National SCIENCE Challenges

SUSTAINABLE SEAS

Ko ngā moana whakauka

An ecological principles-based approach to guide coastal environmental management

Summary

This is a summary of three academic publications from the *Ecological responses to cumulative effects* and *Communicating risk and uncertainty to aid decision making* research projects.

Gladstone-Gallagher, R. V., Thrush, S. F., Low, J. M. L., Pilditch, C. A., Ellis, J. I., & Hewitt, J. E. (2023). Toward a network perspective in coastal ecosystem management. *Journal of Environmental Management, 346*, 119007. doi.org/10.1016/j.jenvman.2023.119007

Low, J. M. L., Gladstone-Gallagher, R. V., Hewitt, J. E., Pilditch, C. A., Ellis, J. I., & Thrush, S. F. (2023). Using Ecosystem Response Footprints to Guide Environmental Management Priorities. *Ecosystem Health and Sustainability, 9*, 0115. doi:10.34133/ehs.0115.

Gladstone-Gallagher, R. V., Hewitt, J. E., Low, J. M. L., Pilditch, C. A., Stephenson, F., Thrush, S. F., & Ellis, J. I. (2024). Coupling marine ecosystem state with environmental management and conservation: A risk-based approach. *Biological Conservation, 292*, 110516. doi:10.1016/j.biocon.2024.110516.

April 2024

Ecological responses to cumulative effects are difficult to predict

A major challenge for coastal marine management is the cumulative effects that arise from human activities and natural events which can alter the ecology of a system and its ability to respond and be resilient to stress. Often ecosystems are exposed to a variety of stressors that are driven by multiple human activities that overlap in space and/or time. Multiple stressors can arise from a single activity and the accumulation and interaction between different stressors can result in ecosystem responses much greater than the sum of the individual stressor effects. Ecosystem responses to cumulative effects, which often come as "surprises" to managers, are driven by a range of characteristics generally specific to place and time. This can make it difficult to predict ecological responses to cumulative effects and the outcomes of different management actions (Rojas-Nazar et al. 2023).

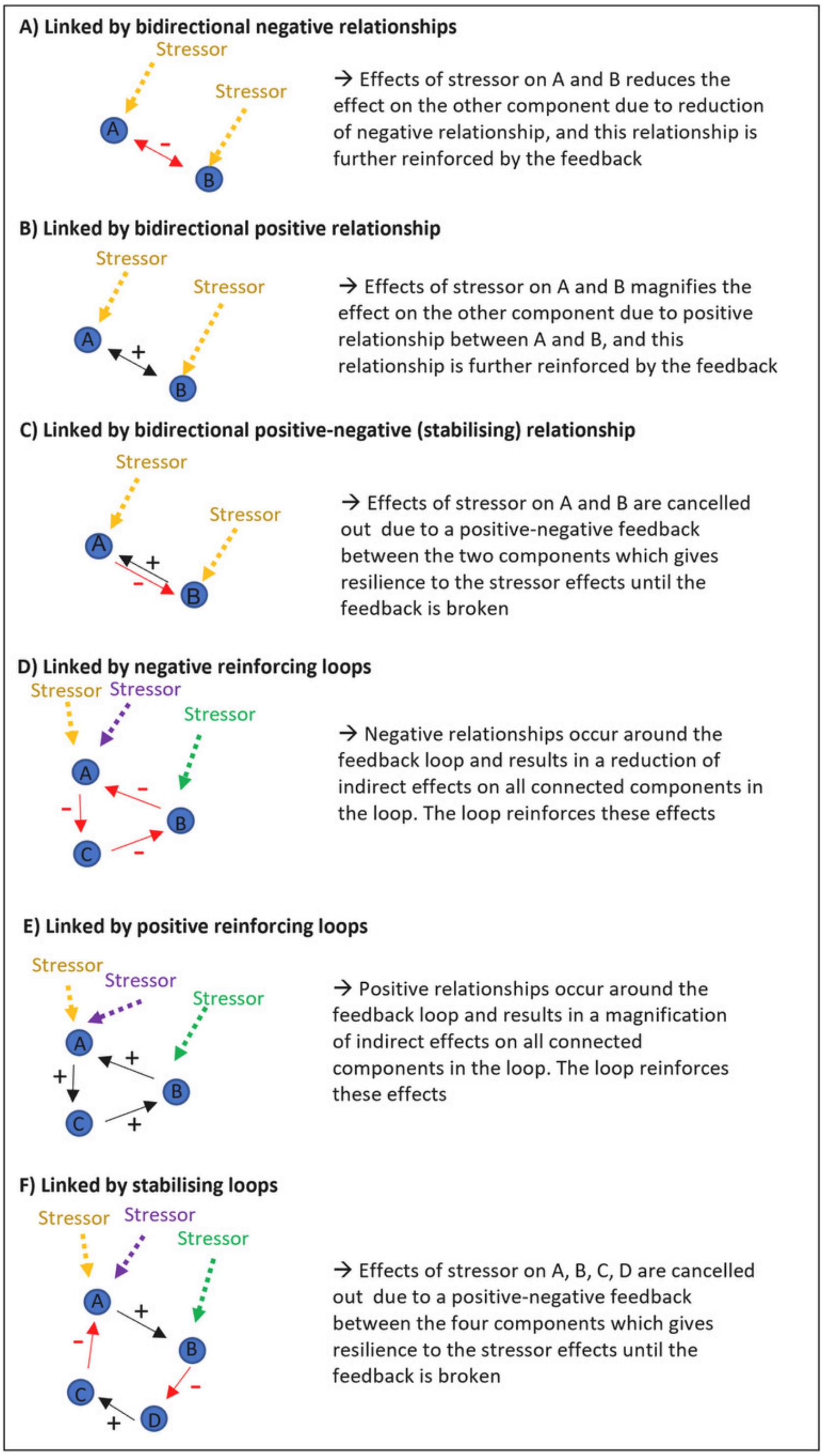
Marine and coastal management approaches have often focused on identifying activity and stressor footprints. These footprints are the areas where an activity is taking place and the area that is being affected by a stressor, and are used to assess the potential scale of impact and the types of stressors that arise from different activities. Current assessments of cumulative effects involve calculating cumulative impact scores by overlapping stressor footprints and ecosystem vulnerability/sensitivity assessments. However, these assessments do not consider the potential spatial and temporal mismatches between the stressor footprints and the areas where the ecological responses occur. As a result, current management approaches are often mismatched with scales of ecosystem degradation and recovery. This mismatch means that the effectiveness of current management actions may be reduced, and ecosystem degradation may continue to occur.

