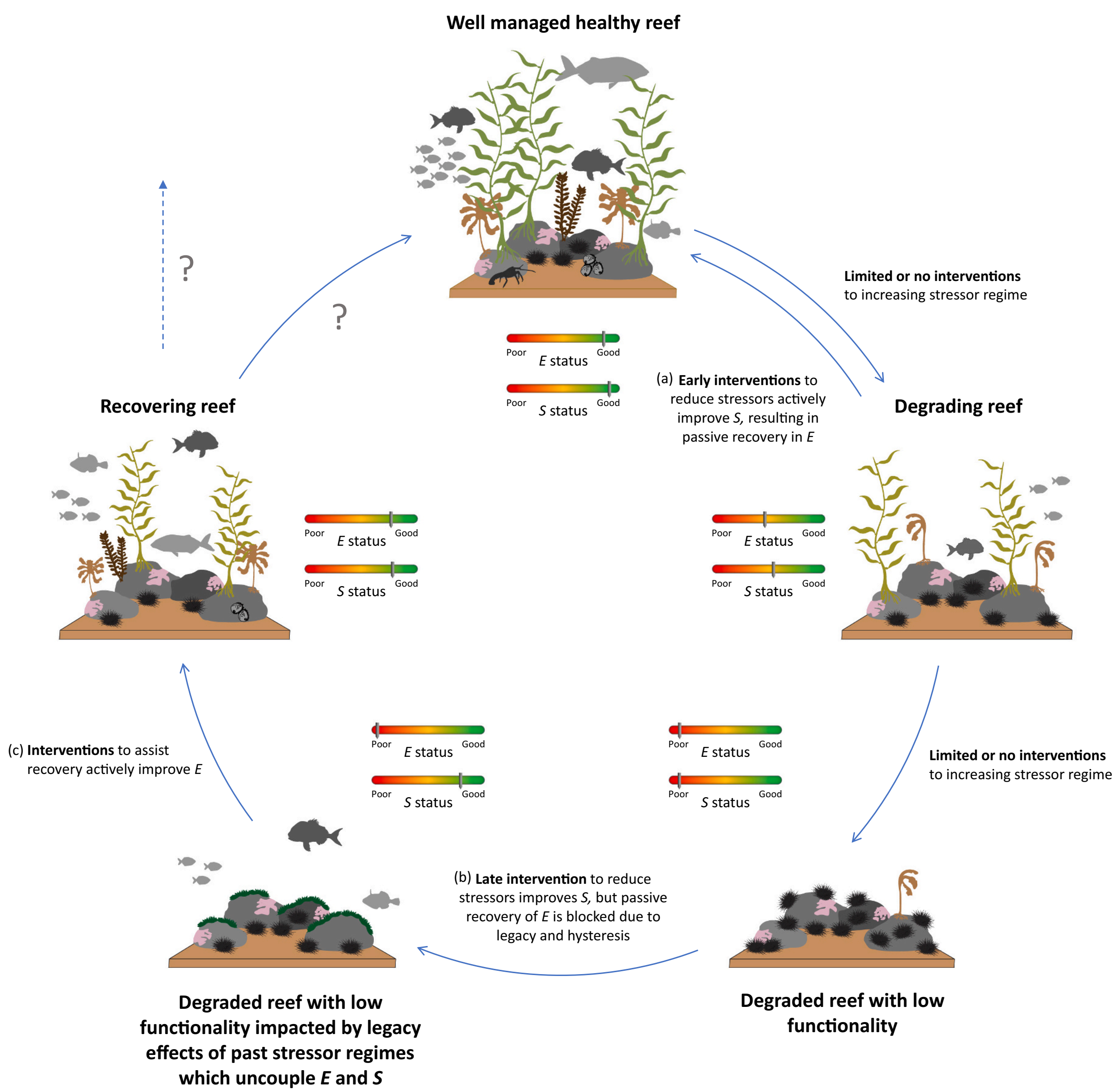

Fig. 1. The appropriate intervention lever depends on the state of the ecosystem (*E*) and the state of the stressor regime (*S*). *E* and *S* can range from good, healthy and desirable (green end of scale), to poor and undesirable (red end of scale). Different types of actions push the ecosystem back along either the *S* scale or the *E* scale. *E* and *S* are not only shifted by different action levers, but they also dictate the likelihood for further degradation and the likelihood for recovery along both scales. For example, an ecosystem with a high *E* means that it has resilience and recovery potential and so the active management of *S* results in the passive ecosystem recovery (higher *E*) (a). However, a low *E* can reduce the resilience and recovery potential even if *S* is actively reduced (b). Thus, late intervention that results in low *E* may result in the need for both actions that reduce *S* and actions that assist recovery to improve *E* status (b and c). The indicators and principles that collectively characterize overall *E* and *S* and therefore assessment of the risk of different actions are described in Section 3 and Box 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. There is no 'one size fits all' to marine environmental improvement

Conceptually, environmental management or conservation actions work as 'levers' moving the ecosystem towards a more desirable state in two ways: 1) stressor reduction which sometimes (but not always) results in improved ecological status; and 2) actively improving elements in the ecosystem that drive resilience and recovery. Importantly, the action needs to be matched with the current overall ecological (*E*) and stressor (*S*) status (as well as the aspirations for its future state) because both influence the ecosystem response (degradation or recovery) to different actions. Different ecological and stressor states therefore call for different approaches to management (e.g., Fig. 1). Within this context we briefly assess three common marine management and conservation approaches and the ecological elements that mediate their outcomes.

