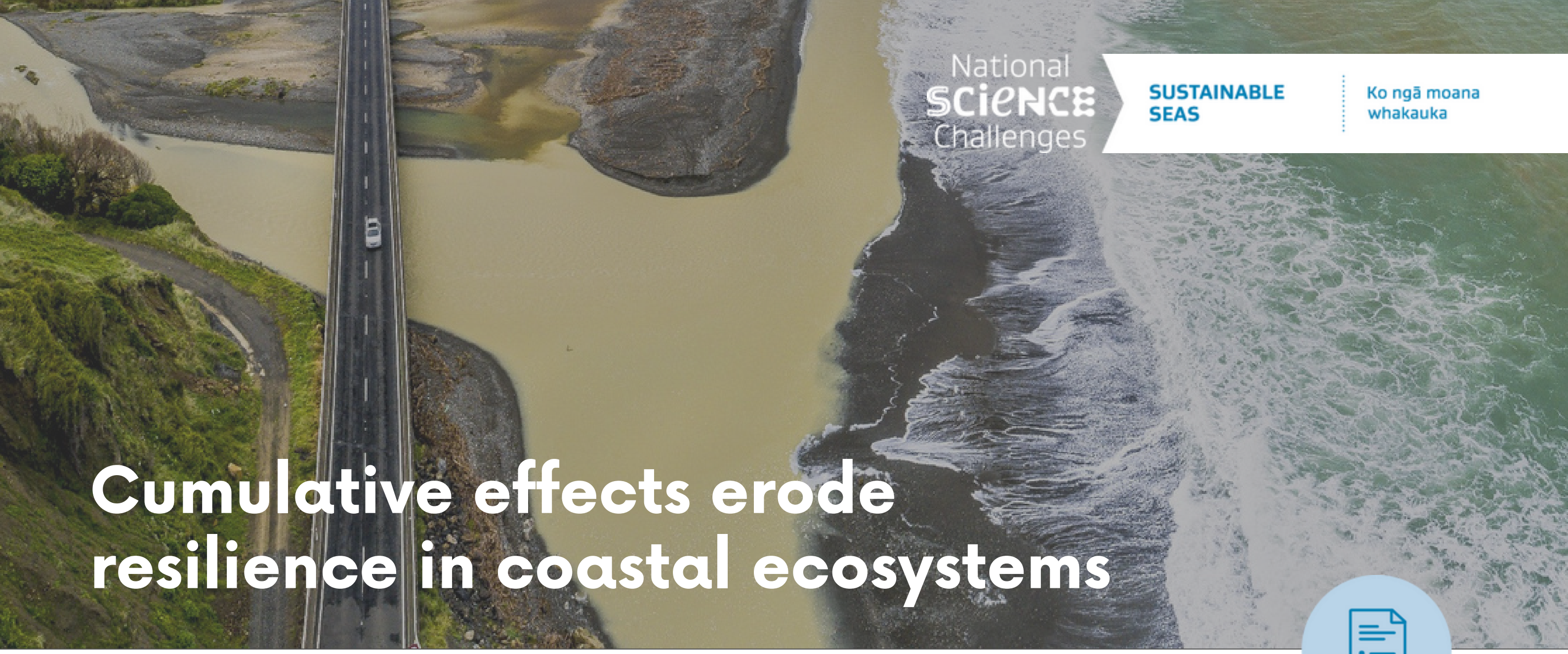
National Science Challenges
SUSTAINABLE SEAS
Ko ngā moana whakauka



Cumulative effects erode resilience in coastal ecosystems

Summary

Research from the *Tipping points in ecosystem structure, function and services* and *Ecological responses to cumulative effects* projects is helping to paint a picture of how the resilience of coastal ecosystems is vulnerable to cumulative effects.

As the number and intensity of environmental stressors increases, ecosystems lose the capacity to cope with additional stress. The research from these three articles offers a real-world demonstration of the erosion of resilience capacity within coastal ecosystems when exposed to an added stressor. Identifying the subtle shifts in resilience that occur due to added stressors helps to inform an understanding of what happens before tipping points are reached. Limiting irreversible damage to coastal ecosystems requires stronger ecological resilience, but this requires understanding the mechanisms that underpin damage, resilience, and recovery.

