National Science Challenges | SUSTAINABLE SEAS | Ko ngā moana whakauka

Addressing cumulative effects in marine management decisions

Cumulative effects need to be urgently addressed to halt the degradation of our marine ecosystems and the decline in services ecosystems provide. The costs of environmental degradation are significant – with impacts to cultural, social, and recreational values, risks to fishery and tourism industries, and the risk of failure to meet national and international obligations.

Moving away from managing activities and stressors in isolation to using an ecological footprint approach is essential. We can achieve better marine outcomes by introducing a decision-making approach that assesses and manages cumulative effects more effectively.

Cumulative effects in marine ecosystems come from incremental, accumulating, and interacting stressors. These stressors come from human activities and natural events, and they can overlap in space and time.

About this document

This guidance document aims to help you improve the ecological assessment of cumulative effects within a consent, plan, or policy context. The advice is based on Sustainable Seas National Science Challenge research. The main audience is regional and central government, as well as people and organisations involved in environmental management. This document:

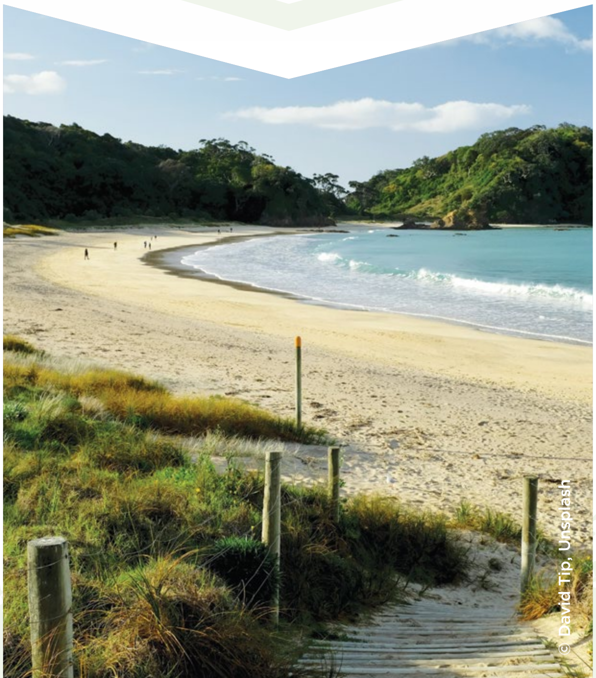
- explains what cumulative effects are and why they matter
- looks at limitations of current ecological assessments
- recommends an ecological footprint approach and a four-step action plan
- gives examples of applying the plan to different types of application.

Recommendations

Addressing cumulative effects is a key step towards arresting further environmental degradation and shifting our focus towards ecosystem recovery – helping to sustain the marine environment and the benefits it provides for future generations.

To address cumulative effects, we recommend that environmental managers:

- transition from managing activities and stressors in isolation to focusing on managing ecological responses to cumulative effects
- ensure assessments of cumulative effects are ecologically relevant and account for:
  - ecological resilience and vulnerability
  - ecological connectivity
  - ecological responses to multiple interacting stressors through space and time.



What are cumulative effects and why do we need to consider them?

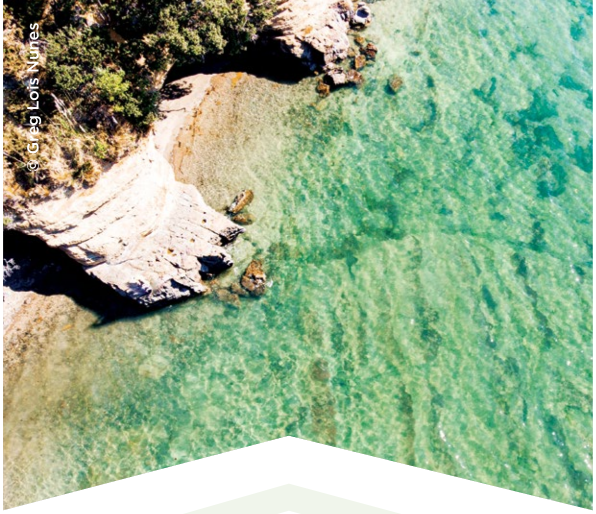
Cumulative effects have been defined as:

'*Those [effects] that 'arise from incremental, accumulating, and/or interacting stressors from human activities and natural events that overlap in space and/or time*' (Rojas-Nazar et al 2023).

Stressors interfere with the normal functioning of a system. Multiple stressors can interact in complex and non-linear ways, which can result in unexpected responses that may be greater or smaller than the sum of the individual stressor effects.

The marine environment is an interconnected system that's influenced by human activities on land and in the sea (figure 1). Each activity can generate multiple cumulative stressors in overlapping spaces. Cumulative stressors cause ecological responses both within the footprint of an activity and outside the original impact zone. This interconnected system can also be influenced by natural events such as earthquakes and cyclones, which often amplify the effects of human activities in unexpected ways.

Marine management actions must be able to cope with the complexity and uncertainty of cumulative stressors and effects – because the interactions between different stressors and the ecological responses can vary and have lag effects that accumulate over time (Hewitt et al 2022).



Failure to adequately assess and manage cumulative effects is a key driver of marine environmental decline

Our Marine Environment, a 2022 report by the Ministry for the Environment, explains that the health of marine habitats and ecosystems in Aotearoa New Zealand is declining due to cumulative effects (for example, sediment from land, climate change, and fishing). The costs of environmental degradation are significant, with risks to the many 'ecosystem services' marine ecosystems provide, and which New Zealanders rely on. These services include climate regulation, food provision, carbon sequestration, and cultural, social and recreational values. Also at risk from cumulative effects are fishery and tourism industries and our ability to meet national and international obligations.