Whilst there is a strong desire among managers to consider the complexity in ecological responses to cumulative effects, uncertainty arises when data and information for a place is limited, as is commonly the case. This uncertainty can delay management action being undertaken, increasing the potential for ecosystem degradation and legacy effects or hysteresis that can make ecosystem recovery (here referred to as the return of ecosystem functionality) more difficult and less timely (Hewitt et al. 2022).

It is now recognised that marine management needs to shift from a focus on individual activities/stressors to an ecosystem-based management approach that holistically considers the implications of human activities on marine ecosystems and characteristics of the ecosystems themselves (Hewitt et al. 2018). A key aspect identified as being needed for an ecosystem-based approach to cumulative effects is the recognition that ecosystems are networks of interacting components (Gladstone-Gallagher et al. 2023). For every combination of stressors, there are often multiple direct and indirect effects on different ecosystem components and these effects can differ through space and time, influencing ecosystem resilience and recovery.

Additionally, interactions and feedbacks within the network can reinforce or slow degradation and recovery depending on their nature (Figure 1). This means that ecosystems have the ability to respond and adapt to stressors (i.e., through network reorganisation or structural shifts), rather than just be 'affected' by stressors. A shift in focus to an understanding of ecosystem attributes, such as network structure and the number of indirect connections, that drive context dependencies and complex unpredictable outcomes could provide a means of managing for cumulative effects applicable to data scarce and data rich situations.

Figure 1: *Bi-directional interactions and feedbacks can reinforce or stabilise against indirect effects (Gladstone-Gallagher et al. 2023). Positive interactions among components are indicated with black arrows and negative interactions are indicated with red arrows. In this diagram, the stressor effects on components A and B are negative, but if the stressor effect was positive, the opposite indirect effect would occur in panels A, B, D and E. Note the yellow stressor arrows could be either a single stressor that impacts multiple components or two different stressors.*



Ecological and stressor principles

The ecological surprises arising from cumulative effects are challenging for environmental managers. To support decision making in an ecosystem-based management approach to cumulative effects, Sustainable Seas researchers have developed a series of principles related to ecological and stressor attributes. These principles are the foundation for 'ecosystem response footprint' (Low et al. 2023) and 'ecological and stressor state risk assessment' (Gladstone-Gallagher et al. 2024) frameworks that can be utilised to inform the most appropriate management actions in the context of cumulative effects.

The ecological and stressor principles are presented in Table 1 and are generally described as follows:

Ecological (E) – principles which account for an ecosystem's ability to respond, resist, or adapt to change. These principles recognise the role of intrinsic ecological dynamics and particular types of species in generating responses.

Stressor (S) – principles that characterise the stressor regime, either past, present, or predicted future. These principles focus on the ecosystem elements they impact on and how stressor effects interact.

