Mai uta ki tai: Cyclone-Driven Suspended Sediment Effects on Early Benthic Juvenile Kōura (*Jasus edwardsii*), Te Ākau o Tokomaru, Aotearoa

A thesis

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Tuhinga Whakarāpopoto - Abstract

Kōura (*Jasus edwardsii*) are ecologically, culturally, and economically significant taonga species central to mahinga kai systems throughout Aotearoa New Zealand. In Te Tairāwhiti, particularly Te Ākau o Tokomaru, Cyclone Gabrielle (February 2023) resulted in unprecedented sediment loads being delivered to coastal waters, smothering inshore rocky reefs that serve as critical nursery habitats for settling puerulus and juvenile kōura. This research investigated how repeated suspended sediment exposure affects the body condition, survival, and physiological condition of early benthic juvenile kōura, integrating Western scientific methods with mātauranga Māori perspectives to support kaitiakitanga and ecosystem recovery.

A 52-day pulse-based laboratory experiment exposed 81 early benthic juvenile kōura to three treatment levels: Control (0 mg/L), Tobserved (1,000 mg/L), and Tmaximised (5,000 mg/L) suspended sediment concentrations, alternating between exposure phases and recovery periods to simulate natural post-storm sedimentation dynamics. Sediment was sourced from the Mangahauini River mouth to reflect local conditions. Kōura were initially housed communally (Days 1-19), and then separated into individual tāruke following observed cannibalism. Across the experiment, body weight to carapace length (BW:CL) ratios, survival, blood refractive index, gill condition, and moult stage were assessed.

All treatment groups began with statistically equivalent body condition ($p = 0.135$), but cumulative effects emerged over time. During communal housing, mortality was highest in the Tobserved treatment (51.9%) compared with Control and Tmaximised treatments (both 18.5%). After separation, Tmaximised individuals showed the greatest losses (45.5%), mostly during the recovery rather than exposure phases. Overall mortality reached 45.7%, with sediment-exposed treatments experiencing 55% (Tmaximised) to 59% (Tobserved) losses compared with 22.2% in the Controls ($p = 0.001$).

By Day 52, sediment exposure significantly reduced body condition ($p = 0.016$), with the Controls maintaining higher BW:CL ratios than Tmaximised ($p = 0.013$). Gill assessments indicated universal and severe damage in sediment-exposed kōura (100%) but none in the Controls (0%). Quantitative image analysis confirmed strong sediment concentration-dependent effects across all damage metrics – particle lodgement, filament integrity, surface discolouration, and composite scores (all $p < 0.001$) – with structural deformities in 66.7% of Tobserved and 100% of Tmaximised individuals. Blood refractive index showed no treatment differences, and 84.1% of kōura remained in intermoult stage at Day 52, with no significant difference in moult stage distribution between treatments ($p = 0.328$). However, moult frequency during the individual phase was lower in sediment-exposed groups compared to the Controls (Control: n = 11, Tobserved: n = 4, Tmaximised: n = 5).

These findings show that suspended sediment exposure poses population-level threats to kōura recruitment through irreversible gill damage and delayed mortality. Elevated cannibalism during communal holding, particularly observed in the Tobserved treatment, likely resulted from temporal clustering of moult events rather than sediment-induced behaviour. For Te Ākau o Tokomaru and the wider CRA 3 fishery, this highlights the need for integrated catchment-to-coast management addressing land-derived sediment inputs and protecting coastal nursery habitats. From a Te Ao Māori perspective, sedimentation represents a disruption to whakapapa relationships with Tangaroa and a weakening of mauri in coastal ecosystems. Restoring these connections requires co-governance frameworks that embed mātauranga Māori, empower kaitiaki-led monitoring and rāhui, and address the cumulative impacts of land-use intensification and repeated cyclone events on ecosystem resilience in Te Tairāwhiti.

Kupu Takamua - Preface

This thesis was undertaken as part of the requirements for the Master of Science (Research) in Ecology and Biodiversity degree at the University of Waikato, Hamilton, New Zealand. This mahi is more to me than I can explain. It's not just a research project, it's a reflection of who I am, where I come from, and who I do this for.

My whānau have shaped me into the person I am today, and they've raised me with values that go beyond the classroom – values of manaakitanga, kaitiakitanga, and whanaungatanga. This thesis is my way of giving back. It's what my whānau want to know, and I've done my best to honour that.

While this research investigates the effects of suspended sediment on the early benthic life stages of kōura (*Jasus edwardsii* – red rock lobster), it is grounded in something deeper than science. I am Māori before I am a student, therefore my whakapapa, my whenua, and my whānau shape the way I see the world, and the way I carried out this mahi. I don't separate my science from my identity, they walk together.

The language used in this thesis includes te reo Māori and a glossary is provided. That choice is intentional, reflecting both the kaupapa of this research and the intended audience. As this work engages concepts of kaitiakitanga and taonga species, the use of te reo Māori acknowledges and upholds our ways of knowing and communicating about te taiao (the environment).

My hope is that this thesis helps inform better management of our taonga species, as well as better management for further upstream – ki uta ki tai. In Te Ākau o Tokomaru, sedimentation is a REAL and ONGOING issue, and if this mahi can support our communities, spark kōrero, and help ensure that our taonga species thrive for generations to come – then I've done what I came here to do. *Mauri ora*.

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To Darc, ngā mihi nui for supporting this kaupapa from DAY ONE and helping me navigate the many layers of this mahi. I know being hapū and having a student isn't always

easy, so thank you (both you and puku pēpi) for putting up with me. Your aroha, manaaki, and awhi have helped me more than you know, and I'm so grateful to have had you in my corner. Best wishes to you and your whānau as you welcome your new pēpi into the world, he aroha mutunga kore <3

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To Dylan, ngā mihi nui, e taku ipo. I'll never forget you saying "Keep going babe, you've got this". Your unconditional love, your patience (with me especially haha), and your words of encouragement have kept me grounded and motivated to carry out this mahi through to the end. Thank you for believing in me and especially thank you for your big muscles because those sediment buckets were heavy hahaha. I love you.

To my mete, Ruaputahanga, ngā mihi nui kia koe for being there when I needed someone the most. For always helping or offering to help at every chance you got, and for letting me stay at your whare whilst doing my lab experiment – it means the world to me. I couldn't give you anything in return that would ever match the amount of awhi you have given me. I wouldn't trade you for the world. Ko te hoa tino pono rawa, ko tērā e toro atu ai tōna ringa ki tōu, engari ka titi kaha ki tōu manawa te kōhengihengi <3

To my Māmā, Pāpā, little big bro and princess – I wish you's could be here, but I know you're all cheering me on from the land down under. Your support from afar has kept me going, and I carry your aroha with me every day. I can’t wait to relax in the hot Perth sun and talk to yous about my Masters experience ☺ Arohanui x

To my whānau in Te Ākau o Tokomaru, thank you for allowing me to achieve what I could for our people back home. I hope to return soon and see how much further I can go with this kauapapa in hopes of contributing even more to our rohe. This is only the beginning i te iwi, watch this space!

And last but definitely not least, to my Koko Allan. The love of my life, my rock, my why, my reason for doing this thesis. You’ve shown me how beautiful our home is, and I promise to keep helping it get back to the way it was. Your love for our home has guided me throughout this entire process and I can’t thank you enough for being my Koko, for showing me aroha and always putting a smile on my face. This mahi is for you.

Te Kuputaka o Te Reo Māori - Glossary of Māori Terms

aroha – love, affection, caring, compassionate

awa – river

hapori – community

hapū – Kinship group/subtribe: a section of a larger iwi, made up of related whānau descended from a common ancestor

hara - issue or offence

hītori – transliteration for history

hoki – to move, return

hurihanga - cycle

iwi – Tribe: a group of related hapū that share common ancestry and usually occupy neighbouring communities

kaumātua – elderly

kaitiaki – guardian, steward

kaitiakitanga – guardianship, stewardship

kōpikopiko – to meander, wander

koiora – biological life

kōrero – to talk, speak

kōura – red rock lobster – *Jasus edwardsii*

mahinga kai – cultivation, food-gathering place or action

marae – sacred, communal space including a wharenui (meeting house), wharekai (dining hall), and a courtyard (maraeātea)

Maramataka – Māori lunar calendar

mātauranga Māori – the body of knowledge originating from Māori ancestry including the Māori world view and perspectives

mauri – life force, vital essence

moana – ocean

mokopuna – grandchild

mokowā – gap, space between

pakaru – broken

pānekeneke – to be vulnerable, insecure

pātai matua – central question, main research question

pūtanga whakamātau – experimental outcomes

rārangi tohutoro – reference list

ripanga – table (data tables, computer tables)

taonga – precious, treasure

tāruke – Traditional kōura pot

tātari – analysis

tau – year

Te Ākau o Tokomaru – Māori name for Tokomaru Bay

Te Tairāwhiti – Māori name for the Gisborne District

tikanga – customary system of values / rules

tūrangawaewae – a place where one has a right to stand

Ūpoko – chapter

urupā – burial ground, cemetery

wā – time, area, space

whāinga – aim, goal

whakaahua – figure

whakahirahira – highly important

whānau - family

whakamaramatanga – to understand, clarification

whakapapa – genealogy, give history

whakawhānaungatanga – relating well to others, establishing relationships

whenua – land

Ūawa – Māori name for Tolaga Bay

Rārangi Ūpoko - Table of Contents

Rārangi Whakaahua - List of Figures

Rārangi Ripanga - List of Tables

Ūpoko Tuatahi (1)

Ko te Pūtake: Whānau, Whenua, me te Moana

Introduction

"Mai i te awa ki te moana"

From the river to the sea

1.1. Introduction

The seeds of this research were planted through my Koko Allan's stories of the inshore rocky reefs of Te Ākau o Tokomaru on the east coast of the North Island, and were watered by the "Kanohi Kitea" experience with NIWA in May 2024 that deepened my commitment to the wellbeing of our moana. My Koko would tell me about walking the shallows at low tide, turning over rocks and checking crevices, finding kōura (*Jasus edwardsii*; Hutton, 1875) so plentiful that you could gather kai without going far from the shore. His kōrero painted pictures of clear water where you could watch kōura move between the rocks, their antennae flickering in the current, the reef alive with abundance. These weren't just nostalgic stories – they were lessons in kaitiakitanga, teaching me how to read the moana, which kōura to take and which to leave, how to practice attention, respect, and reciprocity. He spoke of massive kōura, the kind that seem mythical now, though they still exist – just pushed further offshore.

Today, those inshore reefs tell a different story than the ones I heard growing up. Sediment clouds the water. The rocky substrate lies buried beneath silt. The kōura have moved to deeper, clearer water – if they remain at all. This represents more than ecological change; it marks a breaking of connection, a disruption to intergenerational knowledge transmission, a weakening of mana whenua and mana moana. When the living curriculum of the moana – the embodied mātauranga transmitted through kōrero, observation, and practice – can no longer be accessed in the places where it has always been taught, something fundamental is lost.

This whakapapa – my connection to my Koko, to kōura, to the inshore rocky reefs of Te Ākau o Tokomaru – forms the foundation of this research. It defines my position as both researcher and whānau member, my responsibilities as both scientist and mokopuna, my drive as someone who has witnessed the mauri of these waters fade through the stories of my elders and the reality of what remains. From a Te Ao Māori perspective, research cannot exist separately from the researcher's whakapapa, from their tūrangawaewae, and from their responsibility to past and future generations. This mahi expresses whakawhānaungatanga – a renewal of relationship between people, place, and taonga species. Though rooted in personal whakapapa, this research sits within a collective experience of loss and disruption. Following Cyclone Gabrielle 2023, I listened to whānau across Te Tairāwhiti – not through formal interviews, but in organic spaces where kōrero naturally occurs: kitchen tables, long drives, chance meetings. Whānau spoke of places made unrecognisable, kai that could no longer be gathered, rivers running brown for months. They described not just physical destruction, but spiritual and cultural fracture – the feeling that something fundamental had ruptured.

Driving State Highway 35 through Te Tairāwhiti, Cyclone Gabrielle's impact remains unavoidable. Landslides have exposed the bones of the whenua, hillsides have given way, and raw earth continues to bleed into the sea. Yet these visible scars represent only part of the story. The cyclones violence reaches below the waterline, into coastal ecosystems that sustain mahinga kai, and into sediment-smothered reefs where kōura once found shelter. For many whānau, Gabrielle interrupted the rhythm of life that structures cultural practice and identity. Roads were cut, urupā sustained damage, mahinga kai sites became compromised. The awa, moana, and whenua – sources of both physical and spiritual nourishment – now carry unprecedented sediment loads, reshaping how people engage with their environment, gather kai, and practice kaitiakitanga. The cyclone interrupted the transmission of mātauranga Māori, particularly the embodied, place-based knowledge that can only be learned through direct engagement with the moana.

The transformation of the marine environment of Te Ākau o Tokomaru reflects a broader challenge confronting taonga species like kōura. Western science confirms what kaitiaki have observed: sedimentation threatens early benthic life stages, particularly vulnerable puerulus and juvenile phases (Booth et al., 2000). These taonga are highly sensitive to shifts in water quality, substrate composition, and reef structure (MacDiarmid et al., 2013).

When sediment blankets the reef, it disrupts mauri, smothers ecological relationships that enable kōura recruitment and survival, and degrades the conditions necessary for healthy populations (MacDiarmid et al., 2016).

This research serves as both scientific inquiry and an act of cultural restoration. It aims to understand how sedimentation affects kōura at its most vulnerable life stages, while contributing to the regeneration of mahinga kai in Te Ākau o Tokomaru. This place is not simply a study site – it is my tūrangawaewae, my paradise, the source of my identity and obligations. Through this mahi, I hope to honour my Koko's teachings, support ecosystem resilience, and ensure that future generations can experience the abundance and connection that should be their birthright. This research expresses aroha – for place, for taonga species, for whānau past and future, and for the possibility of healing not only our whenua, but our moana as well.

1.2. Te Tairāwhiti and Cyclone Gabrielle

1.2.1. The Whakapapa of Cyclone Disruption

Te Tairāwhiti has experienced multiple cyclone events over recent decades, each contributing cumulative impacts to the region's landscape and communities. These weather systems generate forces that compromise the mauri of the whenua, awa, and moana, resulting in cumulative damage over time (Heron et al., 2025). Understanding Cyclone Gabrielle's impacts requires recognition of this legacy of disturbance and the land-use practices that have progressively reduced the resilience of both ecosystems and communities (Fellows & Barker, 2021; Fuller, 2022).

Cyclone Bola in 1988 marked a significant event in the region's environmental history. The storm produced intense precipitation, with five-day totals exceeding 800 mm in some locations, which triggered widespread flooding and landslides across the steep terrain of Te Tairāwhiti

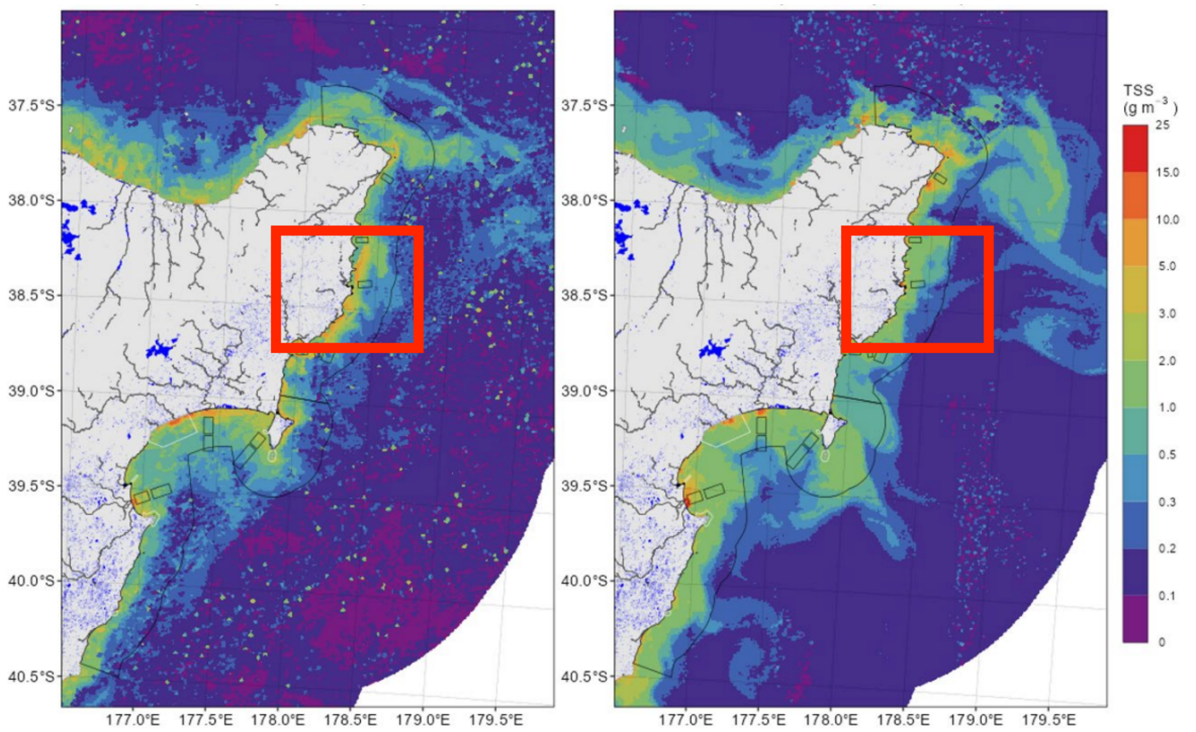
(Sinclair, 1993; McSaveney, 2009). Large volumes of sediment were transported into the awa, smothering riparian vegetation and infilling estuarine and coastal areas (Marden & Rowan, 1993; Fellows & Barker, 2021). The whenua – our sustainer, our life-source – sustained severe damage. Road networks connecting communities and providing access to mahinga kai sites experienced substantial damage, with slope failures and channel scour patterns recurring in subsequent storm events (Fellows & Barker, 2021).

Following this, large-scale pine plantation establishments were promoted as an erosion management approach, particularly on at-risk hillslopes (Marden & Rowan, 1993). While intended to stabilise land, this approach created new risks and the commercial forestry system guided by economic drivers rather than kaitiakitanga values, set the stage for further harm (Norton, 2023). In subsequent decades, forestry debris – mobilised during heavy rain events – became a persistent source of environmental and cultural distress (Fellows & Barker, 2021). As Norton (2023) argues, pine afforestation after Cyclone Bola had devastating long-term consequences, prompting calls to invest in native restoration aligned with kaitiakitanga principles.

Cyclones Cook (2017) and Hale (2023) continued this pattern of disruption. Each storm, regardless of category, added pressure to catchments already strained by historical forest clearance, intensive agriculture, and climatic shifts (Cave et al., 2017; Gisborne District Council, 2024; Fellows & Barker, 2021). These were not isolated events but interconnected chapters in a continuing narrative of environmental stress.

This historical record shows that the susceptibility Te Tairāwhiti has to cyclone damage is not inherent or unavoidable – it reflects decades of land management choices prioritising short-term economic gain over ensuring ecological and cultural health (Marden & Rowan, 1993; Heron et al., 2025). The capacity of the whenua to absorb and recover from these storms has been weakened by exploitative practices. As Heron et al. (2025) emphasise, recloaking the whenua is required in this instance to resolve the hara and restore balance within the system. Māori frameworks are therefore essential for guiding recovery in ways that honour tikanga and uphold ecological resilience. Understanding this whakapapa of disruption is vital to comprehending the full impact of Cyclone Gabrielle.

1.2.2. Mauri Disruption: Cyclone Gabrielle



Whakaahua 1. Satellite imagery of total suspended sediment concentrations pre (12th of February 2023 - left) Cyclone Gabrielle and post (20th of February 2023 – right) Cyclone Gabrielle (Leduc et al., 2024). Within the red box is Te Ākau o Tokomaru, highlighting the changes in sediment levels caused by the cyclone.

Cyclone Gabrielle impacted Aotearoa in February 2023, producing extreme rainfall, strong winds and widespread flooding (Stone et al., 2024; Thorpe et al., 2025). Within Te Tairāwhiti, rainfall was particularly intense in the Hikuwai River catchment, adjacent to the Mangahauini River, with 488 mm recorded, while other stations recorded rainfalls that exceeded 400 mm (Murray, 2023).

The cyclone generated substantial suspended sediment transport throughout rivers, estuaries, and coastal waters. Landslides, riverbank erosion, and catchment runoff carried large volumes of soil, forestry debris, and organic material downstream, elevating turbidity and altering water chemistry (Leduc et al., 2024; Te Puni Kōkiri, 2024; Allen et al., 2024). Increased sediment loads reduced light availability, suppressed primary productivity, and smothered benthic habitats, with cascading effects on estuarine and nearshore ecosystems (Tait, 2024). In rocky reef habitats such as those in Te Ākau o Tokomaru, sediment deposition altered shelter and foraging opportunities for species including kōura, while shellfish and other fisheries were disrupted by smothering and debris accumulation (Whakaahua 1 (Thorpe, et al., 2025; Leduc, et al., 2024; Tait, 2024)). The event illustrates the strong connectivity between terrestrial and marine systems, showing how extreme rainfall and catchment destabilisation combine to produce prolonged ecological disturbances in the moana (Allen et al., 2024; Heron et al., 2025). Analysing these impacts through both mātauranga Māori and Western scientific frameworks provides critical insights for restoration, kaitiakitanga, and resilience planning in coastal ecosystems (Te Puni Kōkiri, 2024; Rout, 2021).

Across Te Tairāwhiti, the impacts of Cyclone Gabrielle were extensive. Communities including Te Ākau o Tokomaru and Ūawa experienced not only infrastructure damage but also prolonged interruptions to daily life, with some areas effectively cut off for months (Te Puni Kōkiri, 2023; Te Puni Kōkiri, 2024). The awa – our ancestor and source of life – became pathways of devastation, carrying sediment and forestry debris downstream. Rivers overtopped their banks, transporting the consequences of decades of inadequate land stewardship into farmland, homes, and coastal zones (Te Puni Kōkiri, 2023; Allen et al., 2024; Fellows & Barker, 2021; Fuller, 2022). The cyclone's effects extended beyond physical infrastructure; marae and urupā were damaged or rendered inaccessible, disrupting spiritual and cultural practices for whānau, iwi, and hapū (Te Puni Kōkiri, 2023; Te Puni Kōkiri, 2024; Partsch, 2023), while mahinga kai systems, already stressed by environmental decline, suffered additional losses (Te Puni Kōkiri, 2023; Thorpe et al., 2025; Leduc et al., 2024). Storm-driven sedimentation heavily blanketed coastal areas, altering marine habitats and disrupting fisheries, while sediment plumes in nearshore zones caused prolonged changes in benthic communities, water quality, and habitat structure (Leduc et al., 2024; Tait, 2024).

Despite these challenges, iwi and hapū across Te Tairāwhiti demonstrated the enduring strength of manaakitanga and kaitiakitanga. Community led-responses rapidly mobilised resources, coordinated aid, and advocated for affected whānau. The Cyclone Gabrielle Māori Communities Response Fund distributed $9 million through 95 arrangements, providing essential support to marae and hapori Māori (Te Puni Kōkiri, 2023). These efforts embodied tikanga, reinforcing responsibilities that connect people to each other and to place, and highlighted how Te Ao Māori values can provide culturally responsive resilience frameworks that complement standard emergency management approaches (Rout, 2021; Heron et al., 2025; Te Puni Kōkiri, 2024).

Cyclone Gabrielle demonstrated the fragility of systems designed without sufficient regard for ecological boundaries or cultural principles (Stone et al., 2024; Thorpe et al., 2025; Allen et al., 2024). It underscored the consequences of treating our whenua, awa and moana as commodities rather than kin (Heron et al., 2025). Post-storm assessments emphasised the interconnected nature of impacts, showing how terrestrial damage cascaded into freshwater and marine environments (Allen et al., 2024). Recovery requires environmental management approaches that foreground kaitiakitanga, acknowledge land-sea interconnectedness, and prioritise restoration of mauri (Te Puni Kōkiri, 2024; Rout, 2021).

For this research, Cyclone Gabrielle serves as both context and driver; the storm’s unprecedented sediment loads transformed coastal environments, including the inshore rocky reefs of Te Ākau o Tokomaru, where kōura shelter and establish themselves (Thorpe et al., 2025; Leduc et al., 2024; Tait, 2024). Understanding these impacts through a framework that honours both mātauranga Māori and Western science offers pathways for meaningful restoration and resilience in an era of escalating climate disruption (Te Puni Kōkiri, 2024; Heron et al., 2025).

1.3. Te Ākau o Tokomaru – A Nursery for Taonga Species

Te Ākau o Tokomaru holds particular significance within this study. Its coastal and marine environments serve as critical nursery habitats for numerous taonga species, supporting early life stages that determine long-term population health and abundance (Ross, 2021). Inshore rocky reefs, kelp forests, and sheltered coastal waters provide essential refuge, food sources, and settlement sites for juvenile fish and invertebrates (Ross, 2021; Leduc et al., 2024). For generations, these ecosystems have sustained customary harvests and served as living classrooms where mātauranga is transmitted from kaumātua to mokopuna through observation, practice, and kōrero (Wilson et al., 2007). The richness of Te Ākau o Tokomaru and its marine environment reflects not only favourable physical conditions but also generations of kaitiakitanga practice, with local hapū maintaining detailed knowledge of seasonal cycles, species behaviour, habitat requirements, and sustainable harvest methods – knowledge refined through centuries of observation and a reciprocal relationship with the moana (Ross, 2021; Wilson et al., 2007; Harmsworth & Awatere, 2013). When such systems are actively practiced, they support both ecological resilience and cultural continuity (Williams et al., 2017; Ellis, 2024).

However, scientific documentation of kōura decline mirrors the environmental changes transforming Te Ākau o Tokomaru (Gibb, 2008). Clear waters and abundant kōura have been replaced by sediment-heavy conditions, severely compromising their recruitment and survival.