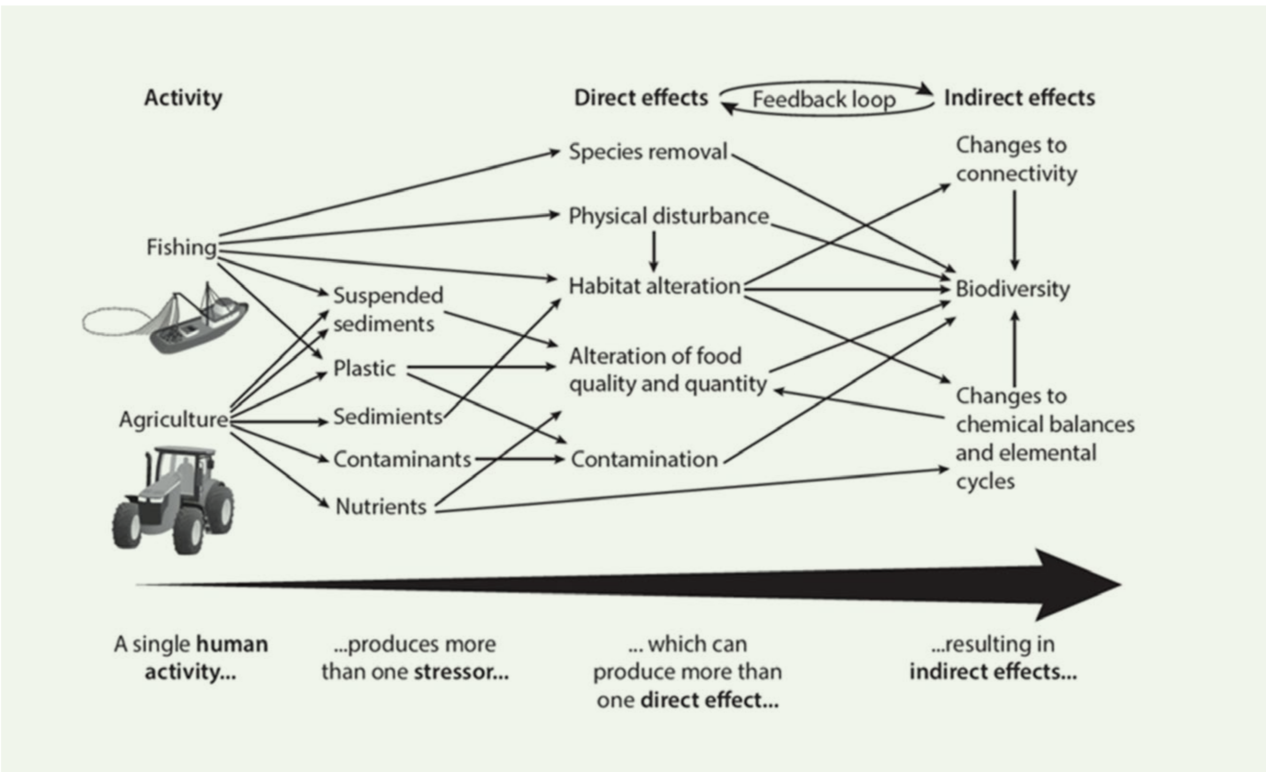


Figure 1 Single activities can produce more than one stressor, which can produce more than one direct effect and result in a range of other indirect cumulative effects on marine ecosystems (Thrush et al 2021)

Current cumulative effects assessments are limited

Aotearoa New Zealand's legal and policy frameworks (Macpherson et al 2023) does not account for dynamic, varied and complex interactions between marine, coastal, and terrestrial ecosystems.

Existing legislative requirements for decision-makers to consider cumulative effects when making decisions about the use and management of the environment, include:

- section 3(d) of the Resource Management Act 1991 (RMA)
- policies 4(c)(v) and 7 of the New Zealand Coastal Policy Statement 2010 (NZCPS).

Policy 5 of the NZCPS requires RMA decision-makers, usually regional councils, to consider the effects on land or waters in the coastal environment held or managed under a range of other environment/conservation legislation, not just the RMA (*Enabling ecosystem-based management in Aotearoa New Zealand's marine law and policy*[1]).

These requirements have been further developed in local government planning documents, been interpreted and expanded by the courts, and are increasingly recognised at the international level.

Marine law and policy in Aotearoa New Zealand is fragmented (Macpherson et al 2021). Marine and coastal laws, policies, governance institutions, and sectoral frameworks are not well-aligned across different marine spaces and timescales. This fragmentation presents challenges for cumulative effects management because marine decision-makers and managers may not be directed by legislation or policy to consider stressors that are managed under another sectoral legal framework. For example, implementation of the Fisheries Act 1996, to date, has focused on setting the conditions for and regulating the allocation of rights to use single-stock fisheries in isolation from impacts on any other fish stock, without considering broader ecosystem impacts such as impacts on marine habitat or communities or the cumulative impacts of fishing alongside other marine uses, for example aquaculture.

Poorly managed cumulative effects lead to inappropriate management decisions and environmental decline

Despite plans, policies and legislation stating that cumulative effects should be accounted for in decision making, cumulative effects are not well addressed in current management practices. This result has been driven by a continued focus on managing individual activities and associated stressors, often in isolation, due in part to the inherent complexity and uncertainty of cumulative stressor effects and associated ecosystem responses.

The management of cumulative effects is often mismatched with the scale of degradation and recovery. Current management processes to assess the effect of a stressor or activity on the marine environment typically involve assessing individual 'stressor and activity footprints'. These footprints demonstrate the spatial extent over which the impacts from individual stressors and activities are acting.

However, stressor footprints from individual activities do not recognise ecosystems as networks of responding and interacting components or that ecosystem responses to stressors may differ in space and time (ie due to ecological resilience and/or connectivity). Other activities and existing stressors in the area are also typically not considered when assessing a new activity. As a result, activity and stressor footprints alone do not meaningfully consider ecological responses to stress (Low et al 2023).

If cumulative effects continue to be poorly managed, management decisions will continue to be inappropriate for the activity of interest and avoidable environmental decline will continue to occur and ecosystem resilience will reduce.