These principles incorporate attributes of the ecosystem interaction networks described by Gladstone-Gallagher et al. 2023 (Table 1: E2, E3, S1 & S5) and characteristics of an ecosystem's ecology and stressor regimes that are likely to contribute to the speed of ecological degradation or recovery. These principles can provide an understanding of not only the recovery potential of an ecosystem, but also the timescales involved which is paramount to informing the most appropriate action and managing societal expectations. By focusing on ecological, mātauranga Māori and local knowledge, these principles can be applied even in data scarce situations and reduce the need to measure or know every single cause and effect relationship that exists in each place.

Table 1*: Summary of the ecological (E) and stressor (S) principles. Principle names and definitions/explanations are as listed in Gladstone-Gallagher et al., 2024 with linkages to the principle/characteristic names used in Gladstone-Gallagher et al., 2023 (see Appendix Table A1) and Low et al., 2023 (see Appendix Table A2).*

Ecological principles		*Definition/Explanation*
E1	The status of the 'slow' to regenerate ecosystem structural components. (D4 in Low et al. 2023).	High = slow structural components present (e.g., kelp, corals, shellfish or other key habitat forming species). Low = the slow structural components have been lost from/not present in the system, therefore additional stress is less likely to result in further degradation as species have already been lost.
E2	The status of the ecological network structure - the number and type of feedback loops. (D5 in Low et al. 2023; NC4 in Gladstone-Gallagher et al. 2023).	High = there are a number of balancing/stabilising loops (containing positive and negative connections) which provide resilience to increasing stress. Low = network structure is dominated by unidirectional loops (all positive or negative) which generate runaway effects (i.e., reinforcing indirect stressor effects). Extremely low = a simple network with some balancing loops that maintain ecosystems in a degraded state and prevent recovery.
E3	Status of ecological principal processes (e.g., nutrient removal, oxygen production) that regulate ecosystem resilience. (NC4 in Gladstone-Gallagher et al. 2023).	High = ecosystems with a good state of ecological regulating functions (such as shellfish or seagrass beds) may have high nutrient processing capacity and oxygen generation through photosynthesis. Low = ecosystems with low ecological regulating functions (e.g. mudflats) may possess low capacity to process nutrients and therefore have lower resilience to eutrophication. When E3 is low but E1 and E2 are still high, the system may be on the verge of an unexpected change in status. When E3 is extremely low and E1 and E2 are also low, a regime shift to a more degraded state may have occurred, slowing recovery.
E4	The connectivity to other ecologically similar areas. (S3 in Low et al. 2023).	High = ecosystems with habitats that have a high level of connectivity within and outside of the area of interest, such as through the provision of spat or juveniles or acting as a pathway to facilitate this process (e.g. the movement of juvenile pipi from one area of a harbour to another). Low = ecosystems with habitats that are isolated from a supply of recruits which can limit future recovery.
E5	The diversity of habitat types (environmental and biotic) at the seascape scale. (S4 and S5 in Low et al. 2023).	High = areas with higher habitat diversity are linked to high connectivity (E4) which provides resilience and quicker recovery by providing more ‘options’ for recovering communities. Low = areas with low habitat diversity are linked to low biodiversity and connectivity. In areas where the impact area is large relative to the area that provides potential recruits for recovery, recovery lags are likely.
E6	The size of the ecosystem of interest. (S5 in Low et al. 2023).	High = large spatial extents are less likely to have stressor footprints that encompass the whole area and thereby may have higher resilience. Low = smaller areas where the stressor footprint is more likely to encompass the entire area which increases the likelihood of ecosystem degradation.

Table 1 continued.

Stressor principles		*Definition/Explanation*
S1	The number of stressors. (S1 and D1 in Low et al. 2023; NC2 in Gladstone-Gallagher et al. 2023).	High = multiple stressors present which increases the potential for non-linear and rapid ecosystem degradation. Low = no (or one) stressor present.
S2	The number of stressors that accumulating over time. (D2, D3 & S2 in Low et al. 2023).	High = stressors present that are chronic and accumulating which are more likely to cause non-linear ecosystem degradation and slow recovery. Low = none or one stressor that accumulates slowly is present.
S3	Levels of stressors that generate unimodal responses. (e.g., initial increases in stressors such as temperature, nutrients and sediment mud content can result in an initial positive effect on biodiversity and/or slow structural components (E2) then switch to a negative effect).	High = high levels of such stressors can result in cumulative stressor effects that can be greater than the individual effects of different stressors (i.e., synergistic responses). Low = low levels of such stressors can mitigate the negative effects of other stressors.
S4	Levels of stressors that generate responses other than unimodal. (e.g., toxic contaminants and microplastics decrease biodiversity exponentially).	High = if multiple stressors are present, these stressors can increase the likelihood of synergistic responses (i.e., responses that are greater than the sum of individual stressors). Low = none/few of such stressors.
S5	Number of points of impact and indirect effects on an ecological network. (NC1 & NC3 in Gladstone-Gallagher et al. 2023).	High = stressors present which impact multiple ecosystem components and cause multiple indirect effects and are more likely to increase the rate of degradation (e.g. increasing soil inputs from land initially elevates water column turbidity effecting photosynthesis, but also modifies sedimentation altering sediment porosity, bacteria, and the macrofauna which generate cascading impacts on nutrient processing and oxygen production). Low = none/few of such stressors.
S6	Size of the impacted area (relative to the ecosystem of interest or managed area (i.e., stressor footprint)).	High = large impacted areas increasing the probability of spillover impacts to other areas and when combined with low E5 or E6 make lags in ecosystem recovery more likely. Low = small impacted area (relative to the managed area) is more likely to result in positive recovery outcomes.