Kōura now inhabit silted substrates rather than the structurally complex reefs that previously provided shelter and foraging opportunities. This decline reflects wider national trends in which sedimentation from land-based runoff poses one of the greatest threats to coastal fisheries and kaimoana (Morrison et al., 2023; Morrison et al., 2009). Although Cyclone Gabrielle amplified these pressures, the deeper vulnerability stems from decades of catchment degradation (Massey et al., 2025). Massive sediment accumulation has rendered many mahinga kai sites unsafe or inaccessible (Hutchings et al., 2020). In places such as Te Ākau o Tokomaru, the loss of habitat and clarity has restricted kai gathering that has persisted for generations. For Māori communities, these effects extend far beyond food scarcity, representing breaks in intergenerational knowledge transmission, limitations on fulfilling guardianship roles, and spiritual disconnection from familiar landscapes (Hutchings et al., 2020). When kaumātua cannot take mokopuna to gather kai and customary grounds become unfamiliar, cultural continuity is threatened.

1.3.1. Te Awa Mangahauini – A Catchment Under Pressure

Whakaahua 2. The Mangahauini River during Cyclone Gabrielle, showing the murky waters, debris and forestry slash that travelled downstream towards the ocean (Photo by Uenuku Kohatu, February 2023).

Te Awa Mangahauini, flowing through Te Ākau o Tokomaru and a part of the Ūawa catchment, carries with it a complex history of catchment degradation, intensive land use, and storm-driven sedimentation (Fuller, 2022; Gibb, 2008). The river drains a catchment characterised by steep topography, erodible soils, and high rainfall – conditions that naturally generate significant sediment yields, but which anthropogenic activities have dramatically intensified (Whakaahua 2; Fuller, 2022).

Over recent decades, the Mangahauini river has undergone extensive modification. Indigenous forest has been replaced by *Pinus radiata* plantations and converted to agricultural land, fundamentally reducing the catchments resilience and increasing both the frequency and magnitude of sediment delivery to the sea (Parkner et al., 2007; Marden & Rowan, 1993). Fuller's (2022) geomorphological analysis documented the scale of this transformation: clear-cutting exposes soil to erosion, logging roads concentrate runoff, and poor slash management has allowed woody debris to accumulate in channels. When mobilised during floods, this material produces debris flows that scour the riverbed and deposit heavy sediment loads directly into coastal waters.

Historical forestry practices have left the Mangahauini burdened with a substantial "sediment debt" – legacy material stored across slopes and floodplains that continues to wash downstream long after logging has ceased (Fuller, 2022; Gisborne District Council, 2024). Even without further clearance, this stored sediment will influence coastal systems for decades to come. Further compounding these pressures is a legacy landfill located near the river mouth, which poses ongoing risks to water quality and marine ecosystems and has prompted a remediation project costing nearly $5 million NZD (Fuller, 2022). This landfill underscores how the degradation of the Mangahauini Awa that is cumulative, layering contamination atop chronic sediment delivery.

The river discharges directly into the nearshore reef habitats that are critical for juvenile kōura and other taonga species (Ross, 2021; Fuller, 2022). Flood-borne sediment blankets these nursery areas in fine deposits that persist for months, drastically altering recruitment conditions and smothering the complex reef structures upon which young kōura depend (Morrison et al., 2023; Morrison et al., 2009).

1.4. Kōura - *Jasus edwardsii* (red rock lobster)

1.4.1. Taonga Species

Within the assemblage of taonga species, kōura (*Jasus edwardsii* – red rock lobster), distributed in New Zealand and southern Australian waters (Morgan et al., 2013), represent a key component of both ecological integrity and cultural practice (MacDiarmid et al., 2013). Along the Ngāti Porou coastline, kōura form part of a customary marine system, where harvesting supports manaakitanga and intergenerational knowledge exchange. Their abundance and health serve as indicators of marine ecosystem condition and the strength of human-environment relationships (Ellis, 2024).

Ecologically, kōura function as a keystone predator within the coastal reef systems of Aotearoa, regulating benthic community structure and maintaining reef ecosystem balance (MacDiarmid et al., 2013). As both predator and prey, they influence community structure and energy flow throughout benthic environments, with their grazing shaping the abundance and distribution of invertebrates and algae, while they themselves feed larger predators such as fish, octopus, and marine mammals (MacDiarmid et al., 2013; Ross, 2021). Beyond ecological function, kōura can be seen as kaitiaki – guardians of the reef – maintaining conditions that support diverse species and ecological integrity (Ross, 2021).

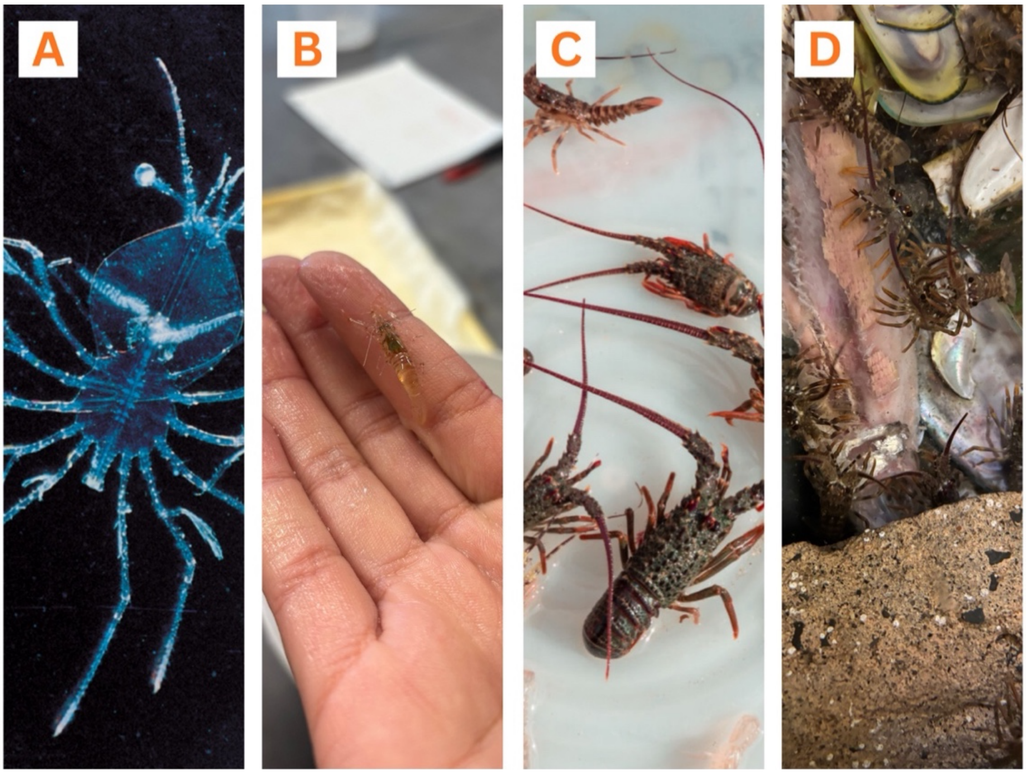
A key role played by kōura is the regulation of kina (the sea urchin *Evenchinus chloroticus* (Valenciennes, 1846)) populations. By preying on kina, kōura prevent the creation of kina barrens – degraded reef areas where uncontrolled grazing strips kelp and macroalgae, turning vibrant habitats into bare rock (MacDiarmid et al., 2012; Andrew & MacDiarmid, 1999). Healthy kōura populations support kelp forest persistence, which in turn sustains habitat, nursery grounds, and food sources for numerous species (MacDiarmid et al., 2013). In this way, kōura presence safeguards the mauri of the reef – enabling ecological health and mahinga kai. Recent shifts in northeastern Aotearoa demonstrate the consequences of kōura decline: expansion of long-spined sea urchin populations has been linked to reduced predation pressure from diminished kōura stocks (Spyksma, 2025). When numbers drop below ecological thresholds, grazers proliferate, kelp retreats, and reef habitat complexity degrades (Andrew & MacDiarmid, 1999; MacDiarmid et al., 2012). Such changes affect biodiversity, ecosystem stability, and the cultural foundations of mahinga kai, with fluctuations in kōura populations reflecting broader changes in environmental condition, habitat quality, and ecological relationships (Morrison et al. 2023; Morrison et al., 2009; Ross, 2021; Ellis, 2024).

Economically, kōura supports the most valuable inshore commercial fishery in Aotearoa, with approximately $300 million annually in export revenue (Roberts & Webber, 2024). Demand in Asia and North America drives strong market value (McGarvey et al., 2024), but this economic pressure can undermine sustainability. Overharvesting and illegal fishing compromise stocks, and incidents of extreme non-compliance underscore the need for stronger enforcement and adaptive management (Nessia et al., 2025). From a Te Ao Māori perspective, such exploitation without restoring conditions for abundance breaches kaitiakitanga – taking from the moana without ensuring renewal.

Culturally, kōura represent far more than kai. They embody connection to place, mark seasonal cycles, and facilitate the transmission of knowledge across generations (Phillips, 2015). Harvesting kōura requires intimate understanding of reefs, sustainable collection practices, and adherence to tikanga that guides when, where, and how much to take (Wilson et al., 2007). When kaumātua teach mokopuna to find kōura, they pass on not just skills but entire frameworks of ecological knowledge, cultural value, and spiritual relationships that constitute mātauranga Māori (Williams et al., 2017; Ellis, 2024). The ability to gather kōura therefore sustains identity, maintains ancestral connections, and reinforces the obligations of kaitiakitanga (Phillips, 2015).

1.4.2. Te Hurihanga o te Koiora: Life Cyle and Developmental Vulnerability

Understanding the kōura life cycle reveals when and how environmental stressors like sedimentation most influence population variability, underscoring why sedimentation effects are so severe. Protecting kōura means protecting whole reef ecosystems and the intergenerational mahinga kai practices they sustain.



Whakaahua 3. **The critical life stages of kōura. A**. Phyllosoma – flat, transparent, ocean-living larval stage (Photo: Alan Blacklock, Earth Sciences New Zealand), **B.** Puerulus – non-

feeding, transparent, non-swimming larvae (Photo: Vijuan Karaha-Paki), **C & D.** Early Benthic Juveniles – settlement, feeding stage (Photo C Source: Earth Sciences New Zealand; Photo D Source: Vijuan Karaha-Paki).

1.4.2.1. Te Wā Kōpikopiko (The Wandering Phase) – Phyllosoma

Kōura hatch into a naupliosoma stage and then undergo moulting that results in a phyllosoma larvae (Whakaahua 3A) – delicate, leaf-like forms drifting in the open ocean for up to two years (MacDiarmid et al., 2013; Chiswell & Booth, 2008; Villacorta-Rath, et al., 2022). During this extended pelagic phase, moulting occurs numerous times while larvae are transported by ocean currents across vast distances, which promotes genetic connectivity between geographically separated populations (Villacorta-Rath, et al., 2022). This dispersal enables recolonisation of depleted areas but exposes larvae to high mortality risk from predation, shifting oceanographic conditions, and unsuitable settlement environments (Pederson & Johnson, 2006; Byrne, 2012). Furthermore, climate stressors – including temperature fluctuations, ocean acidification, and pollution – can reduce survival rates during this sensitive stage (Byrne, 2012). Success during this wandering phase depends on favourable, broad-scale ocean conditions, largely beyond direct coastal management control (Hobday & Flint, 2000).

1.4.2.2. Te Wā Hoki (The Return) – Puerulus

Following metamorphosis, phyllosoma transform into pueruli (Whakaahua 3B) – transparent, non-feeding post-larvae that actively swim toward coastal habitats (Booth, 2002). This marks a critical shift from passive drifting to active habitat selection. Pueruli seek structurally complex environments such as kelp beds, rocky crevices, and reefs that provide shelter and suitable conditions for settlement (Booth et al., 2000; Hinojosa et al., 2016). Preferred settlement habitats include rocky reefs less than 20 metres deep, often with kelp presence that enhances juvenile survival by providing shelter and food sources. Settlement success is directly influenced by habitat quality, with puerulus abundance strongly correlating with future fishery recruitment (Booth et al., 2000; Linnane, et al., 2013).

Studies deploying traditional crevice collectors and artificial habitats in locations like Eastland Port, Gisborne, confirm these structures effectively attract settling pueruli and support their survival through early juvenile stages (Skelton & Jeffs, 2021; Mills & Crear, 2004). However, sedimentation during the puerulus stage impairs settlement and disrupts physiology, dramatically increasing mortality (Booth et al., 2000; Roberts & Webber, 2024). Pueruli seeking settlement now encounter reefs stripped of complexity, with benthic habitats smothered by fine particles that fill structural crevices and deplete oxygen (Morrison et al., 2023; Morrison et al., 2009; Page et al., 2000). Because pueruli cannot feed during this stage, and rely solely on limited energy reserves, habitat degradation drastically decreases settlement success (Morrison et al., 2009; Morrison et al., 2023).

Environmental factors such as ocean currents, seasonal cycles (peak settlement from April to October), and water temperature, further influence puerulus settlement dynamics (Hobday & Flint, 2000). Pollution, sedimentation driven by land runoff, and habitat loss, compound these pressures, reducing suitable settlement areas and impacting recruitment and population sustainability (Morrison et al., 2009; Skelton & Jeffs, 2021). The loss or degradation of kelp forests and rocky substrates, critical for puerulus settlement and refuge, threatens the replenishment of adult populations.

1.4.2.3. Ngā Tau Pānekeneke (The Vulnerable Years) – Juvenile Kōura

After successful settlement, pueruli moult into juveniles (Whakaahua 3C & 3D) and inhabit shallow coastal reef areas for several years before reaching maturity (MacDiarmid, 1991; Thomas, 2012). Juvenile kōura have limited mobility and depend strongly on complex habitats such as kelp holdfasts, crevices, and rocky substrates for shelter and feeding (Kelly et al., 2000; Freeman et al., 2012).

Juveniles face significant vulnerabilities from localised environmental pressures. Fine sediments clog respiratory systems, reduce feeding efficiency, and bury essential habitats (Morrison et al., 2009). Juveniles confined to shallow waters face reduced shelter and compromised feeding as sedimentation fills protective reef crevices and smothers food sources, impairing sensory mechanisms and increasing stress (Morrison et al., 2009; Kelly et al., 2000; Clark, 2023). Suspended particles reduce water clarity, disrupting visual cues central to feeding and predator avoidance (Nicholls et al., 2003). Further, prolonged turbidity and sediment cover stress juveniles, slowing growth rates and increasing mortality risk (Booth et al., 2000; Morrison, et al., 2023).

1.4.3. Te Whakahirahira - The Significance of the Early Life Stages of Kōura

1.4.3.1. Recruitment and Sustainability

The early benthic life stages of kōura – particularly the puerulus and juvenile phases – are crucial for population replenishment and sustainability, and are the focus of both mātauranga and contemporary research (Ellis, 2024). Indigenous knowledge recognises the importance of suitable settlement habitat, the vulnerability of young kōura to predation and environmental stress, and seasonal factors influencing recruitment success (Wilson et al., 2007). Habitat quality is the central survival determinant, and research increasingly shows sedimentation and reef degradation as primary recruitment threats (MacDiarmid et al., 2012; Kelly et al., 2000; McGarvey et al., 2024). Chronic sedimentation weakens mauri, leading to lower biodiversity, simplified community structure, and reduced productivity (Morrison et al., 2023). These impacts are especially pronounced in Te Tairāwhiti, where steep, erosion-prone terrain and severe storms intensify sediment inputs (Gisborne District Council, 2024). In Te Ākau o Tokomaru, Cyclone Gabrielle's sediment loads and ongoing turbidity directly degrade juvenile habitats (Gibb, 2008; Morrison et al., 2023). Without protecting settlement and juvenile areas, harvest sustainability becomes impossible regardless of regulation (MacDiarmid et al., 2013; Morrison et al., 2009).

1.4.3.2. Population Bottlenecks and Resilience

Bottlenecks from overharvesting, sedimentation, or climate events reduce genetic diversity, undermining resilience to future stressors (Thomas, 2012; Villacorta-Rath et al., 2022). Lower diversity increases inbreeding risk and compromises adaptive potential (Frankham et al., 2010; Thomas, 2012). For kaitiakitanga, preventing such losses is about sustaining not only numbers but the mauri – genetic health and ecological relationships – necessary for generational resilience (Pecl et al., 2008; Nessia et al., 2025). Recent activities, such as the Kōhanga Pēpi Kōura project (run by Kia Māia Ellis), explicitly integrate mātauranga Māori with marine science to explore how climate change and environmental disruption affect puerulus settlement and juvenile survival (Ellis, 2024). This integration demonstrates robust understanding arises from combining distinct knowledge systems, each offering unique insights (Harmsworth, 2018).

1.5. Sedimentation: Processes & Impacts

1.5.1. Understanding Sediment Sources and Processes

Sedimentation – the accumulation of fine particles such as silt, clay, organic matter, and associated pollutants – is among the most pervasive threats to Aotearoa's coastal marine ecosystems (Morrison et al., 2009). This process alters marine habitats by smothering benthic organisms, reducing light penetration needed for photosynthesis, and disrupting the ecological functions that sustain biodiversity and mahinga kai (Wilber & Clarke, 2001; Russell et al., 2019). From a Te Ao Māori perspective, excessive sedimentation signals a disruption of balance – a break in the natural exchange between whenua and moana.

Under healthy conditions, awa carry the mauri of the mountains to nourish the sea without overwhelming it. When catchments are degraded and sediment loads exceed what the moana can absorb, the mauri of coastal environments, and the taonga species they sustain, are diminished. Sediment entering coastal systems originates from multiple sources, each reflecting particular forms of land-use stress and human modification, such as terrestrial runoff, forestry practices, storm events and flooding, coastal development, and bottom disturbing activities: terrestrial runoff is a major driver of sediment transport to coastal environments, with rainfall-driven flows intensified by deforestation, agriculture, and forestry carrying fine sediments and nutrients from land to sea (Morrison et al., 2009). The replacement of native forest with pasture or exotic plantation weakens soil retention and leaves catchments highly erosion-prone (Fuller, 2022). In Te Tairāwhiti, commercial pine forestry – particularly clear-cut harvesting and poor slash control – has been identified as a significant sediment source (Parkner et al., 2007). *Pinus radiata* (Monterey pine) plantations, with their shallow root systems and sparse canopy cover, provide limited soil stability during heavy rainfall events (Robson, 2025), while harvest debris that accumulates in waterways becomes mobile during floods, combining with sediment to create destructive slash-laden flows (Fuller, 2022).

Storm events such as cyclones further intensify sedimentation pressures by resuspending seabed materials and triggering large sediment pulses that can persist for months and reshape benthic habitats (Hicks et al., 2011; Fuller, 2022; Gisborne District Council, 2024). Coastal development and bottom trawling also contribute to sediment disturbance, as construction and infrastructure projects increase turbidity and release legacy contaminants from the seabed (Wilber & Clarke, 2001; Pickrill, 1977), while repeated trawling activity continually remobilise sediments, degrade habitat quality and hinder ecological recovery (Ramalho et al., 2020).

1.6. Sediment Impacts on Decapod Crustaceans

While considerable research exists on kōura (*Jasus edwardsii*) within New Zealand and southern Australian contexts (Morgan et al. 2013), studies examining sediment impacts remain limited. The broader genus *Jasus*, distributed across temperate Southern Hemisphere waters, has been extensively studied for fisheries management and larval ecology, but research specifically addressing responses to terrestrial sediment stress is sparse across all species. Nevertheless, the genus *Jasus* encompasses multiple species of significant commercial and ecological value across Southern Hemisphere temperate zones, including the West Coast rock lobster (*J. lalandii*) inhabiting southern African waters (Pollock & Beyers, 1981; Pulfrich et al., 2002), the Juan Fernández rock lobster (*J. frontalis*) endemic to Chilean waters (Eddy et al., 2010; Petit et al., 2015; Vera-Duarte et al., 2025) and the eastern rock lobster (*J. verreauxi*) distributed along eastern Australia (Montgomery, 2000). These species share fundamental life history characteristics with *J. edwardsii*, including extended planktonic larval development, settlement onto rocky reef habitats, and dependence on structural complexity for juvenile refuge (Edgar, 1984; Greengrass, 2007).

Marine ecosystem research demonstrates that physiological vulnerabilities translate into population-level consequences. Along Namibia's coast, for example, Pulfrich et al. (2002) and Pulfrich & Branch (2013) showed that diamond mining deposits substantial sediment loads onto rocky reefs supporting *Jasus lalandii* populations. They also documented reduced lobster densities, altered size distributions, and modified spatial patterns in sediment-impacted zones, with effects persisting across multiple years.

Maletzky (2007) further demonstrated that *J. lalandii* exhibits sensitivity to turbidity in combination with other mining-related stressors including oxygen deficiency and hydrogen sulphide. These field observations establish that sediment-stress extends beyond individual physiological impairment to encompass habitat degradation and probable recruitment disruption. Given the shared ecological characteristics among *Jasus* species – all inhabit rocky reef environments and depend on crevice refuges (Edgar, 1984; Pollock & Beyers, 1981) – these findings suggest comparable vulnerabilities across the genus.

Habitat modification through interstitial space filling represents a critical indirect impact. For marine lobsters, three-dimensional habitat structure mediates predation pressure, particularly for vulnerable juveniles (MacDiarmid et al., 2013). *Jasus* species rely heavily on structural complexity during early benthic life stages. Montgomery (2000) found that *J. verreauxi* recruitment abundance varied with reef proximity and wave exposure, while Petit et al. (2015) documented high predation pressure on juvenile *J. frontalis* in the Juan Fernández Archipelago.

Sediment plumes that fill gaps among rocky substrates effectively reduce refuge area, potentially displacing juveniles into marginal habitats with elevated predation risk. Sediment tolerance in decapod crustaceans varies substantially among species and populations, reflecting differences in morphology, habitat use, and environmental history. Research on *Jasus* species demonstrates this variation: *J. lalandii* populations along the South African west coast show differential responses to sediment exposure related to depth distribution and food availability (Pollock & Beyers, 1981), while studies in Namibia have documented population-level impacts from chronic sediment discharge associated with diamond mining operations (Pulfrich & Branch, 2013; Maletzky, 2007). Settlement patterns and early juvenile survival also vary substantially across environmental gradients in other *Jasus* species (Montgomery, 2000;

Greengrass, 2007; Petit et al., 2015), suggesting inherent variation in stress tolerance during critical life stages.

Moreover, sediment impacts are strongly context-dependent: environmental stressors such as temperature, dissolved oxygen, salinity, and nutritional status can interact with sediment exposure to modulate organismal responses, often producing non-additive effects (Maletzky, 2007). This context-dependency is particularly concerning given climate projections for Southern Hemisphere temperate waters, which predict warming, altered circulation patterns, and increased storm intensity (Fulton et al., 2023), changes that may both increase sediment mobilization through intensified runoff events and reduce physiological capacity to cope with sediment stress through elevated metabolic demands and altered oceanographic conditions.

Life cycle stage critically influences vulnerability, with larval and juvenile stages generally showing greater sensitivity. Early life stages in shallow coastal habitats face elevated exposure risk when storm-driven sediment pulses coincide with critical settlement periods – a particular concern for *Jasus* species given their extended planktonic development (12-24 months) and dependence on suitable settlement substrate (Greengrass, 2007).

Collectively, global research indicates sediment is a significant stressor for *Jasus* species. Documented effects such as compromised refuge access, reduced foraging efficiency, and population-level demographic alterations, highlight vulnerabilities across the genus. Evidence from *J. lalandii* populations experiencing mining-related sedimentation (Pulfrich & Branch, 2013; Pulfrich et al., 2002; Maletzky, 2007) demonstrates clear population-level impacts that likely apply to other congeners, including *J. edwardsii*. However, standardised assessment frameworks and species-specific tolerance data remain limited. Research priorities should include quantifying dose-response relationships across life stages, characterising recover dynamics following pulse disturbances, and investigating sediment interactions with climate-change associated stressors. These investigations would establish empirical foundations for managing sediment inputs to ecosystems supporting ecologically and economically important *Jasus* populations.

1.7. Cultural – Ecological Anchors

1.7.1. He Whakamaramatanga - Understanding Mahinga Kai through Whakapapa and Kaitiakitanga

Though commonly defined as food-gathering sites or harvestable resources, mahinga kai represents far more. From a Te Ao Māori perspective, mahinga kai embodies the intricate relationships between people, place, and the natural world – relationships grounded in whakapapa, sustained through manaakitanga, and protected through kaitiakitanga (Ruru, et al., 2022; Harmsworth et al., 2015). These are living systems in which ecological health and cultural vitality are inseparable, where the wellbeing of taonga species mirrors that of the people, and where intergenerational knowledge flows through continuous engagement with the environment (Phillips, 2015). As Phillips (2015) articulates, *"mahinga kai – he tāngata, mahinga kaitiaki – he mauri"* – mahinga kai are the people, and those who act as kaitiaki carry the mauri, or the life force, of these systems. This world view positions humans not as external managers of resources but as participants in reciprocal relationships that demand care, respect, and accountability (Harmsworth, 2018).

Within a Māori worldview, ecosystems are understood through whakapapa – genealogical linkages that connect all living and non-living elements within the environment (Harmsworth & Awatere, 2013; Harmsworth, 2018). This understanding recognises that whenua, awa, moana, and all beings within them share ancestry with people. Thus, ecological harm equates to harm to whānau, while ecological restoration is simultaneously the restoration of cultural and spiritual wellbeing (Reid et al., 2013; Ellis, 2024). Indigenous sustainability indicators for Māori enterprises highlight that environmental health, cultural practice, and economic viability are interdependent dimensions of a unified system (Reid et al., 2013).

