Scale mismatches limit the efficacy of customary management

A Preprint

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Abstract

1. Indigenous lands are some of the most biodiverse areas in the world, providing protection for many species and spillover benefits for wider communities. However, these areas face increasing threats. Indigenous communities face many challenges in protecting and managing these lands, particularly in the form of power imbalances and spatial, temporal, and functional-conceptual mismatches.
2. Here, we explore these issues in the context of a wild *tuna*|eel (predominantly *Anguilla australis*) fishery at *Te Waihora*|Lake Ellesmere in *Aotearoa*|New Zealand. This is the largest commercial eel fishery in New Zealand and is a key customary fishery for Ngāi Tahu (southern-most tribe in New Zealand) communities. To protect the customary fishery, a *Kōhanga*|Indigenous reserve area was established in 2005.
3. We combined *mātauranga* (traditional knowledge) from a Ngāi Tahu elder (a customary fisherman) with 16 months of sampling data to determine whether the Kōhanga currently supports a sufficient population of customary-sized eels. We then developed a matrix population model to simulate the population and size structure of eels inside and outside of the Kōhanga. Informed by the sampling data, we compared the potential of different management scenarios to improve customary-sized eel populations.
4. We find that the abundance of customary-sized eels (>1000g) has plummeted in recent years and customary fishing is no longer viable. The Kōhanga is too small to provide adequate protection, and the benefit it does provide is not fully realized by local Ngāi Tahu communities because eels move from the Kōhanga to the commercially fished part of the lake. Our simulations show that increasing the size of the Kōhanga would help grow the abundance of customary-sized eels, but ultimately growth rate is the most important factor limiting their populations. Improving growth rate would require catchment-scale restoration of water quality and the food chain in Te Waihora.
5. Overall, customary management of the eel population is severely limited by a mismatch between the scale of the customary protected area and the social-ecological processes driving eel populations. An effective solution will call for a recognition of the wide spatial and temporal scales relevant at Te Waihora and the core values, world views and aspirations of Ngāi Tahu and diverse stakeholder groups.

Keywords: Scale mismatch, spillover, traditional knowledge, matrix population model, short-fin eel, Anguilla australis, reserve

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1 Introduction

Indigenous lands are some of the most biodiverse in the world (Schuster et al., 2019; Garnett et al., 2018), often supporting ecological values equal to or greater than formally protected areas (Sze, Carrasco, et al., 2022; Walker et al., 2020; Fa et al., 2020). Indigenous management can mitigate deforestation (Sze, Carrasco, et al., 2022), protect habitat (Garnett et al., 2018; Fa et al., 2020), support critically endangered species (Estrada et al., 2022; Schuster et al., 2019; Sze, Childs, et al., 2024), and maintain natural and critical fire regimes (Hoffman et al., 2021). However, these lands face mounting pressures from resource extraction, land use intensification (Hanna et al., 2016; Leyton-Flor and Sangha, 2024; Singh and Ganguly, 2022; IPBES, 2019), and institutional barriers that limit Indigenous communities' ability to exercise effective stewardship (Herse et al., 2020; Lyver, Timoti, Bellingham, et al., 2024).

A key challenge in managing Indigenous lands is the mismatch between the ecological scales at which species and processes operate and the social or institutional scales at which Indigenous peoples can act (G. S. Cumming, D. H. M. Cumming, and Redman, 2006; Herse et al., 2020; Berkes, 2006). Global environmental change and colonisation, with its associated land tenure changes, legislative barriers, and fragmented governance, have reduced Indigenous communities' jurisdiction over ecosystems which they successfully managed for generations over larger spatial and temporal scales (Berkes, 2012; Herse et al., 2020; Connors, 2023; Berkes, 2006). Large-scale climatic, environmental, and/or anthropogenic factors can affect local populations of cultural keystone species (Humphries and Möller, 2017) and surrounding land use can overwhelm any form of local management (Tscharntke et al., 2012; Bataille, Malinen, and Lyver, 2023). Conversely, if the institutional scale at which resources are managed is too broad, critical local dynamics may be overlooked, or not responded to quickly enough (Herse et al., 2020).