Ecosystem response footprints

Ecosystem response footprints (ERF) describe the spatial and temporal scale of an ecosystem's response to stressors (Figure 2). ERF are conceptualised based on ecological characteristics that are place and time specific. The footprints of activities, the stressors they generate, and resulting ecosystem responses are rarely the same. For example, an ERF that is larger than the stressor footprint can occur when the combination of multiple stressors creates an effect that is larger than the sum of the individual stressors or if legacy and carryover effects cause the ecosystem response to persist for longer than the stressor (Figure 2 Seascape 1.1 A and B). Additionally, areas of an ecosystem may have different sensitivities to stressors, resulting in a patchwork like response (e.g., Figure 2 Seascape 1.2 C).

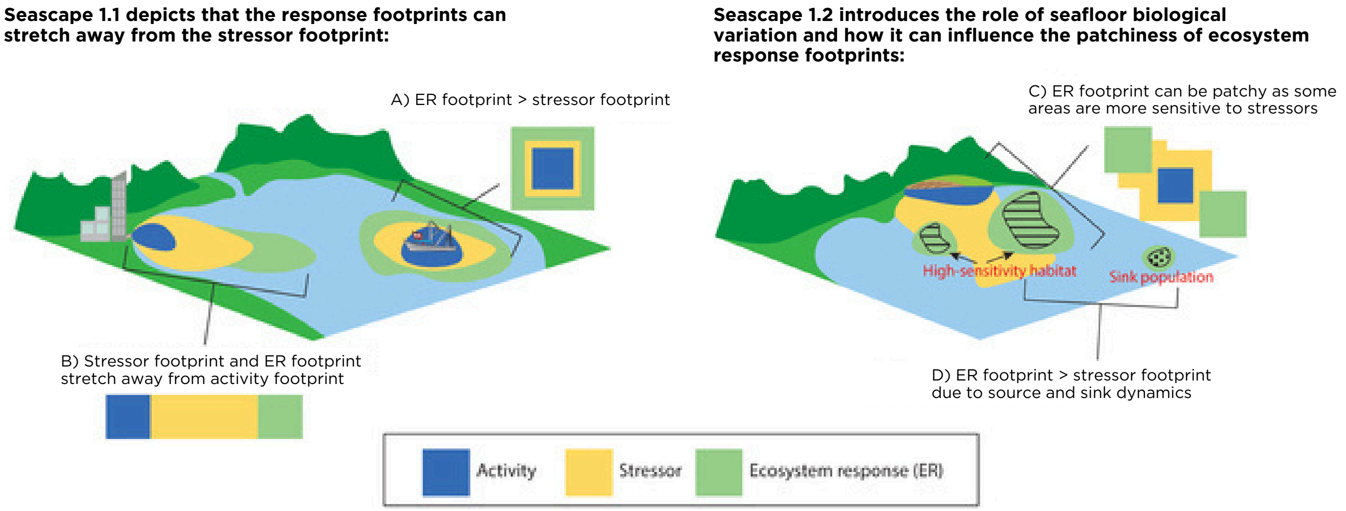


Figure 2*: Activity and stressor footprints generate ecosystem response footprints (ERF) because seascapes can have varying levels of physical and biological variation and connectivity (Low et al. 2023). For simplicity, seascapes 1.1 and 1.2 show single-stressor responses, but in reality, seascapes are mosaics of responding patches to multiple stressors.*

ERF are characterised by both the spatial extent (hereafter 'size') and temporal elements (hereafter 'depth') of ecosystem response (Figure 3);

Size - the area of the ecosystem that is responding to/has been affected by cumulative effects.

Depth - characterises the magnitude of the response that is linked to the potential for recovery.