Kaitiakitanga — often translated as guardianship or stewardship — represents the practice of these relationships (Elmahdy et al., 2025; Hikuroa et al., 2025; Jackson et al., 2017). It is an intergenerational responsibility to protect and enhance the mauri of places, species, and ecosystems, ensuring their vitality for future generations (Wilson et al., 2007). Kaitiakitanga is not simply conservation in a Western sense; it encompasses spiritual obligations, customary rights, and the transmission of mātauranga through lived practice (Elmahdy et al., 2025). When mahinga kai systems are degraded, the capacity to uphold kaitiakitanga responsibilities is disrupted, interrupting the flow of knowledge and weakening the bonds between people and place (Phillips, 2015; Williams et al., 2017).

1.8. Research Gap, Aim, and Central Question

1.8.1. Te Mokowā Mātauranga - Identifying the Knowledge Gap

While kōura have deep ecological, economic, and cultural importance across Aotearoa, a critical gap remains in understanding how sedimentation – especially from land-based sources intensified by climate change and unsustainable forestry – affects its early benthic life stages (Morrison et al., 2009; Roberts & Webber, 2024). Research to date has focused primarily on adult population dynamics, fishery trends, and stock assessments, with far less attention given to the physiological and ecological vulnerabilities of puerulus and juvenile kōura during their most sensitive life stages (Booth et al., 2000).

This knowledge gap is not merely academic; it limits effective kaitiakitanga and evidence-based management of this taonga species (Ellis, 2024). Without understanding how sediment exposure impacts early life stages, predicting recruitment success, developing restoration strategies, and fulfilling obligations to sustain kōura populations remain difficult (Hutchings et al., 2020). This gap is particularly acute for Te Tairāwhiti, where degraded catchments and extreme weather create sediment regimes that differ sharply from those described in most existing literature (Fuller, 2022; Morrison et al., 2023; Gisborne District Council, 2024).

Moreover, prior studies on sedimentation impacts often use constant exposure treatments, failing to replicate the pulsed, variable conditions that follow storm events (Wilber & Clarke, 2001; Morrison et al., 2009). In runoff-affected coastal systems, organisms experience alternating periods of high sediment loads and clearer water (Fuller, 2022; Gibb, 2008; Haddadchi & Hicks, 2019). Understanding kōura responses to such fluctuating conditions — whether recovery occurs between sediment pulses or whether cumulative stress leads to progressive decline — is essential for designing restoration priorities and realistic management strategies (Morrison et al., 2023; Roberts & Webber, 2024).

1.8.2. Te Whāinga - Research Aim

This thesis addresses the identified gap by investigating the effects of suspended sediment exposure on puerulus/early benthic juvenile *Jasus edwardsii* using a pulse-based experimental framework. Alternating between sediment loaded and clear water phases, this study will simulate natural sedimentation cycles typical of erosion-prone coasts such as Te Ākau o Tokomaru following storms or heavy runoff (Fuller, 2022; Morrison et al., 2023; Gisborne District Council, 2024).

The primary aim is to evaluate how pulse-based suspended sediment exposure influences the survival, behavioural, and physiological condition of early benthic juvenile *Jasus edwardsii* under controlled laboratory conditions. This aim encompasses three complementary dimensions; survival (the fundamental measure of persistence through sediment exposure), behavioural change (observed shifts in activity, shelter use, feeding, or stress response that may reduce long-term viability), and physiological condition (underlying indicators such as haemolymph chemistry, immune function, or body condition that indicate chronic stress or compromised heath).

Together, these variables provide a multi-scale understanding of how sediment affects kōura – from cellular condition to population-level outcomes. Ultimately, this knowledge guides restoration priorities, refines sediment management, and strengthens kaitiakitanga for kōura and the mahinga kai systems they underpin (Ellis, 2024; Gisborne District Council, 2024).

1.8.3. Te Pātai Matua - Central Research Question

This study is driven by one guiding question: How do alternating phases of suspended sediment and clear water affect the survival, behavioural, and physiological responses of puerulus/early benthic juvenile kōura (*Jasus edwardsii*)?

This question reflects the dynamic nature of coastal sedimentation, which operates not as a steady state but through pulses and cycles (Fuller, 2022). After storm events, sediment concentrations spike as terrestrial material floods into coastal waters, then gradually decline as particles settle or disperse (Morrison et al., 2023; Gisborne District Council, 2024). In Te Tairāwhiti, recurrent storm driven pulses like those from Cyclone Gabrielle expose kōura to periodic sediment stress, making understanding of these fluctuating conditions vital (Fuller, 2022; Leduc et al., 2024).

The critical distinction lies in recovery capacity. If kōura can physiologically recover between sediment exposures, populations may retain resilience; if cumulative stress compounds without adequate recovery periods, population decline becomes inevitable (MacDiarmid et al., 2013; Morrison et al., 2009). This pulsed experimental design thus mirrors real environmental patterns, seeking to determine whether kōura can recover between disturbances or whether chronic, repeated exposures cause irreversible decline (Morrison et al., 2023; Roberts & Webber, 2024). The question aims not only to confirm impact but to reveal the temporal dynamics of vulnerability (Hutchings et al., 2020) – knowledge critical for developing management and restoration actions that align with natural cycles (Ellis, 2024).

1.9. Thesis Structure: Weaving Knowledge Through Whakataukī

1.9.1. Te Whāriki o te Mātauranga: The Narrative Tapestry

This thesis is structured around four chapters, each guided by a whakataukī that reflects the ecological, cultural, and spiritual dimensions of this research journey. These whakataukī provide far more than a theme or ornament – they create a narrative arc that weaves together sedimentation and kōura ecology with the whakapapa of whānau, whenua, and moana (Harmsworth, 2018; Heron et al., 2025; Rout, 2021).

The sequence from *"Mai i te awa ki te moana"* (the connected pathway from source to ocean) through *"He manako te kōura i kore ai"* (the imperative of action) to *"Matariki hunga nui"* (collective assembly) reflects the journey of this research: beginning with recognising relationships, proceeding through cultural knowledge and ecological understanding as complementary threads in a single whāriki, linking knowing, doing, and why.

1.9.2. Ngā Wāhanga: Chapter Overview – Excl. Ūpoko Tuatahi (Chapter 1)

1.9.2.1. Ūpoko Tuarua (Chapter 2) – Te Huarahi Rangahau: Navigating the Waters of Inquiry

Whakataukī: *"Ka hoki te kōura ki tōna kōhanga i te tangi o te kihikihi"*

Translation: *The kōura returns to its nursery at the song of the cicada*

This whakataukī speaks to ecological rhythms and seasonal cues that guide kōura settlement and development (Wilson et al., 2007), symbolising timing, response, and adaptation – themes mirrored in the pulse-based experimental design (Morrison et al., 2009; Fuller, 2022). The chapter details the methodological framework including kōura collection, housing transitions from communal buckets to individual tāruke, sediment sourcing from the Mangahauini River mouth, and controlled exposure regimes modelling natural disturbance cycles. It outlines measured variables – baseline body condition, growth trajectories, survival, gill condition, blood refractive index, and moult stage – explaining how each reveals different dimensions of sediment stress (Day et al., 2022; Wilber & Clarke, 2001). The analytical approach emphasises three key comparisons: baseline equivalence testing, complete trajectory visualisation, and final outcome assessment, positioning this research as both methodologically rigorous and ecologically grounded.

1.9.2.2. Ūpoko Tuatoru (Chapter 3) – Ngā Hua o te Mahi: What the Kōura Reveal

Whakataukī: *"E whiwhi ana koe i ngā hua o te moana me mākū koe"*

Translation: *If you want to obtain the fruits of the sea, you must get wet*

This whakataukī emphasises the reciprocal bond between us and the ocean – that wellbeing and sustenance arise from engaging respectfully with the marine environment. The chapter addresses three core questions: Were kōura equivalent at the experiment's start? What happened across the 52-day trajectory? How did treatments differ at the conclusion? Beginning with baseline equivalence (Day 1), results show all treatments started with statistically comparable body condition. Growth trajectories reveal apparent stability during individual exposure phases masking progressive cumulative deterioration. Mortality patterns demonstrate phase-dependent vulnerability, with Tobserved (representing concentrations commonly observed in Te Ākau o Tokomaru) experiencing catastrophic losses during communal housing and Tmaximised showing delayed mortality during individual housing. Final assessments reveal significant treatment effects on body condition, universal gill damage in sediment-exposed survivors, and suppressed moult progression, demonstrating that cumulative stress produced irreversible physiological damage despite maintained function during individual exposure events.

1.9.2.3. Ūpoko Tuawhā (Chapter 4) – Te Whakamaramatanga: Interpreting the Tides of Change

Whakataukī: “*He manako te kōura i kore ai*”

Translation: *Wishing for the crayfish won’t bring it*

This whakataukī underscores that abundance and recovery require deliberate action rather than aspiration alone (Phillips, 2015). This chapter interprets the findings within ecological, cultural, and management contexts, examining how cumulative sediment impacts create recruitment bottlenecks for kōura populations in Te Ākau o Tokomaru, and the broader Te Tairāwhiti region. It explores multiple pathways of impact – direct respiratory damage, social stress amplification, and persistent legacy effects – emphasising that Tobserved concentrations producing the highest mortality represent routine environment conditions in Te Ākau o Tokomaru. The discussion frames conventional harvest controls as insufficient when environmental degradation impairs recruitment, advocating for integrate catchment-to-coast management and co-governance structures empowering kaitiaki through tau kōura monitoring, mātaitai, and rāhui (Fuller, 2022; Gisborne District Council, 2024; Ellis, 2024; Harmsworth, 2018). It concludes by emphasising that kōura recovery depends on reweaving whakapapa relationships, restoring mauri, and addressing cumulative impacts through collaborative, community-led stewardship – ki uta ki tai.

Ūpoko Tuarua (2)

Te Huarahi Rangahau: Navigating the Waters of Inquiry

Methods

"Ka hoki te kōura ki tōna kōhanga i te tangi o te kihikihi"

The kōura returns to its nursery at the song of the cicada

2.1. Kōura Pueruli Collection and Care

2.1.1. Collection Site and Method

On 12 June 2025, kōura pueruli were collected from long-term monitoring traps located at Castlepoint on the southeastern coast of the Te Ika-a-Māui (North Island) (collection undertaken by Jeff Forman, fisheries technician, Earth Sciences New Zealand (ESNZ)). These traps are part of an established national monitoring network that has tracked puerulus settlement across Aotearoa for more than three decades, providing valuable baseline data on recruitment trends and population dynamics (Booth et al., 2000; Breen et al., 2005; Earth Sciences New Zealand, 2020). The collection yielded over 100 kōura pueruli. Individuals were transported in 25-litre buckets filled with seawater, seaweed, and nylon mesh catch bags to provide shelter and minimise stress during transit to the ESNZ Wellington facility.

2.1.2. Holding Conditions

Upon arrival, pueruli were transferred into a 0.7 x 0.7 m black plastic tank with a water depth of approximately 20 cm. The tank received a continuous flow of fresh seawater and was furnished with rocks and macroalgae to mimic natural shelter. Freshly opened green lipped mussels (*Perna canaliculus*) were provided daily as food. Mortalities were removed each day. During this period, approximately 13 individuals died (13% mortality), leaving 87 kōura for experimental trials. This mortality rate falls within the expected range for pueruli maintained under laboratory conditions (Booth et al. 2000).

2.2. Experimental Design

2.2.1. Ethics Approval

This research was approved by the Earth Sciences New Zealand Animal Ethics Committee (Approval AEC286). The proposed impact grade for the experiment was assessed as high, reflecting the potential for stress associated with repeated handling, sediment exposure, and confinement within experimental containers. All procedures were carried out in accordance with the Animal Welfare Act 1999 and New Zealand's ethical requirements for the care and use of animals in research.

2.2.2. Pulse-Based Experimental Design

The experiment was designed to assess the effects of suspended sediment exposure on early benthic juvenile kōura through a pulse-based format. This consisted of three 10-day suspension phases alternating with clean phases (Ripanga 1), simulating sediment resuspension dynamics commonly observed in coastal environments following cyclonic or storm events (Khodayar et al., 2025).

Ripanga 1. Experimental phase timeline

Phase	**Duration**	**Dates**
Suspension Phase 1	10 days	18-27 July 2025
Clean Phase 1	15 days	28 July – 11 August 2025
Suspension Phase 2	10 days	12-21 August 2025
Clean Phase 2	7 days	22-28 August 2025
Suspension Phase 3	10 days	29 August – 7 September 2025

Overview of experimental phases in the early benthic juvenile kōura sediment exposure trial, detailing the sequence and duration of alternating sediment (suspension) and recovery (clean) periods conducted between 18 July and 7 September 2025.

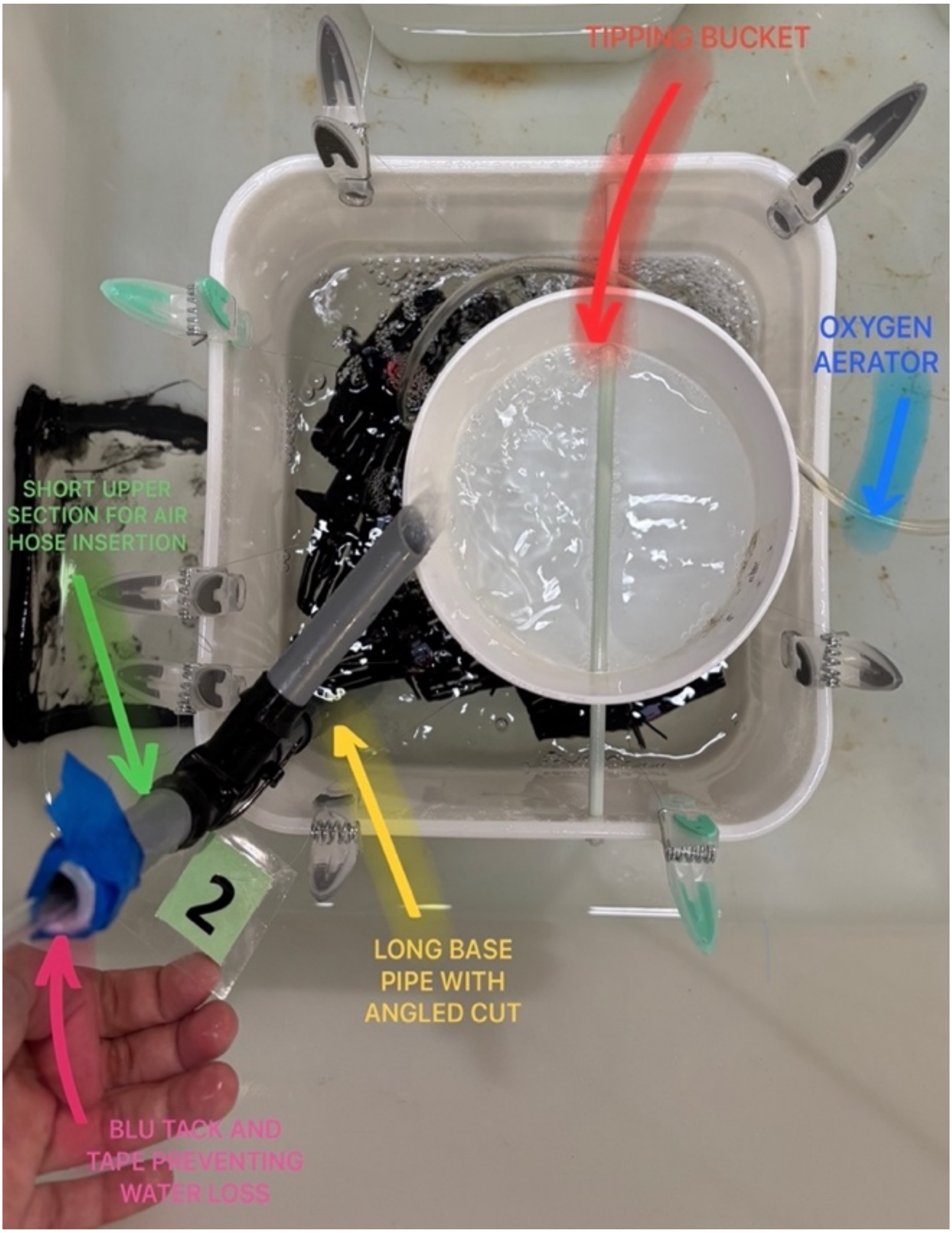
Clean Phase 1 was extended to 15 days (compared to 7 days used in Clean Phase 2) to reflect natural variability in sediment clearance observed in coastal systems (Miselis et al., 2021). In dynamic marine environments, sediment settling and recovery periods are influenced by wave action, tidal mixing and residual turbidity, which can delay return to baseline conditions (Lopez et al., 2025).

During suspension phases, sediment was circulated using an airlift system described below, and manually stirred three times daily (morning, midday, and evening) to maintain consistent suspension. During clean phases, no sediment was added, and buckets were maintained with clean seawater to allow recovery. This pulsed format allowed assessment for both acute and cumulative effects of suspended sediment on kōura under controlled conditions.

2.2.3. Recirculation System for Suspended Sediment

Suspension was maintained using a custom-built recirculation system (Whakaahua 4) installed across all buckets. Each system included an airlift mechanism connected to a tipping bucket, creating continuous sediment movement without adding external water or sediment. Air was supplied from a central aeration unit, with pipette tips (2 mm diameter) used at hose ends for uniform airflow.

The airlift system comprised of a long base pipe with an angled cut to reduce clogging, a short upper section for air hose insertion, and an angled outlet directing sediment-laden water into the tipping bucket. The tipping bucket released pulses of water back into the main bucket into maintain suspension. To prevent water loss, the base pipe opening was sealed with Bostick Blu-Tack and tape. Airflow was distributed via three 3-way and one 4-way connector (5 mm diameter). Each bucket also contained an oxygen aerator.



***Whakaahua 4.* Recirculating system for sediment suspension treatments.** The system includes a tipping bucket (red) for continuous flow, an oxygen aerator (blue), a long base pipe with angle cut (yellow) and short upper pipe (green) for air hose insertion. Blu-Tack and tape (pink) allowed little to no water loss.

2.3. Sediment Collection and Preparation

2.3.1. Collection Site and Rationale

Whakaahua 5**. Collection Site.** GPS coordinates: 38°07'39.7"S, 178°18'58.4"E.

Fine-grained sediment, composed primarily of clays and silts, was collected from the Mangahauini River mouth in Tokomaru Bay (–38.1277°, 178.3162°; Whakaahua 5). The site was selected for its ecological relevance, as the Mangahauini catchment is a documented source of elevated sediment loads influencing the inshore rocky reefs of Tokomaru Bay, especially following storm events such as Cyclone Gabrielle (Fuller, 2022).

The Mangahauini River is my awa, flowing through the rohe of my whānau. In keeping with tikanga, I informed my kōkā, Lilian Ward, about the purpose, location, and timing of the sediment collection to maintain transparency with my whānau and ensure that all research activities were conducted with appropriate respect for place and relationship (Harmsworth, 2018).

2.3.2. Collection Method

Sediment was collected on 24 May 2025 at 10:00 a.m., timed to coincide with low tide to maximise access to freshly deposited material at the river mouth. Approximately 2.5 full 20-liter buckets (~50 litres wet weight, estimated at 65 kg based on a bulk density of ~1.3 kg/L; (Vale et al., 2021) were gathered using shovels and buckets. The material was left to settle in the collection buckets, allowing overlying water to naturally separate from the denser sediment layer below.

2.3.3. Processing

An initial subsample of approximately 12 litres was processed to begin experimental preparations. This portion was evenly distributed in a 2 cm-thick layer across 15 Jumbuck BBQ grill trays (32 cm × 23 cm × 2.5 cm) and oven-dried at 80°C at the ESNZ Hamilton facility for four days which effectively sterilised any biological material – meaning additional freezing of the sediment was deemed unnecessary – and removed moisture content. Following drying, the sediment was manually broken down and passed through a 180 µm mesh sieve to isolate finer particles. The processes material was stored at room temperature in a clean, sealed, and labelled 20-litre bucket.

2.4. Treatment Levels and Replication; Housing System and Adaptations

Ripanga 2. Sediment addition protocol for experimental treatments, showing buckets and their assigned treatment level, sediment quantities, and target concentrations for the Control, Tobserved, and Tmaximised exposure groups.

Treatment	Bucket Numbers	Sediment per Bucket (g)	Total Sediment (g)	Target concentration (mg/L) per treatment bucket

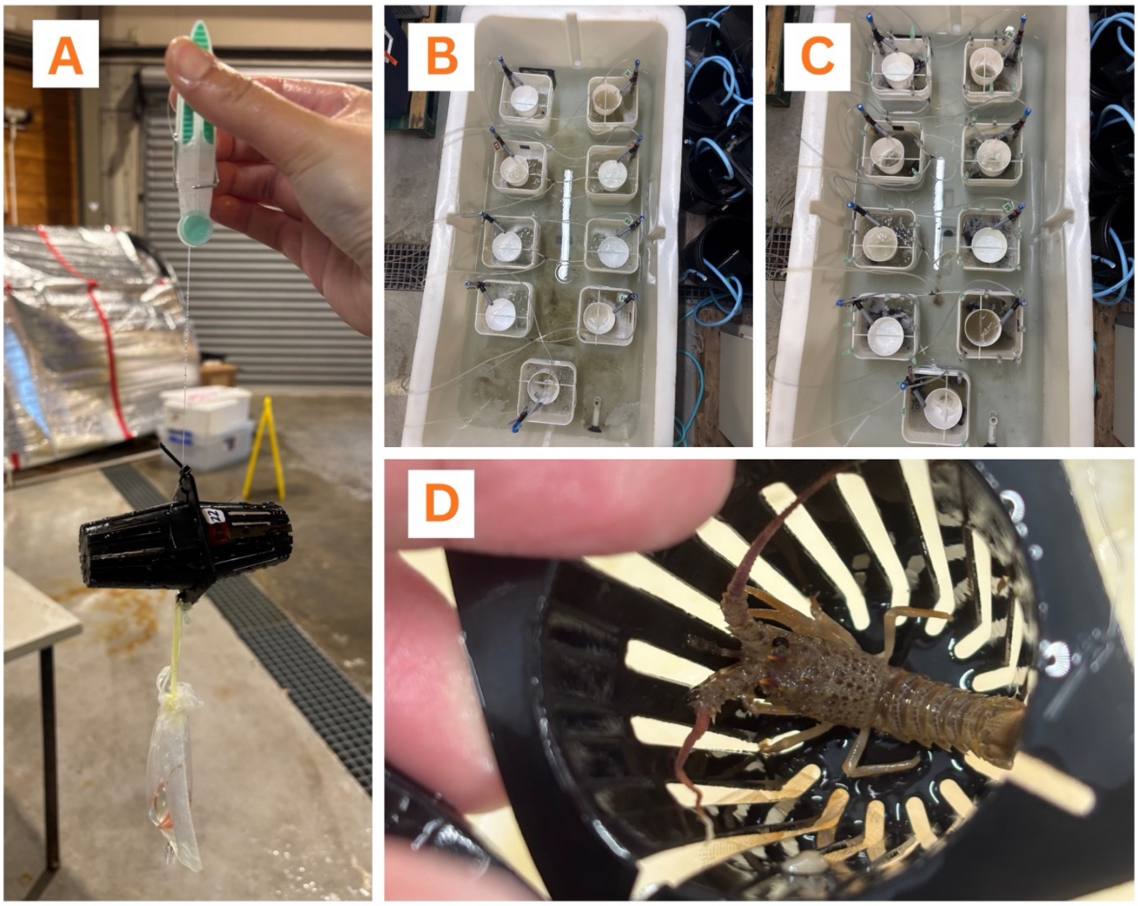
Control	2, 13, 35	0	0	0
Trial Observed	7, 30, 28	10	30	1,000
Trial Maximised	36, 37, 14	50	150	5,000

Nine 10-litre buckets were used, arranged as three replicates per treatment level, each containing filtered seawater sourced from Evans Bay, Wellington (–41.3014°, 174.8064°). Treatment concentrations reflected suspended sediment levels commonly observed in New Zealand rivers during high-flow and cyclonic events (Hicks et al., 2011; Hicks et al., 2019). The Control treatment received no sediment (0 mg/L), Trial Observed received 1,000 mg/L, and Trial Maximised received 5,000 mg/L (Ripanga 2). Sediment additions were made at the start of each suspension phase, using weights measured on a digital scale. Buckets were cleaned and refilled every three days and sediment was reintroduced to maintain target concentrations.

At the start of the experiment, kōura were housed communally, with nine individuals per bucket. Following Suspension Phase 1 and Clean Phase 1, cannibalism was observed in one bucket within the Tobserved treatment, during vulnerable moulting periods and feeding periods. This prompted a transition to individual containment from day 19 onwards.

2.4.1. Tāruke Design and Cultural Relevance

Custom-built perforated containers, or tāruke (crayfish pots), were constructed to house individual kōura within each bucket (Whakaahua 6). The term tāruke reflects traditional Māori kōura-trapping practices, adapted here for laboratory conditions to ensure welfare while maintaining cultural connection (Wilson et al., 2007). Each tāruke was made by joining two Egmont Hydroponic pots (5.5 cm diameter) with zip ties, weighted with a glass marble in an organza slip bag, and suspended via nylon string clipped to the bucket rim with a peg. This design allowed water and sediment to pass freely while preventing physical interaction. Mortality following Suspension Phase 1, Clean Phase 1, and later phases necessitated redistribution of kōura within treatment groups to balance numbers across buckets. Redistribution occurred only within the same treatment level to preserve experimental integrity.



***Whakaahua 6.* Experimental setup and tāruke design for juvenile kōura (*Jasus edwardsii*).** **A.** Individual tāruke design constructed from two Egmont Hydroponic pots joined with zip ties, weighted with a glass marble in an organza bag, and a suspended with nylon strong clipped to the bucket rim. **B.** Communal housing of kōura prior to individual separation. **C.** Post-separation setup showing individual tāruke placements and peg attachments. **D.** Suspected cannibal kōura from bucket 7 observed inside its tāruke.