2.1. Stressor reduction

Stressor limit setting is one of the most common approaches in marine environmental management and conservation. Limits can be set on the amount of pollutants entering an ecosystem (e.g., nutrients and sediments), or on the removal of resources (i.e. through fishing quotas). Stressors can also be limited through spatial and temporal activity restrictions (e.g., via Marine Protected Areas; MPAs). If stressor limits are set with the goal of ecological improvement, it is effectively a 'reduce stress and let recover' strategy with success dependent on the potential for the ecosystem to recover following stressor limitation. Even though recovery potential is a critical element that dictates outcomes, it is rarely included in the decision-making process. For example, MPAs have been established in kelp forests globally to reverse urchin barren regime shifts. However, kelp forest recovery has been variable because the focus is on reducing fishing pressure, ignoring other stressors (e.g., sedimentation) and importantly how feedbacks (e.g., turf macroalgae-kelp interactions) can slow recovery (Filbee-Dexter and Scheibling, 2014; Filbee-Dexter and Wernberg, 2018). Critical to the success of a 'reduce stress and let recover' approach, is that the 'right' stressor(s) are managed at the right scale before they have generated legacies that can limit or block recovery and that ecological status is moderate to high (e.g., Fig. 1). In addition to the ecological aspects of recovery, there are also important social-ecological feedbacks and issues that arise at the science-policy interface that dictate the success of stressor reductions and these include responses between ecological domains (land, freshwater and sea), sectoral governance, and compliance and uptake of the management intervention (Alexander and Haward, 2019; Cormier et al., 2018; Gladstone-Gallagher et al., 2022).

2.2. Adaptive management

'Adaptive management' involves an iterative process of reducing uncertainty in assessments of environmental state and effectiveness of management actions through monitoring environmental indicators (Allen et al., 2011). It has mostly been implemented for large-scale industry specific sectors (e.g., aquaculture/mining) but has not typically considered interactions with other activities (i.e., cumulative effects), far-field effects, or ecological states (Satterstrom et al., 2007). In some countries (e.g., New Zealand) adaptive management cannot be implemented for a new industry activity with limited knowledge of ecological effects or in areas with limited baseline data (Supreme Court of New Zealand, 2014). EBM is the goal for environmental management in most countries, and integral to that goal, an adaptive management approach must enable monitoring the right indicators (of both degradation and recovery) at the appropriate spatial and temporal scale (Hewitt and Thrush, 2019) and align these indicators with the ability of managers to act quickly (also at the right scale) if degradation is going to be halted (Gladstone-Gallagher et al., 2022). This requires cross-industry and cross-ecosystem domain management collaboration.

2.3. Assisted recovery

When natural recovery of ecosystem health is not possible within societally acceptable timeframes (Lotze et al., 2011; Lotze et al., 2006) active interventions are required (e.g., Fig. 1). In such instances, hysteresis and recovery lags limit the effectiveness of 'reduce stress and let recover' actions (Hewitt et al., 2022) demanding the addition of 'recovery assist' actions that target the restoration of the feedbacks responsible for maintaining a resilient restored state (or changing the feedbacks responsible for the hysteresis) (Diefenderfer et al., 2021; Suding et al., 2004). Importantly, in highly stressed environments, 'recovery assist' approach will be most successful when coupled with appropriate stressor reduction. For example, seagrass restoration is most successful when water quality is high, a minimum threshold for plant density is exceeded, and sites are located close to donor beds, all of which facilitate the reintroduction of natural resilience feedbacks (van Katwijk et al., 2016). Risk assessments focused on the missing ecosystem element(s) and stressors blocking natural recovery, will be invaluable for informing 'reduce stress and assisted recovery' approaches (Hewitt et al., 2022). In general, the costs associated with restoration are high compared to other management or preventative measures. The use of a principles-based risk framework therefore has the potential to enhance the cost effectiveness of management through reductions in the need for assisted recovery. Further, our framework can assist with the selection of priority habitats and location attributes that are associated with an enhanced likelihood of success (see Bayraktarov et al. 2016).

3. Assessing ecological status and trend determines likely rates of ecosystem degradation and recovery

To begin aligning risks of actions with assessments of ecological status and trends, we identified a number of ecological and stressor regime indicators that collectively determine ecosystem degradation and recovery trajectories. These indicators allow us to place an ecosystem on a spectrum of poor to good ecological status, and develop principles that describe the likely direction and rate of change in status in response to stressors and different management and conservation interventions. These indicators and principles are designed to 1) inform risk assessments where ecological and stressor information is incomplete or unknown (e.g., as described in Box 1); 2) incorporate the critical elements that drive ecosystem change; and 3) facilitate a shift in focus towards a situation where the likely outcomes of management actions are appraised against the context-dependencies in the place of interest.

The indicators and principles include two types: 1) *ecological (E)* – which account for an ecosystem's ability to respond, resist or adapt to change, recognizing the role of the intrinsic ecological networks in generating responses (which are generally overlooked in environmental risk assessments but are an integral part of an EBM focus), and 2) *stressor (S)* – that characterize the stressor regime (either past (i.e., legacies), present or predicted future), with a focus on the ecosystem elements they impact on and how stressor effects interact. Stressor characteristics are the predominant focus of current mainstream assessments of environmental degradation and risks (Holsman et al., 2017), which generally ignore the ecosystems capacity to respond and be resilient and thus limit the capacity to enact true EBM. We emphasize the importance of combining E and S principles which allows context dependency in ecological responses to stressors to be considered.

3.1. Ecological indicators and associated principles - how the ecosystem responds to change/stress

E1. The status of the 'slow' to regenerate ecosystem structural components. The slow to regenerate habitat/structure forming species (e.g., kelp, corals, shellfish or other key habitat forming species) are associated with the health and functioning of the ecosystem, as well as the recovery potential. If these structure forming species are lost (particularly on the seafloor), recovery can be blocked due to loss of facilitatory relationships and feedbacks (Cranfield et al., 2003; Hewitt et al., 2022; Maxwell et al., 2017; Nyström et al., 2012; Reeves et al., 2020). **Principle associated with indicator E1**: If E1 is low, the slow to regenerate structural components have been functionally lost from the ecosystem, and this can signal an ecosystem that has already undergone a state change. Therefore the rate of further ecosystem degradation from that current state may have slowed (though this is highly context dependent). Similarly, low E1 is likely to result in recovery lags (slow rates of improvement), in relation to the long timescales of regeneration of the key species, which may be further hindered by the ability of the landscape to supplying recruits (see E4, E5 and S6).