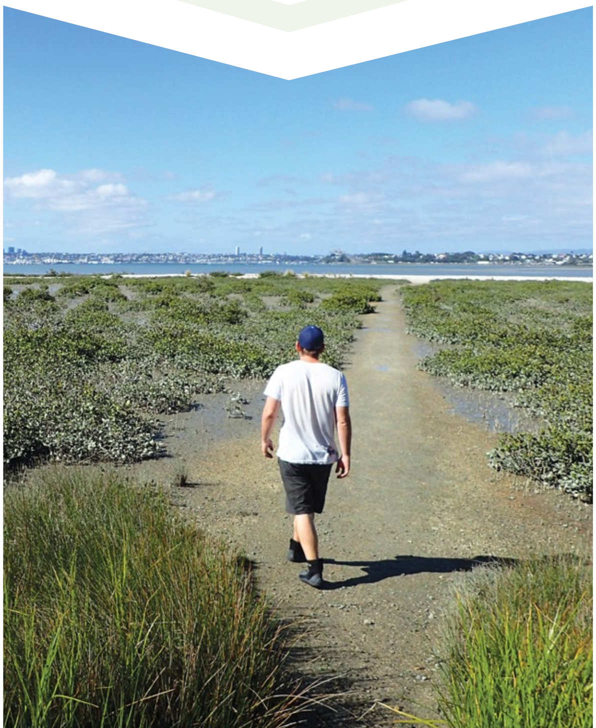
A new approach needs to focus on ecological responses to cumulative effects

We need to transition away from focusing on managing activities and stressors in isolation to focus on the ecological responses to cumulative effects. Managing cumulative effects is challenging because of the complexity, lack of data, and uncertainty in underpinning ecological relationships. For cumulative effects to be incorporated into marine management and to facilitate ecosystem-based management, new frameworks are needed to help link cumulative effects and appropriate management actions.

Our research has defined and explored the concepts of 'ecosystem response footprints' (Low et al. 2023) and 'ecological and stressor principles' (Gladstone-Gallagher et al 2024) and how they can be used to inform management decisions (Gallagher et al 2024 and Appendix 2).

Determining 'ecosystem response footprints' and the ecological and stressor state of an ecosystem can indicate the likely rate of ecosystem degradation and recovery and what's driving that change. Even though stressor effects and ecosystem responses are complex, this understanding can inform the most appropriate management action to halt ecosystem degradation and aid ecosystem recovery. Management actions might include:

- approving, modifying, or declining consents
- establishing location-based rules in plans
- monitoring for further change
- triggering interventions to limit stress
- identifying requirements for assisted recovery.



Ecosystem response footprints account for dynamic ecosystem responses to change

The 'Ecosystem response footprints' concept (Low et al 2023) incorporates the ability of an ecosystem to respond to and adapt to change (figure 2). These footprints are dynamic in space and time and are related to the physical and ecological components of the stressor regime and the receiving ecosystem.

Ecosystem response footprints are characterised by principles of size and depth.

- Size – the spatial extent of the ecosystem's response to cumulative effects ie, stressor dispersal, ecological connectivity, and species diversity or sensitivities etc
- Depth – the time elements of the ecosystem response and the magnitude of the response to cumulative effects, which is linked to the potential for recovery, ie duration of stress, stressor half-life, stressor interactions, and habitat resilience etc

Ecosystem response footprints can inform management strategies by indicating the:

- risk of an ecosystem undergoing a functional shift to a more degraded state
- likelihood of an ecosystem naturally recovering
- uncertainty associated with different management actions.

Ecological and stressor principles can help inform the status of an ecosystem

Ecological and stressor principles developed by Gladstone-Gallagher et al (2024) can inform the ecological and stressor status of an ecosystem. This status can indicate the likely response to protective and restorative interventions to maintain or improve ecosystem health (figure 3). We've described these principles below:

- **Ecological principles** 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 principles** 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.