Globally, coastal ecosystems are heavily impacted by multiple stressors that originate from land-based activity, including agriculture, horticulture, urban development, and forestry. Dramatic changes from stressors interacting with ecosystem functions makes coastal ecosystems prone to tipping points. A tipping point can move an ecosystem between functionally different states, and once the point is reached, it's hard to reverse. Tipping points can happen due to large external factors, like climate change, severe weather, and resource extraction, or through minor, gradual changes that impact the interactions taking place within an ecosystem.

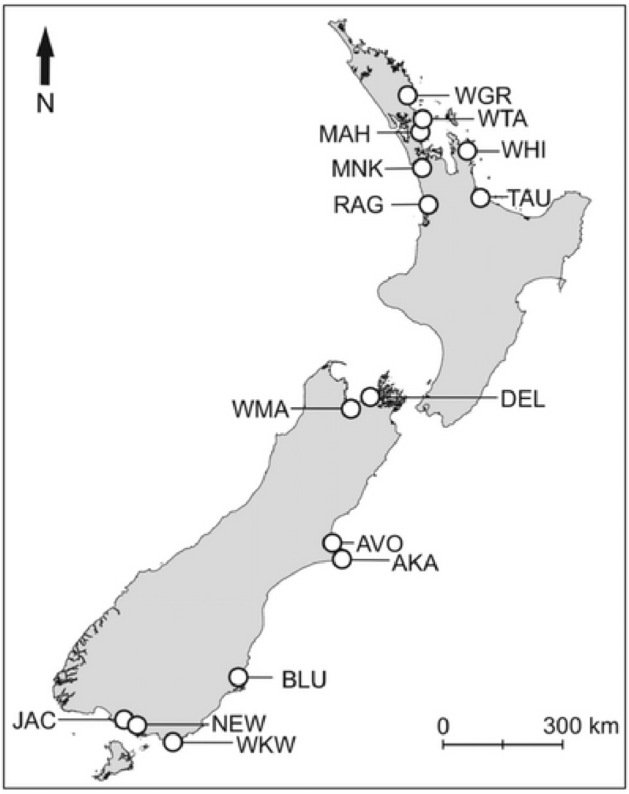


Figure 1: Location of study estuaries from Thrush et al. (2020)

Clear systems are more resilient than turbid systems

Thrush et al. (2021) assessed how lower light levels at the seafloor due to higher turbidity impacted the processing of sediment nitrogen in estuaries (*Fig. 1*). This study identified light penetration thresholds in relation to distinct changes in the ecosystem interaction networks (EINs) that drive nutrient processing.

The results suggest that changes in interactions between sediment, nutrients, and the environment can alter the biological and chemical processes that drive ecosystem function. These results give further evidence that cumulative effects can exceed tipping points even at low levels.

In both turbid and moderately turbid systems, a decrease in the diversity, abundance, or functional richness of species can lead to a decline in the functioning of that ecosystem. In clear systems, the functioning remained more constant despite decreasing biodiversity, suggesting that clear systems are more resilient towards a loss of biodiversity compared to turbid systems. This may be underpinned by more pathways between species, environmental properties, and functions in clear (oligotrophic) conditions compared to the more turbid and nutrient rich conditions (*Fig. 2*).

