9.4 Shellfish bed extent and quality

Author, affiliation: Drew Lohrer (NIWA)

Citation for this chapter: Lohrer, D. (2024). Shellfish bed extent and quality. *In:* Lohrer, D., et al. *Information Stocktakes of Fifty-Five Environmental Attributes across Air, Soil, Terrestrial, Freshwater, Estuaries and Coastal Waters Domains*. Prepared by NIWA, Manaaki Whenua Landare Research, Cawthron Institute, and Environet Limited for the Ministry for the Environment. NIWA report no. 2024216HN (project MFE24203, June 2024). [https://environment.govt.nz/publications/information-stocktakes-of-fifty-five-environmental-attributes]

Preamble: When referring to "shellfish" in this information stocktake, we are referring to bivalve mollusc shellfish only. Although there are hundreds of species of bivalve molluscs in New Zealand, the term "shellfish beds" is generally applied to 8-10 species only. Bed-forming shellfish are generally large, common, and well-known species including: **cockles, dog cockles, pipi, wedge shells, oysters, green-lipped mussels, horse mussels, and scallops**. Most of the bed-formers listed above are recognised as kaimoana or as ecologically important 'key' species. Although some bivalves such as mussels and rock oysters occur on hard substrates, the term "shellfish bed" usually refers to bivalve-dominated soft-sediment habitats. Some bed-forming shellfish live on the sediment surface (e.g., green-lipped mussels, oysters, scallops), whilst others live deeper in the sediment (e.g., pipi, cockles, wedge shells). Green-lipped mussels and oysters are farmed in many estuarine and coastal areas throughout New Zealand, but we are not including cultured bivalves in our information stocktake of "Shellfish bed extent and quality".

State of knowledge of the "Shellfish bed extent and quality" attribute: Medium / unresolved – some studies/data but conclusions do not agree

Shellfish biology is generally well understood. Shellfish populations are monitored in many parts of the country to keep track of stocks. However, shellfish bed extent is not often monitored, especially for infaunal and subtidal species that are difficult to directly observe. "Quality" is also not usually assessed, though it may be possible to assess quality using a combination of abundance, size structure, and other metrics (e.g., body tissue contaminant concentrations). Therefore, we generally have a medium / unresolved state of knowledge of this attribute.

Part A—Attribute and method

A1. How does the attribute relate to ecological integrity or human health?

Shellfish are a key indicator of ecological integrity in intertidal and shallow subtidal coastal and estuarine systems [1-5]. The denser and more extensive the shellfish beds are (bed extent), and the healthier the shellfish are within them (bed quality), the greater the ecosystem's ecological integrity.

Almost all the shellfish species mentioned in the pre-amble are sensitive to sediment eroded from land (suspended and deposited sediments) and shellfish population collapses throughout New Zealand have been attributed to multiple stressors such as direct overharvesting, indirect damage/disturbance from trawling and dredging, mass mortalities in heat waves, smothering under eutrophication-related nuisance macroalgae outbreaks, ocean acidification effects on larval/juvenile life-stages, and more. Different shellfish perform different ecological roles, therefore, having a diversity of shellfish bed types (e.g., cockle and wedge shell beds on intertidal flats; pipi beds in estuarine tidal channels; green-lipped mussels, horse mussels, and dog cockles in deeper areas) is also integral to ecological integrity.

Shellfish are critical to ecological integrity because of the key ecological roles they perform and the ecosystem functions/services they deliver [1,2,6-8]. Bed forming shellfish stabilise and armour seafloor sediments. Bivalve shell hash (dead/broken shell material) creates habitat heterogeneity in soft-sediment habitats and has a positive influence on soft-sediment macroinvertebrate community diversity [9]. Banks comprised of dead bivalve shells are utilised by rare and threatened shorebirds (e.g., as high tide roosts), and living shellfish are eaten by birds and fish (e.g., oystercatchers, eagle rays). Some of the bed forming shellfish are relatively mobile (e.g., cockles) and bioturbate surface sediments, influencing primary production and nutrient release rates [10,11]. Others (e.g., wedge shells) create porewater pressure gradients that influence fluxes of solutes across the sediment water interface. Green-lipped mussels, horse mussels, and oysters create hard structure and vertical relief above the sediment-water interface in soft-sediment seafloor habitats, creating biodiversity hotspots. Organisms settle on their shells (sessile invertebrates) or take refuge in the shell clusters (mobile invertebrates and fish). Most bed forming shellfish are filter-feeders and have the potential to cleanse/clarify turbid water [12,13]. Some shellfish are used as time-integrative biomonitors (e.g., to track environmental contaminants such as metals) because of the large volumes of water they filter over periods of weeks to months. Biodeposition of faeces and pseudo-faeces by horse mussels organically enriches surrounding sediments, affecting macrofaunal communities and microbial remineralisation rates [2,14]. All bivalve shellfish have calcium carbonate shells, though their potential role in blue carbon sequestration is generally thought to be related to the trapping and burial of organic carbon rich particles within beds. Some studies suggest that shellfish beds positively influence denitrification, a microbially mediated process that converts nitrate to di-nitrogen gas in a series of dissimilatory steps [15]. Inorganic N removal is an important ecosystem service in N-enriched (eutrophic) systems [16,17]

A2. What is the evidence of impact on (a) ecological integrity or (b) human health? What is the spatial extent and magnitude of degradation?

One of the most recognisable indicators of estuarine degradation has been the collapse of natural shellfish populations. The scale of shellfish bed declines is massive and nationwide. We have lost an estimated 500 km^2 of green-lipped mussel beds (*Perna canaliculus*) in the Hauraki Gulf and 100 km^2 from the Marlborough Sounds [18-22]. High density horse mussel beds (*Atrina zelandica*) have almost completely disappeared, with just relict beds remaining [1-4]. Lucrative scallop fisheries have crashed nationwide, and populations have not rebounded despite harvesting bans including both rāhui and national-scale MPI fisheries closures. Pipi beds (*Paphies australis*) at the mouth of Whangārei Harbour covered 0.5% of the area in 2017 that they covered in 2005 [23,24], a ~10,000 tonne collapse in a little more than a decade. Hundreds of hectares of former shellfish habitat in Southland estuaries are now smothered under nuisance macroalgal mats [25,26]. Shellfish on tidal flats adjacent to large cities are exposed to landfill leachate and sewage effluent, a potential threat to people collecting and eating them. Even in rural areas, leaky septic systems and poor water/sediment quality (e.g., from upstream agriculture) can affect the fitness of shellfish for human consumption.