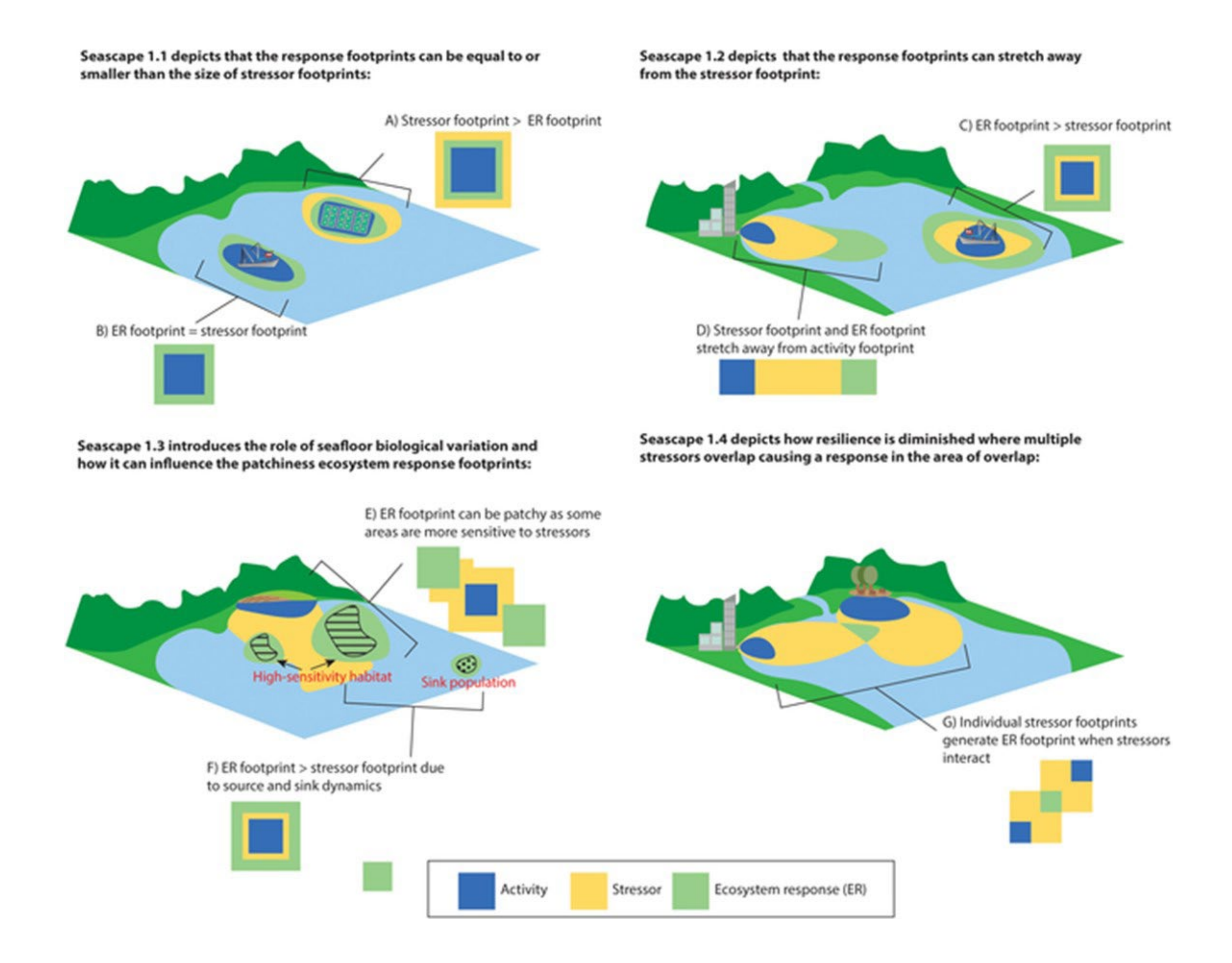


Figure 2 Activity and stressor footprints generate ecosystem response (ER) footprints because seascapes can have varying levels of physical and biological variation and connectivity. For simplicity, seascapes 1.1, 1.2, and 1.3 show single-stressor responses, but seascapes are mosaics of responding patches to multiple stressors (Low et al 2023)

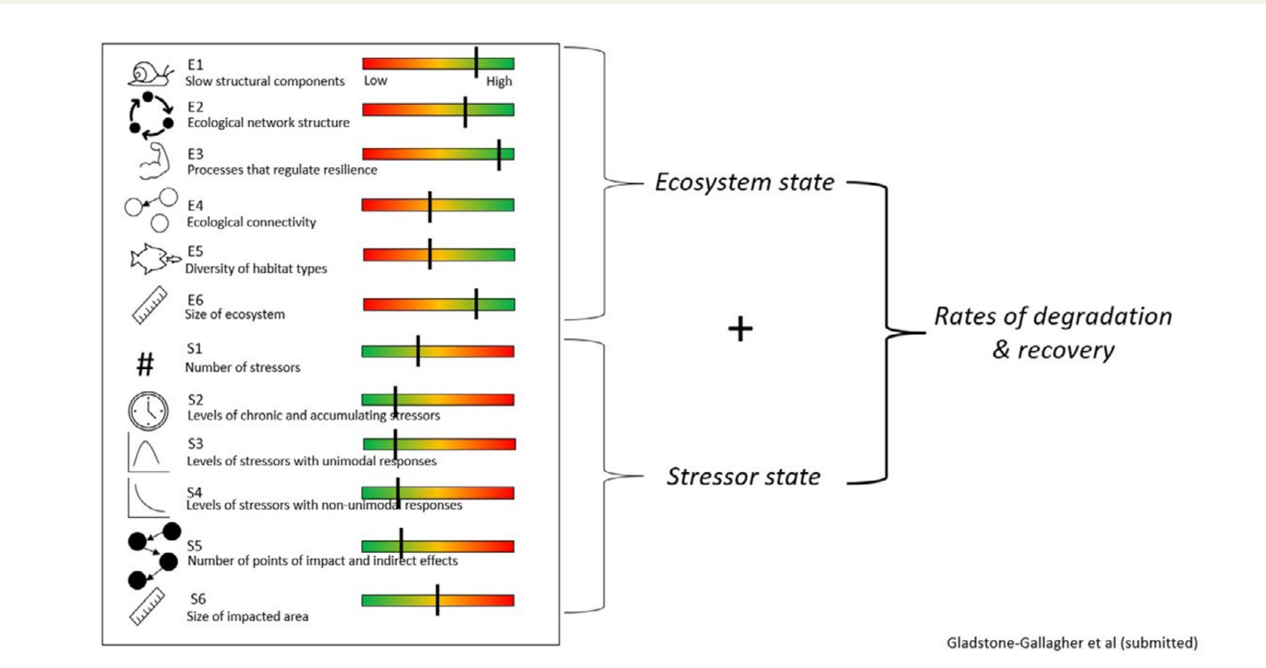


Figure 3 Ecological and stressor principles can be used to assess ecosystem and stressor states.
Green = high and red = low. See Appendix 2

Use a four-step action plan to assess and manage cumulative effects

The following action plan aims to provide guidance on how cumulative effects could be better assessed and managed when making consenting decisions, developing targets or limits, or for informing strategic planning.

A key step towards arresting further environmental degradation means taking an ecosystem-based management approach to cumulative effects. This approach:

- has Te Tiriti o Waitangi at the core
- enables decisions to be informed by multiple sources of knowledge and experience
- is adaptive and tailored to relevant space and time scales
- is underpinned by ecological principles.

In the short-term, assessments of cumulative effects must be ecologically relevant and account for ecological resilience and vulnerability, ecological connectivity, and the ecological responses to multiple interacting stressors through space and time (including existing and potential stressors; figure 2).

Our four-step action plan steps through how to assess potential cumulative effects using ecological principles to identify both stressor and ecosystem response when making consenting decisions or for informing strategic planning decision-making.

Sustainable Seas guidance on how to manage risk and uncertainty can help inform this process. For example, as the number of stressors and therefore cumulative effects increases, the risk of ecological tipping points also increases (Gladstone-Gallagher et al 2024). Therefore, it's useful when thinking about appropriate management interventions to link cumulative effects with tools and approaches to managing risk and uncertainty *(Addressing risk and uncertainty in decision-making[2])*.

We also note that many other non-ecological considerations exist when making marine management decisions. The first step of the action plans asks 'Where do we want to be?'. A plan or strategy starts with a broad range of knowledge from tangata whenua, local people, mātauranga Māori, and other expert knowledge. Our other guidance documents in this series can help inform some of these other considerations.

Below are the key steps identified in the action plan, followed by a short explanation of each step with links to relevant research and tools to assist assessments (Appendix 1). Detailed definitions of the ecosystem and stressor principles underpinning the action plan can be found in Gladstone-Gallagher et al (2024). We've also included a summary of the ecological and stressor principles underpinning the key steps in Appendix 2.