Compounding the challenges of social-ecological mismatches, *functional-conceptual* mismatches can arise from differences or conflicts among user or cultural groups (Bataille, Malinen, and Lyver, 2023; Winkler, Dade, and Rieb, 2021) and may be caused by or exacerbate inequities (Ingalls, 2017). Indigenous peoples are often excluded from decision making because of the reluctance of governments to share power and because some consider their knowledge and customary management to be unsubstantiated and insufficient relative to western science (Herse et al., 2020), even though they have repeatedly demonstrated their ability to effectively manage their ecosystems (Gadgil, Berkes, and Folke, 1993; Sobrevila, 2008; Kendrick, 2013; Fernández-Llamazares et al., 2021). Evidence — both western science and traditional ecological knowledge — that traditional ecological knowledge and customary management are effective is often still ignored, to the detriment of Indigenous peoples and their customary engagement with land and ecosystems (Lyver, Timoti, Bellingham, et al., 2024). To overcome these mismatches and effectively manage their lands and ecosystems, Indigenous peoples require full decision making capacity and jurisdiction over an area and time frame at an appropriate spatial, temporal, and functional scale.

Indigenous contributions to managing ecosystems have the potential to benefit all people, as biodiversity contributes to people's lives and livelihoods (Millenium Ecosystem Assessment, 2005; IPBES, 2019). Mobile species, such as eels, pollinators, and predators, move between habitats and jurisdictions, creating ecological spillovers that support neighbouring ecosystems (Kremen et al., 2007) but may be particularly vulnerable to scale mismatches (Berkes, 2006; Frost et al., 2015; Hackett et al., 2024). Spillover benefits are recognised in resource management — for example, spillover from marine protected areas (MPAs) can benefit surrounding fisheries (Di Lorenzo, Claudet, and Guidetti, 2016; Lynham and Villaseñor-Derbez, 2024). This kind of movement can create source-sink dynamics, where high-quality "source" areas support populations in lower-quality "sinks" (Gonzalez and Holt, 2002; Hansen, 2011). While this can stabilize sink populations (Kremen et al., 2007), excessive pressure in the sink habitat—such as habitat loss or overexploitation—may degrade both sink and source populations (Hansen, 2011). As providers of critical habitat, Indigenous lands can act as source habitat for species that roam to benefit surrounding areas, and can support services such as carbon sequestration where benefits are felt globally. However, despite the substantial spillover benefits generated by Indigenous lands (Boillat, Ceddia, and Bottazzi, 2022), they are vulnerable to external pressures beyond Indigenous jurisdiction, creating scale mismatches that threaten both local stewardship and the broader subsidies these lands provide.

Here, we explore the issues of scale mismatch and spillover in the context of a key eel fishery in Te Waihora|Lake Ellesmere in *Te Wai Pounamu*|the South Island of *Aotearoa*|New Zealand. Te Waihora was a significant *mahinga kai*|food gathering location for Ngāi Tahu (the Indigenous tribe that occupies the majority of the South Island) and is the largest commercial eel fishery in New Zealand. However, the population of large eels, suitable for customary harvest, has plummeted to the point that customary fishing practices cannot be maintained. To try and protect these populations, approximately 1/8 of the lake was set aside as a Kōhanga (fish nursery) in 2005, where only customary and recreational fishing could occur, of which eels are a key component. Other pressures on the lake, including upstream nutrient runoff and water extraction, also impact eel populations, but are outside the jurisdiction of *tangata tiaki*|local guardians, leading to scale mismatches in management.