The inability to find, collect, and safely consume shellfish is devastating to mana whenua, whose identity and wellbeing has relied upon connections to shellfish and their wider ecosystems for generations. Declines in shellfish bed extent and quality also affect recreational and commercial fishers, and any who appreciate the roles shellfish play in coastal ecosystems. Shellfish provide jobs and business opportunities for many New Zealanders (e.g., mussel and oyster aquaculture; scallop fisheries).

A3. What has been the pace and trajectory of change in this attribute, and what do we expect in the future 10 - 30 years under the status quo? Are impacts reversible or irreversible (within a generation)?

Shellfish populations have declined rapidly in some areas, with “collapse” (rather than “steady decline”) often used to describe the pace of change. The extremely large green-lipped mussel populations that covered 500 km^2 of seafloor habitat in the Hauraki Gulf were decimated in just 50 years coincident with a bottom-contact dredge fishery (1910-1960). Ten tonnes of pipi disappeared from Mair/Marsden bank in Whangarei Harbour in ~10 years (2005-2017). Horse mussels in Mahurangi Harbour declined from densities of 10-20 m^{-2} to <0.5 m^{-2} in ~ 10 years (1998-2009) and continue to be scarce where they once occurred in dense beds (e.g., Pakiri, eastern Coromandel, Tauranga Harbour, Marlborough Sounds).

Survey data indicate serial depletions of scallop populations in the Marlborough Sounds as fishers move from overharvested beds to new beds. There is some indication that seafloor habitat quality, rather than the supply of larvae to those habitats, is the factor most responsible for the lack of scallop recovery [27]. Habitat quality has been impacted by bottom-contact fishing and terrigenous sediment inputs, which have resulted in muddy seafloor sediments with insufficient biogenic structure [27].

Without management interventions (e.g., restricting bottom contact fishing, reducing catchment sediment input, improving water quality), the prospects for shellfish recovery are poor. Climate change and increased frequency/intensity of storms over the next 10-30 years is predicted to increase sediment loading and sediment resuspension in estuarine and coastal areas [28], potentially limiting recovery prospects further. However, it is hypothesised that in-estuary interventions, combined with catchment management, can create places and times in which stressors are sufficiently reduced and aligned with biological requirements to enable shellfish recovery. Restoration that involves moving adult shellfish from one area to another is a zero-sum gain and poses biosecurity risks. Therefore, advances in our ability to consistently/successfully produce new spat for restoration is critical, though significantly technically challenging [29].

A4-(i) What monitoring is currently done and how is it reported? (e.g., is there a standard, and how consistently is it used, who is monitoring for what purpose)? Is there a consensus on the most appropriate measurement method?

Some shellfish populations are monitored (using various standard survey techniques suited to the species of interest). However, the attribute “Bed extent and quality” is rarely quantified.

Infaunal bivalves including cockles, wedge shells, and pipi are monitored at sentinel monitoring sites by many councils using standard sized cores [30-32]. This produces highly standardised data on bivalve abundance and size structure (often in classes, e.g., 0-5 mm, 5-10, 10-15, 15-20, 20-30, 30-40, >40 mm). An Estuarine Toolkit published by NIWA (in English and te reo Maori) provides guidance on standard shellfish monitoring methods for intertidal shellfish (cockle, wedge shells, juvenile pipi; [33]. Most councils have started reporting estuarine monitoring data on the Land, Air, Water Aotearoa (LAWA) website [34]. MPI has funded surveys of cockles and pipi in many harbours and estuaries, which are generally designed to characterise both abundance and distribution of shellfish across the seascape [35-37]. Semi-quantitative 'rapid habitat assessment' techniques developed by NIWA have been used by some councils to define the spatial extent of 'high density cockle' and 'high density pipi' beds [38,39]. The 'rapid habitat assessment' method is semi-quantitative because broad areas are walked with regular spot checking to assign habitats to pre-defined categories (i.e., "High Density Pipi habitat" = areas with >10 pipi sized >40 ml shell length in a 15 x 15 cm square quadrat). Some iwi groups have mapped cockle, pipi and green-lipped mussel beds using quantitative (usually quadrat-based) techniques [40].

For subtidal species like green-lipped mussels and horse mussels, scuba transects and underwater towed video transects may be used to quantify abundance. Auckland Council-funded diver surveys of horse mussel abundance/size using transects and quadrats in Mahurangi Harbour were abandoned after densities dropped to the point where this type of survey technique was no longer affordable/practical. Diver and towed video surveys generally do not quantify shellfish bed extent (i.e., they only quantify shellfish density and size at specific sites). Observations of shellfish (e.g., size, degree of fouling or sediment smothering) and the number of live vs dead, may provide information on "bed quality".

Scallop beds have been surveyed for many years by MPI using standard benthic trawling techniques [41-43]. Because of the destructiveness of the technique, methods are being developed to transition towards underwater towed camera surveys [44]. Transitioning to camera-based surveys may also increase the availability of useful ancillary information on the appearance/condition of the habitat.

A4-(ii) Are there any implementation issues such as accessing privately owned land to collect repeat samples for regulatory informing purposes?

Practical/logistical barriers to conducting surveys of shellfish bed extent and quality are species-specific. Intertidal sandflats where cockles, wedge shells and pipi are common are generally highly accessible and present very few practical/logistical barriers. Measuring shellfish bed extent and quality in subtidal areas (e.g., for green-lipped mussels, horse mussels, dog cockles, scallops) is much more difficult; such surveys may require access to Worksafe accreditations for boating and diving, access to expensive dive and camera gear, and the securing of permits to sample. Suspension-feeding shellfish often occur in areas of high current flow, which can pose risks to divers and affect the positioning/speed of towed cameras (affecting the quality of the footage). Diving and camera work in areas with low water clarity reduces the scales of observation, and observing large areas of seabed with either type of technique is generally difficult in coastal/estuarine areas.