E2. The status of the ecological network structure – the number and type of feedback loops. Network complexity and the presence of feedbacks among ecosystem components has long been suggested to confer ecological resilience (Berlow, 1999; Janssen et al., 2006; Simmons et al., 2021). The network architecture and nature of interactions can make ecosystems prone to runaway effects (i.e., changes that accelerate), tipping points, and flow-on indirect effects to connected ecosystems (Nyström et al., 2012). **Principle associated with indicator E2**: If E2 is high, the network contains balancing loops which can enhance resilience and slow down reductions in ecological status. As E2 is reduced, balancing loops become simpler and dominated by unidirectional loops that can generate runaway effects and accelerated declines in status. Extremely low E2 may be characterized by a simplified network with a few balancing loops that can maintain ecosystems in a degraded state and prevent recovery (i.e., hysteresis).

E3. Status of ecological processes that regulate ecosystem resilience. Some ecosystem processes are central to resilience, and if functioning well, can slow down non-linear declines in ecosystem state following stressor exposure. For example, in coastal soft-sediments with high ecological status, denitrification removes excess bio-available nitrogen providing resilience against eutrophication (Howarth et al., 2011). **Principle associated with indicator E3:** When E3 status is low (i.e., poor state of ecological regulating functions), this risk principle needs interpreting in conjunction with the status of other *E* principles. For example, if E3 is low, but the slow to regenerate structural components of the ecosystem (E1) and the status of the network feedback loops (E2) are still good, this could indicate a system on the verge of a non-linear and unexpected change if the status of other indicators is reduced. Conversely, extremely low E3, in conjunction with low E1 and E2, might suggest a regime shift has occurred locking it in a poor state and slowing recovery state.

E4. The connectivity to other ecologically similar areas. A high degree of connectivity among spatially discrete habitats enhances the potential for the seascape to supply recruits (Thrush et al., 2013). **Principle associated with indicator E4**: If E4 is low, habitats are isolated from a supply of recruits, and recovery lags are more likely. High E4 may also reduce the negative effects of stressors.

E5. The diversity of habitat types (environmental and biotic) at the seascape scale. Because the diversity of habitat types is linked to species diversity at the seascape scale (Zajac, 1999) it provides resilience (Vozzo et al. 2023) and speeds up recovery of connected ecosystems by providing more 'options' for recovering communities. **Principle associated with indicator E5**: High E4 and high E5 increases the likelihood of recovery of disturbed areas within the seascape. However, if the impacted area is large (S6 below) relative to the seascape that supplies recruits, recovery lags are likely. Heterogeneous areas (high E5) are also more likely to contain habitats that are resilient to stressors.

E6. The size of the ecosystem of interest. The spatial extent of the ecosystem is related to its resilience, larger extents may be more resilient than smaller ones given that stressor footprints are less likely to encompass the whole area. **Principle associated with indicator E6:** High E6 decreases the likelihood of non-linear degradation in ecosystem status.

Stressor indicators and associated principles.

S1. The number of stressors. Multiple stressors are now the default in many coastal systems (due to emerging contaminants and climate change) increasing the frequency/intensity of non-linear ecological surprises (Crain et al., 2008). **Principle associated with indicator S1**: If S1 is high (multiple stressors present), the risk of non-linear degradation in ecosystem status is increased.

S2. Levels of stressors that are ongoing and accumulating. Chronic and accumulating stressors are more likely to generate regime shifts and legacy effects. **Principle associated with indicator S2**: If there are stressors that are chronic and accumulating (high S2), ecosystem degradation can be non-linear. High S2 can also slow rates of recovery in ecological status due to legacy effects if the stressor residence times are high (e.g., accumulation of toxic metals in seafloor depositional zones).

S3. Levels of stressors that generate unimodal responses. Initial increases in stressors such as temperature, nutrients and sediment mud content can result in increased biodiversity and/or status of slow structural components (E2) up to a point and then decreases occur. **Principle associated with indicator S3**: Low levels of such stressors (low S3) can mitigate the negative effects of other stressors. For example, small increases in nutrients can offset the effects of acidification on coral calcification up to a point (Ban et al., 2014). Low S3 coupled with any level of S4 can result in stressor interactions.

S4. Levels of stressors that generate responses other than unimodal. Some stressors (e.g., toxic contaminants and microplastics) decrease biodiversity removing structural components (E1) and species critical to ecosystem processes (E3) in a non-random manner. **Principle associated with indicator S4**: If S4 is present and there are multiple stressors present the rate of degradation in ecosystem status can be exacerbated (because stressors with non-unimodal responses give less chance for amelioration as in S3).

S5. Number of points of impact and indirect effects on an ecological network. Stressors impact networks of interacting ecological components and the number of points of impact and indirect effects are likely to determine the nature of ecological responses (Harley et al., 2017). As the magnitude and numbers of stressors increase, so does the number of points in a network that they act upon increasing the likelihood of indirect effects. For example, increasing soil inputs from land initially elevates water column turbidity effecting photosynthesis, but intensification results in sedimentation altering sediment porosity, bacteria, and the macrofauna via a cascade of effects (Thrush et al., 2004; Thrush et al., 2021; Thrush et al., 2003a; Thrush et al., 2003b). **Principle associated with indicator S5**: Stressors that impact multiple ecosystem components and result in multiple indirect effects (high S5) are more likely to increase the rate of degradation.