Here, we ask whether a customary protected area - the *Horomaka Kōhanga* - is effective and at what scale. Through a collaboration between scientists and tangata tiaki, we test whether the Kōhanga is effective at increasing the size and abundance of *tuna*|eels, a key mahinga kai species, and the spatial scale over which this impact occurs. We ask whether the Kōhanga is large enough to sustain a sufficient population of customary-sized eels for harvest by Ngāi Tahu people. Specifically, we combine two seasons of fishing data across the boundary of the Kōhanga with a population model to understand how eel densities respond to the Kōhanga and its surroundings, and the extent to which the scale of the Kōhanga can compensate for drivers of fishery decline.

Figure 1: Location and size of the Horomaka Kōhanga in *Te Waihora*|Lake Ellesmere. Inset shows the location of the lake (red rectangle) in *Aotearoa*|New Zealand.

2 Methods

2.1 Background

For this research, we partnered with *Te Rūnanga o Ngāi Tahu*, (the authority for the southern-most Indigenous tribe in New Zealand), whose traditional territory covers 80% of the South Island and comprises over 84,969 members (StatsNZ 2023). The Ngāi Tahu Advisory Committee (NTAC; eight men, four women), in conjunction with the customary practitioners among our coauthors, together directed and co-designed the study with researchers.

2.2 Study location

Te Waihora is a shallow, brackish coastal lake on the east coast of the South Island (Fig. 1), which periodically opens to the sea. The area of the lake is approximately 20,000ha, although it varies between 16,000ha to 27,000ha depending on water level (*Te Waihora Joint Management Plan = Mahere Tukutahi o Te Waihora* 2005). Historically, Te Waihora periodically opened naturally to the sea when lake levels were high enough, but the lake is now opened manually a few times a year to control lake levels and allow the passage of fish. It held abundant populations of important *mahinga kai*|customary harvest species such as *tuna*|eels (primarily short-fin eel, *Anguilla australis*, with long-fin eels, *Anguilla dieffenbachia* occurring in lower densities in the lake and tributaries), *āua*|yellow-eyed mullet (*Aldrichetta forsteri*) and *pātiki*|flounder (*Rhombosolea* sp.), in addition to important waterfowl such as *kakīānau*|black swans (*Cygnus atratus*). However, fishing pressures, nutrient run-off and water extraction for upstream agriculture, and natural disasters have led to dramatic habitat changes; converting from a macrophyte dominated habitat that provided extensive cover for eels and their food resources, to turbid waters with very few macrophytes (Kelly and D. J. Jellyman, 2007). This change was precipitated by the "Wahine Storm" of 1968 which largely removed the macrophyte beds and caused a regime shift from clear, macrophyte-dominated waters to turbid, algal-dominated waters (Kelly and D. J. Jellyman, 2007). Additionally, the lake height is maintained at a low level favourable to surrounding farmland. Despite these issues being noticed as early as the 1950s, decades of delays in protective and regulatory legislation and increased agricultural intensification across the catchment has led to a system that has been deemed as too costly to restore to previous water quality levels (Jenkins, 2023).

Creation of a small non-commercial fishing area exclusively for customary fishing in Te Waihora initially occurred in an area adjacent to Taumutu and Te Pa o te Moki at the western end of the lake around 1970. This was to protect the lake opening and the short-fin eels migrating out of the lake through the opening from commercial fishing. However, the area agreed was too small to protect eel stocks, so extensions to the Kōhanga were proposed between 2003-04. This proposal was held back by the commercial fishers on the lake. Ownership of the Te Waihora lake bed (but not the water) was returned to Ngāi Tahu as part of the Treaty of Waitangi claims process in 1998. Authorisation to designate an area (the Horomaka Kōhanga), at the eastern end of the lake for customary and recreational fishing was granted by the Te Waihora Management