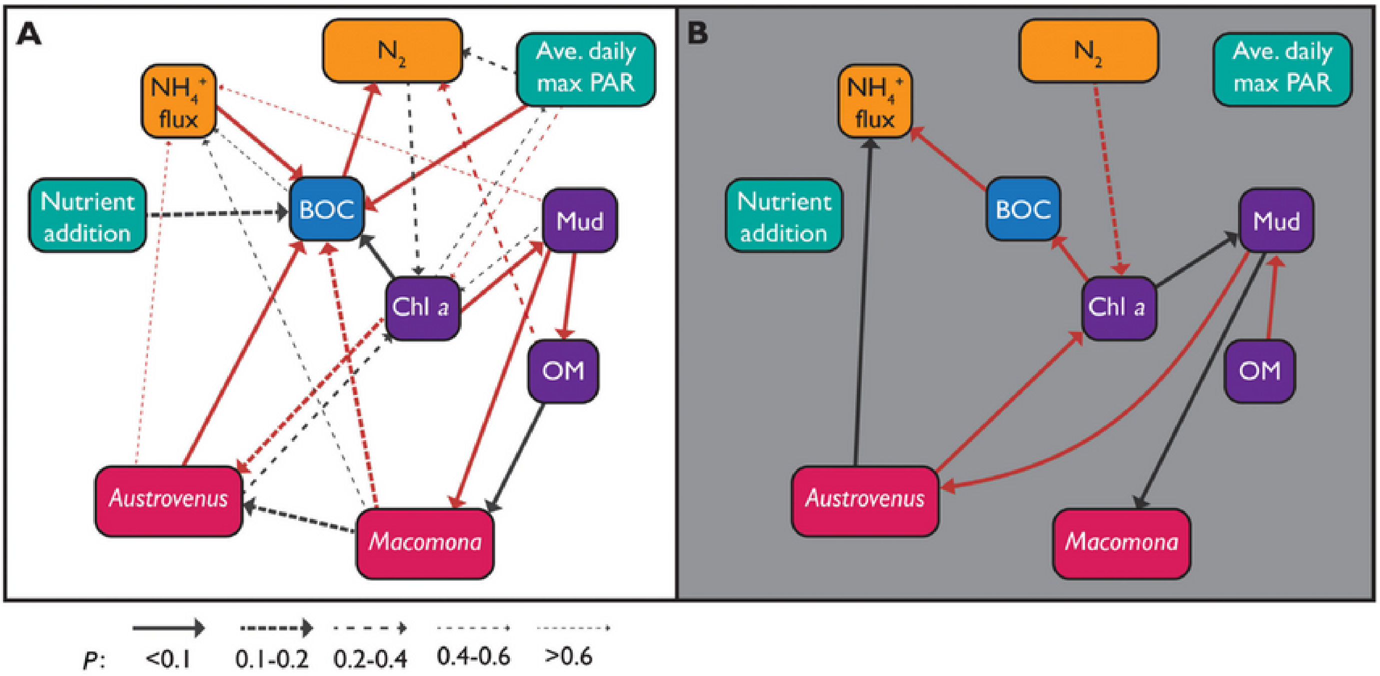


Figure 2: Ecosystem interaction network from clear (A) and turbid (B) study sites. Teal boxes relate to external factors (nutrient addition is experimental manipulation; Ave. daily max PAR is the effect of turbidity on available photosynthetically active radiation). Purple boxes denote sediment characteristics (Chl a represents the standing stock of microphytobenthos; mud, mud in sediment; OM, organic matter in sediment). The blue box relates to oxygen (BOC, benthic oxygen consumption). Yellow boxes relate to nitrogen processing (Denitrification (N2); NH4 flux, flux across the sediment-water interface. Pink boxes relate to the abundance of large shellfish (individuals >20mm shell length). Red arrows indicate positive relationships and black negative. Arrow thickness indicates relationship strength. From Thrush et al. (2020).

Stressed estuaries are more vulnerable to high nutrient levels

Based on the same study locations, Gammal et al. (2022) investigated the combined effects of two common stressors on estuaries: turbidity and nutrient enrichment.

This research found that added nutrients negatively impact the richness of species (*Fig. 3*). While there was no direct interaction with turbidity, the research found that turbid environments are more vulnerable to losses of function due to declines in species richness.

These findings imply that estuaries that are already stressed due to high turbidity are likely to be more vulnerable to increased levels of nutrients. This may be due to the negative effects that increased nutrients can have on benthic macrofauna communities, which in turn has a negative effect on functioning.

In both turbid and moderately turbid systems, a decrease in the number of species, abundance or functional richness within an estuary may lead to poorer ecosystem functioning. In contrast, in clear systems the functioning remained more constant despite decreasing biodiversity, suggesting that clear systems are more resilient to biodiversity loss compared to turbid systems.

The functioning of ecosystems not stressed by turbidity is potentially underpinned by having more pathways between species, environmental properties, and functions compared to the more turbid and nutrient rich conditions. As seen in *Figure 2*, Thrush et al. (2021) showed through EIN analysis that, within clear systems, there was high connectivity between the different ecosystem components compared to the simpler networks in turbid systems.