S6. Size of the impacted area (relative to the ecosystem of interest or managed area). The spatial extent of the impact determines how far colonists have to travel and thus recovery rate (Pilditch et al., 2015; Whitlatch et al., 1998). The size of the impacted area is also likely to scale with the number of habitats affected influencing the regional biodiversity in the managed area (E5) and the potential for the area to be maintained by within-area dynamics. **Principle associated with indicator S6**: High S6 with low E4 or E5 make recovery lags in ecosystem status more likely. High S6 also increases the probability of spillover impacts to other areas due to nutrient, food and recruitment source-sink dynamics and expansion of scavenger/predator habitat. Low S6 relative to the managed area (E6) is likely to result in more positive outcomes for recovery than high S6.

Actions to manage the state of the environment must be aligned with both the state of the ecosystem (*E*) and stressor regime (*S*); recognizing both aspects allows the appraisal of a full range of future states and possibilities for interventions (e.g., Fig. 1). Collectively the principles provide a way to envisage that status of a place based on its overall *E* and *S* and this status allows an appraisal of likely trajectory and rate of ecosystem change and should foster appropriate action (see Box 1 on operationalizing *E* and *S* principles in risk assessment).

Box 1
Linking ecological and stressor principles to risk assessments.

Our indicators and associated principles could be used to inform decision making by following a process to assess risks of different management approaches given the status of E1-E6 and S1-S6. We have developed a series of IF-THEN rules for each indicator state, which we link to the risk of different actions (see Supplementary Material spreadsheet). These rules are purposefully broad so that they can be used to inform risk assessments in a variety of situations. The rules are a stepping-stone to link the concepts in this paper to the generation of risk profiles associated with different action types. Since some indicators are conditional on other indicators (i.e., increasing or reducing the risk associated with other indicators), ideally they could be used to construct a network type risk assessment (e.g., Bayesian Network; Fig. B1). In this type of analysis, the indicator nodes can be adjusted along sliding scales and the principles define the connections to explore the resulting risk of different intervention scenarios (stressor reduction, adaptive management, assisted recovery), which importantly depend on likely rates of ecological degradation and recovery.

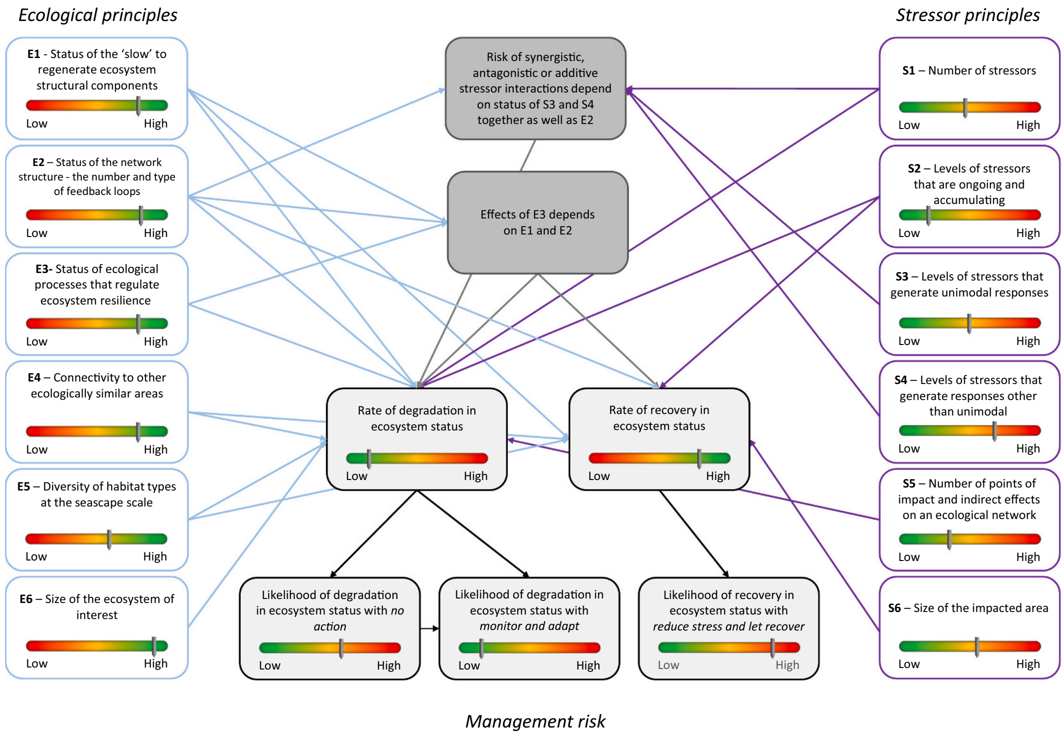

Fig. B1. A conceptual network model to operationalize the ecological (*E*) and stressor (*S*) indicators and principles. The network allows exploration of the risk of decline or improvement in ecological status with different types of actions. Note that in reality, indicators and principles could be given unequal weighting depending on the context and relative importance of some over others. Based on the Supplementary Material full matrix of IF-THEN principles, weightings for the relative importance of each stressor principle can be obtained and the overall *S* status can then be estimated as sum of *S*iwi where *S*i is the relative status of principle *S*i and wi is the weighting of that principle. If principle status values shift from low to high then the most heavily weighted principle is S5, followed by S1. S2 and S6 have the next heaviest weighting, while S3 and S4 would only need weighting by the number of stressors in each category. See Supplementary Material for a full matrix of IF-THEN principles for risk associated with each indicator state and action.

4. Different ecological (*E*) and stressor (*S*) states call for different actions

The baseline or starting overall *E* and *S* state (i.e., a collective score based on the status of the ecosystem resilience and the stressor regime) determines how well an ecosystem will respond to different management actions (Fig. 2). For example, some ecosystems have a level of inbuilt resilience and recovery capacity (i.e., provided by a healthy ecosystem), and this allows ecosystem 'revival' by actions that reduce stress (*S*) but other ecosystems may decline and then 'flat line' if actions are not taken to actively assist the recovery (compare Fig. 2C & 2D). A principles-based approach to explore how the combination of *S* and *E* indicators influence ecological trajectories through time is helpful for both place-based environmental action plans to be designed and prioritized, but also for the management of expectations.