Consenting or strategic planning four-step action plan

Step 1: Identify where you want to be

What ecological state do you want for the area? Determine the aims and objectives for this location.

Some considerations may include:

- In the context of a strategic plan, iwi management plan, iwi settlement provisions, community groups, policy or recovery action, what are the desired outcomes? We note that this is typically wider than an ecological outcome and considers other factors such as social, cultural and economic objectives (and who makes these decisions).
- How does this proposed activity sit within the desired outcomes for the area. Are there policies or plans that impact how this type of proposed activity would be assessed?

Step 2: Identify what's affecting the place*

- Assess the existing stressors based on stressor principles.
- Assess new or proposed activity(s) and consequent stressors based on stressor principles.

Step 3: Identify the state of the current ecosystem within the area of concern and over a wider relevant spatial scale (eg estuary, bay etc) and how it's responding to the stressors*

- Assess the ecosystem response footprint and any associated areas relative to the ecological principles.
- Quantify the risks and uncertainties, including of doing nothing.

Step 4: Identify the best management approach to achieve the outcome of Step 1

Possible agency approaches depending on the result of assessment.

- Consult expert advice to refine assessment
- Monitor
- Reduce stressors and let the environment or place recover
- Go further and reduce stressors but recognise the need for assisting active management and recovery
- Accept, modify, or decline an activity

For a potential consent activity this could mean:

- Consult expert advice to refine assessment
- Develop mitigation actions
- Change the location for the activity
- Include adaptive management requirements in the consent conditions, including monitoring
- Accept, modify, or decline the activity

*Roadmaps on how to do steps 2 and 3 will soon be available on Tohorā.

Appendix 1
Example scenarios

Here are three hypothetical scenarios of how cumulative effects could be considered. These scenarios cover different scales of impact and different aims or objectives. These scenarios are not an exhaustive list of considerations for the activity of interest but show how to use ecological principles to assess cumulative effects within the marine environment.

We link these examples with risk assessment processes to guide cumulative effects management where the level of assessment will be linked to the scale and complexity of the scenario. More details, tools, and approaches to managing risk and uncertainty can be found in our guidance document *Addressing risk and uncertainty in decision-making*[2].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Example 1: Finfish aquaculture – a large-scale consent application

Proposal to develop a finfish aquaculture operation in an open coastal bay (figure 4).

What is the cumulative impact of the activity?

Step 1. What are the aims or objectives? Where do you want to be?

- Determine if an aquaculture development could be accommodated within a coastal bay by assessing its cumulative impact.
- Consider what the short and longer term goal is for the area. For example, look for outcome statements about the bay and surrounding area and its existing values or restoration goals, either already written or being consulted on.
- Identify current uses of the area (customary, commercial and others) and the multiple values held.

Step 2. What's affecting the place? (A consent officer, planner, council scientist, or consultant would work through this and a roadmap to help will soon be available on Tohorā.)

- Consider present stressors: sedimentation, nutrients, low nutrient processing capacity, moving water lowering hypoxia, fishery impacts – moderate to high stressor status as assessed using stressor state principles.
- Consider new or proposed activity stressors: food, carbon footprint, organic matter to seafloor, microplastics, barriers to migratory species, genetic changes to wild species, pesticides/drugs, excretion, noise, structures, shading, biosecurity – high stressor status as assessed using stressor state principles.

Step 3. What is the state of the current ecosystem and how is it responding to the stressors?

- What is the status of the ecological communities within the activity footprint?
  - Consider species and communities present, resilience and vulnerability to additional stress. For example, moderate biodiversity with few slow-growing species and historic evidence of shellfish beds but no longer present – moderate ecological status as assessed using ecosystem state principles.
- What is the status of the ecological communities within the ecological response footprint?
  - Consider species and communities present, resilience or vulnerability to additional stress, connectivity with species within activity footprint for example, *Atrina* (horse mussel) beds, scallop beds, subtidal seagrass adjacent to proposed development – high ecological status as assessed using ecosystem state principles.
- What is the direct effect of the activity?
  - For example, the load of organic matter to the seafloor is small but deep causing loss of habitat diversity within the – Moderate ecological status, High stressor status
- What are the cumulative effects of the activity?
  - Impacts on ecological connectivity within or outside of footprint, resilience/vulnerability of ecological communities, historic potential (LSFB) recovery potential, spatiotemporal variability in ecological connectivity/biodiversity/stressor footprints – moderate to high ecological status, High stressor status.

- What are the risks and uncertainties?
  - » Impact of the proposed activity on ecological connectivity within the Ecosystem response footprint. Uncertainty about larval connectivity between the proposed activity footprint and Ecosystem response footprint. Uncertainty in future Ecosystem response footprint in response to chronic stressor impacts such as sedimentation and how this will impact ecological resilience to proposed activity. Potential for upside surprises generating greater ecological declines than expected outside of the direct activity footprint.
  - » For large scale projects a formal risk assessment should be considered such as Bayesian networks, which allow iwi and stakeholder participation in the building of the model, a range of ecological, cultural, social and economic outcomes and drivers, location-specific ecological complexity, cumulative stressors and a range of knowledge types to be used for example, numeric, expert judgement, mātauranga, and local knowledge.

    Where there are high levels of data, mechanistic biophysical models with separate social models can be used, although care should be taken to ensure that critical connections and components are encompassed by the models. These methods can produce risk measures and their associated uncertainties central to management decision.

Step 4. What's our management approach for this place?

- Possible approaches based on result of assessment are:
  - » As the cumulative effects of the proposed development assesses the area to have high ecological status and high stressor status, the risks of the development justify further in-depth assessment of cumulative effects from the activity before decision to proceed with the application.