Board in 2005. Of the total 20,000 ha area of the lake, 2,500 ha was set aside as a Kōhanga, where only customary and recreational fishing could occur, of which eels are a key component. Outside of the Horomaka Kōhanga, commercial fisheries still operate. The Kōhanga was a proactive move by Ngāi Tahu through the Joint Management Plan (*Te Waihora Joint Management Plan = Mahere Tukutahi o Te Waihora* 2005) to sustain the vitality of Ngāi Tahu culture by restoring their resource-centered relationships. However, the Kōhanga - the scale at which customary fishers can act to improve the fishery - leaves no jurisdiction over water quality or commercial fishing outside of the Kōhanga. Traditionally, *mātauranga*|traditional knowledge of Ngāi Tahu *hapū*|sub tribes and their *whānau*|families was applied at the catchment scale, if not wider. Customary fishers have felt that legislation has led to a loss of *tino rangitiratanga*|chiefly authority, which was guaranteed under Article 2 of the Treaty of Waitangi 1840, and that *tangata tiaki*|local guardians do not have the same status as the Crown around decision making (Bataille, Malinen, Yletyinen, et al., 2021).

2.3 Interviews

Data were gathered in seven face-to-face semi-structured interviews (39 to 157 minutes in length) conducted quarterly between January 2023 and October 2024 (by P.O'B.L) with Ngāi Tahu elder and customary fisher, Mr Donald Brown. We include Mr Brown as both an interviewee and an author in recognition of the value and contribution of his knowledge and his role in instigating, designing, and executing this study in conjunction with researchers. In this, we follow repeated calls and precedents to recognize traditional knowledge holders appropriately (M'sɨt No'kmaq et al., 2021; Cooke et al., 2021; Castleden, Morgan, and Neimanis, 2010; Sarna-Wojcicki et al., 2017).

Mr Brown was introduced to fishing on Te Waihora as a child in 1948, and has continued to regularly (once a fortnight) fish for short-fin eel, pātiki (flounder) and āua (mullet). Mr Brown commercially fished for pātiki and āua during his working life, and for short-fin eel on a customary basis. Interviews with Mr Brown were recorded in English at his fishing hut on the shores of Te Waihora. Audio files were transcribed, and the narrative aligned within different themes: (i) state of the eel fishery; (ii) eel size and condition; (iii) factors influencing the fisheries; and (iv) the perceived efficacy of the Horomaka Kōhanga. This study was conducted as per Manaaki Whenua Landcare Research's Human Ethics Permit (ref: *2223/11 – Te Weu o te Kaitiaki: The roots of the guardian*) with operating principles and guidelines agreed as part of Te Kāuru, the research programme's Cultural Safety Agreement.

2.4 Eel sampling

To determine whether the Kōhanga is effective at increasing the abundance of customary sized eels, we sampled eels at locations both inside and outside of the Kōhanga. Eel numbers and biomass were sampled at 16 sites situated at logarithmically increasing distances either side of the boundary of the Kōhanga. Sites were staggered perpendicular to this transect to minimize overlap in the area fished and avoid distance from the boundary being confounded by distance between sampling points. The logarithmic arrangement of sites was chosen to increase the resolution of data near the Kōhanga boundary so as to probe the strength of the relationship over this boundary. Sampling took place between January 2023 and April 2024. No sampling occurred during the winter months of May-September when eels are not active (D. J. Jellyman, Glova, and Todd, 1996). The remaining months were broken into six two-month sampling blocks; each site was sampled once during each sampling block, for a total of six times per site. Due to logistical reasons, a maximum of six sites could be sampled on the same day.

At each site, unbaited coarse-mesh fyke nets (12mm mesh, with a 6 meter leader and no escapement tubes) were set perpendicular to the shoreline. These fyke nets are used for customary purposes and have been developed and modified by Don and Les Brown over 40 years. The design has been modified to enhance capture with a low angle entry point, which is seamless to fish entry. Eel capture is highly dependent on lake depth (D. Brown pers. comm.; P. G. Jellyman, Crow, and Sinton 2017), so nets were always set at a depth of 700-850mm. Because the depth of the lake fluctuates substantially, the exact location of the net varied across sampling periods to accommodate the net depth requirement. Nets were set for a period of 24 hours, after which the catch was separated into size categories that were counted, weighed, and released. All sampling was carried out by customary fishers, Don and Les Brown (Ngāi Tahu) and Katherine Trought (researcher). In total they caught 9000 eels [3463kg].