More complex networks have more diverse response strategies

Gladstone-Gallagher et al. (2023) aimed to simulate the chronic effects of eutrophication stress in estuaries. Eutrophication is a key stressor for estuaries across the world and occurs when increases in nutrients such as nitrogen lead to the excessive growth of aquatic plants and algae. Research on the effects of eutrophication in estuaries tends to be biased towards already eutrophic and degraded estuaries, limiting the understanding of indicators of change that occur before major shifts.

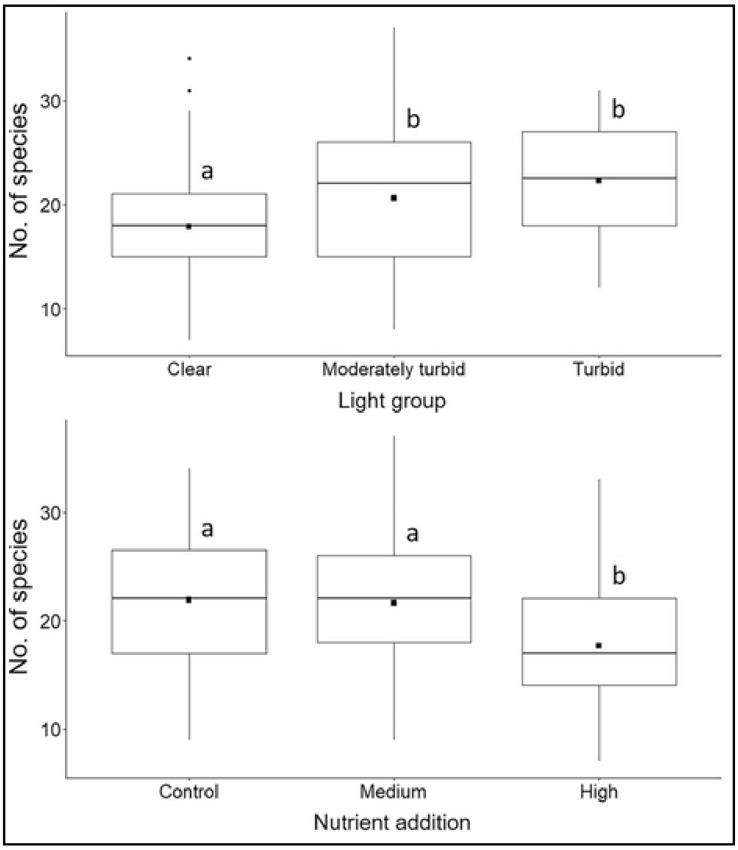


Figure 3: Species richness as a function of A the light groups and B the nutrient addition treatment group. Lower case letters above the boxes indicate significant differences among groups ($p < 0.05$). From Gammal et al. 2022

This research assigned traits to all macrofauna based on their ability to influence three ecological dynamics, with the last two constituting 'response' traits

- Ecosystem regulation traits (or 'effect' traits): those that impact sediment biogeochemistry, nutrient cycling, primary and secondary production, and habitat stability
- Recovery traits: individual and population level traits that influence recovery potential following disturbance, such as reproduction, mobility, and time to maturity
- Resistance traits: those associated with resistance to a range of stressors and disturbances (for example, predators may benefit from disturbance, surface dwelling species may have more exposure to stress)

By characterizing the networks based on the interrelationships among the different traits, the research was able to determine how stressors will impact the resilience of ecosystem functions. Researchers found that the trait networks of seafloor communities varies from very simple networks made up of small numbers of trait nodes, with only a few connections between them, to more complex networks characterized by high numbers of trait nodes and many connections among them (see *Fig. 4*). In theory, the more complex the network, the higher the diversity of response strategies within the community.

The results suggest that the thresholds for nutrient effects are more unpredictable at sites that have simpler networks. High levels of nutrients resulted in negative effects on networks, but the effect sizes were more variable at sites with simpler networks (*Fig. 4*).