A4-(iii) What are the costs associated with monitoring the attribute? This includes up-front costs to set up for monitoring (e.g., purchase of equipment) and on-going operational costs (e.g., analysis of samples).

Costs are extremely variable and depend on type of shellfish bed being assessed. For example, almost anyone can sample intertidal cockle and pipi populations using a garden sieve, a quadrat/core made from PVC plastic, a ruler, and a cell phone. Surveys of scallops funded by MPI (involving divers, cameras, and large vessels), in contrast, can cost hundreds of thousands of dollars.

A5. Are there examples of this being monitored by Iwi/Māori? If so, by who and how?

There are likely many examples of iwi and hapū representatives monitoring (formally or informally) shellfish bed extent and quality using a range of mātauranga Māori based and western science based methods. Cultural practices surrounding the collection of shellfish have been handed down through generations and declines in shellfish bed extent and quality are well known and deeply impact hapū and iwi throughout Aotearoa (e.g., [67]).

Cockles, pipi, and mussels are monitored by local kaitiaki throughout Aotearoa. This includes the monitoring of cockles, pipi, and mussels by Patuharakeke Te Iwi Trust on intertidal banks in outer Whangārei Harbour (Snake Bank, Mair/Marsden Bank), the monitoring of cockles by Ngāti Whakehemo in intertidal soft-sediment habitats of Waihī Estuary, and the monitoring of subtidal mussel populations and beds, as well as other species of shellfish by Ngāti Awa and the Te Ūpokorehe Resource Management Team in Ōhiwa harbour. Similarly, many hapū and iwi led have co-led and/or driven the assessment of shellfish and associated ecosystems, including Te Papatipu Rūnanga o Koukourarata, Te Papatipu Rūnaka o Ōraka-Aparima, Te Papatipu Rūnaka o Kāti Huirapa ki Puketeraki, and many more. In addition to this, there are many hapū and iwi led shellfish species and ecosystem assessments, e.g., including co-development of appropriate indicators of estuarine mahinga kai [68-70].

Standard methods that local kaitiaki and mana whenua can use to monitor shellfish are described in Ngā Waihotanga Iho (Estuary Monitoring ToolKit; [33]). The degree of use and uptake of Ngā Waihotanga Iho by iwi and hapū, and the degree of method standardisation across New Zealand, is unclear.

A6. Are there known correlations or relationships between this attribute and other attribute(s), and what are the nature of these relationships?

Shellfish bed extent and quality is likely to be inversely correlated with “Mud Extent” and “Suspended sediment/water clarity/turbidity” (as most bed-forming shellfish are intolerant of high suspended sediment concentrations, high rates of sediment deposition, and high bed sediment mud content). Bed-forming shellfish are likely to be positively correlated with “Phytoplankton/Chlorophyll *a*” as this is a food source for sessile benthic bivalves. For both Suspended Sediment and Phytoplankton, intermediate concentrations are likely most favourable for shellfish (water that is too clear does not have enough food, but water that is too turbid or eutrophic is harmful). Shellfish Bed Extent and Quality could potentially be measured in intertidal estuarine habitats at the same time as “Mud Extent”, “Seagrass Extent” and “Seagrass Quality” (e.g., using the Rapid Habitat Assessment techniques developed by NIWA), though it is not advisable to group these attributes given that they indicate different elements of ecological integrity. The “Macroinvertebrate Community Composition” attribute may provide information on the densities and sizes of some bed-forming shellfish species (e.g., cockles, wedge shells, pipi) but it will not inform or necessarily correlate with the Shellfish Bed Extent and Quality attribute.

Part B—Current state and allocation options

B1. What is the current state of the attribute?

The current state of Shellfish bed extent and quality—poor due to impacts from multiple stressors—is relatively well understood at the National scale. However, most of the monitoring of shellfish is for population density, rather than bed extent or quality, and our understanding is considerably better for some species (e.g., cockles) than it is for others (horse mussels, dog cockles). Much of the change in shellfish bed extent and quality may have occurred before coastal and estuarine benthic habitats were sampled effectively and broadly using modern survey techniques, so it is difficult to know exactly what has been lost and when it happened (although mana whenua recollections may fill gaps). Rates of terrigenous sediment input to estuarine and coastal areas increased 10-100 fold following the arrival of Europeans in New Zealand [45], and widespread trawl fisheries were established as early as 1910. Despite all this, increases in the extent and quality of bed-forming shellfish from today’s generally poor state could be used as a indicator of improving ecological integrity. Targets could be set for shellfish bed extent and quality, and restoration efforts could be aimed at improving shellfish recovery prospects.

B2. Are there known natural reference states described for New Zealand that could inform management or allocation options?

Natural reference states for Shellfish bed extent and quality are not known. Moreover, reference states would be species specific. Although maps showing the purported extent of green-lipped mussel coverage in outer Tamaki Strait / Hauraki Gulf from the early 1900s are available, information on the natural reference state of cryptic non-harvested species like dog cockles is almost entirely lacking. It is likely, however, that natural reference states of all bed-forming shellfish species were likely better than today’s degraded state.

B3. Are there any existing numeric or narrative bands described for this attribute? Are there any levels used in other jurisdictions that could inform bands? (e.g., US EPA, Biodiversity Convention, ANZECC, Regional Council set limit)

To my knowledge, numeric or narrative bands do not exist for the attribute Shellfish bed extent and quality.

B4. Are there any known thresholds or tipping points that relate to specific effects on ecological integrity or human health?

Relatively sudden collapses of several bed-forming shellfish species in New Zealand suggests the existence of tipping points and thresholds. However, disentangling the underlying causes of bed-forming shellfish collapse is difficult. A recent review of cumulative effects of stressors on scallops and scallop habitats in the Marlborough Sounds suggested a clear negative impact of specific human activities both on land (land clearance and forestry) and in adjacent coastal zones (bottom contact fishing). However, the spatial and temporal resolution of the available data on stressors, and on the specific times and places of scallop population declines, precluded tight linkage of cause and effect [27].