EBM calls for adaptive approaches and adaptive management frameworks (Allen et al., 2011). Conceptually, determining whether an adaptive management approach will be suitable for achieving aspirations depends on the likelihood of non-linear degradation in response to stressors and the ability to detect change early enough to act. If non-linear degradation in ecosystem status are possible, then adaptive management will be risky unless thresholds are known (Fig. 2B). The principles most important for informing risks associated with an adaptive management approach include those that consider the likelihood of non-linear degradation (E1–3, and S1–5; see risk matrix in Supplementary Material for more details). Adaptive management to improve ecosystem state could also apply the risk principles to identify whether an ecosystem is in a state where stressor reduction would work to achieve natural recovery, or whether actions to assist recovery are needed.

When stressor limits are imposed either through limits on pollutants

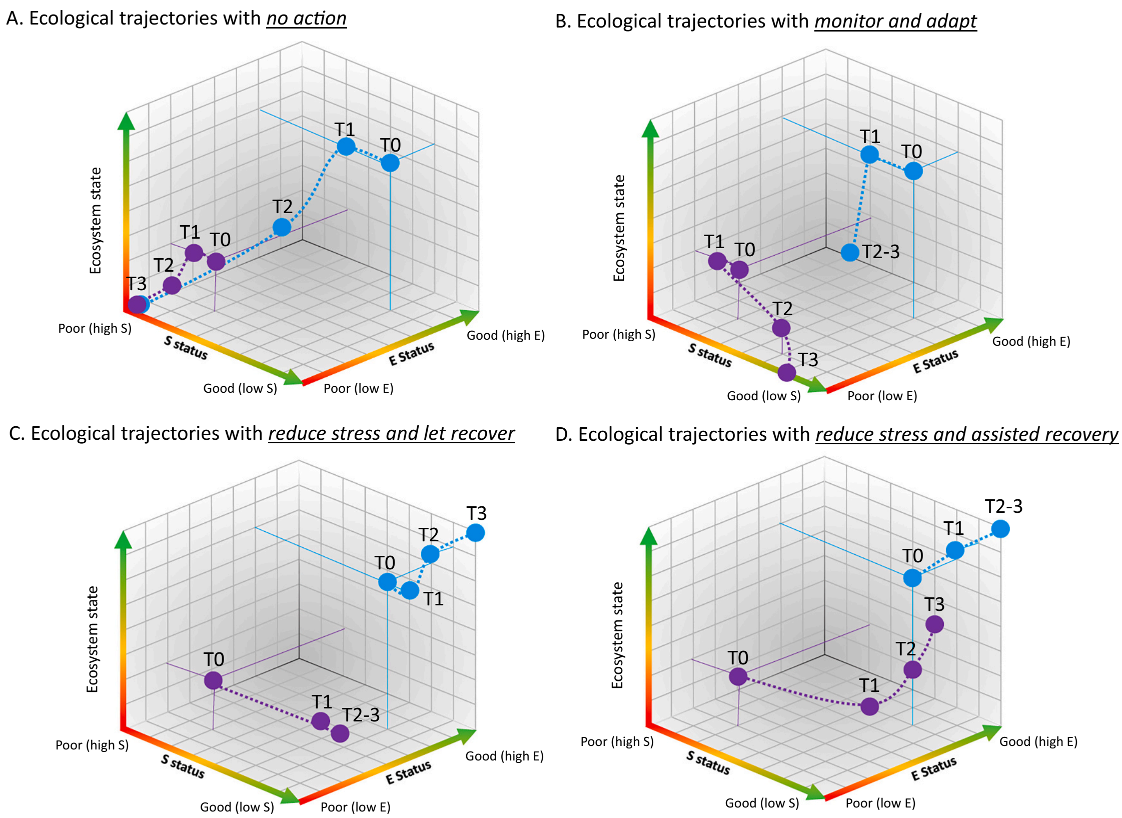

Fig. 2. Ecosystem state trajectories for two hypothetical ecosystems in response to management actions. The two ecosystems have differing initial ecological indicator (*E*) status (blue higher than purple), and they respond differently to different interventions: (**A**) With no actions to prevent decline or improve ecological status, both hypothetical ecosystems degrade in state through time (T0 to T3) (though at different rates); (**B**) If there are lag effects of stressors, monitor and adapting (at T2 in response to decline) may not be able to prevent further degradation due to lag effects (occurs for purple); (**C**) A reduce stress and let recover approach (where stressors are reduced at T0 will be successful in situations where the stressor regimes (*S)* have not created biological or physical legacies (i.e., *E* is still relatively good) (e.g., blue), otherwise there will be no improvement in ecosystem status (e.g., purple); (**D**) If reduce stress and let recover is unsuccessful on its own, interventions that assist recovery may be needed and speed of improvement depends on the starting ecosystem state (compare blue and purple). The bottom front left corner of each box represents the worst case scenario and the top back left corner of each box represents the best case scenario. For simplicity, we depict the *S* (stressor indicator status) and *E* based collectively as *E* and *S* scores (but see Box 1 which links each *S* and *E* indicator to risks of actions based on IF-THEN principles) on the x and z axes. The y axis represents the heath and functional status of the ecosystem. For example, a high 'Ecosystem State' represents an ecosystem's ability to respond, resist or adapt to change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or by protecting areas from certain activities, there is usually an assumption that ecosystem recovery is possible. However, this is not always the case and so 'reduce stress and let recover' actions will be timely if 1) there are not significant biological or physical legacies (E1 and S2), 2) the changes have not created new feedbacks that block recovery and result in hysteresis (E1, E2 and S5), and 3) the area is not large and isolated which prevents recovery occurring (E4–6 and S6) (Fig. 2C). If any of these are likely, recovery may slow, and active intervention to assist recovery may be required to change the future ecological trajectory to a desired one (Fig. 2D).