The size and depth of the ERF can be characterised using the ecological and stressor principles (Figure 3). Stressor principles (S1) number of stressors and (S2) how many stressors are accumulating and ongoing, inform both the size and depth (via physical legacies) of the ERF, which can be increased with higher S1 and S2. Ecological principles (E4) ecological connectivity to other areas, (E5) diversity of habitat types, and (E6) the size of the ecosystem, also inform the size, shape, and patchiness of the ERF. If these ecological principles are high, this can cause patchy response footprints or create mismatches between response and stressor footprints (e.g., impacts on source areas of recruits can affect sink areas; Figure 2 Seascape 1.2). Additionally, ecological principles (E1) the status of the slow to regenerate ecosystem components and (E2) the status of the ecological network structure, inform the depth of the ERF, which is increased with lower E1 and E2.

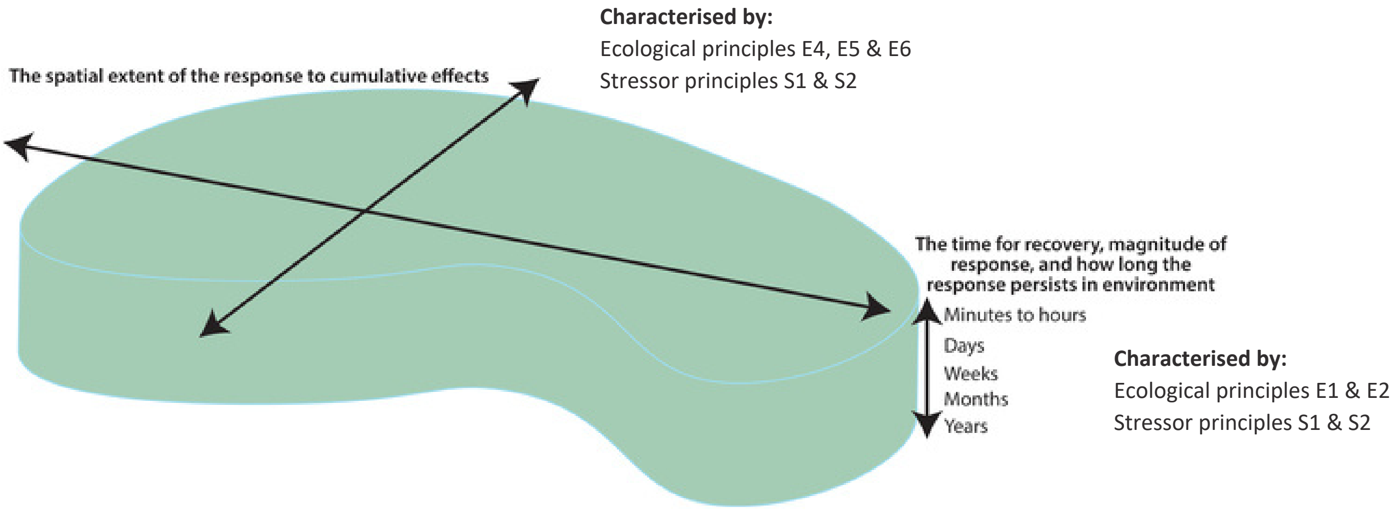


Figure 3*: Conceptual footprint of the ecosystem's response to multiple stressors. We suggest that response footprints need to be characterised by spatial extent and depth.*

Ecological and stressor states

Collectively, the ecological and stressor principles can be used to define the ecological and stressor state of an ecosystem (Figure 4). The ecological and stressor states of a system can be used to dictate the degree of ecological degradation coupled with the stressor regime. Importantly, a high ecological state means that the ecosystem has resilience to increasing stress and recovery potential.