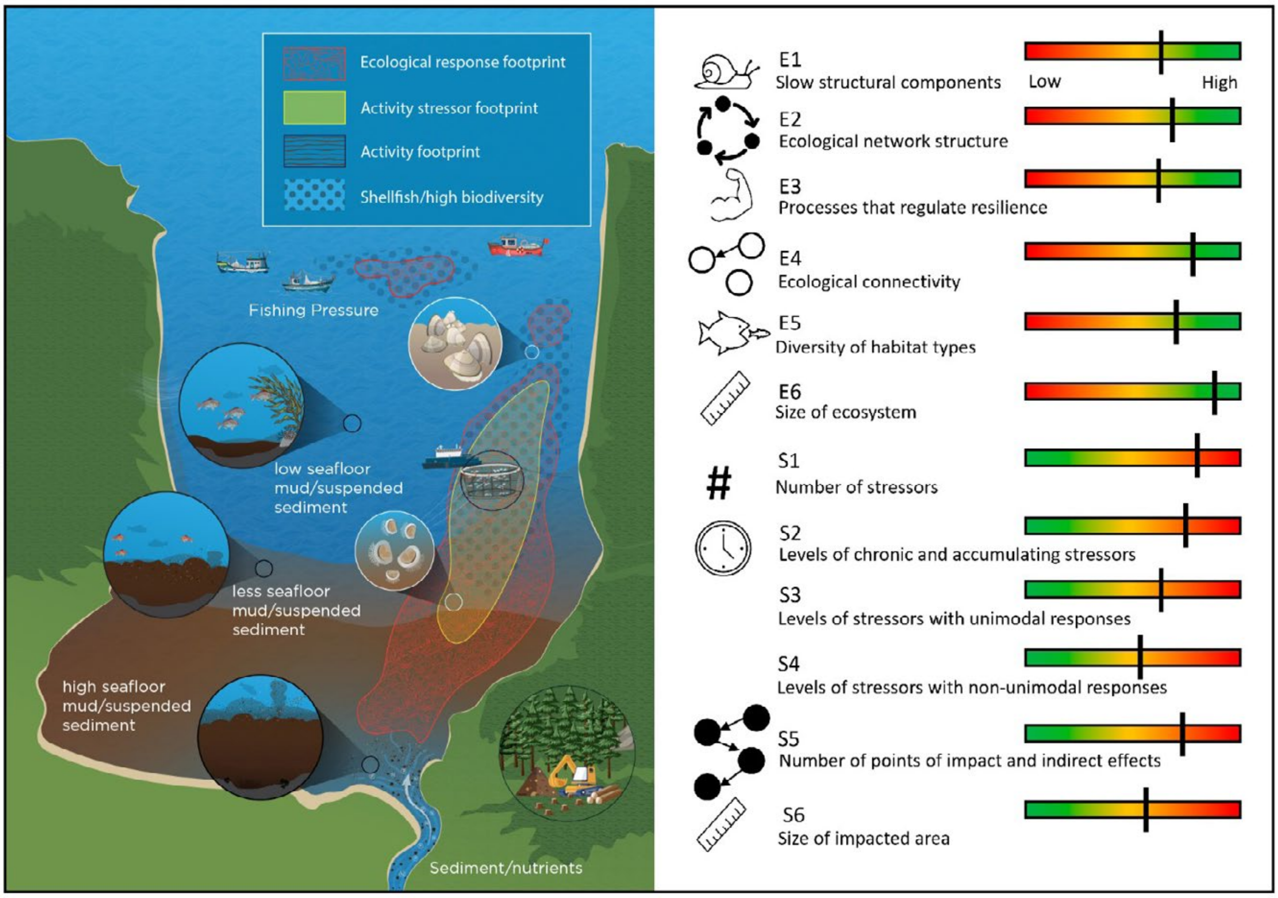

Figure 4 Large scale finfish aquaculture scenario showing the status of associated ecological and stressor principles (based off Gladstone-Gallagher et al. 2024). Green = low risk and red = high risk

Example 2: Seawall – a small-scale consent application

Proposal to build a seawall at two locations within a harbour to protect land from storm surges associated with climate change (figure 5). The first location is proposed in an area of high biodiversity with a known shellfish bed nearby, and a gradual elevation profile to low lying farmland with some saltmarsh behind. The second location is located next to a steep eroding cliff dropping down onto a small area of degraded mudflat.

» Step 1. Determine your aims and objectives. Where do you want to be?

- To assess the cumulative impact of a seawall development in two different locations within a harbour.
- Consider what the short and longer-term goal is for the area. For example, look for historical and current use of the two locations and overall, who are mana whenua , what the harbour means to tangata whenua and local people, ask what the short- and long-term outcomes they and other stakeholders want for the harbour.

» Step 2. What's affecting the place? Assess the stressors associated with the activity or management action of interest.

- Consider present stressors: sedimentation, nutrient loading, heavy metal contamination, fishing, sea level rise – moderate stressor status.
- Consider new or proposed activity stressors: intertidal or subtidal reclamation and loss of organisms within the immediate area, prevention of inland migration of marine environments or coastal squeeze, modification of hydrodynamics, accumulation of drift algae and rubbish at the base of the seawall – moderate stressor status.

» Step 3. What is the state of the current ecosystem and how is it responding to the stressors?

Seawall 1. Example of when a consenting officer may request a more in-depth ecological cumulative effects assessment:

- High density large size cockle bed immediately down shore of the proposed development (last remaining within the harbour), where seawall will prevent future migration. Pipi populations on either side of proposed seawall (whose larval connectivity may be impacted) and mangroves or saltmarsh located in the upper elevations (high ecological status).
- What are the risks and uncertainties?
  - Impact of the proposed activity on ecological connectivity within the ecosystem response footprint. Uncertainty about how the proposed seawall may impact pipi larval and juvenile connectivity between the proposed activity footprint and the Ecosystem response footprint. Effects of the changes in hydrodynamics on the area, for example a change where fine sediments accumulate. Potential exists for generating greater ecological declines than expected outside of the direct activity footprint. Development of a seawall in this location may impact future restoration or recovery action.
  - Risk assessment methods such as Likelihood Consequence (LC) or Bayesian Network (BN) methods could be employed to produce more formal estimates of risk and uncertainty associated with the seawall. Elicited information from scoping exercises can be used to populate LC and BN assessments aiding in the cost and speed of producing more formal assessments.

Seawall 2. Example of when further ecological CE assessment may not be required:

- Proposed seawall is in the muddy arm of a harbour, with very low benthic (bottom layer) biodiversity. No evidence of slower growing structural species, low ecological network structure, low ecological service provision, low ecological connectivity from current location to elsewhere, low diversity of habitats, large amount (relative to the amount of proposed seawall) of similar area surrounding the proposed seawall location – low ecological status and low stressor status.
- What are the risks and uncertainties?
  - Development of a seawall in this location may impact future restoration or recovery action.