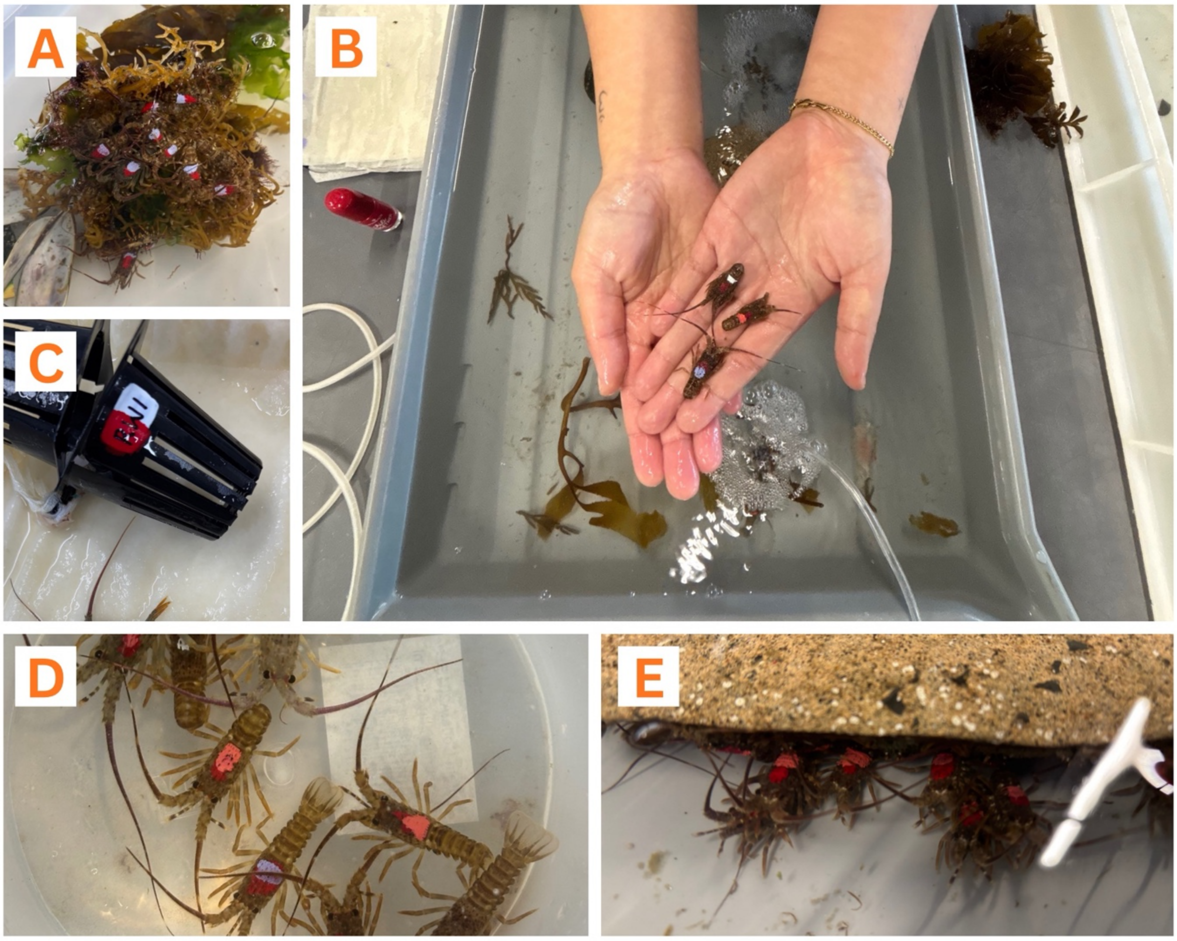
2.5. Individual Tagging System

To enable individual identification and facilitate repeated non-lethal measurements, all *Jasus edwardsii* individuals were marked using a non-toxic nail polish tagging system (Whakaahua 7). This method is widely used in crustacean and insect research to temporarily mark animals with hard exoskeletons, offering a simple and effective approach for visual tracking (Ramalho et al., 2010).

At the beginning of the experiment, 87 early benthic juvenile kōura were available. The original design intended to separated individuals into distinct groups for specific physiological assessments. However, due to mortality and reduced sample sizes over time, all surviving kōura were ultimately used for every test. As a result, the tagging system was adapted to serve as a unique identifier for each kōura rather than strictly separating them by test type.

Each kōura was randomly assigned a unique identifier, and randomly distributed across treatment buckets to avoid bias in treatment effects: RO (red & orange) kōura were labelled RO1 to RO30, RW (red & white) kōura were labelled RW1 to RW30, and RP (red & purple) kōura were labelled RP1 to RP27. To facilitate haemolypmh sampling, six individuals from the RW group were removed for one-time sampling. This left 24 RW, 27 RP and 30 RO kōura (81 kōura in total).

This tagging system allowed efficient identification during routine measurements and behavioural observations while minimising handling stress and maintaining consistency across the experimental period. To maintain individual identification following changes to housing and containment, the containers themselves were tagged using the same colour-coded nail polish system previously applied to the kōura. This adjustment significantly reduced the risk of tag loss due to moulting and improved the consistency of individual tracking throughout the experiment.



***Whakaahua 7.* The individual tagging system. A.** Kōura uniquely identified with RP (red & purple) nail polish before separation into the nine treatment buckets. **B.** A photo of the 3 uniquely identified kōura from each tagged group; RP (red & purple), RO (red & orange), and RW (red & white) before separation into buckets. **C.** Individual tagging system now on the tāruke themselves for efficient individual tracking. **D.** Clean out day kōura separation – after clean out some tags came off as a result of moulting or other social behaviours. **E.** Kōura uniquely identified with RO (red and orange) before separation into the nine treatment buckets.

2.6. Feeding Protocol

Live, green-lipped mussels (*Perna canaliculus*) were housed in a separate 0.7 x 0.7 m black plastic tank with 20 cm water depth, supplied with continuous clean, aerated seawater. Each morning, five mussels were shucked and divided among buckets. Initially, each bucket received half a mussel daily, with uneaten food removed before new portions were added. As mortality reduced kōura numbers in some buckets, mussel portions were adjusted proportionally to maintain water clarity and balance nutrient load.

After the shift to individual tāruke housing (Day 19), mussel portions were cut up evenly and distributed directly into each tāruke using fine-tipped tweezers, with uneaten food removed daily to maintain water quality.

2.7. Data Collection and Analytical Measures

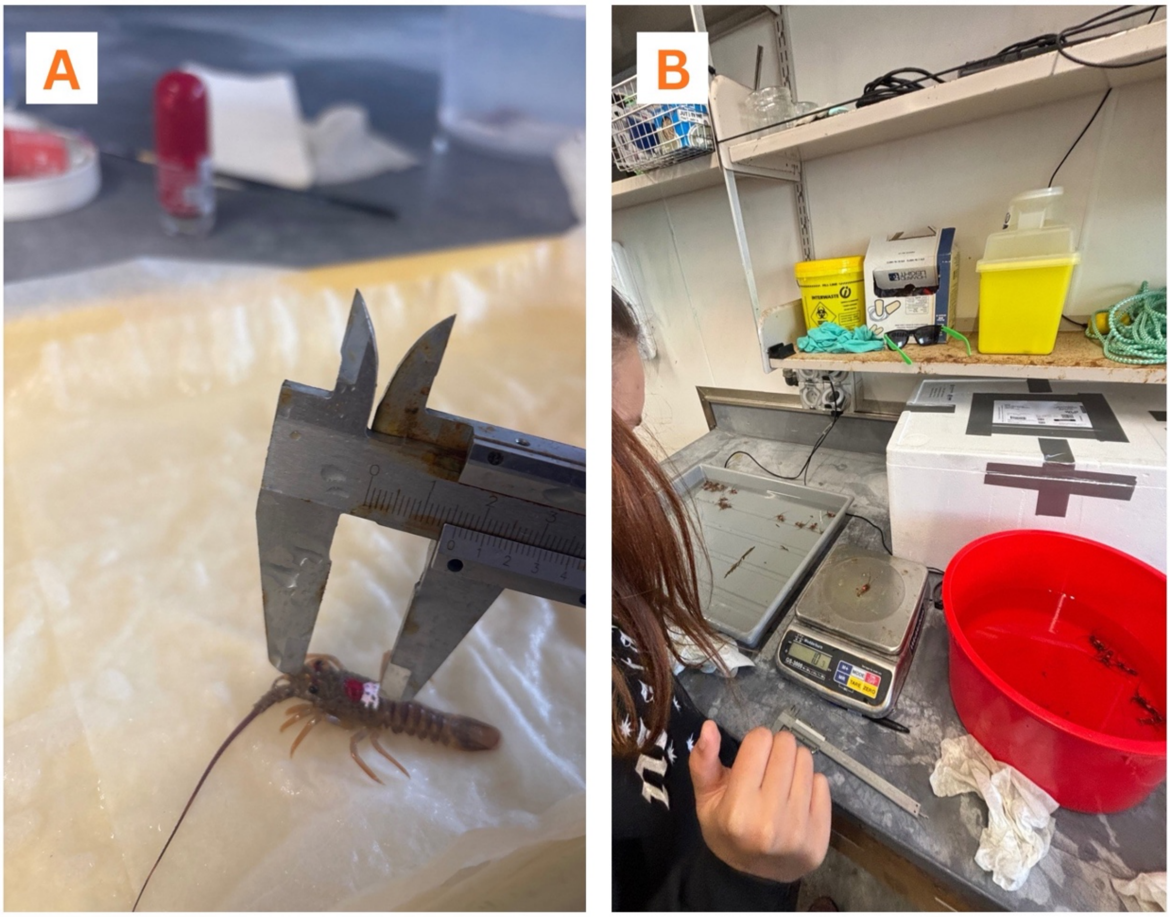
2.7.1. Body Weight to Carapace Length Ratio

The body weight to carapace length ratio (BW:CL) was used as a morphometric indicator of body condition (Whakaahua 8). This metric reflects the relationship between mass accumulation and structural growth, both of which can be influenced by environmental stressors such as suspended sediment exposure. A declining BW:CL ratio may indicate reduced feeding efficiency, impaired weight gain/loss, or increased metabolic demands (Ko, 2025).

Measurements were taken every three days during scheduled clean-out intervals. Carapace length was measured with callipers from the base of the antennal platform to the posterior dorsal margin of the carapace. Body weight was recorded on a digital scale to the nearest 0.5 g. The BW:CL ratio was calculated as:

$$BW\!:CL\ Ratio = \frac{Body\ Weight\ (g)}{Carapace\ Length\ (mm)}$$

During Suspension Phase 1, only 6 individuals per bucket were measured to minimise handling stress. From Suspension Phase 2 onwards, all surviving kōura were measured at each clean-out interval to improve data resolution and to capture individual-level variation. This non-lethal monitoring approach enabled continuous assessment of condition throughout the trial, while maintaining animal welfare.



Whakaahua 8. **Collecting growth data using the BW:CL ratio. A.** Using metal callipers for accurate measurement of the carapace. **B.** Using digital scales (Wedderburn GS-3000) to weigh each kōura to the nearest 0.5g.

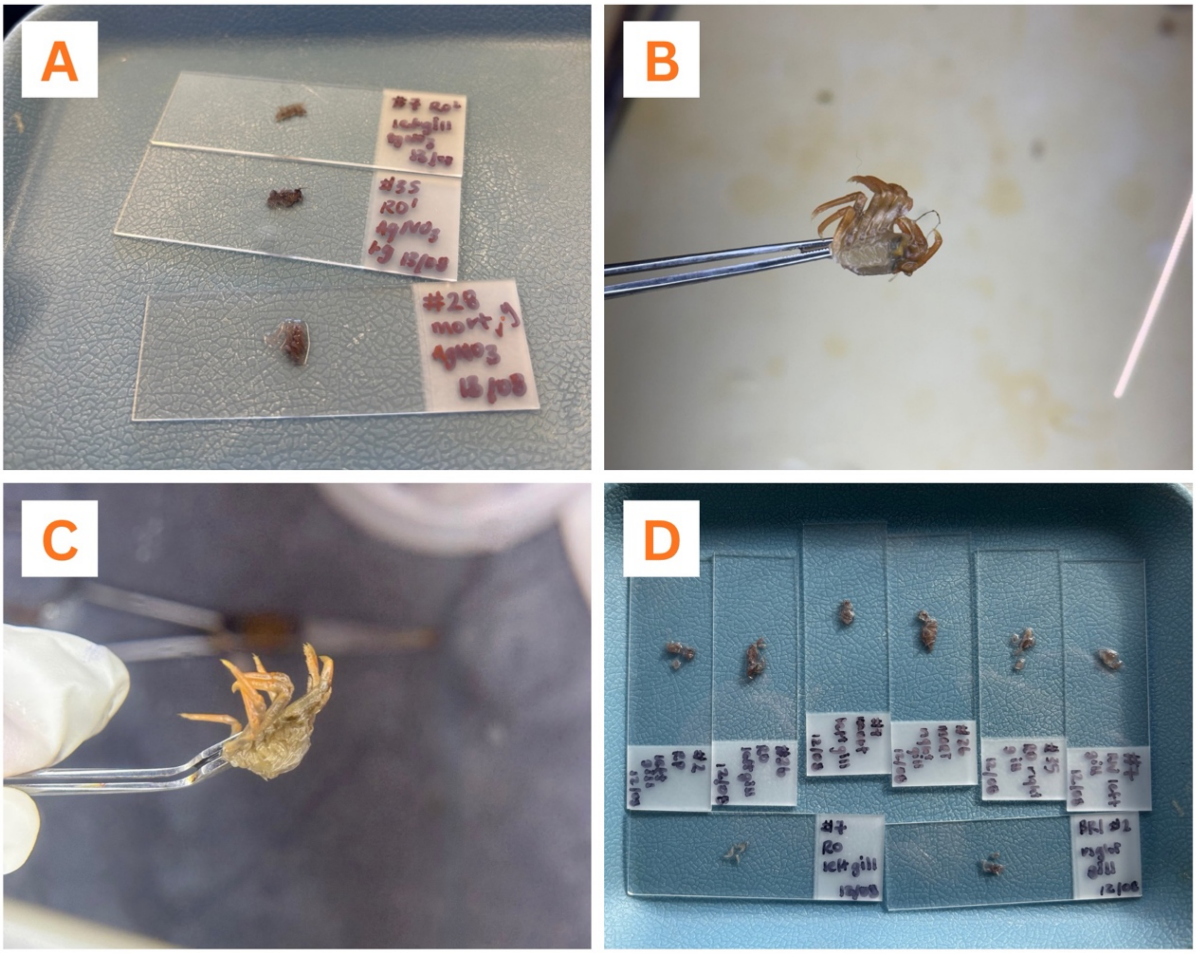
2.7.2. Gill Condition Assessment

Gill health was assessed as an indicator of respiratory stress, particularly where fine sediment may obstruct respiratory surfaces or cause tissue abrasion (Rosewarne et al., 2013). Assessments were conducted on kōura that died during the experiment and on all surviving individuals at trial conclusion (Whakaahua 9). At the end of the final suspension phase, remaining kōura were humanely euthanised by cooling in ice-cold seawater, followed by rapid brain piercing with a fine sewing pin. For analysis, one gill was dissected from each individual, with the side alternated between left and right across the sample set to reduce any potential bias associated with unilateral tissue variation.

Gill tissues were examined under light microscopy using a standard four-point scoring system indicating increasing severity of sediment impact or damage. A score of zero represented clean and healthy gills with no visible sediment; a score of one corresponded to slight sediment presence or mild discolouration; a score of two designated moderate browning, mucus build-up, sediment build-up or visible tissue damage; and a score of three indicated blackening, severe clogging or significant deterioration of gill tissue (Whakaahua 9).

To assist visualisation of gill structure and sediment-related damage, a silver nitrate staining protocol was used (Whakaahua 9), adapted from Dickson et al. (1991). Gills were fixed in 10% formalin, rinsed, and incubated in 0.05% $AgNO_3$ solution in darkness for 30 minutes, then exposed to bright light to develop the stain. Tissues were rinsed, placed on a microscopic slide, and imaged using a Bio-Strategy Leica camera microscope at 2.0x magnification.

A subset of nine kōura per treatment group (3 kōura per bucket) was selected for detailed scoring to quantify variation within and across individuals. Where available, moulted exoskeletons were examined for gill morphology as early indicators of physical damage. Sediment burden in moults was not assessed due to potential post-moult deposition affecting measurement reliability.



Whakaahua 9. **Assessing kōura gill health. A.** A close-up photograph of kōura gills that have undergone silver nitrate staining. **B.** Kōura gills under a magnifying glass with a gill score of three (due to blackening). **C.** Kōura gills under a magnifying glass with a gill score of two (browning, moderate mucus and sediment build up). **D.** A photograph of kōura gills that have undergone silver nitrate staining, ready for microscopic analysis.

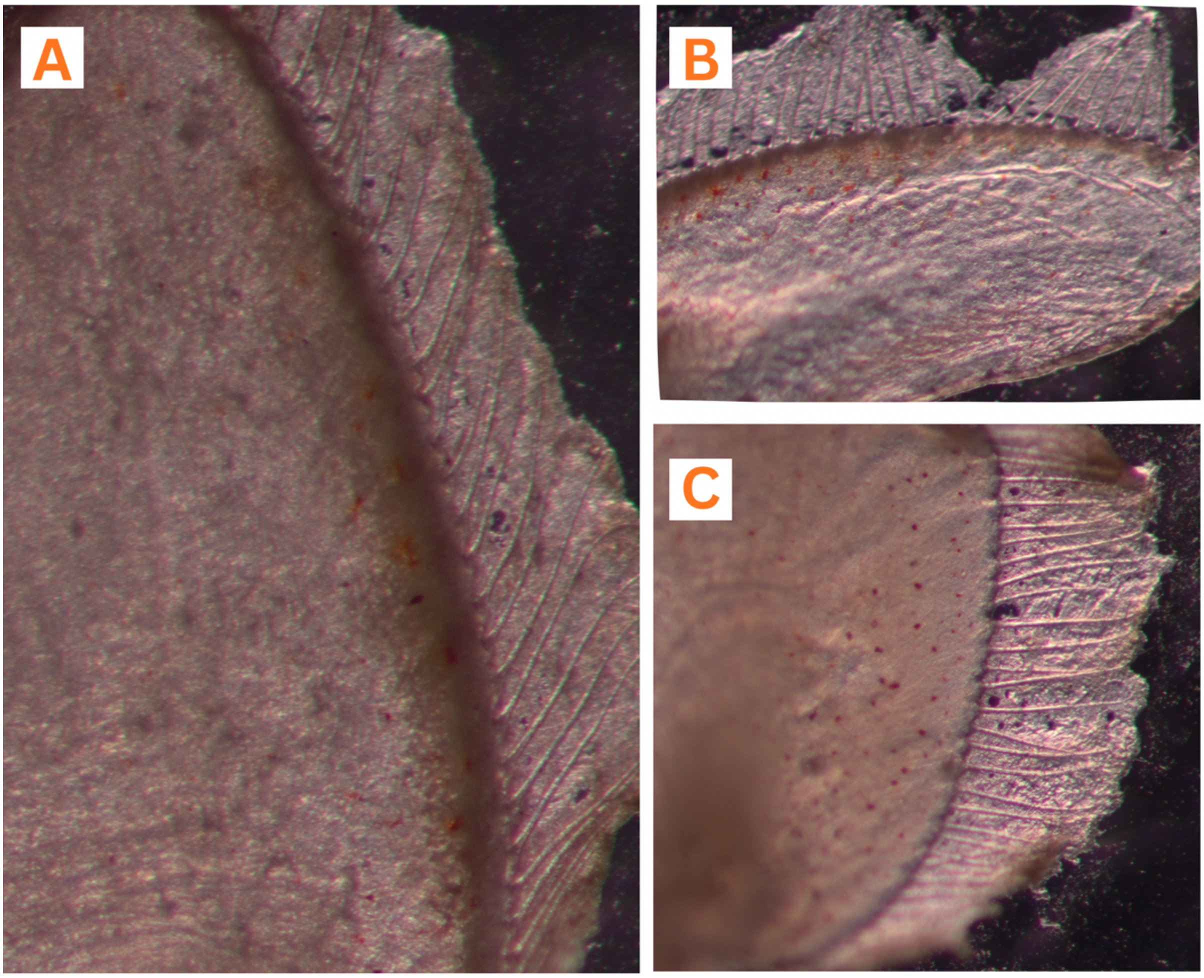
2.7.3. Haemolymph Analysis: Blood Refractive Index

Blood refractive index (BRI) was used to evaluate sublethal physiological stress. BRI reflects haemolymph solute concentration and can indicate changes in hydration status, nutritional state, and stress response (Ozbay & Riley, 2002). Haemolymph was sampled at two timepoints; at the start of the experiment to establish baseline values, and at the end of the experiment from all surviving individuals. Samples (100-200 µL) were collected using 27G surgical needles and sterile syringes from the base of the second walking leg (Whakaahua 10) – a standardised access point that minimises tissue damage in crustaceans (NIWA protocol – *Taking blood from a Lobster and reading its blood refractive index*). Immediately following collection, haemolymph refractive index measurements were taken using a handheld refractometer to ensure rapid an accurate assessment of solute concentration. All sampled kōura were humanely euthanised following extraction. Chemical anaesthetics were avoided to prevent interference with haemolymph chemistry and refractive index measurements.

Whakaahua 10. Extracting blood from a kōura for BRI testing using a surgical needle (27G) and a sterile syringe.

2.7.3.1. Moult Stage Determination

Incorporating moult stage data into BRI interpretation improved the reliability and ecological relevance of physiological measurements. Because BRI can vary with moult stage, each individual moult phase – pre-moult, post-moult, or inter-moult – was determined through pleopod examination (Whakaahua 11). A single pleopod was carefully snipped from each kōura (after euthanisation) using fine tweezers and viewed under light microscopy. Identification of moult stages was guided by comparison with detailed pleopod images provided in Oliver & MacDiarmid (2000), which served as a key reference for accurate stage determination.



Whakaahua 11. **Pleopod clippings collected from juvenile kōura, *Jasus edwardsii*; A.** Bucket #7 (Tobserved), **B.** Bucket #13 (Control), and **C.** Bucket #37 (Tmaximised). All specimens are in intermoult phase (Oliver & MacDiarmid, 2000), identified by the absence of developing setae beneath the existing cuticle and the presence of orange pigmentation along the pleopod surface. Images were taken under a dissecting microscope at 2.0x magnification.

2.8. Data Handling and Analysis

The analytical framework for this research integrates quantitative statistical methods with qualitative observational insights, combining scientific rigour with mātauranga-informed interpretation. The pulse-based experimental design produced three analytical sets based on housing transitions and treatment phases, enabling exploration of both immediate responses and cumulative effects across time.

2.8.1. Baseline Conditions and Overall Growth Trajectories

2.8.1.1. Baseline Equivalence (Day 1)

To establish that all treatment groups began with comparable initial condition, baseline body weight to carapace length (BW:CL) ratios as well as baseline body weight and carapace length at Day 1 were compared among treatments using one-way analysis of variance (ANOVA). This analysis confirmed whether observed differences at the experiment's conclusion could be attributed to treatment effects rather than pre-existing variation among groups.

2.8.1.2. Complete Experimental Trajectory (Days 1-52)

Growth patterns across the entire 52-day period were visualised and described to capture the overall response of kōura to repeated sediment pulses interspersed with recovery periods. Rather than analysing each phase independently, this approach emphasised cumulative patterns and the temporal integration of stress effects. The complete trajectory encompassed an initial pre-separation communal housing phase (Days 1–19), which included Suspension Phase 1 (Days 1–10) followed by Clean Phase 1 (Days 11–19). This was succeeded by a short separation transition period (Days 19), after which kōura were individually housed for the remainder of the experiment (Days 20–52). During this post-separation period, individuals experienced a second suspension event (Suspension Phase 2, Days 26–35), a subsequent recovery period (Clean Phase 2, Days 36–42), and a final exposure event (Suspension Phase 3, Days 43–52).

2.8.1.3. Final Body Condition

Treatment effects on final body condition were assessed using one-way ANOVA comparing BW:CL ratios among Control, Tobserved, and Tmaximised groups at Day 52. Post-hoc pairwise comparisons using Tukey's HSD test identified specific treatment differences. Effect size was calculated using eta-squared (η^2) to quantify the proportion of variance explained by treatment.

2.8.1.4. Housing Effect on Body Condition

To assess whether the transition from communal to individual housing immediately influenced body condition, a linear mixed-effects model was applied comparing matched three-day periods: communal housing (Days 16-19) versus individual housing (Days 22-25). The model included Treatment, Housing Period (communal vs. individual), Day, and the Treatment × Housing Period interaction as fixed effects, with individual identity nested within bucket as random effects. Type II Wald chi-square tests assessed significance of fixed effects.

2.8.1.5. Hypothesis

If kōura are exposed to suspended sediment, then treatment groups beginning with equivalent baseline body condition will diverge by the experiment's conclusion, with the Controls maintaining significantly better final condition than sediment-exposed treatments due to cumulative physiological deficits accumulated across repeated exposure cycles. Additionally, individual housing is predicted to improve body condition outcomes relative to communal housing by eliminating competition for resource and reducing cannibalism.

2.8.2. Mortality Patterns Across the Experiment

2.8.2.1. Overall Cumulative mortality (Days 1-52)

Total cumulative mortality across the complete 52-day experimental period was calculated for each treatment as the proportion of individuals that died relative to the initial sample size (n = 27 per treatment). Overall survival rates were compared among treatments to quantify the total population-level impact of repeated sediment exposure.

2.8.2.2. Phase-Specific Mortality Patterns

Mortality patterns were analysed separately for pre-separation communal housing (Days 1-19) and post-separation individual housing (Days 20-52) to identify context-dependent vulnerability. Two-way ANOVA models tested the effects of Treatment, Day, and their interaction on survivor counts during each phase.