B5. Are there lag times and legacy effects? What are the nature of these and how do they impact state and trend assessment? Furthermore, are there any naturally occurring processes, including long-term cycles, that may influence the state and trend assessments?

Shellfish bed extent and quality within estuaries has likely contracted as terrigenous sediment loading and Mud Extent in estuaries have expanded. It has likely taken many decades for Mud Extent to build to its current levels, and reductions will also likely take many decades. Lags in recovery of bed-forming shellfish are likely to be longer than for Mud Extent due to Allee effects; most of the bed-forming shellfish are broadcast spawners whose reproductive success (fertilisation probability) depends on them being present in high density beds. Moreover, some bed-forming shellfish species are long-lived and may take years to reach full size and maximum fecundity. Therefore, legacies of past degradation and lags in recovery need to be considered by mana whenua kaitiaki and other resource managers.

B6. What tikanga Māori and mātauranga Māori could inform bands or allocation options? How? For example, by contributing to defining minimally disturbed conditions, or unacceptable degradation.

To our knowledge, there are no bands for shellfish bed extent and quality in existence in New Zealand. Thus tikanga Māori and mātauranga Māori have not been utilised to develop bands, targets, or allocation options. Tikanga Māori and mātauranga Māori should be included, in collaboration with whānau, hapū and iwi, in decision making and band/threshold definition.

Part C—Management levers and context

C1. What is the relationship between the state of the environment and stresses on that state? Can this relationship be quantified?

There is evidence that the natural extent of shellfish beds in New Zealand, and the size of shellfish within those beds, was much greater prior to the arrival of Europeans than it is today [19,20]. Shellfish beds once covered hundreds of square kilometres of seafloor but have dramatically declined or disappeared due to overharvesting, habitat destruction, terrigenous sediment loading, and other stressors. Declines in Shellfish Bed Extent and Quality are not unique to New Zealand. However, declines in this attribute have likely occurred more recently in New Zealand relative to elsewhere. Although the drivers of declines in Shellfish Bed Extent and Quality are generally understood, specific causal relationships with stressors are not well quantified. The options available to managers to reverse shellfish declines are unclear because of multiple stressor interactions and biological and physical factors that promote hysteresis (e.g., density-dependent spawning and Allee effects; legacies of past sediment loading and biogenic habitat removal that may take years to improve). Nevertheless, there are large-scale oyster restoration projects being undertaken overseas (e.g., Chesapeake Bay) and there are promising new examples of green-lipped mussel restoration success from New Zealand, suggesting that shellfish bed recovery may be possible for some species with a combination of stressor reduction and active mitigation.

C2. Are there interventions/mechanisms being used to affect this attribute? What evidence is there to show that they are/are not being implemented and being effective?

C2-(i). Local government driven

Many councils and local/regional authorities have taken steps to control sediment and nutrient inputs, which should result in the eventual improvement of shellfish bed extent and quality. However, current sediment and nutrients inputs to coastal ecosystems are likely still high and driven by external events (such as Cyclone Gabrielle). Some of the Jobs for Nature initiatives (while Central government driven) are being implemented locally, but outcomes for shellfish bed extent and quality are not yet known. Some of the 'local' initiatives are being undertaken on relatively large scales (e.g., the $100m Kaipara Moana Remediation project; [46]).

C2-(ii). Central government driven

Fisheries NZ (MPI) is tasked with managing Quota Management Species, which includes some of the bed-forming shellfish (e.g., scallops, green-lipped mussels, cockles, pipi, horse mussels). Due to recent collapses of scallops, FNZ has instituted (almost) National scale scallop fisheries closures.

The Jobs for Nature programme (administered by five central government agencies) has directed hundreds of millions of dollars towards riparian planting in catchments to prevent sediments and nutrients from entering freshwater and coastal receiving environments downstream. Obviously, the Jobs for Nature funding was not targeted at improving the Shellfish bed extent and quality attribute, though the attribute may be useful at tracking the successes of individual catchment interventions (with the caveat that there will be temporal lags and legacy effects). Several central government agencies are commissioning work on the effects of catchment contaminants in estuarine/coastal ecosystems and/or have strategies for catchment contaminant load reductions, but specific actions are not likely being widely implemented yet.

C2-(iii). Iwi/hapū driven.

Rāhui on collections of bed-forming shellfish have been implemented in many areas of New Zealand. Rāhui is often misappropriated and confused with 'temporary closures' and their protection status contrast to each other; for instance, rāhui has no legal teeth, and are therefore followed voluntarily, while temporary closures are a 'two-year' fishery ban that can be applied once a Customary Management Area is established [71]. There are numerous examples of how CMA tools including temporary closures are not providing for the needs of whānau, hapū, iwi and their taonga/marine ecosystems. For example, CMAs have failed to deliver meaningful governance, timely responses, or localised and ecologically relevant solutions [72-75].

For scallops, at least three temporary closures have been set for the Hauraki Gulf. Ngāti Manuhiri set a two-year scallop closure. Coromandel residents declared a voluntary rāhui on scallop collecting on the eastern side of the peninsula. Patuharakeke have supported a series of two-year temporary closures for the collection of pipi from Mair/Marsden bank. Ngāti Awa have set a temporary closure for the collection of recently settled (restored) seabed mussels in Ōhiwa Harbour.

Iwi and hapū have been heavily involved in Jobs for Nature projects across New Zealand to address land and water quality, including downstream estuary health (though not necessarily shellfish bed extent and quality specifically). Iwi and hapū are also leading and contributing to shellfish restoration initiatives in partnership with Councils and National Science Challenge researchers from various universities, CRIs, and other research institutes/providers [47,48].

C2-(iv). NGO, community driven

Revive Our Gulf is a broad partnership designed to restore mussel reefs in the Hauraki Gulf [49] and there are similar shellfish restoration initiatives at the Top of the South Island.