Importantly, actions to assist recovery must be targeted to move the ecosystem back along the ecological status scale (*E*) to restore resilience (Fig. 1). For example, placing structure that other organisms can grow on (E1) specifically targets assisted recovery by restoring some of the feedbacks associated with facilitatory relationships (E2) that can be lost (Ceccarelli et al., 2020; Reeves et al., 2020; Suding et al., 2004). If managing for recovery, the principles that will be informative for a 'reduce stress and recovery assist' approach are those that inform which aspects of the ecosystem that restoration could target to improve resilience (those associate with indicators E1–6) as well as ones that inform about the status of the remaining stressors (those associate with indicators S1–2).

5. Closing remarks

Our evaluation of ecological resilience and stressor status facilitates a novel appraisal of the likelihood of success of different interventions and importantly how to link a range of actions to match degradation states in marine ecosystems (Figs. 1 and 2). Our framework is a movement forward from mainstream environmental risk assessments that only focus on the stressors as the key drivers of change. Integrating this with principles about the ecosystem resilience expands capacity to deal with context dependencies and uncertainty in stressor responses. The focus on ecological and stressor principles are helpful for exploring likely rates of degradation and recovery in areas where information is limited and decisions may be postponed. There is vast empirical evidence that shows the significant consequences of delayed or mismatched actions and we urge managers and decision makers in coastal spaces to consider this evidence now.

Author contributions

All authors: Conceptualization; RGG, JE, JH: Writing – original draft; All authors: Writing – review and editing; JE, FS, JH, ST, CP: funding acquisition.

CRediT authorship contribution statement

Rebecca V. Gladstone-Gallagher: Conceptualization, Writing – original draft, Writing – review & editing. **Judi E. Hewitt:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Jasmine M.L. Low:** Conceptualization, Writing – review & editing. **Conrad A. Pilditch:** Conceptualization, Funding acquisition, Writing – review & editing. **Fabrice Stephenson:** Conceptualization, Funding acquisition, Writing – review & editing. **Simon F. Thrush:** Conceptualization, Funding acquisition, Writing – review & editing. **Joanne I. Ellis:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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.

Data availability

No data was used for the research described in the article.

Acknowledgements

We thank Lizzie Harrison for support with the graphical design.

Funding: This work was supported by the New Zealand National Science Challenge Sustainable Seas Projects 1.1 (Ecological responses to cumulative effects) and 3.2 (Communicating risk and uncertainty to aid decision making) established by the Ministry of Business, Innovation, and Employment, New Zealand (C01X1901).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2024.110516.

References

Abram, J.J., Dyke, J.G., 2018. Structural loop analysis of complex ecological systems. Ecol. Econ. 154, 333–342.

Alexander, K.A., Haward, M., 2019. The human side of marine ecosystem-based management (EBM): 'sectoral interplay' as a challenge to implementing EBM. Mar. Policy 101, 33–38.

Allen, C.R., Fontaine, J.J., Pope, K.L., Garmestani, A.S., 2011. Adaptive management for a turbulent future. J. Environ. Manage. 92, 1339–1345.

Andersen, J.H., Carstensen, J., Conley, D.J., Dromph, K., Fleming-Lehtinen, V., Gustafsson, B.G., Josefson, A.B., Norkko, A., Villnas, A., Murray, C., 2017. Long-term temporal and spatial trends in eutrophication status of the Baltic Sea. Biol. Rev. 92, 135–149.

Ban, S.S., Graham, N.A.J., Connolly, S.R., 2014. Evidence for multiple stressor interactions and effects on coral reefs. Glob. Chang. Biol. 20, 681–697.

Berlow, E.L., 1999. Strong effects of weak interactions in ecological communities. Nature 398, 330–334.

Ceccarelli, D.M., McLeod, I.M., Boström-Einarsson, L., Bryan, S.E., Chartrand, K.M., Emslie, M.J., Gibbs, M.T., Gonzalez Rivero, M., Hein, M.Y., Heyward, A., Kenyon, T. M., Lewis, B.M., Mattocks, N., Newlands, M., Schläppy, M.-L., Suggett, D.J., Bay, L. K., 2020. Substrate stabilisation and small structures in coral restoration: state of knowledge, and considerations for management and implementation. PloS One 15, e0240846.

Commito, J.A., Jones, B.R., Jones, M.A., Winders, S.E., Como, S., 2019. After the fall: legacy effects of biogenic structure on wind-generated ecosystem processes following mussel bed collapse. Diversity 11, 11.

Cormier, R., Stelzenmüller, V., Creed, I.F., Igras, J., Rambo, H., Callies, U., Johnson, L.B., 2018. The science-policy interface of risk-based freshwater and marine management systems: from concepts to practical tools. J. Environ. Manage. 226, 340–346.

Crain, C.M., Kroeker, K., Halpern, B.S., 2008. Interactive and cumulative effects of multiple human stressors in marine systems. Ecol. Lett. 11, 1304–1315.

Cranfield, H.J., Manighetti, B., Michael, K.P., Hill, A., 2003. Effects of oyster dredging on the distribution of bryozoan biogenic reefs and associated sediments in Foveaux Strait, southern New Zealand. Cont. Shelf Res. 23, 1337–1357.

Diefenderfer, H.L., Steyer, G.D., Harwell, M.C., LoSchiavo, A.J., Neckles, H.A., Burdick, D.M., Johnson, G.E., Buenau, K.E., Trujillo, E., Callaway, J.C., Thom, R.M., Ganju, N.K., Twilley, R.R., 2021. Applying cumulative effects to strategically advance large-scale ecosystem restoration. Front. Ecol. Environ. 19, 108–117.

Duarte, C.M., Agusti, S., Barbier, E., Britten, G.L., Castilla, J.C., Gattuso, J.-P., Fulweiler, R.W., Hughes, T.P., Knowlton, N., Lovelock, C.E., Lotze, H.K., Predragovic, M., Poloczanska, E., Roberts, C., Worm, B., 2020. Rebuilding marine life. Nature 580, 39–51.