Kaplan-Meier survival curves were constructed for the post-separation phase, with log-rank tests comparing survival distributions among treatments. This approach accounts for censoring (individuals surviving to the experiment's end) and provides probability estimates of survival over time.

2.8.2.3. Within-Bucket Variability as Early Warning Signals

To assess whether sediment stress increased heterogeneity among individuals – potentially signalling social stress and competitive interactions – within-bucket coefficient of variation (CV%) in BW:CL ratios was calculated for each bucket at each measurement timepoint during the pre-separation phase (Days 1-19). Linear mixed-effects models tested the effects of Treatment, Day, and their interaction on CV%, with bucket as a random effect.

2.8.2.4. Hypothesis

If kōura are exposed to suspended sediment during communal housing, then mortality will increase in sediment concentration, with higher concentrations (Tmaximised) producing greater cumulative physiological stress and mortality over the experimental period. Overall cumulative mortality will be significantly elevated in both sediment-exposed treatments compared to Controls, with phase-specific patterns revealing context-dependent vulnerability.

2.8.3. Final Physiological Condition Assessment (Day 52)

2.8.3.1. Haemolymph Physiology

Blood refractive index (BRI) measurements at Day 52 were compared among treatments using one-way ANOVA to determine whether sediment exposure depleted haemolymph protein/lipid reserves. Linear regression and Pearson correlation analyses examined relationships between BRI and current body condition (Day 52 BW:CL ratio), as well as between BRI and initial body condition at separation (Day 19 BW:CL ratio). An interaction model tested whether the relationship between initial condition and final BRI differed among treatments. Day 19 was used as the baseline for individual-level comparisons as this marked the beginning of individual tracking following separation from communal housing. An interaction model tested whether the relationship between Day 19 condition and final BRI differed among treatments.

2.8.3.2. Moult Stage Distribution

Moult stages of surviving kōura at Day 52 were classified according to established criteria (Oliver & MacDiarmid, 2000) and categorised as Intermoult, D1.1 (early pre-moult), or D1.2 (mid pre-moult). Fisher's Exact Test assessed whether moult stage distribution differed among treatments, testing the hypothesis that sediment stress suppresses moulting progression.

2.8.3.3. Hypothesis

If kōura are exposed to repeated sediment pulses, then survivors will exhibit depleted physiological reserves measured by reduced BRI values, and sediment-exposed treatments will show suppressed moult progression with higher proportions remaining in intermoult stage compared to the Controls.

2.8.4. Gill Damage Assessment

2.8.4.1. Quantitative Photographic Analysis

To validate the assigned gill condition scores and quantify treatment-induced damage with greater precision, standardised photographs of gill filaments were captured from a subset of individuals at the conclusion of the study (Day 52).

Nine individuals per treatment were photographed, with three randomly selected from each replicate bucket. High-resolution images of both left and right gills were then scored blindly for three quantitative metrics using 0–3 ordinal scales. The first metric, *particle lodgement*, measured the extent of sediment particles trapped within gill lamellae, with scores ranging from 0 (nonvisible) to 3 (extensive). The second, *filament integrity*, assessed the degree of structural damage, fraying, or tissue loss, where 0 indicated intact filaments and 3 represented severe damage or loss. The final metric, *surface discolouration*, captured melanisation and pigmentation changes indicative of immune response or necrosis, scored from 0 (normal appearance) to 3 (extensive or dark discolouration). A composite photographic score was calculated as the mean of the three ordinal metrics to provide an integrated measure of gill damage severity.

2.8.4.2. Structural Deformities

In addition to quantitative metrics, the presence or absence of gross structural deformities (filament clumping, fusion, abnormal architecture, or apparent tissue collapse) was recorded categorically for each individual.

2.8.4.3. Statistical Analysis of Gill Damage

Treatment effects on individual damage metrics and composite scores were analysed using Kruskal-Wallis tests (non-parametric ANOVA for ordinal data), with Dunn's post-hoc tests applying Bonferroni corrections for multiple pairwise comparisons. Fisher's exact test assessed whether structural deformity prevalence differed among treatments.

Because gill damage represents a largely irreversible endpoint without successful moulting, it provides the most direct measure of long-term respiratory stress accumulation. Gill regeneration depends on complete moult cycles; therefore, the persistence of damage despite extended recovery periods indicates that repair mechanisms were insufficient to reverse cumulative sediment-induced deterioration.

2.8.4.4. Hypothesis

If kōura are exposed to three complete sediment pulses at one of three concentration levels (Control: 0 mg/L < Tobserved: 1,000 mg/L < Tmaximised: 5,000 mg/L), then survivors will exhibit dose-dependent cumulative gill damage manifested as increased particle lodgement, reduced filament integrity, and extensive tissue discolouration. Treatment effects will demonstrate clear hierarchical severity (Control < Tobserved < Tmaximised; where < indicates increasing damage) across all metrics, with sediment-exposed treatments showing significantly higher prevalence of structural deformities compared to Controls.

All statistical analyses were performed using RStudio (version 2025.05.0-496). Key R packages included: tidyverse for data manipulation and visualisation, lme4/lmerTest for mixed-effects models, emmeans for post-hoc comparisons, car for ANOVA, survival/survminer for survival analyses, and effectsize for effect size calculations. Additional packages used were Hmisc (correlations), ordinal (ordinal regression), dunn.test (non-parametric tests), patchwork (figure composition), and readxl (data import).

2.9. Qualitative Observations and Mātauranga-Informed Interpretation

Quantitative results are supported by qualitative observations of kōura behaviour, feeding, moulting, and mortality timing. The notable cannibalism event in Bucket 7 (Tobserved treatment), which occurred during the clean phase rather than during active sediment exposure, suggests that stress responses in kōura can persist or shift even after sediment is removed. However, because moult stage was not deliberately balanced across treatments at the start of the experiment, any final differences in vulnerability or cannibalism risk may reflect an initial imbalance rather than a treatment effect. This alternative explanation needs to be considered alongside the observed pattern. Taken together, the combination of physiological and behavioural indicators still provides important context for assessing kōura resilience, but interpretation must remain cautious given the potential influence of moult status.

From a mātauranga Māori perspective, the persistence of stress into recovery phases reflects an understanding that when the moana is disturbed, healing is neither instant nor isolated from the relationships that sustain life. Kōura carry the impacts of disruption forward, embodying the way environmental changes affect species and communities over time.

Integrating these perspectives ensures that analyses capture not only measurable biological effects but also their ecological and cultural significance. The combination of statistical evaluation and mātauranga-informed interpretation therefore provides a holistic understanding of kōura responses to suspended sediment exposure, informing discussions of taonga species resilience, mahinga kai restoration, and broader environmental wellbeing.

Ūpoko Tuatoru (3)

Ngā Hua o te Mahi: What the Kōura Reveal

Results

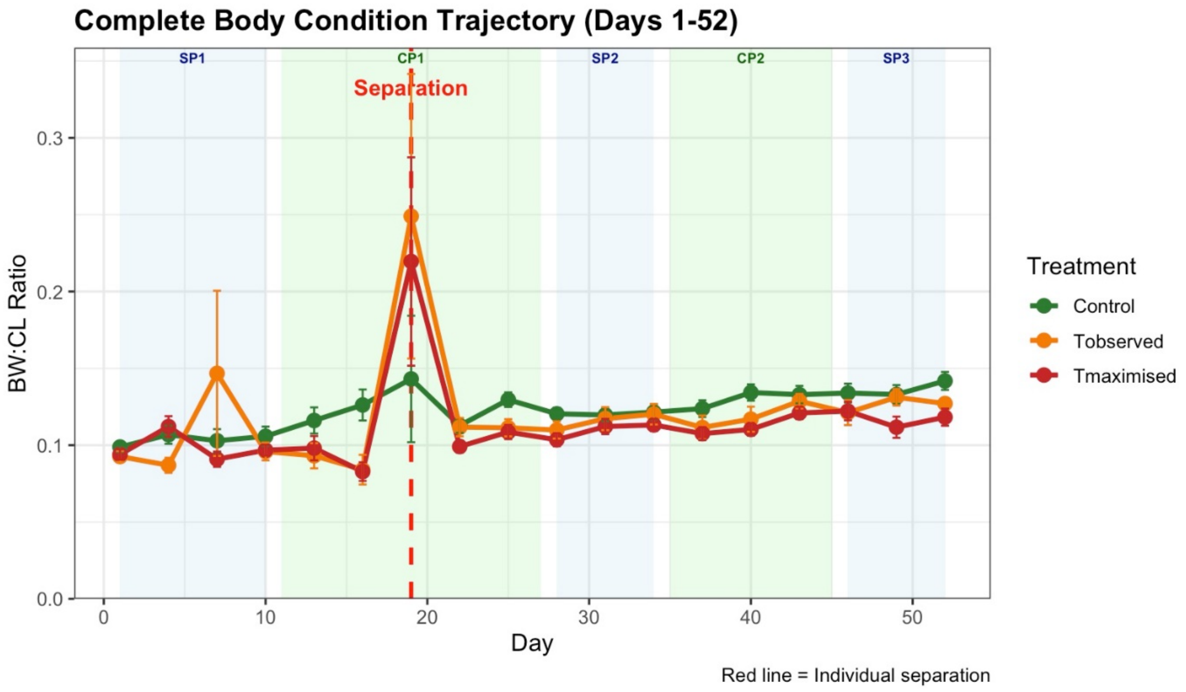
“E whiwhi ana koe i ngā hua o te moana me mākū koe”

If you want to obtain the fruits of the ocean, you must get wet

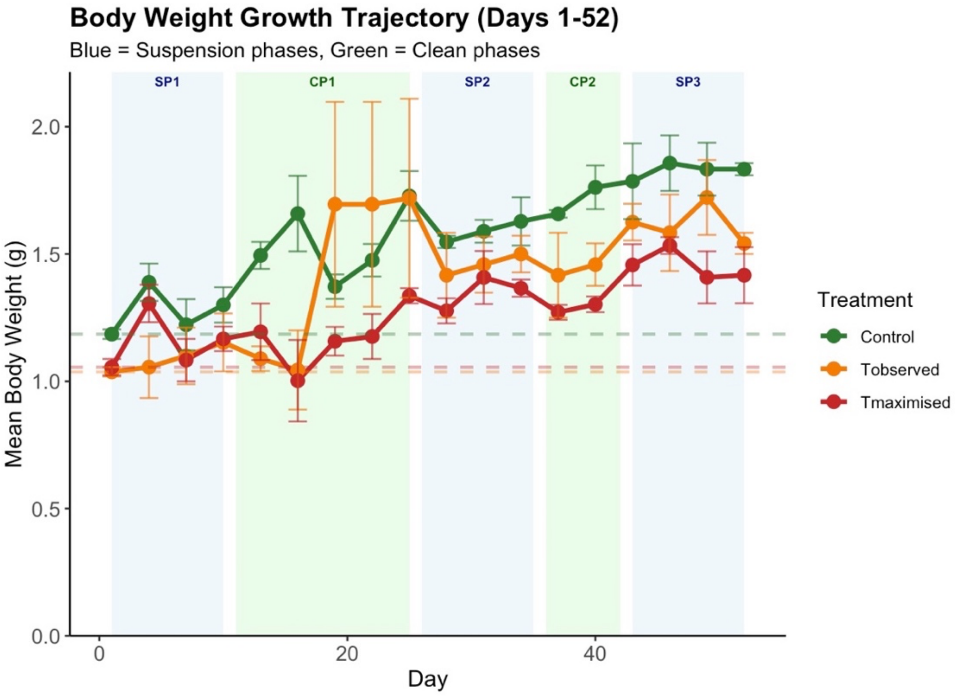
3.1. Overview of Experimental Timeline

The 52-day experiment consisted of two distinct housing phases. During the pre-separation phase (Days 1-19), 81 kōura were housed communally in buckets and exposed to their first sediment pulse (Suspension Phase 1: Days 1-10) followed by clean water recovery (Clean Phase 1: Days 11-19). Survivors were then separated into individual tāruke on Day 19, where they experienced two additional sediment exposure cycles: Suspension Phase 2 (Days 26-35) and Suspension Phase 3 (Days 43-52), interspersed with clean water recovery periods.

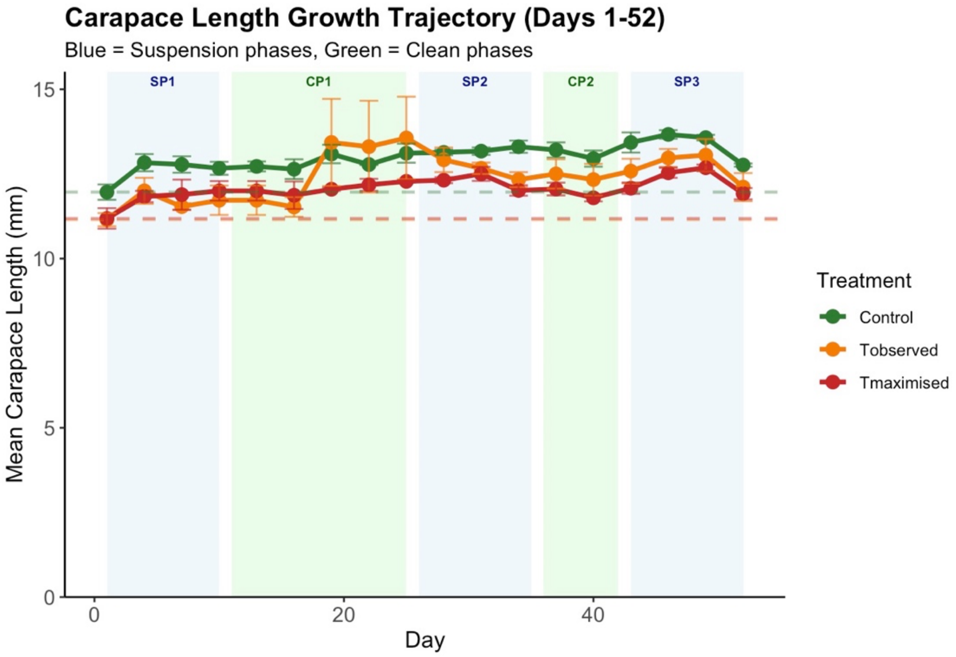
3.2. Body Condition Trajectory Across the Experiment



***Whakaahua 12*. Complete body condition trajectory (BW:CL ratio) across the full 52-day experimental period.** A spike in body condition occurred around Day 19 (Clean Phase 1) during the separation period (red vertical line), particularly pronounced in Tobserved (orange) and Tmaximised (red) groups. Blue shaded regions indicate suspension phases (SP1, SP2, SP3); green shaded regions indicate clean phases (CP1, CP2). After Day 30, all groups converged to similar body conditions. Error bars represent the standard error of the mean (SEM). Sample (n) size represents the number of individual crayfish measured per treatment group every 3 days, which varied across the experiment.



Whakaahua 13. Kōura in the Control treatment showed a steady increase in body weight across the experiment, suggesting normal growth under clear-water conditions. Error bars represent the standard error of the mean (SEM). Sample (n) size represents the number of individual crayfish measured per treatment group every 3 days, which varied across the experiment.



Whakaahua 14. Carapace length remained largely unchanged for all treatments over the 52 days, and trajectories were highly similar between groups. Error bars represent the standard error of the mean (SEM). Sample (n) size represents the number of individual crayfish measured per treatment group every 3 days, which varied across the experiment.

3.2.1. Baseline Body Condition (Day 1)

At the start of the experiment, all treatment groups had statistically equivalent body condition. Mean BW:CL ratios were similar across treatments: Control (0.099 ± 0.002 g/mm), Tobserved (0.093 ± 0.001 g/mm), and Tmaximised (0.094 ± 0.01 g/mm). One-way ANOVA indicated that no significant differences existed among the control and treatments at baseline ($F_{2,6} = 2.89$, $p = 0.135$), establishing that all groups began the experiment with comparable initial condition. Treatment groups showed slight differences in absolute body size, however, none with statistically significant at Day 1 (Ripanga 3; Controls: 12.0 mm CL, 1.18 g BW; Tobserved: 11.1 mm CL, 1.04 g BW; Tmaximised: 11.2 mm CL, 1.06 g BW) due to stochastic allocation to communal buckets but were still considered statistically equivalent. Growth analyses accounted for these initial differences by examining trajectories relative to treatment-specific Day 1 baselines.

3.2.2. Overall Body Condition Patterns

Ripanga 3. Summary of average carapace length (CL) and body weight (BW) growth across treatments from Day 1 to Day 52. Values represent treatment-level means (n = 3 buckets per treatment).

Treatment	n	Day 1 CL (mm)	Day 52 CL (mm)	CL Growth (mm)	CL Growth (%)	Day 1 BW (g)	Day 52 BW (g)	BW Growth (g)	BW Growth (%)
Control	3	12.000	12.800	0.799	6.680	1.180	1.830	0.648	54.700
Tobserved	3	11.100	12.100	0.963	8.640	1.040	1.540	0.505	48.700
Tmaximum	3	11.200	11.900	0.731	6.540	1.060	1.420	0.361	34.200

Growth percentages calculated relative to Day 1 baseline values.

Body condition (BW:CL ratio) remained relatively consistent across all treatments throughout the 52-day experiment, with minimal effects observed during sediment-exposure phases (Whakaahua 12). Overall growth patterns (Whakaahua 13, 14) from Day 1 to Day 52 showed significant increases in both carapace length ($F_{1,150} = 33.65$, $p < 0.001$) and body weight ($F_{1,150}$

= 117.09, $p < 0.001$) across all treatments. However, there was no significant Treatment × Day interaction for carapace length ($F_{2,150} = 0.99$, $p = 0.372$) or body weight ($F_{2,150} = 2.55$, $p = 0.081$), indicating parallel growth trajectories across treatments. A notable spike in body condition (BW:CL ratios) occurred around Day 19 during the transition from communal to individual housing, particularly pronounced in the sediment-exposed groups (Tobserved and Tmaximised). After Day 30, all groups converged to similar trajectories with slight oscillations corresponding to sediment exposure and recovery cycles.

3.2.3. Final Body Condition (Day 52)

Ripanga 4. One-way ANOVA results on final body condition (BW:CL) at the end of the experimental phases (Day 52).

	df	Sum Sq	Mean Sq	*F* value	Pr(>F)
Treatment	2	0.004216	0.0021082	4.602	0.016 *
Residuals	41	0.018784	0.0004581		

Significance codes: * (p < 0.05)

Ripanga 5. Final body weight at Day 52 by treatment. Values are means ± SE (n = 3 buckets per treatment)

Treatment	n	Mean BW (g)	SD	SE
Control	3	1.830	0.041	0.024
Tobserved	3	1.540	0.072	0.042
Tmaximised	3	1.420	0.191	0.110

One-way ANOVA showed significant treatment effect: $F_{2,6} = 9.49, p = 0.014$.

By the end of the experiment, significant treatment differences were apparent in final body condition. One-way ANOVA showed significant treatment effects ($F_{2,41} = 4.602$, $p = 0.016$, $\eta^2 = 0.18$: Ripanga 4). Control kōura maintained the best body condition (mean BW:CL = 0.144 ± 0.041 SE), significantly greater than Tmaximised individuals (mean BW:CL = 0.121 ± 0.028 SE; difference = 0.023, $t_{41} = 2.97$, $p = 0.013$). Tobserved showed intermediate condition (mean

BW:CL = 0.131 ± 0.026 SE), but did not differ significantly ($p = 0.247$). These differences in body condition were likely driven by treatment effects on body weight rather than carapace length. Final body weight at Day 52 differed significantly among treatments ($F_{2,6} = 9.49$, $p = 0.014$; Ripanga 5), with Controls (1.83 ± 0.024 g) significantly heavier than Tmaximised individuals (1.42 ± 0.110 g; $p = 0.013$), while the difference between Controls and Tobserved (1.54 ± 0.042 g) approached significance ($p = 0.056$). In contrast, final carapace length showed no significant treatment differences ($F_{2,6} = 2.91$, $p = 0.131$), indicating that sediment exposure affected body mass accumulation but not skeletal growth.

3.2.4. Housing Effect on Body Condition

Ripanga 6. Linear mixed-effects model results of treatment, housing period, and day on BW:CL ratios under suspended sediment conditions.

Terms	df	Chisq (χ^2)	Pr(>Chisq)
Treatment	2	0.680	0.712
Housing Period	1	6.394	0.011 *
Day	1	8.397	0.004 **
Treatment × Housing Period	2	0.806	0.668

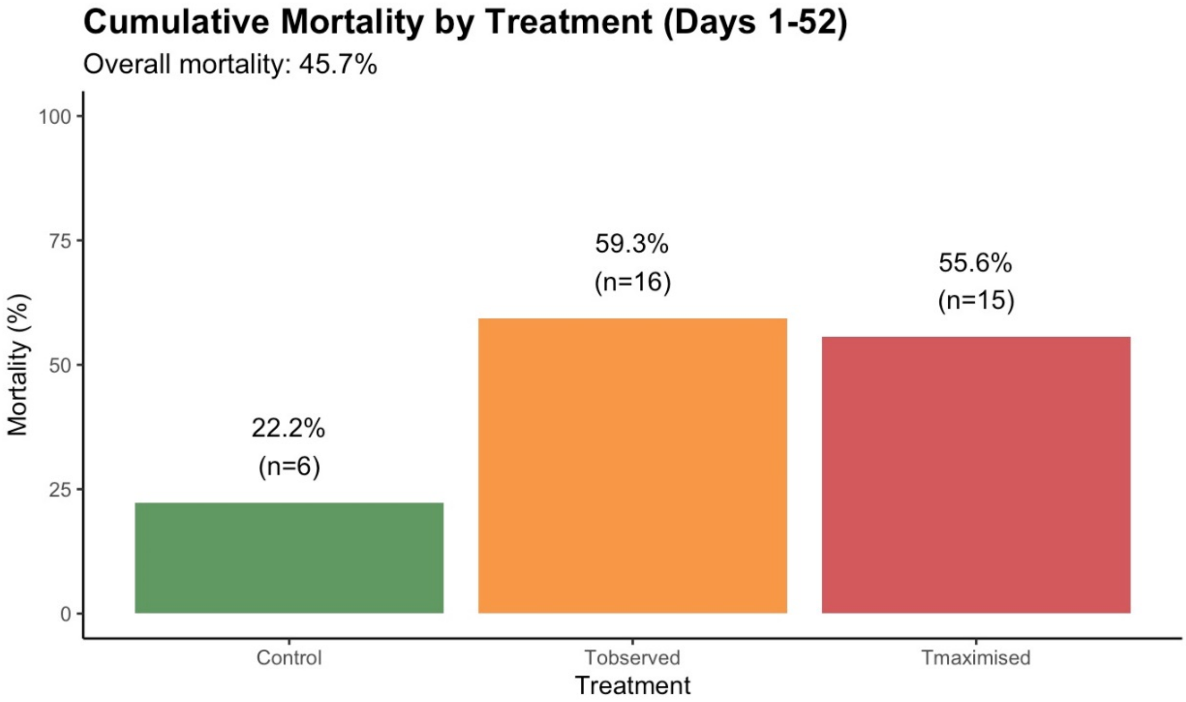
Significance was assessed using Type II Wald chi-square tests: * ($p < 0.01$), ** ($p < 0.001$)

The transition from communal to individual housing had an immediate effect on body condition. A linear mixed model (Ripanga 6) comparing matched three-day periods (communal: Days 16-19 vs individual: Days 22-25) identified a significant main effect of housing period ($\chi^2_1 = 6.39$, $p = 0.011$). Post-hoc comparisons indicated that sediment-exposed kōura (Tobserved and Tmaximised) showed significantly higher BW:CL ratios during communal housing (differences of 0.217, $p = 0.012$, and 0.191, $p = 0.005$, respectively), with values declining upon separation. This pattern likely reflects selective mortality of smaller individuals during communal holding rather than true condition improvement. Controls showed no significant difference between housing periods, suggesting that sediment-exposed individuals were particularly sensitive to the housing transition.

3.3. Cumulative Mortality Patterns

3.3.1. Overall Mortality

Cumulative mortality over the 52-day period was substantial and treatment-dependent (Whakaahua 13). Of the 81 individuals that began the experiment, only 44 survived to Day 52 (45.7% total mortality). Mortality (Whakaahua 15) was highest in Tobserved (59.3%, 16 of 27 deaths) and Tmaximised (55.6%, 15 of 27 deaths), while Controls experienced the lowest mortality (22.2%, 6 of 27 deaths).



Whakaahua 15. **Cumulative mortality by treatment group over 52 days.** Overall mortality was 45.7%. Tobserved group (orange) showed highest mortality at 59.3% (n=16), followed by Tmaximised (red) at 55.6% (n=15), while Control group (green) had lowest mortality at 22.2% (n=6).

3.3.2. Phase-Specific Mortality Patterns

Ripanga 7. Results of a two-way ANOVA testing the effects of treatment and day on survivor counts during the post-separation phase (Days 22-52). Including F-statistics, degrees of freedom, and p-values (α = 0.05).

Terms	**df**	**Sum Sq**	***F* value**	**Pr(>F)**
Treatment	2	119.29	48.76	< 0.001***
Day	1	2.05	1.67	0.207
Treatment × Day	2	74.84	30.59	< 0.001***
Residuals	27	33.03		

This analysis was based on the survivor counts per treatment (Control, Tobserved, and Tmaximised) measured from Day 22-52. Significance codes: * (p < 0.05), *** (p < 0.001).

Mortality patterns differed markedly between the pre-separation communal phase and post-separation individual tāruke phase. During pre-separation (Days 1-19), Tobserved experienced catastrophic mortality (51.9%, 14 deaths) with the majority concentrated in Bucket 7 (8 deaths), while the Controls and Tmaximised showed similar moderate rates (both 18.5%, 5 deaths each). A two-way ANOVA (Ripanga 7) confirmed a significant Treatment × Day interaction ($F_{2,18} = 52.104$, $p < 0.001$), indicating that Tobserved experienced significantly faster mortality accumulation during communal housing.