C2-(v). Internationally driven

To the best of our knowledge there are no initiatives to improve Shellfish Bed Extent and Quality in coastal ecosystems of New Zealand that are being driven by international entities. However, the Department of Conservation and other agencies set many of their policy goals to align with Convention of Biological Diversity targets, e.g., CBD Aichi Target 11 (biodiversity and ecosystem services are conserved using effective area-based conservation measures integrated into wider landscapes and seascapes).

Part D—Impact analysis

D1. What would be the environmental/human health impacts of not managing this attribute?

Shellfish population collapses have impacted Māori identity and wellbeing (e.g., whakapapa, mātauranga, taonga) and cultural values and practices (e.g., kaitiakitanga, kaimoana harvest) [50,51]. Shellfish restoration is high priority for many hapū and iwi nationwide [51,52]. Māori also have substantial economic interests (e.g., fisheries, aquaculture, tourism) that will benefit from restored estuaries and shellfish populations. Shellfish restoration can clean estuarine waters of nitrogen pollution [53-55] and increase fish diversity and abundance through habitat provision [56,57]. Shellfish also provide ecosystem services such as food web support and carbon sequestration [58].

D2. Where and on who would the economic impacts likely be felt? (e.g., Horticulture in Hawke's Bay, Electricity generation, Housing availability and supply in Auckland)

Food budgets, regional economies, and national exports have been impacted by the decline in shellfish populations resulting from estuarine degradation. The scallop fishery of Te Tauihu, worth over $70m [59] in the mid-1970s (approx. $700m today) is closed. Habitat restoration would make sustainable harvests of 10-20% of this level achievable, with a value in the order of $100m/year. Restoration of other degraded shellfish habitats and populations (e.g., the inner Hauraki Gulf/Firth of Thames, Bay of Islands) could support sustainable fisheries with a combined value of a further $100m/year. The mussel industry anticipates that restoring the supply of seed mussels in Kenepuru Sound alone is worth >$15m/year. It is estimated that a $350m investment in estuary repair could be returned in <5 years from improved commercial fisheries of fish, shellfish and crustaceans [109].

While the value of job creation is not presently quantifiable for Aotearoa-NZ, we note that shellfish restoration in Chesapeake Bay, Maryland, created 313 jobs while increasing fisheries output and nitrogen removal value by US$22.3m and US$3-18m, respectively [60]. Restoration would create a range of job opportunities in aquaculture, tourism and restoration-focused businesses.

D3. How will this attribute be affected by climate change? What will that require in terms of management response to mitigate this?

There is evidence that heat waves (specifically, extreme air temperatures coincident with mid-day low tides) contributed to mass mortality in an intertidal cockle bed in Whangateau Estuary, Auckland [61,62]. Heat waves and thermal stress are likely to become more and more problematic in a warming world. Although there is little to no evidence that marine heatwaves and heat stress contributed to bed-forming shellfish population collapses, shellfish recovery may be affected by climate change if heat stress continues to increase. Coastal sea surface temperatures (SST) near the mouths of several North Island estuaries have increased over the last 20-30 years and SST was a significant driver of estuarine macroinvertebrate variables in some long-term time-series datasets [63]. SST around New Zealand in 2024 was the warmest on record, and the long-term trend of increasing SST is predicted to continue.

Some bed-forming shellfish inhabit intertidal flats and banks. Climate-related increases in sea level will eventually permanently inundate these areas, thereby reducing the suitability of the habitat for intertidal species [64]. Sea level rise also has the potential to alter current flow regimes and the positions of tidal channels, which could affect various bed-forming shellfish species (as most of suspension feeders that rely on high-current flows to bring them suspended particulate food material).

Finally, the shells of bivalve shellfish are made of calcium carbonate. Ocean acidification (due to increasing atmospheric CO_2 concentrations) negatively affects the calcification and growth of shellfish [65,66]. Acidification can also result from excess nutrient/organic matter loading, which depletes oxygen and elevates CO_2 production. Eutrophication-related acidification may be the greater risk to coastal shellfish in New Zealand, relative to climate-related acidification, though a slowly shifting baseline towards lower pH waters associated will not help.

References:

1. Thrush, S.F., Hewitt, J.E., Gibbs, M., Lundquist, C., Norkko, A. 2006. Functional role of large organisms in intertidal communities: Community effects and ecosystem function. Ecosystems 9(6): 1029-1040. https://doi.org/10.1007/s10021-005-0068-8
2. *Norkko*, A., *Hewitt*, J.E., *Thrush*, S.F., Funnell, G. A. 2006. Conditional outcomes of facilitation by a habitat-modifying subtidal bivalve. Ecology 87(1): 226-234. https://doi.org/10.1890/05-0176
3. **Lohrer, A.M.**, Chiaroni, L.D., Thrush, S.F. and J.E. Hewitt. 2010. Isolated and interactive effects of two key species on ecosystem function and trophic linkages in New Zealand soft-sediment habitats. New Zealand Aquatic Environment and Biodiversity Report No. 44, 69 p.
4. *Lohrer*, A.M., Rodil, I.F., *Townsend*, M., Chiaroni, L.D., *Hewitt*, J.E., *Thrush*, S.F. 2013. Biogenic habitat transitions influence facilitation in a marine soft-sediment ecosystem. Ecology 94: 136–145.
5. *Thrush*, S.F., *Townsend*, M., *Hewitt*, J.E., Davies, K., *Lohrer*, A.M., *Lundquist*, C., Cartner, K. 2013. The many uses and values of estuarine ecosystems. Pp 226-237 in Dymond, J. (ed) Ecosystem Services in New Zealand – Condition and Trends. Manaaki Whenua Press, Lincoln, New Zealand.
6. Rullens, V., Lohrer, A., Townsend, M., Pilditch, C. 2019. Ecological mechanisms underpinning ecosystem service bundles in marine environments – a case study for shellfish. Frontiers in Marine Science. 10.3389/fmars.2019.00409
7. 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.A. 2021. Cumulative stressors reduce the self-regulating capacity of coastal ecosystems. Ecological Applications 31(1): e02223.
8. Rullens, V., Townsend, M., Lohrer, A.M., Stephenson, F., Pilditch, C.A. 2022. Applying ecological principles to predict the spatial distribution of shellfish-generated ecosystem services. Science of the Total Environment 842:10. https://doi.org/10.1016/j.scitotenv.2022.156877