At each sampling occasion and location, net depth, water temperature, lake height, and lake turbidity were recorded to be used as covariates in analyses. Wind speed, wind direction, and precipitation data were obtained from records taken at the Christchurch Aerodrome (meteostat.net). Moon illumination was calculated using the date of sampling and the function `lunar.illumination.mean()` from the R package `lunar` (Lazaridis, 2022).

To supplement the data specifically for large eels from the additional point sampling, we also sampled at eight locations within the Kōhanga and eight outside of the Kōhanga using fyke nets with a 40mm escape tube. Sampling occurred four times at each location between December 1st 2024 and 7 March 2025. The length and weight of each eel was measured.

2.5 Statistical analysis

We examined the relationship between the abundance of eels caught at locations across the lake and distance inside versus outside the Kōhanga.

We divided eel abundance data into four size classes: 200-400g, 400-800g, 800-1000g, and >1000g. We excluded eels below 200g because they can escape from the net, and migrators of any size, because they are actively swimming across the lake and are therefore not associated with a particular location. Migrators are readily distinguished by physical characteristics including head shape and belly colour (Williams et al., 2017). The independent variable was therefore the number of eels of a given size class caught per fyke net (N_S). We fit a generalized linear mixed model, using a negative binomial distribution to deal with the data being overdispersed relative to a Poisson distribution. We compared two approaches to measuring distance to determine whether a change in abundance was i) a consistent gradient across the lake or ii) had different slopes inside versus outside of the Kōhanga. In both cases we took the log of the distance (D) from the Kōhanga boundary, but then we i) multiplied the logged distances inside the Kōhanga by -1 to create a continuous measure of distance from -log(2000m) to log(6000m) (D_{lin}) or ii) included location (L) (inside versus outside the Kōhanga) as a binary variable with an interaction with distance. We compared the two measures of distance using AIC and found that the continuous measure of distance was the better fit. We also compared model fit for absolute values of distance versus logged values, and used AIC (Akaike information criterion) to choose logged distance as the better explanatory variable. This also fits better with the experimental sampling design, which sampled at distances on a log scale.

We added a random effect for net, because eels of multiple size classes were caught in each net. We included a temporal autoregressive function with an Ornstein–Uhlenbeck covariance structure to account for non-uniform time differences between samples. As independent variables, we used a categorical variable for size class (S) and its interaction with logged distance ($log(D)$). To account for seasonal and environmental variation, we included variables for lake temperature (T), lake height (H), lunar illumination (I), precipitation (P), wind direction (W_d), and wind speed (W_s). We also included the square of lake height (H^2) and the square of wind speed (W_s^2), because initial exploration of the data suggested that the relationships between lake height and wind speed and number of eels caught was quadratic. We began with a full model of $N \sim log(D) * S + T + H + H^2 + I + P + W_d + W_s + W_s^2 + (1|net)$ then used the `dredge()` function from the R package (Bartoń, 2024) to find the best model from among all possible subsets, based on minimising the AIC. We ran this model using the function `glmmTMB` with family = nbinom1, from the R package of the same name (Brooks et al., 2017).

For the large eel data, we used a Welch's t-test to compare (i) the number of eels caught per net and (ii) the weight of each eel caught inside versus outside of the Kōhanga.