» Step 4. What's our management approach for this place?

- Possible approaches based on the result of assessments, noting that building a seawall in either location could impact future restoration or recovery action.
  - Seawall 1: seek further advice on potential cumulative effects.
  - Seawall 2: assess potential cumulative effects as being relatively low.

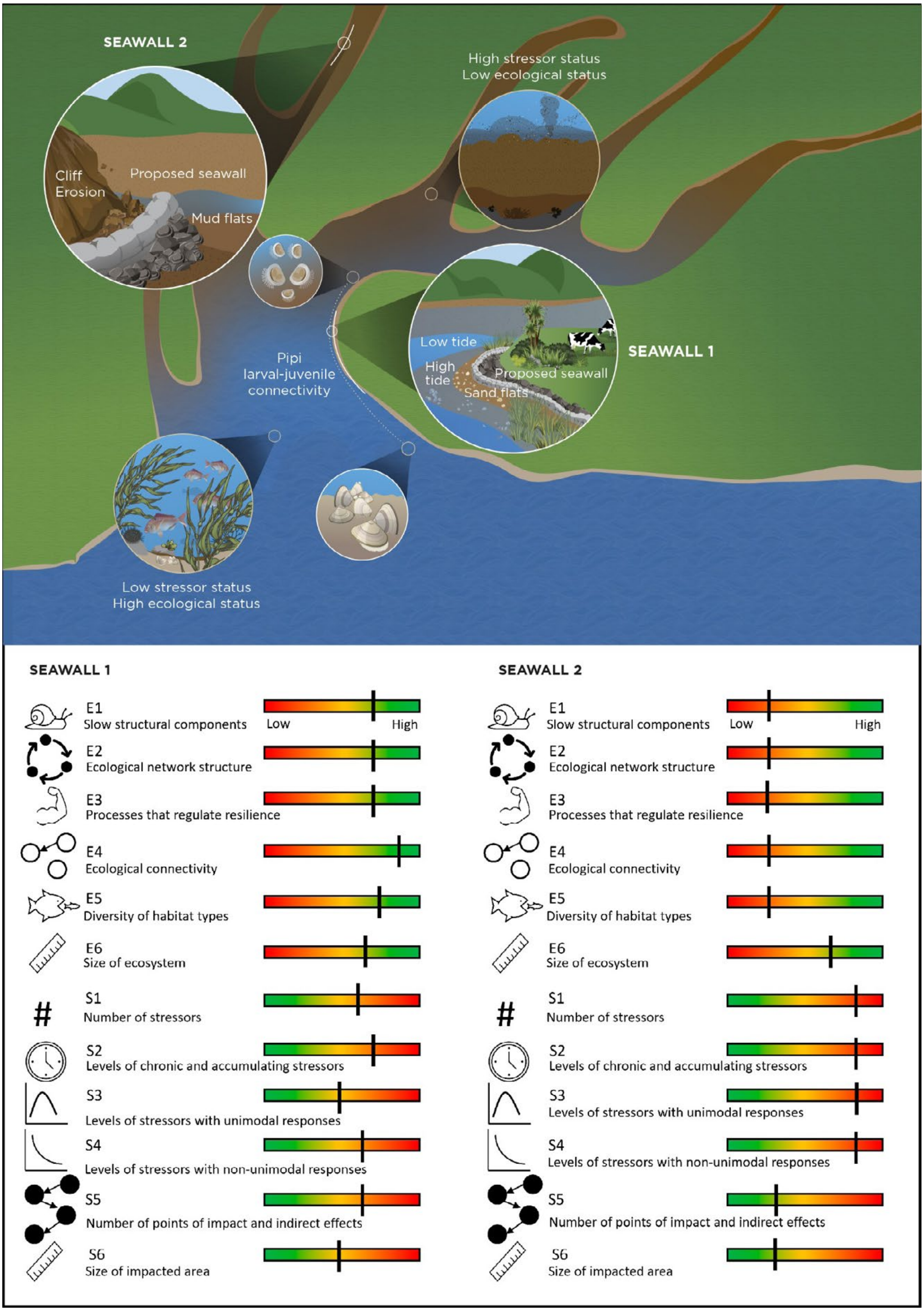

Figure 5 Small scale seawall scenario showing the status of associated ecological and stressor principles and how this varies based on location within a harbour (based off Gladstone-Gallagher et al 2024)

Example 3: Ecological recovery of kina barrens – a medium-to-large scale restoration action

Restoration of a kina barren within an open coastal environment that has high fishing pressure (figure 6).

Step 1. Where do you want to be? Determine your aims and objectives.

- Assess whether active restoration action to reduce kina barrens is required to recover kelp dominated reef environments. Is the area currently under rāhui/ fisheries closure?

Step 2. What's affecting the place? Assess the stressors associated with the activity or management action of interest.

- Present stressors: sedimentation, nutrient loading, heatwaves, extreme weather, and fishing – high stressor status.
- New or proposed activity stressors: Sedimentation, removal of kelp by kina predation, heatwaves – high stressor status.

Step 3. What is the state of the current ecosystem and how is it responding to the stressors?

- High density kina barrens with low density of kelp, low density of larger snapper and crayfish, both within the management area of interest and in the wider region – low ecological status.
- Kina barrens common within the Ecosystem response footprint, few larger predators – low ecological status.
- What are the risks/uncertainties?
  - » Localised rāhui/mataitai/closure of fisheries. However, fishing is still occurring around the outside of the management area. Uncertainty about how fishing of larger predators outside of the restoration area may impact restoration success. High certainty that kina barrens will remain if restoration action is not initiated.
  - » Similar to the large-scale aquaculture example above, consider a more formal risk assessment including Bayesian Network or agent-based models. Where there are high levels of data, you can use mechanistic biophysical models with separate social models .

Step 4. What's our management approach for this place?

- Possible approaches based on assessment results are:
  - » reducing stressors that are unlikely to result in kelp recovery in the short-to-medium term. Active management through kina removal together with reduced take of large predators is likely to be required to achieve kelp recovery within the next 10 years.