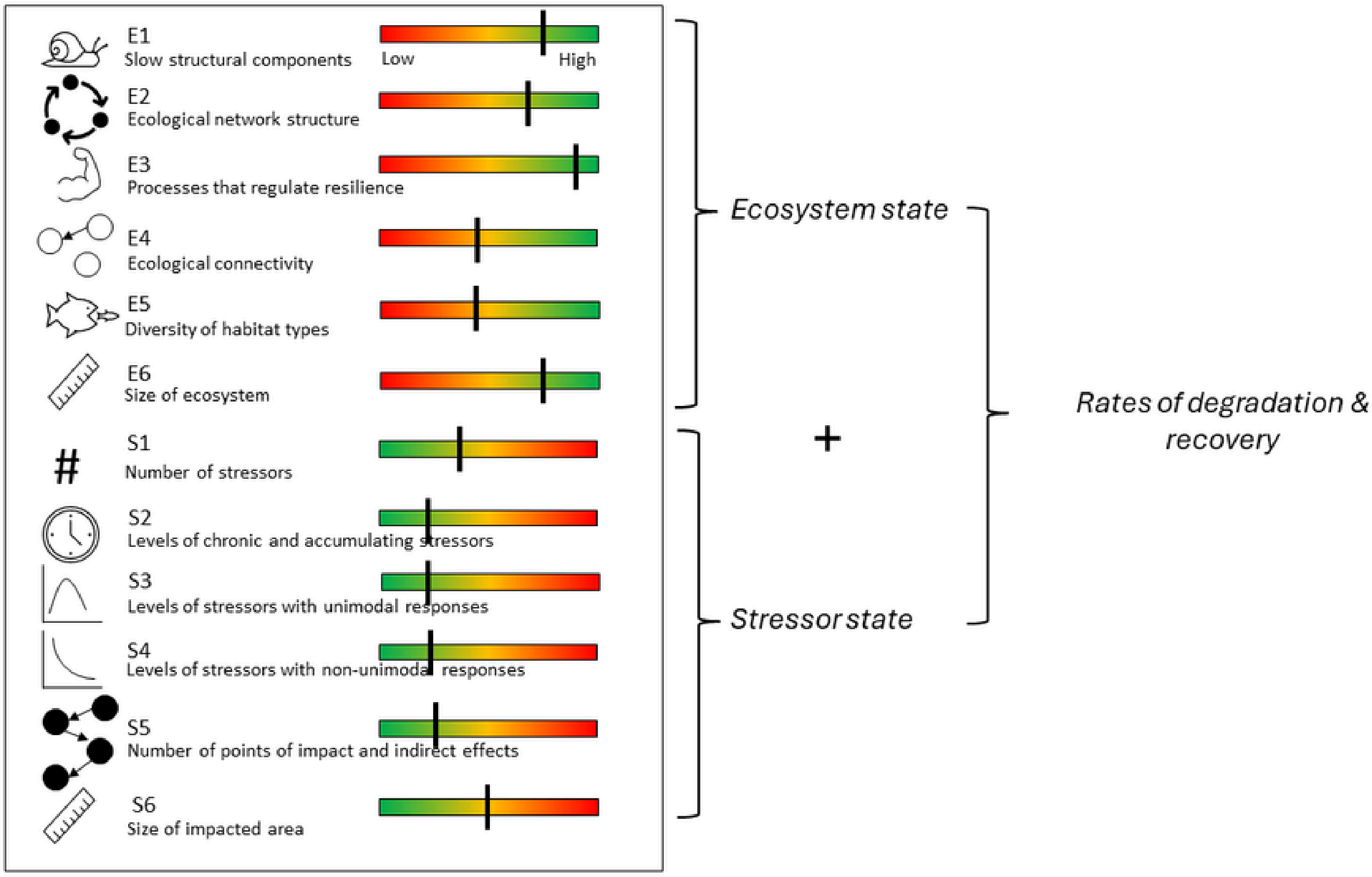


Figure 4*: Example of how ecological (E) and stressor (S) principles can collectively inform ecosystem ecological and stressor sates and rates of degradation or recovery.*

Guiding management actions: A path to decision-making

The size and depth of the ERF and the ecological and stressor state of an ecosystem call for different management actions to improve and/or retain ecosystem health and functionality (Figure 5 & 6). Management options include:

Stressor reduction ('reduce and let recover') – 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.

Adaptive management – involves an iterative process of monitoring environmental indicators to assess the effects of stressors on environmental state and/or the effectiveness of management actions. To be effective, monitoring the right indicators at an appropriate spatial and temporal scale must be aligned with the ability of managers to act quickly to halt degradation.

Active intervention ('assisted recovery') – active intervention is required when the natural recovery of ecosystem health is not possible within socially acceptable timeframes. In these circumstances, recovery lags and the shifting of an ecosystem to a new, but less desirable state, limiting the effectiveness of 'reduce stress and let recover' actions. In highly stressed environments, the active intervention approach will be most successful when coupled with appropriate stressor reduction.

The use of the principle-based frameworks can facilitate place-based conversations regarding the risk of different management actions. ERFs can indicate the likelihood of an ecosystem to undergo an ecological shift, which conceptually increases as the ERF increases in size and depth (Figure 5B). Further, ERFs can inform the uncertainty associated with different management actions and ecosystem responses (Figure 5C). Due to our poor ability to predict when an ecosystem may undergo an ecological shift, the uncertainty of ecological outcomes is highest when ERFs are moderate in size and depth.