9. 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. Ecological Applications 23: 226–238.
10. Lohrer, A.M., Halliday, N.J., Thrush, S.F., Hewitt, J.E. and I.F. Rodil. 2010. Ecosystem functioning in a disturbance-recovery context: contribution of macrofauna to primary production and nutrient release on intertidal flats. Journal of Experimental Marine Biology and Ecology 390: 6–13.
11. Lohrer, A.M., Townsend, M., Hailes, S.F., Rodil, I.F., Cartner, K.J., Pratt, D.R., Hewitt, J.E. 2016. Influence of New Zealand cockles (Austrovenus stutchburyi) on primary productivity in sandflat-seagrass (Zostera muelleri) ecotones. Estuarine, Coastal and Shelf Science 181: 238-248.
12. Bricker, S.B., Ferreira, J.G., Zhu, C., Rose, J.M., Galimany, E., Wikfors, G., Saurel, C., Miller, R.L., Wands, J., Trowbridge, P. 2018. Role of shellfish aquaculture in the reduction of eutrophication in an urban estuary. Environmental Science & Technology 52(1): 173-183.
13. Golen, R.F. Sulkowski, A.J. 2010. The Basis for Estuarine Habitat Restoration and Nutrient Trading Schemes in the Clean Water Act. IUP Journal of Environmental Sciences 4(1): 41-50.
14. Hewitt, J., Thrush, S., Gibbs, M., Lohrer, D., and A. Norkko. 2006. Indirect effects of Atrina zelandica on water column nitrogen and oxygen fluxes: the role of benthic macrofauna and microphytes. Journal of Experimental Marine Biology and Ecology 330:261-273.
15. Hillman, J.R., Lohrer, A.M. O'Meara, T.A., Thrush, S.F. 2021. Influence of restored mussel reefs on denitrification in marine sediments. Journal of Sea Research 175 (2021) 102099.
16. Rullens, V., Townsend, M., Lohrer, A.M., Stephenson, F., Pilditch, C.A. 2022. Applying ecological principles to predict the spatial distribution of shellfish-generated ecosystem services. Science of the Total Environment 842:10 https://doi.org/10.1016/j.scitotenv.2022.156877
17. Lohrer, A.M., Stephenson, F., Douglas, E., Townsend, M. 2020. Mapping the estuarine ecosystem service of pollutant removal using empirically validated boosted regression tree models. Ecological Applications 30(5): e02105. 10.1002/eap.2105 https://esajournals.onlinelibrary.wiley.com/doi/10.1002/eap.2105
18. State of our Gulf 2020 Hauraki Gulf / Tīkapa Moana / Te Moananui-ā-Toi. 2020. State of the Environment Report 2020. https://www.aucklandcouncil.govt.nz/about-auckland-council/howauckland-council-works/harbour-forums/docsstateofgulf/state-gulf-full-report.pdf
19. Toone, T.A., Benjamin, E.D., Hillman, J.R., Handley, S., Jeffs, A. 2023. Multidisciplinary baselines quantify a drastic decline of mussel reefs and reveal an absence of natural recovery. Ecosphere.
20. Toone, T.A., Hunter, R., Benjamin, E.D., Handley, S., Jeffs, A., Hillman, J.R. 2021. Conserving shellfish reefs—A systematic review reveals the need to broaden research efforts. Restoration Ecology 29: e13375.
21. Anderson, T., Morrison, M., MacDiarmid, A., Clark, M., D'Archino, R., Nelson, W., Tracey, D., Gordon, D.P., Read, G., Kettles, H., Morrisey, D., Wood, A., Anderson, O., Smith, A.M., Page, M., Paul-Burke, K., Schnabel, K., Wadhwa, S. 2019. Review of New Zealand's Key Biogenic Habitats. NIWA Client Report No: 2018139WN. Prepared for the Ministry for the Environment.
22. Urlich, S.C., Handley, S.J. 2020. From 'clean and green' to 'brown and down': A synthesis of historical changes to biodiversity and marine ecosystems in the Marlborough Sounds, New Zealand. Ocean & Coastal Management 198: 105349. https://doi.org/10.1016/j.ocecoaman.2020.105349
23. Williams, J.R., Roberts, C.L., Chetham, J. 2017. Initiation of a community-based pipi monitoring programme. Unpublished report Prepared for Patuharakeke Te lwi Trust Board, July 2017. Accessed from https:ljpatuharakeke.maori.nz/wp-content/uploads/2018/01/NIWA-clientreport-2017255AK.pdf
24. Patuharakeke Te Iwi Trust Board. Letter to Hon Stuart Nash, Ministry of Fisheries, re: Proposal to re-apply a Section 186A Closure on Mair and Marsden Banks, Marsden Point to the harvesting of ALL SHELLFISH. https://www.mpi.govt.nz/dmsdocument/39908-Patuharakekerequest-Mair-and-Marsden-Banks