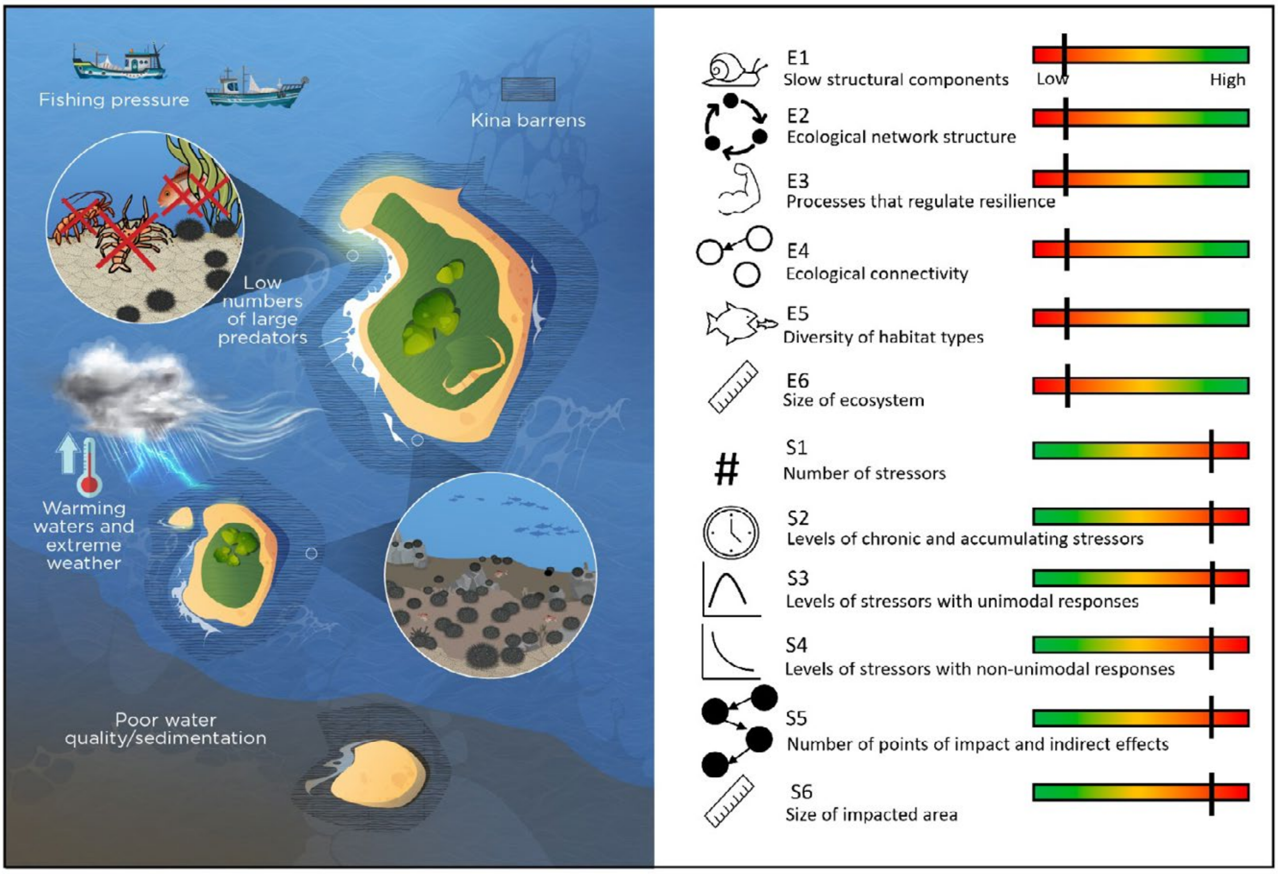

Figure 6 Moderate-to-large scale kina barren and kelp reef restoration scenario showing the status of associated ecological and stressor principles, based off Gladstone-Gallagher et al 2024

Appendix 2
Summary of the ecosystem and stressor principles underpinning the key steps within this guideline

Further details on these can be found in Gladstone-Gallagher et al (2024).

Table 1 Summary of the ecological (E) and stressor (S) principles underpinning key steps of the cumulative effects action plan. Principle names, definitions, and explanations are modified from Gladstone-Gallagher et al (2024)

Principle type		Definition and explanation
Ecological principles		
E1	The status of the 'slow' to regenerate ecosystem structural components.	High = slow structural components present (eg kelp, corals, shellfish or other key habitat forming species). Low = the slow structural components have been lost from or 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.	High = there are a number of balancing or 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 (ie 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 (eg nutrient removal, oxygen production) that regulate ecosystem resilience.	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 (eg 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.	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 (eg 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.	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.	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.

Principle type		Definition and explanation
Stressor principles		
S1	The number of stressors.	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.	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. (eg 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 (ie 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. (eg 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.	High = stressors present which impact multiple ecosystem components and cause multiple indirect effects and are more likely to increase the rate of degradation (eg 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 (ie 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.

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Glossary

Connectivity: The ecological connections between components within and across ecosystems.

Cumulative effects (within an ecosystem-based management context): Cumulative effects come from incremental, accumulating, and/or interacting stressors from human activities and natural events. These events can overlap in space and time. (Rojas-Nazar et al 2023).

Ecosystem response footprint: Ecosystem response footprints describe the spatial and temporal scale of ecosystem response to stressors. They can be characterized by both ecological and biophysical context dependencies including; non additive and non-linear ecosystem responses and interactions, temporal mismatches, place and time characteristics, and indirect effects of stressors and connectivity between places (Low et al 2023).

Ecosystem-based management: A holistic and inclusive way to manage competing uses, and demands on, marine environments in a way that maintains or improves ecosystem health (Hewitt et al 2018).

Recovery: Recovery of ecosystem functionality (Low et al 2023).

Resilience: An ecosystem's ability to absorb changes in state variables, driving variables and parameters, and still persist (Low et al 2023). Resilience and stability of ecological systems (Holling 1973).

Vulnerability: Sensitivity of an ecosystem to the effects of a stressor.

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For more information and support with marine management decisions, please see our other synthesis project summaries and guidance documents in this series.