Filbee-Dexter, K., Scheibling, R.E., 2014. Sea urchin barrens as alternative stable states of collapsed kelp ecosystems. Mar. Ecol. Prog. Ser. 495, 1–25.

Filbee-Dexter, K., Wernberg, T., 2018. Rise of turfs: a new battlefront for globally declining kelp forests. BioScience 68, 64–76.

Gladstone-Gallagher, R.V., Tylianakis, J.M., Yletyinen, J., Dakos, V., Douglas, E.J., Greenhalgh, S., Hewitt, J.E., Hikuroa, D., Lade, S.J., Le Heron, R., Norkko, A., Perry, G.L.W., Pilditch, C.A., Schiel, D., Siwicka, E., Warburton, H., Thrush, S.F., 2022. Social–ecological connections across land, water, and sea demand a reprioritization of environmental management. Elem. Sci. Anth. 10.

Harley, C.D.G., Connell, S.D., Doubleday, Z.A., Kelaher, B., Russell, B.D., Sarà, G., Helmuth, B., 2017. Conceptualizing ecosystem tipping points within a physiological framework. Ecol. Evol. 7, 6035–6045.

Hewitt, J., Gladstone-Gallagher, R., Thrush, S., 2022. Disturbance-recovery dynamics inform seafloor management for recovery. Front. Ecol. Environ. 20, 564–572.

Hewitt, J.E., Thrush, S.F., 2019. Monitoring for tipping points in the marine environment. J. Environ. Manage. 234, 131–137.

Holsman, K., Samhouri, J., Cook, G., Hazen, E., Olsen, E., Dillard, M., Kasperski, S., Gaichas, S., Kelble, C.R., Fogarty, M., Andrews, K., 2017. An ecosystem-based approach to marine risk assessment. Ecosyst. Health Sustain. 3, 16.

Howarth, R., Chan, F., Conley, D.J., Garnier, J., Doney, S.C., Marino, R., Billen, G., 2011. Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. Front. Ecol. Environ. 9, 18–26.

Janssen, M.A., Bodin, Ö., Anderies, J.M., Elmqvist, T., Ernstson, H., McAllister, R.R.J., Olsson, P., Ryan, P., 2006. Toward a network perspective of the study of resilience in social-ecological systems. Ecol. Soc. 11.

Johnston, E.C., Counsell, C.W.W., Sale, T.L., Burgess, S.C., Toonen, R.J., 2020. The legacy of stress: coral bleaching impacts reproduction years later. Funct. Ecol. 34, 2315–2325.

Kanwischer, M., Asker, N., Wernersson, A.-S., Wirth, M.A., Fisch, K., Dahlgren, E., Osterholz, H., Habedank, F., Naumann, M., Mannio, J., Schulz-Bull, D.E., 2021. Substances of emerging concern in Baltic Sea water: review on methodological advances for the environmental assessment and proposal for future monitoring. AMBIO. https://doi.org/10.1007/s13280-13021-01627-13286.

van Katwijk, M.M., Thorhaug, A., Marbà, N., Orth, R.J., Duarte, C.M., Kendrick, G.A., Althuizen, I.H.J., Balestri, E., Bernard, G., Cambridge, M.L., Cunha, A., Durance, C., Giesen, W., Han, Q., Hosokawa, S., Kiswara, W., Komatsu, T., Lardicci, C., Lee, K.-S., Meinesz, A., Nakaoka, M., O'Brien, K.R., Paling, E.I., Pickerell, C., Ransijn, A.M.A., Verduin, J.J., 2016. Global analysis of seagrass restoration: the importance of large-scale planting. J. Appl. Ecol. 53, 567–578.

Leadley, P., Gonzalez, A., Obura, D., Krug, C.B., Londoño-Murcia, M.C., Millette, K.L., Radulovici, A., Rankovic, A., Shannon, L.J., Archer, E., Armah, F.A., Bax, N., Chaudhari, K., Costello, M.J., Dávalos, L.M., Roque, F.d.O., DeClerck, F., Dee, L.E., Essl, F., Ferrier, S., Genovesi, P., Guariguata, M.R., Hashimoto, S., Ifejika Speranza, C., Isbell, F., Kok, M., Lavery, S.D., Leclère, D., Loyola, R., Lwasa, S., McGeoch, M., Mori, A.S., Nicholson, E., Ochoa, J.M., Öllerer, K., Polasky, S., Rondinini, C., Schroer, S., Selomane, O., Shen, X., Strassburg, B., Sumaila, U.R., Tittensor, D.P., Turak, E., Urbina, L., Vallejos, M., Vázquez-Domínguez, E., Verburg, P.H., Visconti, P., Woodley, S., Xu, J., 2022. Achieving global biodiversity goals by 2050 requires urgent and integrated actions. One Earth 5, 597–603.

van de Leemput, I.A., Hughes, T.P., van Nes, E.H., Scheffer, M., 2016. Multiple feedbacks and the prevalence of alternate stable states on coral reefs. Coral Reefs 35, 857–865.

Lotze, H.K., Lenihan, H.S., Bourque, B.J., Bradbury, R.H., Cooke, R.G., Kay, M.C., Kidwell, S.M., Kirby, M.X., Peterson, C.H., Jackson, J.B.C., 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312, 1806–1809.

Lotze, H.K., Coll, M., Magera, A.M., Ward-Paige, C., Airoldi, L., 2011. Recovery of marine animal populations and ecosystems. Trends Ecol. Evol. 26, 595–605.

Månsson, J., Eriksson, L., Hodgson, I., Elmberg, J., Bunnefeld, N., Hessel, R., Johansson, M., Liljebäck, N., Nilsson, L., Olsson, C., Pärt, T., Sandström, C., Tombre, I., Redpath, S.M., 2023. Understanding and overcoming obstacles in adaptive management. Trends Ecol. Evol. 38, 55–71.