Determining ecological and stressor states can provide managers with a risk assessment tool to indicate the potential ecosystem degradation or recovery trajectories of a system in response to different management actions (Figure 6). For example, a reduce stress and let recover management approach may improve ecosystem health in ecosystems with high ecological status, but ecosystems with low ecological status may also require interventions that assist recovery to improve ecosystem health (Figure 6B vs. C). The principle-based frameworks can therefore provide information related to ecosystem vulnerability and can assist in determining which management approaches will be most suitable and inform decisions about when early interventions and/or conservative approaches are needed.

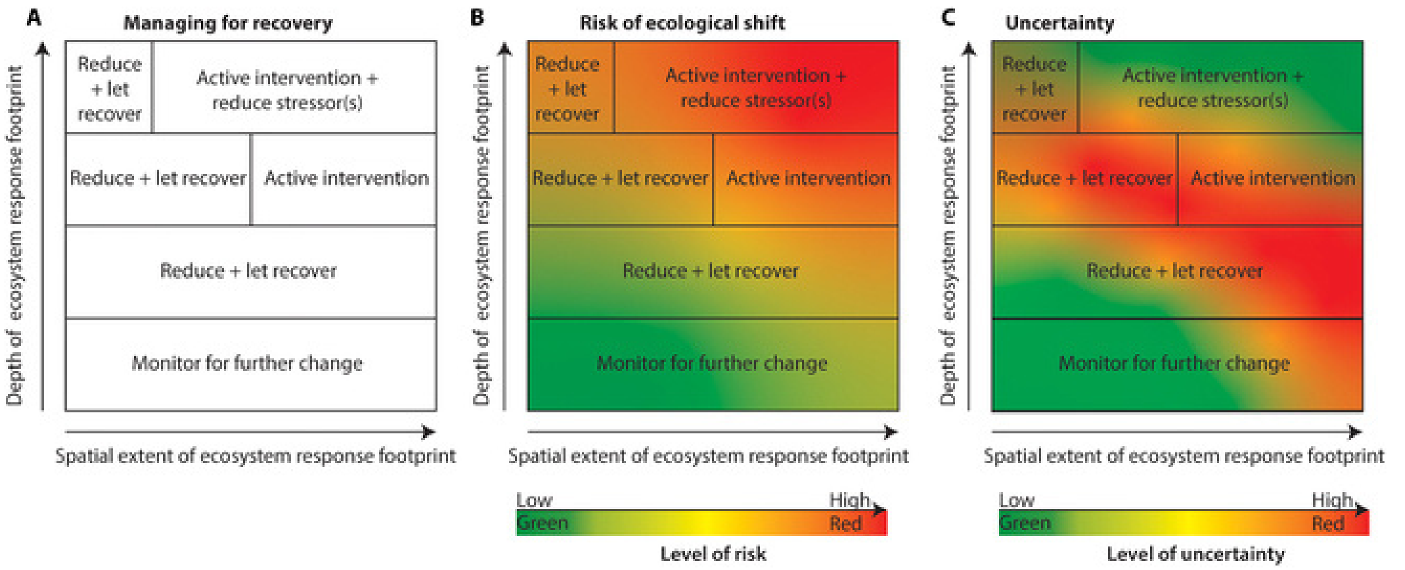


***Figure 5**: (A) Summary of the type of management actions that are likely required to manage different types of response footprints, as well as (B) the level of risk of poor ecological outcomes and (C) the uncertainty surrounding this risk (Low et al. 2023).*

Better management of cumulative effects in marine ecosystems is needed now and further delay in action or use of actions mismatched with rates of degradation and recovery will have significant consequences on the health of marine environments. The principle-based frameworks can facilitate a shift in focus for marine management where outcomes are appraised against the context-dependencies in the place of interest even where ecological and stressor information is incomplete or unknown. These frameworks can help identify best practices for prioritising stressor management alongside prioritising the ecosystem components that are critical for enhancing ecosystem resilience and give environmental agencies some useful anchors for their policies and procedures.