2.6 Population model

To explore the efficacy of management interventions on customary-sized eel populations, we developed a matrix population model to estimate population sizes of eels both inside and outside of the Kōhanga. Our model was based on the discrete-time eel cohort model that was developed and parameterized for Te Waihora by Francis and D. J. Jellyman (1999) and further by Hoyle and D. J. Jellyman (2002). We made a number of changes; first we changed reproduction to be independent of the population within the lake, assuming constant recruitment each year. This is because reproduction is largely driven by factors outside of the lake such as ocean conditions. We converted the model to a matrix population model so we could track all size classes at once. This allowed us to model fishing as a fixed quota taken from the fishable part of the eel population (the vulnerable biomass) rather than a constant proportion of the population. This was important for us to explore scenarios where restricting fishing on some part of the eel population would increase fishing pressure on the remaining population. Finally, we modeled the Kōhanga and the rest of the lake as separate but connected populations. The recruiting population was split proportionally based on the area, not the population size of each area. At the end of each time step, a portion of the Kōhanga population moved from the Kōhanga to the outside population and vice versa to represent spillover across the Kōhanga border. This movement was driven by diffusion, meaning that net flow across the border went from the area of higher density at a given size class to the area of lower density, and when densities were equal, the net flow was zero. After this exchange of individuals, all individuals moved to the next size class in their location, a new population of recruits entered the smallest size class, and the cycle repeated. We modeled the population of female eels in 20 annual size classes starting with the minimum commercially harvestable size ($220g$). The size associated with each annual class depends on the growth rate. At each time step (representing one year), eels were removed from the population due to maturation, natural mortality, and fishing mortality.

We applied this model to four different scenarios, representing different management actions that could be taken. 1) Do nothing, or "Base-line", 2) Double the size of the Kōhanga (but with the same commercial quota outside the Kōhanga), 3) Decrease the commercial fishing quota by half, or 4) Impose a slot fishery where commercial fishers cannot take fish above the minimum customary harvestable size (1000g). To show the impact of growth rate, we applied these four scenarios across low (1.5cm/yr), medium (2.5cm/yr) and high (3.5cm/yr) growth rates that have been measured in Te Waihora over the past 30 years (Crow and P. G. Jellyman, 2017; P. G. Jellyman, Crow, and Sinton, 2017; Graynoth and D. J. Jellyman, 2002). Combinations of these scenarios and different thresholds for the slot fishery are shown in the supplementary results.

For scenarios 1, 2, and 4, the annual quota is set at 50 tonnes, and for scenario 3 at 25 tonnes. To meet this quota, an equal proportion of all commercially fishable size classes are fished until the quota is reached. In some cases, meeting the quota would require fishing up to 100% of the eel population. We set 90% as the point at which fishing effort was too high to be profitable and fishing ceased, meaning that fishers could not meet their quota. This means that the effective fishing pressure ranged from 7% per annum to 90% (Fig. 3b).

For further details on the model, see the supplementary material.

3 Results

3.1 Observed long-term changes in the short-fin eel population by a customary fisher in Te Waihora

In the 1950s and 1960s, a common method for Ngāi Tahu fishers to harvest short-fin eels in Te Waihora would be to spear, gaff, or 'patu' (to kill the eel with a blow to its head) the eels. As water turbidity permitted, two fishers could comfortably harvest 12-20 customary size eels in 2-3 hours from an area that was 5m x 3m using these fishing techniques. Nowadays, an individual would need to fish all night, cover a huge area, and might gaff one or two eels of customary size - if the water clarity ever permitted that - due to the near absence of eels at the historical customary size.

In the three decades following 1970, it was a common occurrence to catch 200-400 eels with each overnight fyke net set. From this catch, the fisher would take 12-20 customary size eels for personal use, releasing the bulk of the catch back into the lake. Prior to 1990, the elder reported that it was usual for about 25% of the eels caught to be $\geq$800g, with around 75% of the eels weighing between 600-800g, and then with some smaller eels. During the period between 1950-1970, a customary-sized eel was considered to be between 800-1100mm long, and $\geq$1800g. Since the early 1990s, the perception of what is considered to be a 'customary sized' eel has decreased from $\geq$1800g to $\geq$1000g.

In the 20 years following 2000, short-fin eel catches began to decline in the main lake, so customary fishing was increasingly concentrated in and around mouths of rivers flowing into Te Waihora. Good numbers of eels (100-200 eels per overnight fyke net set) could still be caught over this time. To avoid 'gorging' the nets and eel deaths, a 40-50mm internal diameter escapement tube was inserted into the net to allow smaller eels ($<$900g) to escape. Again, the fisher would generally harvest 12-20 customary-sized eels for personal use.