25. Plew, D.R., Zeldis, J.R., Dudley, B.D., Whitehead, A.L., Stevens, L.M., Robertson, B.M., Robertson, B.P., 2020. Assessing the eutrophic susceptibility of New Zealand estuaries. Estuaries and Coasts 43: 2015-2033.
26. Stevens, L.M., Forrest, B.M., Dudley, B.D., Plew, D.R., Zeldis, J.R., Shankar, U., Haddadchi, A. and Roberts, K.L., 2022. Use of a multi-metric macroalgal index to document severe eutrophication in a New Zealand estuary. New Zealand Journal of Marine and Freshwater Research, 56(3), pp.410-429.
27. Hale R., Lam-Gordillo, O., Lohrer, D., Williams, J.R., Handley, S., Olmedo-Rojas, P., Middleton, I. 2024. Cumulative effects of stressors on scallops and scallop habitats in the Marlborough Sounds: With insights from sites in Northland, Hauraki Gulf, and eastern Coromandel Peninsula. New Zealand Aquatic Environment and Biodiversity Report 337, 109 pp. (ISSN: 1179-6480; ISBN: 978-1-991308-08-5)
28. Herzig, A., Dymond, J., Neverman, A., Price, R., Barnes, M. 2024. Ki uta ki tai: matapono me te putaiao, nga korero whakamahuki ma te kaitiaki – whenua. From mountains to the sea: values and science for an informed Kaitiaki/Guardian – land. Draft report to Our Land & Water National Science Challenge. 39 p.
29. Ministry for Primary Industries. 2020. SPATnz End of Programme Review: Primary Growth Partnership SPATnz Programme Evaluation Report. Evaluation of SPATnz PGP programme | NZ Government (mpi.govt.nz), https://www.mpi.govt.nz/dmsdocument/41800-SPATnz-Evaluation-Report.pdf. See also SPATnz | New Zealand Greenshell Mussels.
30. Drylie, T.P., Marine ecology state and trends in Tāmaki Makaurau / Auckland to 2019. State of the environment reporting. . Auckland Council technical report. TR2021/09, 2021.
31. Hailes, S.; Hewitt, J.E. (2009). Manukau Harbour Ecological Monitoring Programme: Report on data collected up until February 2009. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council TR2009/121.
32. Halliday, J., Edhouse, S., Lohrer, D., Thrush, S., Cummings, V. 2013. Mahurangi Estuary Ecological Monitoring Programme: Report on Data Collected from July 1994 to January 2013. Prepared by NIWA for Auckland Council. Auckland Council Technical Report 2013/xxx. 95 pp.
33. Ngā Waihotanga Iho: Estuary Monitoring ToolKit. https://niwa.co.nz/te-kuwaha/tools-and-resources/ng%C4%81-waihotanga-iho-the-estuary-monitoring-toolkit.
34. https://www.lawa.org.nz/explore-data/estuaries
35. Berkenbusch, K.; Hill-Moana, T.; Neubauer, P. (2022). Intertidal shellfish monitoring in the northern North Island region, 2021–22. New Zealand Fisheries Assessment Report 2022/57. 142 p.
36. Berkenbusch, K.; Neubauer, P. (2018). Intertidal shellfish monitoring in the northern North Island region, 2017–18. New Zealand Fisheries Assessment Report 2018/28. ISSN 1179-5352 (online); ISBN 978-1-77665-919-7 (online).
37. Williams, J.R., Cryer, M., Hooker, S.H., McKenzie, J.R., Smith, M.D., Watson, T.G., MacKay, G., Tasker, R. 2007. Biomass survey and stock assessment of pipi (Paphies australis) on Mair Bank, Whangarei Harbour, 2005. New Zealand Fisheries Assessment Report 2007/3. 29 p.
38. NEEDHAM, H. R., HEWITT, J. E., TOWNSEND, M. & HAILES, S. 2013. Intertidal habitat mapping for ecosystem goods and services: Waikato Estuaries Report prepared for WRC.
39. LAM-GORDILLO, O., HAILES, S. & CARTER, K. 2023a. Intertidal habitat mapping for: Waikato Estuaries 2023. Prepared for Waikato Regional Council. . NIWA report 2023240HN (project EVW23209). 107 pp.
40. Paul-Burke, K. & Burke, J. (2016). Report on the findings of sub-tidal sampling surveys of Perna canaliculus, Green Lipped Mussel populations in Ōhiwa harbour 2016. Report prepared for the Ōhiwa Harbour Strategic Coordination Group and Te Ūpokorehe Resource Management Team. Bay of Plenty Regional Council. Whakatāne, NZ.
41. Williams, J.R., Bian, R., Olsen, L., Stead, J., Tuck, I. 2019. Dredge survey of scallops in Marlborough Sounds, May 2019. New Zealand Fisheries Assessment Report 2019/69.

42. Williams, J.R., Bian, R., Olsen, L., Stead, J. 2021. Survey of scallops in SCA 7, May 2020. New Zealand Fisheries Assessment Report 2021/09. 54 p.
43. Williams, J.R.; Bian, R., Roberts, C.L. 2018. Survey of scallops in Kaipara Harbour, 2017. New Zealand Fisheries Assessment Report 2018/20. 29 p.
44. Williams, J.R., et al. (In press). Title xxxx. New Zealand Aquatic Environment and Biodiversity Report No. xxxxx
45. Hunt, S. 2019. Summary of historic sedimentation measurements in the Waikato region and formulation of a historic baseline sedimentation rates. Waikato Regional Council Technical Report no. 2019/08.
46. Kaipara Moana Remediation, 2023. Kaipara Moana Remediation Programme. https://kmr.org.nz/
47. Sustainable Seas National Science Challenge, 2020. Early signs of success at mussel 'restoration stations'. https://www.sustainableseaschallenge.co.nz/news-andevents/news/early-signs-of-success-at-mussel-restoration-stations/
48. Te Wahapū o Waihī (TWOW) is a five iwi collective comprised of Ngāti Whakahemo, Ngāti Whakaue ki Maketū, Ngāti Mākino, Ngāti Pikiao, Tapuika. It is focused on the rehabilitation of Waihī Estuary that incorporates upstream and in-estuary mitigations.
49. Revive Our Gulf – The Mussel Reef Restoration Trust. 2023. Restoring the mussel reefs of the Hauraki Gulf. https://www.reviveourgulf.org.nz/
50. Šunde, C., Astwood, J.-R., Young, A. 2019. He Pou Tokomanawa – Kaitiakitanga in Practice Project Report for the Sustainable Seas National Science Challenge. Prepared as part of the Sustainable Seas National Science Challenge. Tiakina te Taiao Report. 45 (p21-25).
51. Chetham, J., Pitman, A. 2014. Patuharakeke hapū environmental management plan 2014. https://www.nrc.govt.nz/media/wnynyiks/patuharakeke-hapū-environmental-management-plan-2014.pdf
52. Cummings, V.J., May, K. 2009. Restoring shellfish beds to harbours and estuaries: a guide for community groups. http://www.niwa.co.nz/our-science/freshwater/research-projects/all/restoration-of-estuarine-shellfish-habitat/active-shellfish-reseeding/Restoring-Shellfish-beds-FINAL.pdf
53. Golen, R.F. Sulkowski, A.J. 2010. The Basis for Estuarine Habitat Restoration and Nutrient Trading Schemes in the Clean Water Act. IUP Journal of Environmental Sciences 4(1): 41-50.
54. Carmichael, R.H., Walton, W. and Clark, H., 2012. Bivalve-enhanced nitrogen removal from coastal estuaries. Canadian journal of fisheries and aquatic sciences, 69(7), pp.1131-1149.
55. Cottingham, A., Bossie, A., Valesini, F., Tweedley, J.R. and Galimany, E., 2023. Quantifying the Potential Water Filtration Capacity of a Constructed Shellfish Reef in a Temperate Hypereutrophic Estuary.
56. Gilby, B.L., Olds, A.D., Duncan, C.K., Ortodossi, N.L., Henderson, C.J. and Schlacher, T.A., 2020. Identifying restoration hotspots that deliver multiple ecological benefits. Restoration Ecology 28(1): 222-232.
57. Creighton, C., Boon, P.I., Brookes, J.D. and Sheaves, M., 2015. Repairing Australia's estuaries for improved fisheries production–what benefits, at what cost?. Marine and Freshwater Research, 66(6), pp.493-507.
58. Coen, L.D., Luckenbach, M.W. 2000. Developing success criteria and goals for evaluating oyster reef restoration: ecological function or resource exploitation? Ecological Engineering 15(3-4): 323-343.
59. Michael, K. P. et al. 2012. Information on drivers of shellfish fisheries production in Golden and Tasman Bays and knowledge gaps: A review summary to inform the development of a plan to rebuild shellfish fisheries.
60. Stewart-Sinclair, P.J., Purandare, J., Bayraktarov, E., Waltham, N., Reeves, S., Statton, J., Sinclair, E.A., Brown, B.M., Shribman, Z.I., Lovelock, C.E. 2020. Blue restoration–building confidence and overcoming barriers. Frontiers in Marine Science 748.