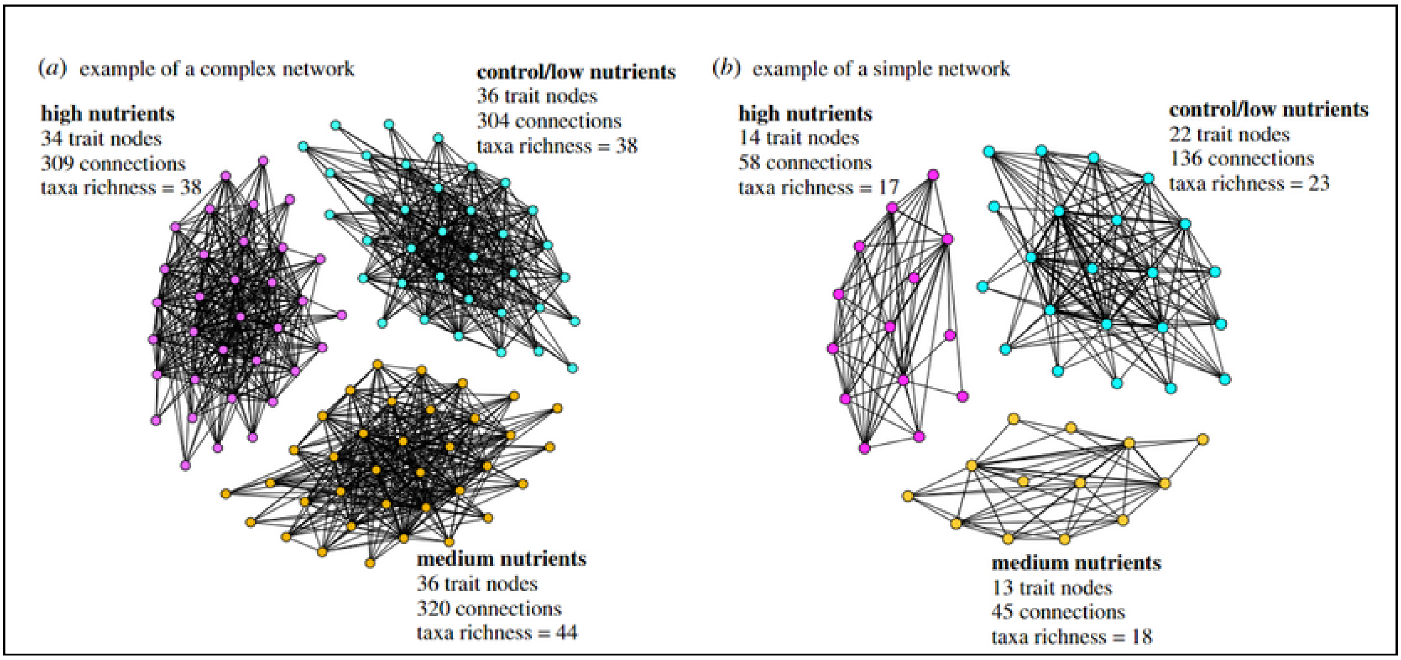


Figure 4: Examples of trait networks. (a) A complex network at a site where nutrient enrichment (medium nutrients = yellow, high nutrients = pink) did not alter network architecture compared to controls (blue). (b) A relatively simple network at a site where nutrient enrichment resulted in a loss of trait nodes (medium nutrients = yellow, high nutrients = pink) and connections among trait pairs compared to the control community (blue). From Gladstone-Gallagher et al. (2023)

This research offers a real-world example of an added stressor reducing resilience. Simpler networks had more variable responses to an added stressor, which implies that a loss of response capacity due to one stressor may reduce the resilience and stability of the system to another stressor. This variability in effect-size may be a demonstration of 'flickering', which indicates instability within an ecosystem before a threshold is reached.

Nutrient and sediment loading into coastal ecosystems are major drivers of coastal ecosystem degradation. Coastal ecosystems are crucial for global carbon and nitrogen cycling and other ecosystem services but are among the most impacted. The findings of these three articles represent a translation of resilience concepts from theory to real-world examples, which will help to improve predictions of how an ecosystem may change after resilience capacity is lost.

References

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Gladstone-Gallagher R, Hewitt J, Siwicka E, Gammal J, Brustolin M, Norkko A, Pilditch C and Thrush S. (2023) Ecological network analysis of traits reveals variable response capacity to stress. *Proc. R. Soc. B.* **290**: 20230403

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