Following separation into individual tāruke (Days 20-52), the mortality pattern reversed. Tmaximised experienced the highest post-separation mortality (45.5%, 10 of 22 deaths), while Controls (4.5%, 1 of 22 deaths) and Tobserved (15.4%, 2 of 13 deaths) showed much lower rates. Kaplan-Meier survival analysis confirmed significant treatment differences (log-rank test: $\chi^2_2 = 10.0$, $p = 0.007$). The Treatment × Day interaction was highly significant ($F_{2,27} = 30.59$, $p < 0.001$), with Tmaximised exhibiting a mortality rate 7.6 times greater than Controls during individual housing.

Strikingly, most post-separation deaths (7 of 13) occurred during Clean Phase 2 (Days 37-43) with 6 deaths in Tmaximised alone. No mortality occurred during Suspension Phase 2, and only 5 deaths occurred during Suspension Phase 3 (all Tmaximised). This pattern suggests delayed mortality from cumulative stress rather than acute toxicity during sediment exposure.

3.3.3. Within-Bucket Variability as an Early Warning Signal

Ripanga 8. Coefficient of variation (CV%) in BW:CL ratio across treatments (Control, Tobserved, and Tmaximised) and measurement days during Suspension Phase 1 and Clean Phase 1 (Days 13-19).

Day	Treatment	Phase	Mean CV%	SE
1	Control	Suspension Phase 1	18.5	3.26
1	Tobserved	Suspension Phase 1	20.5	3.49
1	Tmaximised	Suspension Phase 1	18.6	3.32
4	Control	Suspension Phase 1	23.5	4.89
4	Tobserved	Suspension Phase 1	22.4	2.35
4	Tmaximised	Suspension Phase 1	24.2	4.49
7	Control	Suspension Phase 1	28.2	8.29
7	Tobserved	Suspension Phase 1	70.4	41.00
7	Tmaximised	Suspension Phase 1	22.6	2.22
10	Control	Suspension Phase 1	26.3	2.25
10	Tobserved	Suspension Phase 1	23.7	2.18
10	Tmaximised	Suspension Phase 1	15.9	1.79
13	Control	Clean Phase 1	31.2	4.95
13	Tobserved	Clean Phase 1	37.4	12.90
13	Tmaximised	Clean Phase 1	32.8	7.76
16	Control	Clean Phase 1	34.0	10.60
16	Tobserved	Clean Phase 1	47.9	6.28
16	Tmaximised	Clean Phase 1	29.0	3.20
19	Control	Clean Phase 1	64.8	40.70
19	Tobserved	Clean Phase 1	59.0	43.90
19	Tmaximised	Clean Phase 1	43.7	22.50

The CV% was calculated from within-bucket variability in BW:CL ratios. The data from 9 buckets (3 per treatment) across Days 1-19.

Within-bucket variability in body condition (measured as coefficient of variation in BW:CL ratios, CV%; Ripanga 8) increased significantly over time ($F_{1,56} = 4.26$, $p = 0.044$), rising from 18.5% on Day 1 to 43.7% by Day 19. Notably, Tobserved exhibited a dramatic spike in variability during Suspension Phase 1 at Day 7 (CV% = 70.4 ± 41.0%), while Controls (28.2% ± 8.3%) and Tmaximised (22.6% ± 2.2%) remained stable. This early variability spike in Tobserved preceded the elevated mortality observed in this treatment during Days 7-19, suggesting that increased within-group heterogeneity may serve as an early indicator of population-level stress.

3.4. Physiological Condition at Experiment End

3.4.1. Haemolymph Physiology

Ripanga 9. Regression and correlation analyses examining the relationships between blood refractive index (BRI) and body condition (BW:CL).

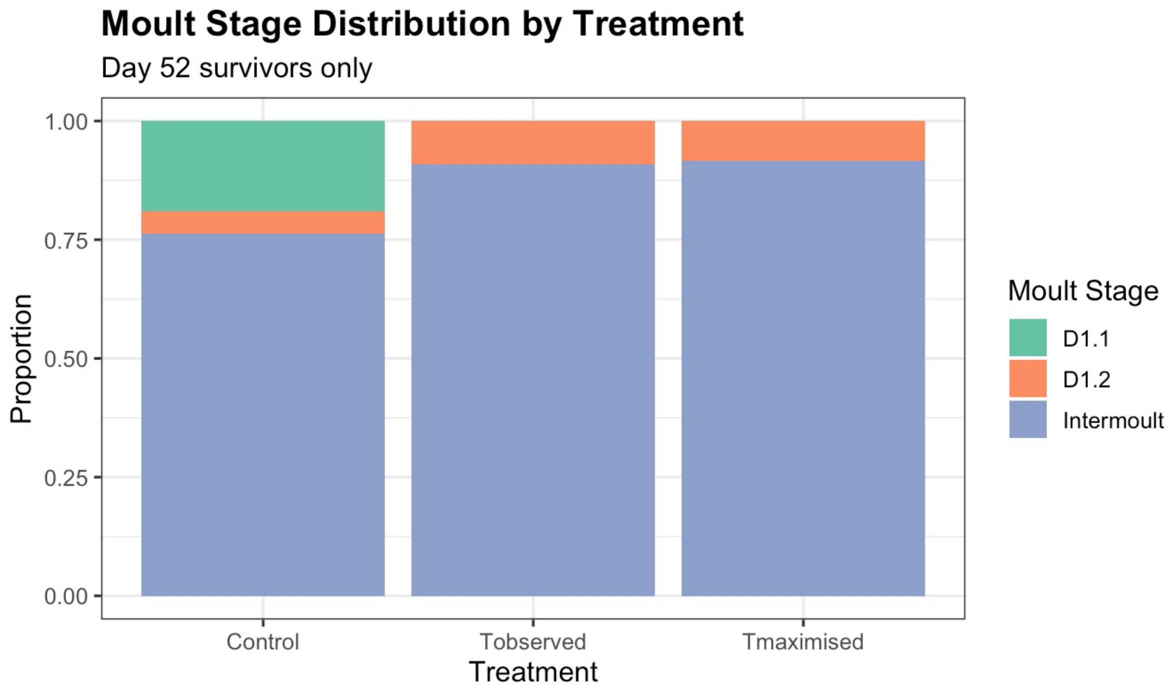
Analysis	**Test**	**df**	***F*/r statistic**	***p*-value**	**R^2 / 95% CI**
BRI ~ Current BW:CL	Linear Regression	1, 42	$F = 0.14$	0.708	$R^2 = 0.003$
BRI vs Current BW:CL	Pearson Correlation	42	r = 0.058	0.708	-0.243 to 0.349
BRI ~ Day 19 BW:CL	Linear Regression	1, 42	$F = 0.30$	0.585	$R^2 = 0.007$
BRI ~ Day 19 BW:CL × Treatment	Interaction Model	5, 38	$F = 0.63$	0.681	$R^2 = 0.076$

All analyses showed no significant associations, indicating that neither current BW:CL ratio (Day 52) nor initial BW:CL (from Day 19 – separation) predicted physiological reserves measured by haemolymph refractive index.

Blood refractive index (BRI) measurements at Day 52 showed no significant differences among treatments ($F_{2, 41} = 1.19$, $p = 0.316$). Mean BRI values were nearly identical across groups: Control (1.344 ± 0.003), Tobserved (1.345 ± 0.003), and Tmaximised (1.344 ± 0.004). These values were consistent with baseline BRI measurements taken prior to exposure (range = 1.337-1.347), suggesting stable haemolymph composition over the experimental period. Furthermore, BRI showed no relationships with current body condition ($F_{1, 42} = 0.14$, $p = 0.708$, $R^2 = 0.003$; Ripanga 9) or with body condition at separation ($F_{1, 42} = 0.30$, $p = 0.585$; Ripanga

9), indicating that haemolymph protein/lipid reserves were independent of both treatment history and individual condition.

3.4.2. Moult Stage Distribution



***Whakaahua 16.* Moult stage distribution among Day 52 survivors by treatment group.** All groups were predominantly in the Intermoult stage (blue, >75% in all groups). The control group showed slightly higher proportions of D1.1 (dark green, ~20%) and D1.2 (orange, ~5%) stages combined 25% compared to Tobserved and Tmaximised groups, which had lower (10%) representation in these earlier moult stages.

Moult frequency across the entire experimental period showed differential patterns between treatments. During the communal phase (Days 1-19), 15 individuals moulted: Control (n = 5), Tobserved (n = 4) and Tmaximised (n = 6). Between Days 13-19 (6 days in total), 7 kōura died. Following separation (Day 19), an additional 20 individuals moulted: Control (n = 11), Tobserved (n = 4), and Tmaximised (n = 5). Moulting activity ceased after Day 46 across all treatments, with no recorded moults during Day 49-52.

The vast majority of surviving kōura remained in the intermoult stage at Day 52 (84.1%, 37 of 44 individuals), with only 9.1% (4 individuals) in early pre-moult stage D1.1 and 6.8% (3 individuals) in stage D1.2 (Whakaahua 16). Fisher’s Exact Test indicated no significant association between treatment and moult stage-distribution ($p = 0.328$). All four individuals showing moult progression (D1.1 stage) were from the Control treatment, though this pattern lacked statistical power due to low sample size.

3.5. Gill Damage Assessment

3.5.1. Quantitative Gill Damage

Photographic analysis of gill morphology from 27 final survivors (9 per treatment) indicated severe, treatment-dependent structural damage. Three quantitative metrics – particle lodgement, filament integrity, and surface discolouration – all showed highly significant treatment effects (all Kruskal-Wallis $H > 15.5$, $p < 0.001$).

Control gills maintained pristine condition across all metrics (all mean scores = 0). In contrast, sediment-exposed gills showed progressive damage with increasing sediment concentration. For particle lodgement (Ripanga 10), Tobserved gills exhibited moderate accumulation (mean = 1.33 ± 0.87), while Tmaximised showed the highest particle density (mean = 1.56 ± 0.88), with particles remaining visible despite undergoing two clean-water phases prior to photography at the experiment's conclusion.

Filament integrity (Ripanga 10) scores indicated even more pronounced deterioration. Tobserved gills showed substantial damage characterised by visible fraying and erosion of filament tips (mean = 1.22 ± 0.67), while Tmaximised exhibited the most severe damage with extensive erosion, filament shortening, and apparent loss of entire filament sections (mean = 1.78 ± 0.97).

Surface discolouration (Ripanga 10) displayed the clearest dose-response gradient. Controls showed minimal natural pigmentation (mean = 0.11 ± 0.33), Tobserved exhibited moderate patchy brown discolouration (mean = 1.22 ± 1.09), and Tmaximised displayed widespread dark down to black regions indicative of severe tissue degradation (mean = 2.33 ± 0.71). Critically, post-hoc testing confirmed that Tmaximised showed significantly greater discolouration than Tobserved ($Z = -2.25$, adjusted $p = 0.036$), demonstrating a clear dose-dependent response.

Ripanga 10. Gill damage scores by treatment (Control, Tobserved, and Tmaximised) including Particle Lodgement score, Filament Integrity score, Discolouration score, and Composite Damage Score based on the 44 final survivors and photo analysis.

Treatment	n	Particle Score	Filament Score	Discolouration Score	Composite Score
Control	9	0.00 ± 0.00 (0)	0.00 ± 0.00 (0)	0.11 ± 0.33 (0)	0.04 ± 0.11
Tobserved	9	1.33 ± 0.87 (1)	1.22 ± 0.67 (1)	1.22 ± 1.09 (1)	1.26 ± 0.63
Tmaximum	9	1.56 ± 0.88 (2)	1.78 ± 0.97 (2)	2.33 ± 0.71 (2.5)	1.89 ± 0.65

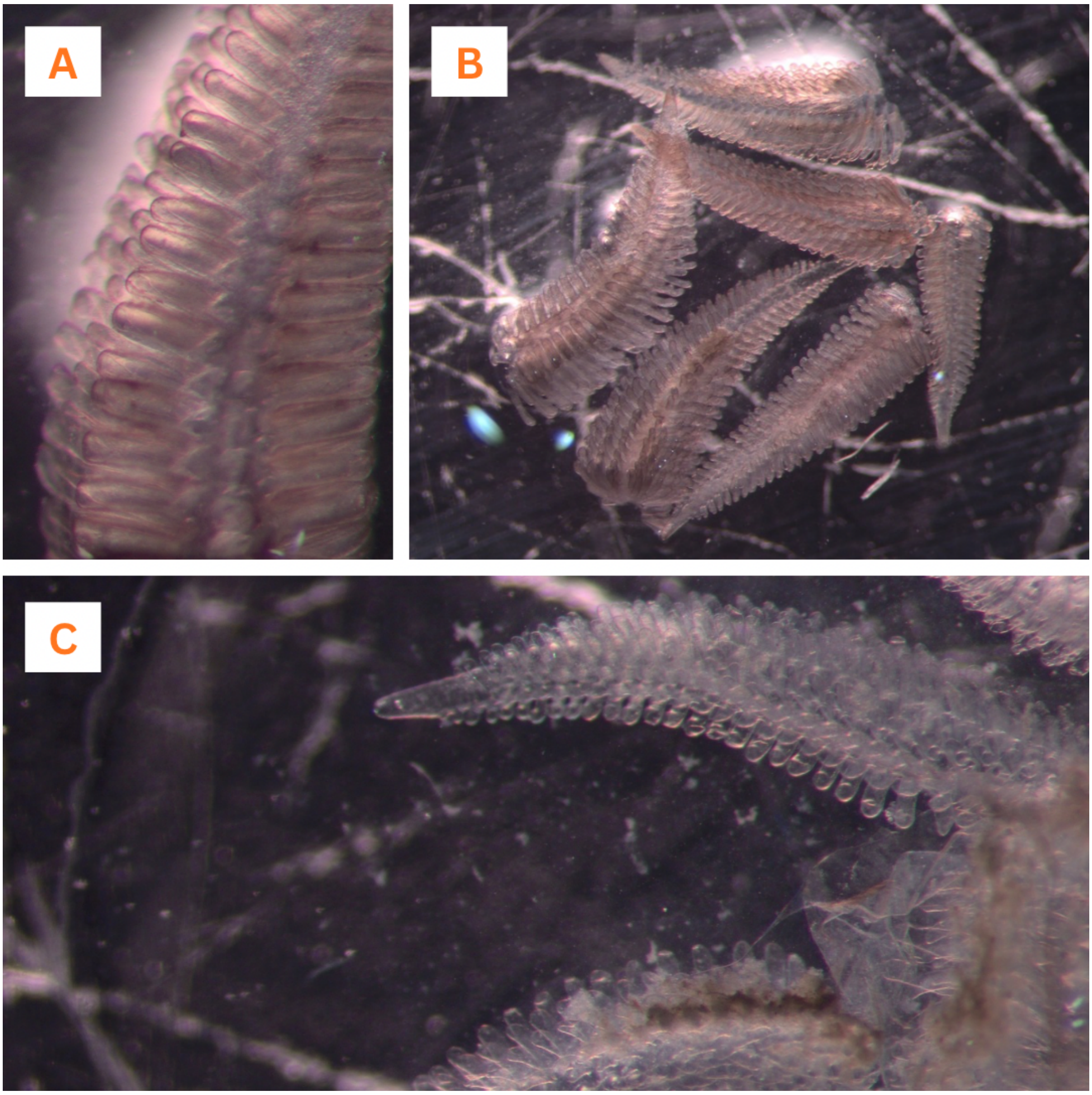
Gill damage assessed from standardised photographs (n = 9 per treatment). The values are shown as ± SD (median). The scores range from 0-3 for each metric. Composite score is the average of the three individual metrics. All metrics showed significant treatment effects (Kruskal-Wallis H > 15.55, p < 0.001).

3.5.2. Composite Damage Score and Structural Deformities

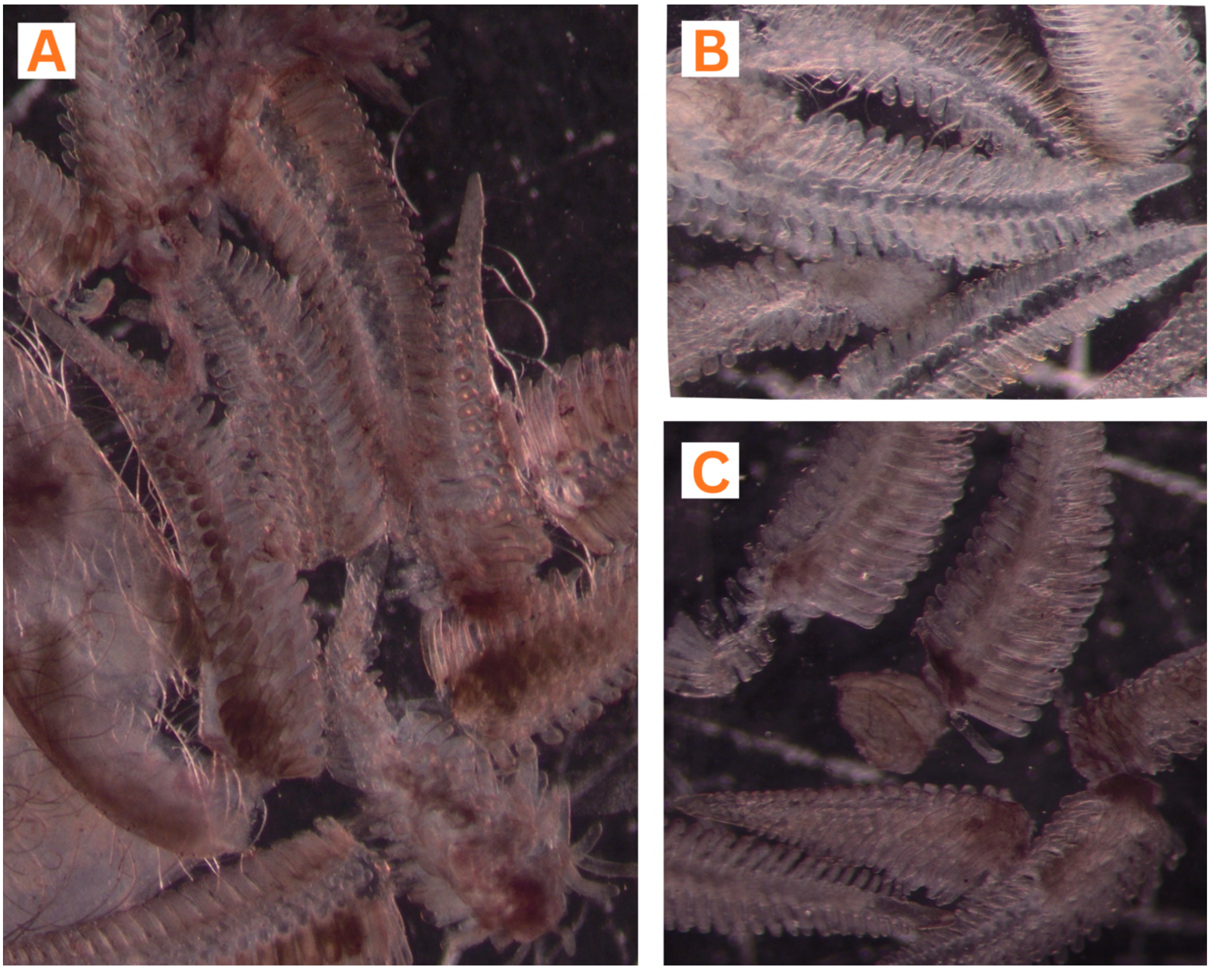
The composite photographic damage score (mean of the three quantitative metrics; Ripanga 10) provided an integrated assessment of overall gill health. Treatment effects were highly significant (Kruskal-Wallis $H = 20.64$, $df = 2$, $p < 0.001$). Controls maintained near-pristine condition (mean = 0.04 ± 0.11), while Tobserved showed moderate cumulative damage (mean = 1.26 ± 0.63) and Tmaximised exhibited severe deterioration (mean = 1.89 ± 0.65).

Beyond quantitative scoring, categorical assessment of structural deformities indicated complete separation between control and sediment-exposed gills (Whakaahua 17, 18, 19). No

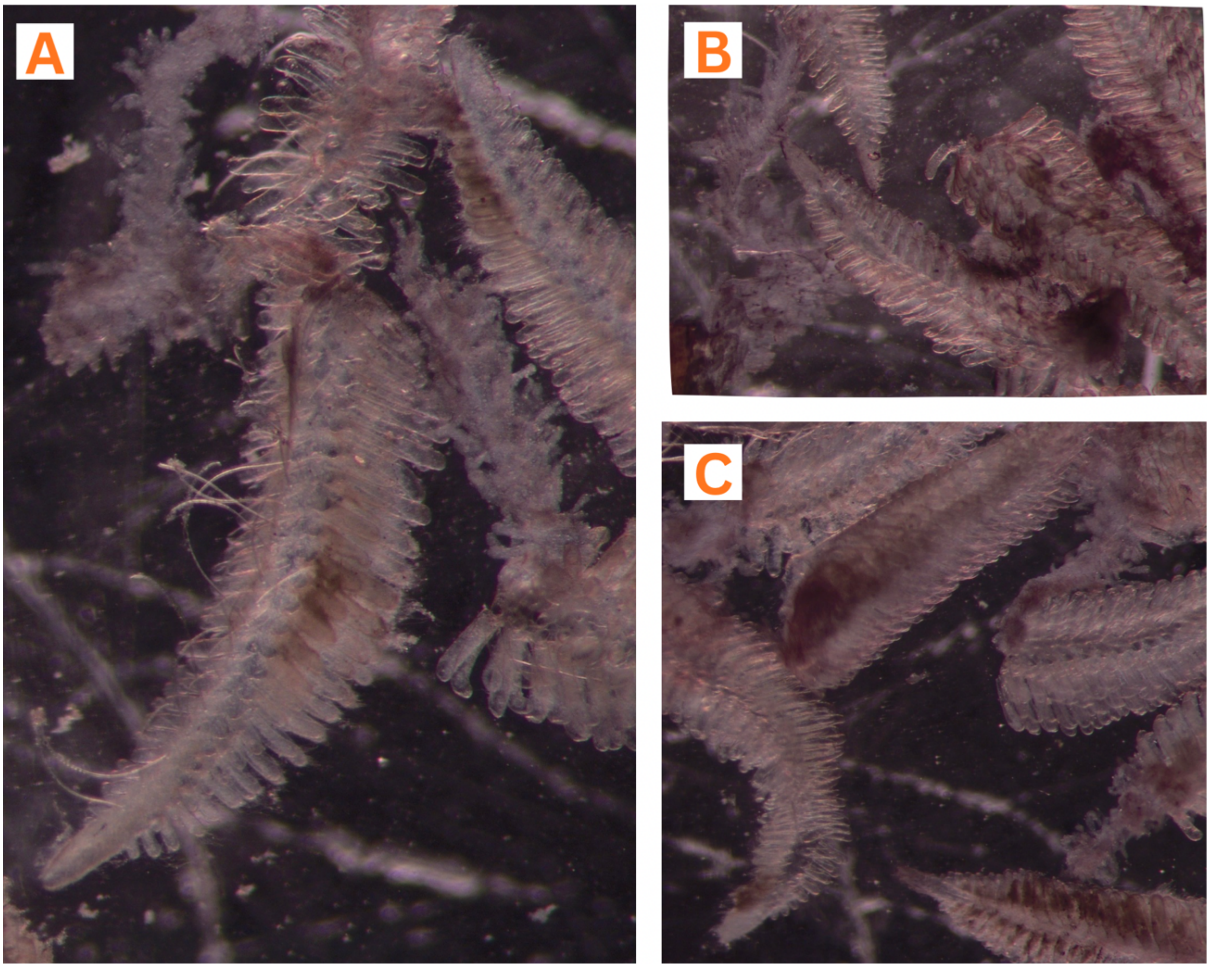
Control individuals (0 of 9, 0%) exhibited any structural abnormalities, with all gills displaying normal filament organisation and spacing. In contrast, structural deformities were present in 66.7% of Tobserved individuals (6 of 9) and 100% of Tmaximised individuals (9 of 9). Fisher's Exact Test confirmed highly significant treatment differences ($p < 0.001$). Deformities included matted filament clusters where individual filaments appeared fused or adhered together, localised regions of disrupted filament spacing, and areas showing apparent tissue collapse or necrotic change.



***Whakaahua 17*. Silver nitrate-stained gill filaments from Control group specimens (A = Bucket #2, B = Bucket #13, C = Bucket #35) examined under light microscopy.** All samples demonstrate pristine gill architecture characteristic of healthy, unstressed organisms. Sample A shows excellent structural integrity with uniform, well-defined lamellae arranged in regular rows and intact filament tips. Sample B displays multiple gill filaments with consistent architecture, well-organized lamellae, and clean tissue surfaces with no evidence of fusion, erosion, or mucus hyperproduction. Sample C exhibits normal morphology with clearly defined lamellar structure extending along the entire visible length. Across all three buckets, gill tissue shows no signs of damage, fraying, particle accumulation, necrosis, epithelial lifting, or structural degradation, confirming the absence of gill destruction in control condition.



Whakaahua 18. **Silver nitrate-stained gill filaments from Tobserved treatment group specimens (A = Bucket #7, B = Bucket #28, C = Bucket #30) examined under light microscopy.** Samples demonstrate moderate to severe gill pathology consistent with particle exposure stress. Sample A shows extensive structural damage with multiple gill filaments exhibiting severe fraying and erosion of filament tips, irregular lamellar spacing, and visible tissue degradation throughout. Thick mucus strands are apparent across gill surfaces, indicating physiological stress response. Sample B displays damaged gill architecture with disrupted lamellar organization, irregular filament margins, and evidence of epithelial lifting or separation in several areas. Sample C shows multiple gill filaments with compromised structural integrity, including frayed edges, loss of regular lamellar pattern, and possible necrotic tissue areas (darker regions). Across all three buckets, gill tissue shows clear signs of environmental stress including particle accumulation, mucus hyperproduction, filament erosion, and loss of normal architectural organisation, indicating significant respiratory impairment in the Tobserved treatment conditions.