61. Jones, H.F., Pilditch, C.A., Hamilton, D.P., Bryan, K.R. 2017. Impacts of a bivalve mass mortality event on an estuarine food web and bivalve grazing pressure. New Zealand Journal of Marine and Freshwater Research 51(3): 370-392.
62. Tricklebank, K.A., Grace, R.V., Pilditch, C.A. 2021. Decadal population dynamics of an intertidal bivalve (Austrovenus stutchburyi) bed: Pre-and post-a mass mortality event. New Zealand Journal of Marine and Freshwater Research 55(2): 352-374.
63. Lam-Gordillo, O., Hewitt, J.E., Douglas, E.J., Dudley, B.D., Holmes, S.J., Hailes, S., Carter, K., Greenfield, B., Drylie, T., Lohrer, A.M. 2024. Climatic, oceanic, freshwater, and local benthic drivers of estuarine macroinvertebrates. Marine Environmental Research 197: 106472. https://doi.org/10.1016/j.marenvres.2024.106472
64. Rullens, V., Mangan, S., Stephenson, F., Clark, D.E., Bulmer, R.H., Berthelsen, A., Crawshaw, J., Gladstone-Gallagher, R.V., Thomas, S., Ellis, J.I. and Pilditch, C.A., 2022. Understanding the consequences of sea level rise: the ecological implications of losing intertidal habitat. New Zealand Journal of Marine and Freshwater Research, 56(3), pp.353-370.
65. Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M. and Gattuso, J.P., 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Global change biology, 19(6), pp.1884-1896.
66. Kroeker, K.J., Kordas, R.L., Crim, R.N. and Singh, G.G., 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecology letters, 13(11), pp.1419-1434.
67. Kitson (2017) Statement of Evidence of Dr Jane Catherine Kitson (Including Attachment E) on Behalf of Ngā Rūnanga (Waihopai Rūnaka, Te Rūnanga O Awarua, Te Rūnanga O Ōraka Aparima, And Hokonui Rūnaka) And Te Rūnanga O Ngāi Tahu. In the matter of a submission by Ngāi Tahu on the Proposed Southland Water and Land Plan, 29 May 2017. Te Rūnanga o Ngāi Tahu, Aotearoa, New Zealand: 1
68. Kainamu-Murchie, A., Williams, A., Kitson, J., Dallas, R., Ratana, K., May. K. (2021) Ngā taonga waimātaitai: Co-developing appropriate tangata whenua approaches to improve estuarine mahinga kai management. Technical report for Te Rūnaka o Ōraka-Aparima. 55p.
69. Te Rūnanga o Ngāi Tahu (2004) State of the Takiwā. Cultural Monitoring and Reporting on the Health of our Environment. Te Rūnanga o Ngāi Tahu, Christchurch, New Zealand: 28.
70. Pauling, C. (2005) State of the Takiwā. Cultural Monitoring and Reporting on the Health of our Environment. Te Āhuatanga o Te Waiau, Te Rūnanga o Ngāi Tahu, ESR, EnviroLink, Ministry for the Environment, Manaaki Whenua, Environment Southland. Aotearoa, New Zealand: 88.
71. Kainamu and Rolleston-Gabel 2023. A review of te ao Māori perspectives of marine sclaes and where these are impeded by contemporary management. Reported prepared for the Sustainable Seas National Science Challenge, by NIWA. 26p.
72. McCormack, F. (2011) Rāhui: A blunting of teeth. The Journal of the Polynesian Society 120(1): 43-55.
73. Jackson, A.-M. (2013) Erosion of Maori fishing rights in customary fisheries management. Waikato Law Review 21: 59.
74. Gnanalingam, G., Hepburn, C. (2015) Flexibility in temporary fisheries closure legislation is required to maximise success. Marine Policy 61: 39-45.
75. van Halderen, L. (2020) Investigating rāhui as a customary fisheries management tool. Thesis, Master of Science. University of Otago