Maxwell, P.S., Eklöf, J.S., van Katwijk, M.M., O'Brien, K.R., de la Torre-Castro, M., Boström, C., Bouma, T.J., Krause-Jensen, D., Unsworth, R.K.F., van Tussenbroek, B. I., van der Heide, T., 2017. The fundamental role of ecological feedback mechanisms for the adaptive management of seagrass ecosystems – a review. Biol. Rev. 92, 1521–1538.

Nyström, M., Norström, A.V., Blenckner, T., de la Torre-Castro, M., Eklöf, J.S., Folke, C., Österblom, H., Steneck, R.S., Thyresson, M., Troell, M.J.E., 2012. Confronting feedbacks of degraded marine ecosystems. Ecosystems 15, 695–710.

Österblom, H., Crona, B.I., Folke, C., Nystrom, M., Troell, M., 2017. Marine ecosystem science on an intertwined planet. Ecosystems 20, 54–61.

Pilditch, C.A., Valanko, S., Norkko, J., Norkko, A., 2015. Post-settlement dispersal: the neglected link in maintenance of soft-sediment biodiversity. Biol. Lett. 11, 20140795.

Reeves, S.E., Renzi, J.J., Fobert, E.K., Silliman, B.R., Hancock, B., Gillies, C.L., 2020. Facilitating better outcomes: how positive species interactions can improve oyster reef restoration. Front. Mar. Sci. 7.

Satterstrom, K.F., Linkov, I., Kiker, G., Bridges, T., Greenberg, M., 2007. Adaptive management. In: Macey, G.P., Cannon, J.Z. (Eds.), Reclaiming the Land: Rethinking Superfund Institutions, Methods and Practices. Springer US, Boston, MA, pp. 89–128.

Schiel, D.R., Howard-Williams, C., 2016. Controlling inputs from the land to sea: limit-setting, cumulative impacts and ki uta ki tai. Mar. Freshw. Res. 67, 57–64.
Selkoe, K.A., Blenckner, T., Caldwell, M.R., Crowder, L.B., Erickson, A.L., Essington, T.E., Estes, J.A., Fujita, R.M., Halpern, B.S., Hunsicker, M.E., Kappel, C.V., Kelly, R.P., Kittinger, J.N., Levin, P.S., Lynham, J.M., Mach, M.E., Martone, R.G., Mease, L.A., Salomon, A.K., Samhouri, J.F., Scarborough, C., Stier, A.C., White, C., Zedler, J., 2017. Principles for managing marine ecosystems prone to tipping points. Ecosyst. Health Sustain. 1, 1–18.
Simmons, B.I., Blyth, P.S.A., Blanchard, J.L., Clegg, T., Delmas, E., Garnier, A., Griffiths, C.A., Jacob, U., Pennekamp, F., Petchey, O.L., Poisot, T., Webb, T.J., Beckerman, A.P., 2021. Refocusing multiple stressor research around the targets and scales of ecological impacts. Nat. Ecol. Evol. 5, 1478–1489.
Suding, K.N., Gross, K.L., Houseman, G.R., 2004. Alternative states and positive feedbacks in restoration ecology. Trends Ecol. Evol. 19, 46–53.
Supreme Court of New Zealand, 2014. Sustain our Sounds Incorporated V the New Zealand King Salmon Company Limited NZSC 40 [17 April 2014]. Supreme Court of New Zealand, Wellington.
Thrush, S., Whitlatch, R., 2001. Recovery dynamics in benthic communities: Balancing detail with simplification. In: Ecological Comparisons of Sedimentary Shores. Springer, Berlin Heidelberg, pp. 297–316.
Thrush, S.F., Hewitt, J.E., Norkko, A., Cummings, V.J., Funnell, G.A., 2003a. Macrobenthic recovery processes following catastrophic sedimentation on estuarine sandflats. Ecol. Appl. 13, 1433–1455.
Thrush, S.F., Hewitt, J.E., Norkko, A., Nicholls, P.E., Funnell, G.A., Ellis, J.I., 2003b. Habitat change in estuaries: predicting broad-scale responses of intertidal macrofauna to sediment mud content. Mar. Ecol. Prog. Ser. 263, e112.
Thrush, S.F., Hewitt, J.E., Cummings, V.J., Ellis, J.I., Hatton, C., Lohrer, A., Norkko, A., 2004. Muddy waters: elevating sediment input to coastal and estuarine habitats. Front. Ecol. Environ. 2, 299–306.
Thrush, S.F., Hewitt, J.E., Lohrer, A.M., Chiaroni, L.D., 2013. When small changes matter: the role of cross-scale interactions between habitat and ecological connectivity in recovery. Ecol. Appl. 23, 226–238.
Thrush, S.F., Hewitt, J.E., Gladstone-Gallagher, R.V., Savage, C., Lundquist, C., O'Meara, T., Vieillard, A., Hillman, J.R., Mangan, S., Douglas, E.J., Clark, D.E., Lohrer, A.M., Pilditch, C., 2021. Cumulative stressors reduce the self-regulating capacity of coastal ecosystems. Ecol. Appl. 31, e02223.
Whitlatch, R.B., Lohrer, A.M., Thrush, S.F., Pridmore, R.D., Hewitt, J.E., Cummings, V.J., Zajac, R.N., 1998. Scale-dependent benthic recolonization dynamics: life stage-based dispersal and demographic consequences. Hydrobiologia 375, 217–226.
Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J., Watson, R., 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314, 787–790.
Zajac, R.N., 1999. Understanding the sea floor landscape in relation to impact assessment and environmental management in coastal marine sediments. In: Gray, J.S., Ambrose, W., Szaniawska, A. (Eds.), Biogeochemical Cycling and Sediment Ecology. Springer, Netherlands, Dordrecht, pp. 211–227.