***Whakaahua 19.* Silver nitrate-stained gill filaments from Tmaximised treatment group specimens (A = Bucket #14, B = Bucket #36, C = Bucket #37) examined under light microscopy.** Samples demonstrate severe gill pathology consistent with high particle exposure stress. Sample A exhibits pronounced structural damage with gill filaments showing extensive fraying and erosion, particularly at filament tips (upper left), irregular lamellar architecture, and substantial mucus accumulation creating a cloudy, opaque appearance across gill surfaces. Visible particle deposition (dark spots) is evident throughout the tissue. Sample B displays compromised gill structure with disrupted lamellar organization, irregular spacing between lamellae, frayed filament margins, and heavy mucus coating obscuring underlying tissue detail. Sample C shows multiple gill filaments with severe architectural degradation, including loss of normal lamellar pattern, extensive fraying along filament edges, and dark discoloration suggesting possible necrotic tissue or heavy particle accumulation. Across all three buckets, gill tissue shows pronounced signs of environmental stress including extensive mucus hyperproduction, widespread particle accumulation, severe filament erosion, epithelial damage, and complete loss of normal structural organisation, indicating critical respiratory impairment under Tmaximised exposure conditions.

3.6. Summary of Key Findings

While no significant treatment effects on body condition trajectories were detected during exposure phases, final body condition at Day 52 showed significant treatment effects, with Controls maintaining significantly better condition than Tmaximised (*p* = 0.013). Mortality patterns were highly treatment-dependent and phase-specific. During communal housing, Tobserved experienced catastrophic mortality (51.9%), while after separation into individual tāruke, Tmaximised showed the highest mortality (45.5%). Overall, cumulative mortality was similar between sediment treatments (Tobserved: 59.3%; Tmaximised: 55.6%) but both far exceeded Controls (22.2%).

Most post-separation deaths occurred during clean water recovery (Clean Phase 2 specifically) rather than during sediment exposure, suggesting cumulative stress effects rather than acute toxicity. Sediment-exposed kōura exhibited severe, dose-dependent gill damage across all metrics, with 100% of Tmaximised survivors showing structural deformities despite 30+ days of recovery in clean water (Clean Phase 1 and Clean Phase 2). Body condition (BW:CL ratios) showed a gradual increasing trend from experiment start to end. The apparent fluctuations in mean body condition during communal phases reflected selective mortality of smaller individuals rather than housing-related effects on condition.

Ūpoko Tuawhā (4)

Te Whakamaramatanga: Interpreting the Tides of Change

Discussion

"He manako te kōura i kore ai"

Wishing for the crayfish won't bring it

4.1. Putanga Whakamātau – Outcomes of the Experiment

This research examined the cumulative impacts of suspended sediment on juvenile red rock lobster (*Jasus edwardsii*) – kōura – through both ecological and cultural lenses. The purpose of this study was to understand how repeated sediment pulses affect kōura body condition (BW:CL ratio), survival, physiological condition, and social dynamics, with particular attention to the sequential and cumulative nature of stressors that mirror contemporary environmental challenges in Te Ākau o Tokomaru.

This discussion moves from the quantitative results presented in the previous chapter toward interpretive meaning that honours both scientific rigour and mātauranga Māori. The findings are grounded in the cultural landscape of Te Ākau o Tokomaru, where the health of kōura populations reflects the broader wellbeing of our coastal ecosystems and the communities who depend upon them. The aspiration for environmental renewal, symbolised by Matariki and the promise of regeneration it brings, frames this work as both ecological investigation and an act of kaitiakitanga.

4.1.1. Integrating Ecological and Cultural Narratives

This discussion serves as a meeting place between science - the empirical evidence of stress responses, mortality patterns, and physiological deterioration - and story - the whakapapa connecting kōura to Tangaroa, the lived experiences of whānau witnessing declining mahinga kai, and the ancestral knowledge embedded in our relationship with the moana.

Kōura are both biological indicators of reef health and taonga with deep genealogical ties to Tangaroa (MacDiarmid et al., 2013). As descendants, they carry within them the mauri of the ocean realm and serve as kaitiaki of rocky reef ecosystems. Through the relational ethic of Te Ao Māori, disturbances to kōura habitats are simultaneously ecological disruptions, familial disconnections, and spiritual imbalances. When sediment suffocates their gills, impairs their feeding, and disrupts their social structures, it does not merely affect individual organisms - it weakens the whakapapa connections that bind ocean, land, and people together.

The rivers of Te Tairāwhiti carry more than sediment into our coastal waters; they carry the accumulated impacts of land-use practices, the legacy of successive cyclones, and the unhealed wounds of environmental degradation. Understanding how kōura respond to these pressures is therefore not simply an academic exercise, but a cultural imperative - one that calls us to restore balance and strengthen the mauri of both whenua and moana.

4.2. Baseline Conditions and Overall Patterns

4.2.1. Starting Conditions

All treatment groups began the experiment with statistically equivalent body condition (Whakaahua 12, Ripanga 4), establishing a valid foundation for comparing treatment effects. While BW:CL ratios were comparable at baseline, treatment groups showed slight differences in absolute body weight due to stochastic allocation of individuals to communal buckets. However, these initial size differences did not confound treatment comparisons, as growth analyses accounted for treatment-specific baselines when assessing sediment effects on trajectories. This baseline equivalence in body condition is critical for interpreting the divergent outcomes observed at the experiment's conclusion, where sediment-exposed treatments showed significantly reduced body condition and survival compared to Controls (Whakaahua 12, 13, 14).

4.2.2. Body Condition Trajectories: Stability Masking Accumulating Damage

The overall body condition trajectory (Whakaahua 12) showed minimal treatment effects during individual suspension and clean phases, with all groups maintaining relatively flat

BW:CL ratios through most of the 52 days, apart from an anomalous spike at Day 19. This apparent resilience during acute exposures might suggest tolerance to short-term sediment pulses, aligning with studies on other *Jasus* species showing resilience to episodic environmental stress (Pulfrich & Branch, 2013; Edgar, 1984).

Previous work has demonstrated that body condition trajectories in juvenile lobsters are sensitive to water clarity and substrate conditions. Body condition *in Jasus edwardsii* is strongly influenced by nutritional status and feeding regime. McLeod et al., 2004 demonstrated that starvation significantly altered body composition in adult male southern rock lobsters, with measurable declines in condition indices over time. Similarly, Bryars & Geddes (2005) found that diet quality directly affected the growth, survival, and condition of sea-caged adult *J. edwardsii*, with lobsters on suboptimal diets showing reduced condition compared to those fed higher quality rations. Blood refractive index and weight-to-length ratios have been established as reliable indicators of physiological condition in this species, providing quantitative measures of nutritional state and overall health. Sediment exposure may influence all these condition parameters through reduced foraging success, impaired respiration, or increased energetic costs, though further research is needed to establish these direct mechanistic links in *J. edwardsii*.

The spike in BW:CL ratios observed around Day 19 reflects measurements taken immediately before separation from communal to individual tāruke (Whakaahua 12; Ripanga 4). At this point, mortality during Days 13-19 had removed smaller, vulnerable post-moult individuals from the population, leaving disproportionately larger survivors that elevated mean BW:CL values. The Day 19 spike was particularly pronounced in sediment-exposed groups, especially the Tobserved treatment. Alternatively, it reflects a chance of a clumped assignment of pre-moult individuals within this treatment, and to one replicate bucket in particular (Bucket 7), resulting in mortality of small vulnerable animals through cannibalism and the survival for measurement of a few large, well-fed individuals (James et al., 2002; Olsson & Nyström, 2008). Following Day 19 measurements, kōura were redistributed among buckets within their respective treatments during the separation process to create more balanced experimental units for individual housing. All kōura remained within their assigned treatment groups to maintain treatment integrity. This redistribution included individuals with a broader range of body conditions, explaining the apparent decline in mean BW:CL ratios at Day 22, as measurements returned to more representative population levels. From Day 22 onwards, body condition showed gradual improvement across all treatments through to Day 52, though the Controls maintained consistently higher BW:CL ratios than sediment-exposed groups throughout this period (Ripanga 4), indicating persistent effects of early sediment exposure.

By the experiment's conclusion, these accumulated deficits manifested as significant treatment effects on final body condition (Ripanga 4), with the Controls maintaining significantly higher BW:CL ratios, indicating better body condition and greater energy reserves than Tmaximised individuals. This pattern indicates that temporary resilience during individual exposure events does not prevent cumulative deterioration when disturbances recur before full recovery is achieved, aligning with cumulative disturbance theory (Burton & Johnston, 2010; Hoegh-Guldberg & Bruno, 2010; Kjelland et al., 2015).

Environmental parallels in Te Tairāwhiti reinforce this interpretation. The region has experienced multiple severe weather events in recent decades – Cyclone Bola (1988), Cyclone Cook (2017), Cyclone Hale (2023), and Cyclone Gabrielle (2023) – each depositing massive sediment loads into rivers and coastal waters (Allen et al., 2024; Fellows & Barker, 2021; McSaveney, 2009). Between these acute pulses, chronic sediment inputs from forestry operations, pastoral land use, and ongoing erosion continue to degrade water quality and benthic habitats, with even minor rainfall events capable of resuspending these accumulated sediments and creating localised turbidity (Morrison et al., 2023; Gisborne District Council, 2024; Robson, 2025). The observed pattern in kōura – apparent stability during individual events masking progressive deterioration across repeated exposures – mirrors this real-world context, where ecosystem recovery intervals are insufficient, leading to progressive degradation of coastal habitats and declining mahinga kai resources (Ross, 2021; Leduc et al., 2024)

From a Te Ao Māori perspective, this resilience mirrors whānau responding to temporary challenges: function is maintained despite external fluctuations, reflecting the system's inherent capacity to absorb episodic stress. However, like communities facing successive disasters, cumulative stress erodes mauri until even inherently resilient systems lose regenerative capacity.

4.3. Mortality Patterns: Phase-Specific Vulnerability

4.3.1. Non-Linear Dose-Response and Housing Context

One of the most striking findings was the non-linear, phase-dependent mortality response across treatments (Whakaahua 15; Ripanga 6, 7). During communal housing (Days 1-19), Tobserved experienced catastrophic mortality (51.9%), far exceeding both Controls and Tmaximised (both 18.5%). Following separation into individual tāruke (Days 20-52), this pattern reversed: Tmaximised exhibited the highest post-separation mortality (45.5%), while Controls (4.5%) and Tobserved (15.4%) showed much lower rates.

Mortality patterns during this experiment require careful interpretation due to confounding factors during the communal phase (Days 1-19). While Tobserved (1000 mg/L suspended sediment) experienced the highest overall mortality (51.9%) during this period, the concentration of 8 deaths in a single bucket (Bucket 7) suggests alternative explanations warrant consideration. Temporal clustering of moult events may have increased vulnerability within this bucket, as newly-moulted individuals are particularly susceptible to both physiological stress and potential cannibalism (Thomas et al., 2003; Codabaccus et al., 2025). The sole survivor from Bucket 7 was noticeably larger than individuals from other buckets, consistent with size-based dominance hierarchies and cannibalistic behaviour observed in juvenile lobsters (Thomas et al., 2003). The lack of a clear physiological mechanism for intermediate sediment concentrations producing higher mortality than extreme concentrations (Tmaximised: 5000 mg/L) further supports the interpretation that social dynamics, rather than direct sediment toxicity, drove the mortality spike in Bucket 7 (Hemsworth et al., 2007).

These Tobserved concentrations are commonly observed in coastal waters at Te Ākau o Tokomaru following rainfall events and terrestrial runoff (Morrison et al., 2023; Gisborne District Council, 2024). The early spike in within-bucket variability in Tobserved at Day 7 (CV% = 70.400 ± 41.000%) preceded this mortality event, suggesting that increased heterogeneity in body condition may indicate emerging population-level stress. Whether this heterogeneity reflects direct sediment impacts or social dynamics that amplify competition and vulnerability remains unclear from this experiment.

In contrast, the highest sediment concentration (Tmaximised) produced more uniform physiological impairment that did not translate to immediate mortality during communal conditions, but manifested as delayed death once individuals were isolated and could no longer benefit from potential collective buffering mechanisms (covered later in the Discussion, Section 3.3). The significant Treatment × Day interaction (Ripanga 7: $F_{2,27} = 30.59$, $p < 0.001$) suggests that these distinct temporal mortality trajectories, with Tmaximised exhibiting a mortality rate 7.6 times greater than Controls during the post-separation phase.

4.3.2. Delayed Mortality and Cumulative Stress

Strikingly, most post-separation deaths occurred during Clean Phase 2 (Days 37-43) rather than during sediment exposure phases, with 6 of 7 deaths during this period occurring in the Tmaximised treatment. This temporal pattern suggests delayed mortality from cumulative physiological stress rather than acute toxicity during sediment exposure itself (Wilber & Clarke, 2001; Kjelland et al., 2015). Kōura that survived initial sediment pulses and appeared to recover during Clean Phase 1 nevertheless carried forward accumulated damage that ultimately proved lethal weeks later.

This finding carries particular significance for understanding sediment impacts on wild populations. Traditional toxicological approaches that assess mortality during or immediately following exposure may substantially underestimate true population-level impacts, as considerable mortality occurs during apparent recovery periods when physiological reserves become depleted and organisms can no longer compensate for accumulated damage (Rowe et al., 2001).

From a Te Ao Māori perspective, this delayed mortality reflects the concept of utu – consequence and reciprocity operating across time. Actions and impacts do not always manifest immediately, but unfold according to their own temporal logic, with consequences emerging sometimes long after initial disturbances have passed. This understanding emphasizes the need for long-term monitoring and precautionary management that accounts for lagged ecological responses.

4.3.3. Social Dynamics and Collective Buffering

Separation into individual housing created a fundamental change in the social environment, allowing clearer interpretation of direct sediment effects independent of communal stress dynamics (Ripanga 5, 6). While isolation improved overall survival by reducing cannibalism and competition for food and refuge (James et al., 2002), it also eliminated potential benefits of collective behaviour (MacDiarmid et al., 2013; Olsson & Nyström, 2008; Kittaka et al., 2005).

The housing effect on body condition (Ripanga 6) indicated that sediment-exposed kōura showed significantly higher BW:CL ratios during communal housing compared to isolated conditions, with values declining upon separation. This pattern suggests that social aggregation may have provided some buffering against sediment stress, perhaps through reduced energetic costs of vigilance or enhanced water circulation and particle clearance within buckets. While Thomas et al. (2003) demonstrated that social context strongly influences feeding behaviour and competition in juvenile *J. edwardsii*, whether group living provides protective benefits under sediment stress specifically remains unexplored.

From a Te Ao Māori perspective, this mirrors the consequences of whanaungatanga disruption, where individuals separated from whānau or community networks lose access to shared knowledge, support, and resources. Contemporary analogues include Māori communities impacted by Cyclone Gabrielle, where isolation due to infrastructure damage and displacement fractured networks precisely when collective resilience was most needed (Te Puni Kōkiri, 2023; Te Puni Kōkiri, 2024). Similarly, the fragmentation of traditional mahinga kai stewardship under colonial policies disrupted systems that once provided buffering and stability (McCarthy et al., 2014; Ruru, et al., 2022).

4.3.4. Variability as an Early Warning Signal

Within-bucket variability in body condition, measured as coefficient of variation in BW:CL ratios (Ripanga 8), increased significantly through time, rising from 18.5-20.5% on Day 1 to

43.7-64.8% by Day 19. The dramatic spike in Tobserved variability at Day 7 (CV% ≈ 70.4 ± 41.0%) preceded the elevated mortality observed in this treatment during the communal phase. This increased within-group heterogeneity may serve as an early indicator of population-level stress, with diverging body conditions reflecting differential vulnerability to sediment exposure or emerging competitive hierarchies. In this study, the subsequent Day 19 spike in mean BW:CL coincided with selective mortality of smaller individuals, with the sole survivor from Bucket 7 being notably larger than individuals from other buckets, indicating the spike reflected selective survival of dominant individuals rather than population-wide condition improvement or physiological bloating. When variability increases dramatically, it may signal that stress has exceeded the population's adaptive capacity, resulting in divergent fates for individuals within the same cohort based on size-dependent vulnerability (Villacorta-Rath et al., 2022).

From a Te Ao Māori perspective, this reflects tikanga principles of balance and reciprocity: the resilience of the collective relies on the contribution and wellbeing of each individual, emphasising the importance of supporting the most vulnerable members to sustain ecosystem function.

4.4. Final Condition: Cumulative Deficits and Irreversible Damage

4.4.1. Final Condition

The 52-day experimental trajectory demonstrated a complex interplay of physiological stress, social dynamics, and cumulative impact. Body condition patterns remained relatively stable during individual exposure phases, yet by Day 52, clear treatment effects had emerged in final body condition (Ripanga 3), mortality rates (Whakaahua 15), and gill structural integrity (Ripanga 10; Whakaahua 17, 18, 19). This pattern indicates that cumulative stress manifests not through acute growth suppression during each exposure event, but through progressive deterioration that becomes evident only when viewed across the complete experimental timeline.

4.4.2. Physiological Deterioration Despite Equivalent Reserves

By the experiments conclusion, kōura subjected to repeated sediment pulses exhibited significant reductions in final body condition (Ripanga 3), with Controls maintaining significantly better BW:CL ratios than Tmaximised individuals.

Body condition trajectories from Day 22 to Day 52 showed gradual improvement across all treatments (Whakaahua 12; Ripanga 4). However, the Controls maintained consistently higher BW:CL ratios than sediment-exposed groups throughout the individual housing phase. The elevated BW:CL values observed at Day 19 likely reflect survivor bias, as mortality during Days 13-19 was concentrated among smaller, post-moult vulnerable individuals, artificially inflating mean body condition values for the remaining population. From Day 22 onwards, trajectories stabilised and showed steady upward trends. Despite this improvement across all treatments, sediment-exposed individuals did not recover to the Control levels by Day 52, suggesting persistent effects of early sediment exposure on body condition that persisted even after sediment removal and improved housing conditions.

Blood Refractive Index (BRI) measurements (Ripanga 9) showed no significant treatment differences, with all groups maintaining similar haemolymph protein/lipid reserves at Day 52. This consistency in BRI, coupled with the observed increases in BW:CL ratios from Day 22 onwards, indicates that surviving kōura across all treatments experienced normal somatic growth while maintaining stable physiological reserves. However, these measurements reflect only the survivors from each treatment group. Individuals that succumbed to mortality during earlier phases – particularly during the communal phase when smaller, post-moult vulnerable individuals were lost – were necessarily excluded from endpoint physiological assessments. This “survivor bias” means that Day 52 measurements represent the most resilient individuals rather than the full range of physiological responses to sediment exposure, potentially masking treatment effects that manifested as differential mortality rather than sublethal physiological impairment in survivors (Hendrick et al., 2016; Park et al., 2025).

Although BRI values were narrowly ranged (1.344–1.345), these measurements were consistent with baseline values, suggesting that survivors were operating near the limits of viable function. Sediment-induced depletion of physiological reserves amplifies vulnerability to concurrent stressors, as individuals have less capacity to mobilise energy for growth, immune responses, wound repair, or stress mitigation (Ozbay & Riley, 2002; Day et al., 2022). This mirrors patterns observed in human communities facing successive disasters, where accumulated trauma and resource depletion compromise resilience to subsequent shocks (Rout, 2021; Te Puni Kōkiri, 2023).

4.4.3. Gill Damage: Physical Evidence of Irreversible Harm

The most unequivocal evidence of sediment impact came from gill analysis, which indicated severe, progressive structural damage across all quantitative and qualitative metrics (Ripanga 10; Whakaahua 15, 16, 17). Gills in the Controls maintained pristine condition with no visible particle accumulation, intact filament structure, and minimal pigmentation (Whakaahua 17). In contrast, sediment-exposed gills showed extensive particle lodgement, severe filament erosion and fraying, and widespread discolouration indicative of tissue degradation (Whakaahua 18, 19).

Critically, these structural abnormalities persisted despite kōura having undergone two complete clean-water recovery phases prior to final sampling. Particles remained lodged within gill lamellae, filament tips showed irreversible erosion, and tissue discolouration indicated permanent damage rather than temporary stress responses. The categorical assessment indicated that 100% of Tmaximised survivors exhibited structural deformities, compared to 0% of Controls – a complete separation that establishes an unambiguous causal relationship between sediment exposure and gill destruction.

The dose-dependent response observed across metrics (Ripanga 10) demonstrates that both Tobserved and Tmaximised concentrations exceeded protective thresholds for gill tissue integrity. Surface discolouration, in particular, showed a clear gradient with Tmaximised significantly worse than Tobserved, indicating that impacts intensify with increasing sediment load.

The gills of crustaceans serve multiple critical functions beyond respiration: they are primary sites of osmoregulation, acid-base balance, nitrogenous waste excretion, and ionic regulation (Dickson et al., 1991). Damage to gill structure therefore affects not only oxygen uptake but the entire suite of physiological processes that maintain homeostasis. Fine sediment particles become lodged within gill lamellae, physically obstructing water flow and gas exchange, while simultaneously triggering inflammatory responses and tissue damage through abrasion and irritation (Rosewarne et al., 2013; Martin et al., 2000).

The sensitivity of spiny lobster gills to suspended sediment has been documented across multiple *Jasus* species and environmental contexts. Maletzky (2007) found that *J. lalandii* exposed to turbidity, oxygen deficiency, and hydrogen sulphide (conditions associated with diamond dredge-mining in Namibia) exhibited significant respiratory stress and behavioural changes, with suspended sediment effects being particularly pronounced at concentrations comparable to those used in the present study. Previous acute exposure studies on kōura have documented similar patterns of gill deterioration, with sediment concentration-dependent increases in filament damage, melanisation (immune response), and structural collapse (Rosewarne et al., 2013).

Crustaceans can actively shed and eliminate trapped particles through specialised gill-cleaning mechanisms (Martin et al., 2000), but these processes are energetically expensive and become overwhelmed under high or prolonged sediment exposure. The persistence of damage weeks after final sediment exposure indicates that gill regeneration capacity was insufficient to repair accumulated structural degradation within the experimental timeframe.

From a cultural perspective, this gill damage represents suffocation or loss of breath, the hā of the ecosystem being constrained. In Te Ao Māori, hā represents the breath of life, the vital force that animates living beings and flows through natural systems. When kōura cannot breathe freely, when their gills are clogged with sediment and their respiratory capacity is compromised, they lose hā, they lose the ability to fully participate in life's processes. This is not merely physical impairment but a spiritual diminishment, a reduction in the fullness of being that connects organism to environment.

4.4.4. Moult Inhibition and Disrupted Life Cycles

At Day 52, the vast majority of surviving kōura remained arrested in intermoult stage (84.1%; Whakaahua 15), with only a small proportion showing early moult progression, all from the Controls. While the Fisher's Exact Test indicated no significant association between treatment and moult stage distribution, the complete absence of pre-moult individuals in sediment-exposed treatments suggests physiological suppression of moulting processes. However, because moult stage was not deliberately balanced across treatments at the start of the experiment, these differences may reflect initial variation in moulting status compounded by cannibalism risk and selective mortality of moulting individuals rather than a direct treatment effect (Thomas et al., 2003).

Moulting represents a critical opportunity for crustaceans to repair damaged tissues, shed accumulated epibionts, regenerate lost appendages, and increase in size. However, the moult cycle is energetically expensive and physiologically demanding, requiring substantial mobilisation of calcium, protein, and other resources (Legrand et al., 2021). Under stressful conditions – including sediment exposure, reduced food availability, or social stress – crustaceans often delay or suppress moulting, presumably as an adaptive response that conserves energy until conditions improve (Legrand et al., 2021; Chiswell & Booth, 2008).

However, prolonged moult suppression creates its own problems: damaged gills cannot be repaired through normal tissue turnover, growth is halted, reproductive development is delayed, and accumulated damage progresses. For kōura experiencing severe gill deterioration from sediment exposure (Whakaahua 18, 19), the inability to progress beyond intermoult stage and regenerate healthy gill tissue likely contributed to the persistent physiological impairment and elevated delayed mortality observed in this study.

This disruption of moulting rhythms parallels the broader disruption of natural cycles observed in sediment-stressed ecosystems. In Te Ao Māori, the concept of Maramataka encompasses the lunar and seasonal cycles that govern ocean life – the patterns of tides, the movements of fish and kōura, the timing of spawning and settlement, the abundance and availability of mahinga kai throughout the year (Ruru et al., 2022). These cycles are not arbitrary, but represent the fundamental rhythms through which life organises itself in relation to celestial, oceanographic, and ecological processes. When sediment stress disrupts these rhythms – when moulting is delayed, when feeding patterns change, when migration and settlement are affected, when spawning success declines – the Maramataka becomes desynchronised. Life cycles that evolved over millennia to align with environmental cues become disconnected from the contexts that shaped them. This desynchronisation has cascading consequences: predators and prey fall out of temporal alignment, recruitment pulses no longer match periods of optimal food availability or habitat suitability, and the intricate web of relationships that sustains ecosystem function begins to unravel.

For kaitiaki, understanding these disrupted rhythms is essential for adaptive management. Traditional monitoring practices based on Maramataka – knowing when and where to harvest, recognising seasonal patterns of abundance, reading environmental signs – become less reliable when the underlying cycles are disrupted by chronic stressors like sedimentation. This does not render mātauranga Māori obsolete but rather underscores the need to integrate traditional knowledge with contemporary scientific understanding. Importantly, mātauranga Māori itself is not static – it continues to evolve as the world changes, new observations and understandings emerge, distinguishing it from more fixed notions of traditional ecological knowledge. This dynamic quality means that both mātauranga Māori and Western science can inform and enrich each other to develop management approaches that respond to changing conditions while working to restore natural rhythms.