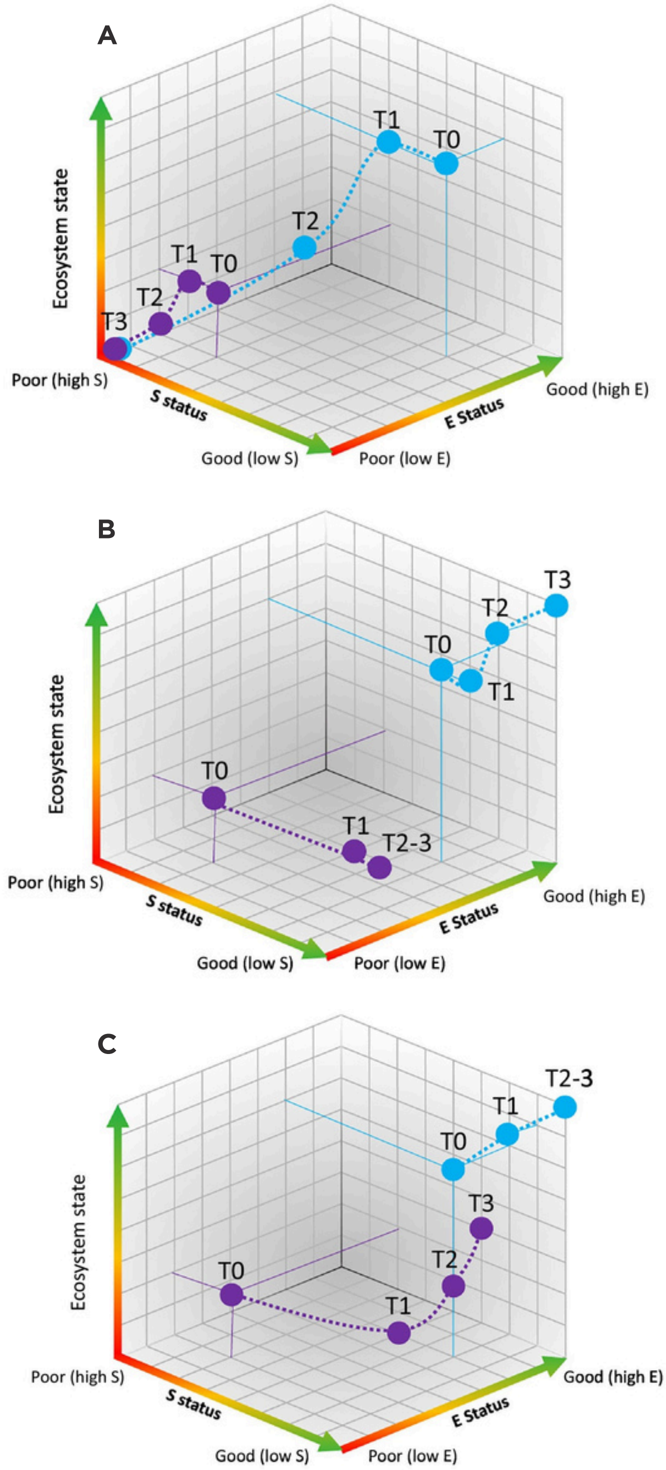


Figure 6: *Ecosystem state trajectories for two hypothetical ecosystems with differing initial ecological (E) status (Blue: high, Purple: low) in response to management actions: (A) with no actions to prevent decline or improved ecological status, (B) with a reduce stress and let recover approach, and (C) with assisted recovery alongside reduced stress. S refers to stressor regime, while the y axis represents the health and functional status of the ecosystem.*

References

Hewitt et al. (2022) Disturbance–recovery dynamics inform seafloor management for recovery. Sustainable Seas National Science Challenge

Hewitt, J., Faulkner, L., Greenaway, A., and Lundquist, C. (2018). Proposed ecosystem-based management principles for New Zealand. Resource Management Journal (Auckland, NZ), 10-13.

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Appendix

Table A1: Summary of network characteristic principles included in Gladstone-Gallagher et al., 2023.

	Characteristic
Network characteristic 1 (NC1)	The number of network components impacted is related to the likelihood of indirect effects.
Network characteristic 2 (NC2)	As the number or magnitude of stressors increases, the complexity, and rate of change, of ecological responses initially increases then decreases.
Network characteristic 3 (NC3)	The nature and direction of ecosystem interactions controls magnification or amelioration of indirect effects.
Network characteristic 4 (NC4)	Feedbacks within ecosystem interaction networks can either 'reinforce' indirect stressor effects or 'stabilise' and provide resilience.

Table A2: Summary of the ecological principles that characterise spatial extent (S) and depth (D) of ecosystem response footprints.

	Spatial extent		**Depth**
S1	Incidence of multiple stressors can increase or decrease the size of the response footprint relative to single stressor footprints.	D1	Incidence of multiple stressors can increase or decrease the depth of the response footprint due to non-additive responses.
S2	Dispersal characteristics of stressors can shape the size of response footprints.	D2	Temporal duration of stressors increases depth of response footprint.
S3	Biological connectivity within or between ecological components is implicated in a mismatch between response footprint and stressor footprint.	D3	Dispersal characteristics of stressor can contribute to depth of response footprint through physical legacies.
S4	Landscape species diversity will be implicated in the patchiness of the response footprint.	D4	Depth of response footprint increases if responses involve slow-to-regenerate ecosystem elements.
S5	Heterogeneity in species and habitat sensitivity to stressors can lead to patchy response footprints.	D5	Depth of response footprint increases if responses involve ecosystem element(s) implicated in feedbacks (e.g., structural components that create recovery lags if lost).