4.5. Pathways of Influence and Cumulative Stress

The complete body condition trajectory (Whakaahua 12, 13, 14) reveals multiple interacting pathways through which sediment exposure influenced final outcomes. These pathways operated both directly through immediate physiological damage, and indirectly through behavioural alterations, social stress, and legacy effects that accumulated through time.

4.5.1. Direct Physiological Pathways

Cumulative sediment exposure inflicted direct respiratory damage to gill structures (Ripanga 10; Whakaahua 17, 18, 19), creating permanent structural abnormalities that persisted through recovery periods. This damage will have constrained gas exchange capacity, osmoregulation, and metabolic function, creating a foundation of physiological compromise that manifested as reduced growth (Ripanga 3, 4; Whakaahua 12, 13, 14) and increased vulnerability to subsequent stressors (Dickson et al., 1991; Martin et al., 2000; Rosewarne et al., 2013).

The “suppression” of moulting (Whakaahua 16) created a self-reinforcing negative feedback loop: sediment exposure disrupted normal physiological processes, physiological compromise blocked moulting initiation, and suppressed moulting prevented regeneration of sediment-damaged tissues. This feedback mechanism helps explain why gill damage remained severe and universal in sediment-exposed treatments despite extended recovery periods in clean water.

4.5.2. Indirect Social and Behavioural Pathways

The phase-specific mortality patterns (Whakaahua 15; Ripanga 7) demonstrate that social context fundamentally shaped how sediment stress manifested. During communal housing, Tobserved individuals experienced catastrophic mortality (51.9%) driven predominantly by social stress amplifying sublethal sediment effects. The early spike in BW:CL ratios within-bucket variability (Ripanga 8) preceded this mortality surge, suggesting that sediment exposure increased heterogeneity in individual condition, which in turn intensified competition, aggression, and cannibalistic interactions (Thomas et al., 2003; Hemsworth et al., 2007).

In contrast, Tmaximised losses were largely deferred, occurring after separation into individual housing (45.5% post-separation mortality), reflecting acute physiological trauma from higher sediment loads that manifested as delayed death during later exposure cycles. The reversal in mortality patterns between communal and individual housing phases (Ripanga 6, 7) confirms that sediment impacts cannot be understood in isolation from social and housing context.

4.5.3. Temporal Integration: From Pulse Events to Cumulative Decline in Body Condition

The overall body condition trajectory (Whakaahua 12) illustrates how individual exposure-recovery cycles integrated over time to produce cumulative deficits. The spike in BW:CL ratios during the separation transition (Days 19-22) was transient and likely reflected stress-mediated metabolic shifts rather than true growth. Subsequent convergence and increase through Days 30-52 confirm that sequential sediment pulses systematically degraded body condition, producing net losses in sediment-exposed treatments (Ripanga 4) while Controls remained stable.

The timing of delayed mortality, concentrated during Clean Phase 2 rather than during sediment exposures, reveals that cumulative impacts manifest not through acute toxicity but through progressive (chronic) depletion of physiological reserves that become lethal only when organisms can no longer compensate for accumulated damage (Wilber & Clarke, 2001; Kjelland et al., 2015).

This dual-pathway framework, where inherited disadvantage is amplified over time while direct damage continues to accumulate, aligns closely with Māori understandings of intergenerational environmental impacts and the enduring effects of historical trauma. The concept of take (foundation, cause, origin) encapsulates the idea that present conditions are rooted in past events, and that effective healing or restoration requires addressing those foundational causes rather than merely their contemporary symptoms.

4.5.4. Regional Context: Linking Experimental Findings to Te Tairāwhiti

These experimental pathways mirror real-world processes affecting kōura populations in Te Tairāwhiti. Historical depletion of adult populations through overfishing has reduced reproductive output and larval supply to coastal reefs (Breen et al., 2005). Habitat degradation caused by trawling, coastal development, and sedimentation has further diminished the availability of suitable settlement and nursery habitat for juveniles (Freeman et al., 2012). Disruptions to connectivity between offshore larval sources and inshore settlement areas – driven by oceanographic changes and habitat loss – have compounded these effects, reducing the likelihood that larvae successfully reach and colonise nearshore environments (Booth et al., 2000; Chiswell & Booth, 2008). Genetic bottlenecks and resulting loss of genetic diversity from historical overharvest have likely constrained the adaptive capacity of local populations to respond to ongoing environmental change (Thomas, 2012; Villacorta-Rath, et al., 2022). Cumulative land-use impacts have fundamentally altered catchment hydrology, sediment regimes, and nutrient dynamics throughout the region (Gisborne District Council, 2024; Morrison et al., 2023).

The Ūawa catchment exemplifies these cumulative pressures, with decades of exotic forestry plantations combined with highly erodible geology and frequent high-intensity rainfall producing some of the highest sediment yields in New Zealand (Gisborne District Council, 2024; Hicks et al., 2011; Vale et al., 2021). The legacy of Cyclone Bola (1988) continues to influence sediment mobilisation, while recent events like Cyclone Gabrielle (2023) have delivered further pulses that have smothered nearshore habitats and caused widespread benthic mortality (Allen et al., 2024; McSaveney, 2009; Leduc et al., 2024; Tait, 2024).

Evidence from other marine systems underscores the compounding nature of environmental change. In the Juan Fernández Archipelago, Vera-Duarte et al. (2025)

documented ecosystem shifts driven by overabundant long-spined sea urchins (*Centrostephanus sylviae*), altering benthic habitat and resource availability for *Jasus frontalis*. Although the proximate drivers differ – sediment stress in Te Tairāwhiti versus trophic alteration in Juan Fernández – both cases demonstrate that cumulative environmental pressures can push lobster populations beyond adaptive thresholds, with cascading consequences for recruitment, growth, and long-term population sustainability.

Together, these interlinked pathways operate synergistically, creating feedback loops and threshold effects that can transition ecosystems from degraded-but-functional states to full ecological collapse, from which recovery becomes increasingly difficult – or impossible – without deliberate, targeted intervention. Recognising these complex causal relationships is essential for prioritising management actions and directing resources toward addressing the root causes of decline rather than merely mitigating surface-level symptoms.

4.6. Implications for Fisheries Management and Restoration

4.6.1. Relevance to CRA 3 Fishery Sustainability

The CRA 3 (Gisborne) rock lobster fishery encompasses the coastal waters of Te Tairāwhiti and represents both an economically significant commercial fishery and a culturally vital customary resource. Stock assessments indicate that CRA 3 has experienced a decline in catch-per-unit-effort and growing concerns about recruitment strength over recent decades (Breen et al., 2005; Roberts & Webber, 2024).

The findings of this research demonstrate that environmental factors, particularly sediment stress on early life stages, may play an equally, if not a more, critical role in determining long-term population dynamics than harvest rates alone. The significant final body condition deficits (Ripanga 4), cumulative mortality exceeding 55% in sediment-exposed treatments (Whakaahua 15), and universal gill damage (Ripanga 10; Whakaahua 18, 19) all indicate severely reduced juvenile resilience with direct implications for recruitment.

If substantial proportions of settling puerulus and early juvenile kōura experience sediment exposure like that simulated in experimental treatments, conditions that are plausible given documented sediment loads in coastal waters surrounding Te Tairāwhiti (Gisborne District Council, 2024; Morrison et al., 2023), then recruitment to the adult population is likely to be impaired regardless of spawning stock biomass or larval supply (Booth et al., 2000; Linnane et al., 2013). This situation creates a recruitment bottleneck, where juvenile mortality constrains population growth even when adult abundance, larval production, and settlement rates appear favourable (Pederson & Johnson, 2006; Hobday & Flint, 2000).

Traditional fisheries management approaches focus primarily on regulating harvest through mechanisms such as catch limits, size restrictions, and spatial or temporal closures. Although these tools are essential to prevent overfishing, they are insufficient when environmental degradation undermines recruitment potential. This research highlights the necessity of integrating sediment regulation and habitat quality considerations into fisheries management frameworks, rather than treating them as external issues. Habitat integrity is as fundamental to stock sustainability as harvest control.

Achieving this integration requires institutional innovation, given that sediment management is driven largely by terrestrial land-use practices that fall outside the traditional jurisdiction of fisheries authorities. Effective management therefore depends on coordinated action across multiple levels of governance, including cross-agency collaboration that links Fisheries New Zealand with regional councils responsible for water quality and resource consents, central government agencies overseeing policy and funding, and local authorities engaged in land-use planning. It also requires catchment-to-coast management that explicitly connects land-use decisions to marine ecosystem outcomes using quantitative sediment budgets and ecological impact assessments (Gisborne District Council, 2024). Finally, co-governance structures that empower iwi and hapū as decision-makers are essential, reflecting the holistic view in Te Ao Māori that land and sea are inseparable systems.

4.6.2. Mātauranga Māori Contributions

The integration of mātauranga Māori into kōura research and management must progress beyond tokenistic consultation toward genuine partnership, in which cultural knowledge is recognised and valued as science rather than anecdote. Achieving this requires fundamental shifts in how research institutions, management agencies, and policy frameworks understand, engage with, and operationalise Māori knowledge systems.

Traditional monitoring and stewardship practices such as tau kōura and mātaitai are not relics of the past, but sophisticated management systems that have sustained kōura populations for generations (Kusabs, 2015). These practices embody principles of adaptive management, precaution, and long-term sustainability – concepts that Western science has only relatively recently begun to formalise (Hutchings et al., 2020; Jackson et al., 2017; Ruru et al., 2022).

The value of integrating local and traditional ecological knowledge with scientific data extends beyond New Zealand's coastal waters. In the Juan Fernández Archipelago, Eddy et al. (2010) successfully applied fishers' ecological knowledge to reconstruct historical lobster stock dynamics and project future trajectories, demonstrating that community-held knowledge provides temporal depth and contextual understanding that formal stock assessments often lack. This approach parallels the integration of mātauranga Māori into kōura management, where kaitiaki observations provide insights into environmental baselines, population trends, and ecological relationships that extend beyond the temporal scope of contemporary scientific monitoring.

Within this integrated framework, community-level kaitiaki networks play a crucial role. Kaitiaki possess deep, place-based knowledge accumulated over generations, encompassing changes in kōura abundance, distribution, and behaviour that are often overlooked in scientific surveys or fishery-dependent datasets (Williams et al., 2017; Wilson et al., 2007). Their observations of seasonality, habitat relationships, and signs of stress or disease provide a temporal depth and cultural context that complement scientific monitoring, offering insights into environmental baselines that pre-date contemporary data collection (Jackson et al., 2017; Phillips, 2015; Ruru et al., 2022).

The tau kōura system, for example, involves systematic observation and assessment of kōura populations, size structures, and habitat conditions using culturally defined indicators alongside quantitative metrics (Reid et al., 2013; Wilson et al., 2007). Likewise, mātaitai establish spatial management areas where iwi and hapū exercise authority over local fisheries, implementing harvest restrictions that often exceed statutory requirements in response to observed declines or to protect critical life stages and habitats (Jackson et al., 2017).

The success of these approaches is well documented. Mātaitai established in areas of kōura depletion have facilitated population recovery by combining harvest restrictions, habitat protection, and community-led stewardship (Jackson et al., 2017; McCarthy et al., 2014). Community-driven monitoring programmes have detected environmental changes and population declines years before they appeared in official datasets, enabling proactive responses and early intervention (Phillips, 2015; Williams et al., 2017; Wilson et al., 2007). These outcomes demonstrate the effectiveness of mātauranga Māori as both a monitoring framework and a management philosophy grounded in responsiveness, observation, and relational ethics.

Co-governance structures that genuinely share decision-making authority between Crown agencies and iwi or hapū provide the institutional foundation through which mātauranga Māori can be meaningfully integrated. The Waikato River co-governance model, Ngāi Tahu's statutory advisory role in South Island fisheries management, and the Hauraki Gulf Forum each offer examples of how shared authority can operate in practice, even as implementation remains contested and evolving (Hikuroa et al., 2025; Elmahdy et al., 2025).

In the context of CRA 3 and Te Tairāwhiti coastal management, co-governance should be understood as an iterative partnership that brings together mātauranga Māori and Western science at every stage of the management process. This involves the collaborative setting of research priorities, in which iwi and hapū define the questions, methodologies, and indicators of success rather than being consulted after research design has concluded. It also entails the shared interpretation of findings, ensuring that scientific data - such as the condition trajectories shown in Whakaahua 12, mortality patterns in Whakaahua 13, and gill damage illustrated in Whakaahua 15–17 - and mātauranga Māori observations are integrated to produce a holistic understanding. Co-designed management interventions further reflect this partnership, blending statutory tools such as catch limits and spatial closures with customary practices including rāhui, seasonal restrictions guided by Maramataka, and place-based protocols grounded in local observation and tikanga. Effective co-governance also depends on dedicated resourcing for kaitiaki-led monitoring, restoration projects, and capacity-building initiatives, rather than relying on unpaid volunteerism. Finally, accountability mechanisms are required to ensure that management agencies and industries act on iwi concerns and uphold Treaty obligations.

The rationale for this transformation is clear. Mātauranga Māori contributes unique information, interpretive depth, and management capacity that cannot be replicated through conventional scientific approaches alone. It offers long-term temporal perspectives, place-based knowledge, and holistic understanding of ecological relationships that integrate social, spiritual, and environmental dimensions. When meaningfully integrated, it strengthens the legitimacy, responsiveness, and effectiveness of marine management, ensuring that kōura stewardship reflects not only ecological realities but also cultural responsibilities and intergenerational values.

4.7. Lessons for Kaitiakitanga and Future Stewardship

Several key lessons emerge from this work. First, cumulative impacts matter more than individual events. The overall body condition trajectory (Whakaahua 12, 13, 14) demonstrated that kōura maintained function during individual exposure phases yet accumulated irreversible damage over time. Management frameworks that treat stressors in isolation or assess effects one project at a time fail to recognise the progressive deterioration that arises from repeated disturbances (Burton & Johnston, 2010; Hoegh-Guldberg & Bruno, 2010). From a kaitiaki perspective, cumulative effects assessment must account for the combined burden of all past, present, and foreseeable future pressures, acknowledging that even minor additional impacts can tip already stressed systems beyond recovery thresholds.

Second, recovery requires both time and intentional restoration. The persistence of gill damage (Ripanga 10; Whakaahua 18, 19) despite extended clean-water recovery periods demonstrates that simply ceasing harmful activities is rarely sufficient when ecosystems have already degraded below critical thresholds. Active interventions – such as replanting riparian margins, reconstructing habitat, augmenting depleted populations, and controlling invasive species – are often needed to rebuild mauri and re-establish functional ecological trajectories (Harmsworth & Awatere, 2013; Heron et al., 2025).

Third, early life stages represent critical vulnerabilities. The disproportionate impacts observed on juvenile kōura, with cumulative mortality exceeding 55% in sediment-exposed treatments (Whakaahua 15) and universal gill damage in survivors (Whakaahua 18, 19), highlight that protecting nursery habitats and the timing of recruitment is essential for long-term sustainability (Booth et al., 2000; Kittaka et al., 2005). Traditional practices such as seasonal harvest restrictions guided by Maramataka reflect ancestral understanding of these ecological dynamics and provide culturally grounded frameworks for protection during sensitive life history phases (Ruru et al., 2022).

Fourth, resilience emerges from relationships. The combined effects of sediment stress and social stress observed during communal housing (Ripanga 6, 7, 8), and the housing effect on body condition (Ripanga 6), underscore that resilience arises from relationships – among organisms, within communities, and between people and place – rather than from individual robustness alone (Hemsworth et al., 2007; Thomas et al., 2003). Strengthening whanaungatanga, both within ecosystems and human collectives, enhances collective capacity to adapt to and recover from disturbance (Hutchings et al., 2020).

Finally, long-term, participatory monitoring is essential. The early warning signal provided by increased within-bucket variability (Ripanga 8) demonstrates that sustained ecological monitoring provides the evidence base for adaptive management, while participatory approaches that engage local communities generate not only valuable data but also enduring stewardship and accountability (Williams et al., 2017; Wilson et al., 2007).

4.7.1. Application to Te Ākau o Tokomaru

From this perspective, resilience encompasses both ecological recovery and the reweaving of relationships between people and place. When communities engage in kaitiakitanga – monitoring local reefs, restoring riparian vegetation, advocating for policy change, or practising customary harvest protocols – they simultaneously restore ecological function and revitalise cultural identity. The health of kōura populations thus becomes both an indicator and an outcome of this wider process of renewal.

For Te Ākau o Tokomaru specifically, the findings of this research reinforce the importance of addressing sediment sources in the Mangahauini and broader Ūawa catchment while supporting nearshore restoration initiatives such as artificial reef deployment, marine protected areas, and community-led monitoring programmes (Fuller, 2022; Gibb, 2008; Gisborne District Council, 2024; Skelton & Jeffs, 2021). These parallel efforts (reducing sediment inputs on land while enhancing habitat and rebuilding populations in the sea) create the preconditions for long-term ecological and cultural recovery.

Ultimately, the broader lesson is one of interconnection: the fate of kōura is inseparable from the fate of forests, rivers, and communities throughout Te Tairāwhiti. Sustainable fisheries cannot be achieved through harvest controls alone; they depend on integrated, landscape-scale stewardship that honours the whakapapa links that bind all life together – ki uta ki tai.

4.8. Limitations and Considerations

While this study provides valuable insights into sediment impacts on juvenile kōura, several important limitations must be acknowledged when interpreting the findings and applying them to wild populations or management contexts.

4.8.1. Experimental Simplifications

The controlled laboratory environment necessarily simplified the complex realities of natural ecosystems. In the wild, kōura inhabit structurally complex habitats with crevices, boulders, and macroalgae that may buffer or alter sediment exposure (MacDiarmid, 2025; Booth, 2002). Their diets are also far more diverse, comprising algae, small invertebrates, detritus, and carrion (Thomas, 2003), whereas the laboratory feeding regime was standardised. Moreover, natural populations experience predation pressure, oceanographic variability (such as currents, waves, and upwelling), and fluctuating environmental conditions including temperature and dissolved oxygen levels—all factors absent from the constant, static experimental conditions. These simplifications likely reduced experimental variability but may not fully represent the interactive stressors present in dynamic coastal environments.

4.8.2. Sample Size and Statistical Power

The experiment involved 81 individuals distributed among nine buckets (three per treatment). This limited within-bucket replication constrains the detection of subtle effects and individual variation in stress tolerance. While clear treatment effects emerged in final body condition (Ripanga 4), cumulative mortality (Whakaahua 15), and gill damage (Ripanga 10), some potentially important patterns –such as the apparent moult suppression in sediment-exposed treatments (Whakaahua 16) – lacked sufficient statistical power for definitive conclusions. Future research employing larger sample sizes could more precisely quantify dose-response relationships and identify variability among individuals.

4.8.3. Temporal Scope

The 52-day duration captured short-term juvenile responses in body condition (Whakaahua 12, 13, 14) but did not encompass full life-cycle processes. It remains uncertain whether sediment-stressed juveniles experience long-term disadvantages such as reduced growth to legal size, impaired reproductive capacity, or shortened lifespan. Longitudinal studies following cohorts across multiple life stages would clarify these potential carry-over effects and determine whether the cumulative deficits observed at Day 52 (Ripanga 3, 4) persist or intensify over longer timeframes.

4.8.4. Sediment Properties

Although sediments were sourced from the Mangahauini river mouth and characterised for particle size, they may differ from those encountered elsewhere in the CRA 3 region in terms of mineralogy, organic content, or contaminant load. Sediments derived from forestry catchments, for example, can include wood fibres, bark fragments, or chemical residues that alter their toxicity relative to natural terrigenous material (Fuller, 2022). The observed gill damage (Whakaahua 17, 18, 19) and mortality patterns (Whakaahua 15) are specific to the sediment properties tested and may not be directly transferable to all sediment types or sources.

4.8.5. Population-Level Extrapolation

This study assessed individual-level responses – body condition (Whakaahua 12, 13, 14; Ripanga 3, 4), survival (Whakaahua 15; Ripanga 6), and physiological condition (Ripanga 9-10; Whakaahua 17, 18, 19) – under controlled exposure. Understanding population implications requires additional information about the spatial and temporal extent of sediment exposure in recruitment habitats, the proportion of these habitats affected during critical settlement and nursery periods, the degree to which density-dependent or compensatory processes might mitigate individual losses, and connectivity patterns, including larval dispersal and source-sink relationships that determine whether localised impacts scale up to affect regional populations.

4.8.6. Cultural Integration

Finally, while this study endeavoured to integrate mātauranga Māori perspectives, it remains grounded predominantly in Western scientific frameworks. A fully kaupapa Māori approach would involve iwi and hapū participation from the project's conception, employ mātauranga-based methodologies alongside conventional techniques, and prioritise outcomes defined by local communities. This research represents a step toward such integration but acknowledges its limitations in fully realising those principles.

4.8.7. Implications of Limitations

These considerations do not diminish the validity of the findings but situate them appropriately. The experiment's clear demonstration of dose-dependent physiological damage (Ripanga 10; Whakaahua 17, 18, 19), cumulative mortality (Whakaahua 15), and lasting deficits in final body condition (Ripanga 4) among sediment-exposed kōura provides compelling evidence of impact—evidence that warrants precautionary management, even as uncertainties remain regarding precise population-level consequences.

Whakakapi - Conclusion

"Matariki hunga nui" - Matariki, the gatherer of people. As the Matariki constellation rises in the winter sky, it signals a time of renewal, reflection, and collective action. The stars that gather in this celestial cluster remind us that resilience emerges not from isolation but from connection – from the relationships that bind whānau, communities, and ecosystems into functional wholes.

This research demonstrates that suspended sediment exposure creates severe, cumulative impacts on juvenile kōura, compromising body condition (BW:CL), survival, physiological condition, and respiratory function. The significant treatment effects on final body condition (Ripanga 4), cumulative mortality reaching 55-59% in sediment-exposed treatments (Whakaahua 15), and complete gill damage in 100% of Tmaximised survivors (Ripanga 10; Whakaahua 19) provide unequivocal evidence that fine sediment poses a fundamental threat to kōura recruitment and population sustainability.

These impacts are not merely ecological statistics but represent the breaking of whakapapa links – the disruption of relationships between kōura and their reef habitats, between juvenile and adult life stages, between coastal populations and the offshore larval sources that supply them. The body condition trajectory (Whakaahua 12, 13) indicated that impacts manifest through multiple pathways: direct physiological damage to gill structures, indirect effects through social stress dynamics, and temporal integration of repeated exposures that produce cumulative deficits even when individual events appear survivable.

For Te Ākau o Tokomaru and the CRA 3 fishery specifically, these results underscore the urgency of integrated catchment-to-coast management that addresses sediment generation at its source while simultaneously supporting restoration of degraded coastal habitats. Conventional fisheries management tools – catch limits and spatial closures – are necessary but insufficient when environmental degradation impairs recruitment. Sediment regulation must become a core component of fishery sustainability, implemented through cross-sector collaboration and co-governance arrangements that empower kaitiaki as decision-makers.

The role of mātauranga Māori in this integrated approach is not supplementary but foundational. Traditional monitoring practices such as tau kōura, customary management tools including mātaitai and rāhui, and the relational ethics of kaitiakitanga provide both practical methods and philosophical frameworks for restoration. Understanding sediment stress on kōura is not merely ecological science but cultural duty, a responsibility to strengthen whakapapa connections and restore mauri to ecosystems diminished by decades of cumulative disturbance.

Like Matariki gathering the stars, effective stewardship requires gathering people – scientists and kaitiaki, agencies and iwi, landowners and fishermen – into collaborative networks capable of addressing complex, interconnected challenges. The fate of kōura is inseparable from the fate of forests that stabilise slopes, rivers that carry sediment, policies that govern land use, and communities who depend upon healthy mahinga kai. Restoring abundance requires reweaving these relationships through sustained, intentional action guided by both empirical evidence and ancestral wisdom.

As we look toward future aspirations for kōura, whenua, and moana, the lesson is clear: resilience emerges from connection, recovery requires collective action, and the path forward must honour the whakapapa links that bind all life together. Just as Matariki marks the time when the earth renews itself and communities gather to plant seeds for the coming year, so too must our efforts to restore degraded ecosystems be grounded in the understanding that healing requires patience, persistence, and the coming together of diverse knowledge systems in service of shared wellbeing.

This research offers evidence to support those efforts, demonstrating through clear experimental results that cumulative sediment stress creates persistent, severe impacts on kōura that threaten both ecological sustainability and cultural wellbeing. But evidence alone is insufficient. Action is required – informed by science, guided by mātauranga, empowered by co-governance, sustained by community commitment, and animated by the vision of healthy ecosystems supporting thriving communities.

E kore au e ngaro, he kākano i ruia mai i Rangiātea - I will never be lost, for I am a seed sown from Rangiātea. Like the ancestors who voyaged across vast oceans guided by stars, we too must navigate uncertain waters with courage, drawing strength from whakapapa connections and collective purpose. The kōura that settle on our reefs carry within them the whakapapa of millions of years of evolution and the promise of future generations yet to come. Our role as kaitiaki is to ensure that promise can be fulfilled, that the seeds of resilience sown today will flourish into abundance tomorrow.

Matariki hunga nui – Matariki gathers the people. May our collective efforts, guided by the wisdom of our tīpuna and informed by rigorous inquiry, restore the mauri of Te Moana-nui-a-Kiwa and ensure that kōura thrive for generations to come. The work of restoration is the work of reconnection, of healing relationships between land and sea, between people and place, between past and future. In this work, every contribution matters, every voice has value, and every action ripples outward to strengthen the whole. The rising of Matariki reminds us that even in the darkest, coldest time of year, the promise of renewal persists. The stars gather, the people gather, and together we plant the seeds of a more sustainable, equitable, and culturally vibrant future. For kōura, for whenua, for moana, and for all the communities whose wellbeing depends upon them – this is our work, our responsibility, and our privilege as kaitiaki of these precious taonga.

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