Since 2020, the elder reported that 99% of short-fin eels caught in fyke nets set overnight in the main lake were $<$650g, with $<$1% of eels caught being of customary size ($\geq$1000g) – in the majority of nights, eels of customary size were not caught. To increase the probability of catching a customary sized female short-fin eel, fyke nets were set in and around river mouths entering Te Waihora. However, after one night of fishing, a fisher was unlikely to catch another customary sized eel at that site if the net was set for a second or third night. Between January to May 2024, no short-fin eels were harvested for food by the elder because none were considered large enough to harvest. Out of thousands of eels netted, only a single 2.16kg female short-fin eel was caught (and released), while the remaining eels were $<$700g (most around 300-400g) which are considered too small for harvesting by the elder.

Observations of eel stocks over the last 2-3 years suggest the stock is healthy, free of disease, and abundant. Despite their small size, the eels were reported to be lively, boisterous, and of good colour (green dorsal surface with silver or bronze-tinted underbellies). It was believed, however, that the eels were lacking food, and therefore hungry. Observations by the elder of fat amounts in harvested eels indicated they were leaner than normal, and suggested a potential issue with the availability of their prey. He believed that there had been a collapse in the food chain at Te Waihora and the eels are hungry. Short-fin eels switch from eating invertebrates to eating cockabullies (Eleotridae spp.) and small fish when they are approximately 300-400mm in length. Prior to 1980s, abundant cockabullies and small fish (e.g. smelts) were caught in fyke nets at Te Waihora. Historically, customary fishers would remove and release two-thirds of a 10-litre bucket of cockabullies and small fish from the cod-ends of fyke nets after each overnight set. This would happen every net and every time. By 2020, no cockabullies were being caught in the fyke nets and only a few āua (yellow-eyed mullet) were caught by the lip in nets. Fishers noted that there is only the occasional cockabully in the stomachs of the eels, whereas in the past they would be full of cockabullies. For the elder, this pointed to deterioration of the food chain posing issues for the eels.

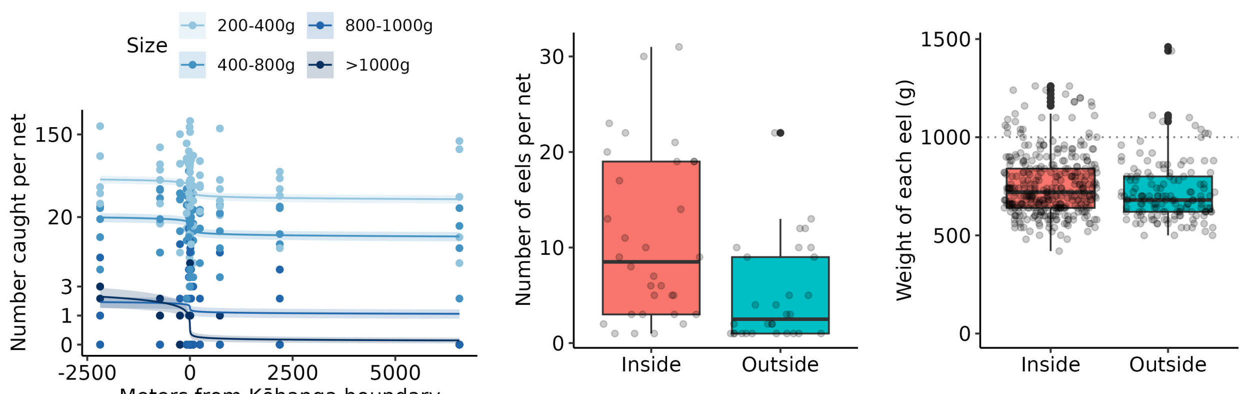
Abnormal predation behaviour of eels was also reported. The elder reported that over the last two years, eels had started heavily scavenging the pātiki and āua caught in set nets during spring, summer and autumn, which they historically would not do. Never in the elder's 70 years of fishing on Te Waihora had he observed the eels scavenging fish caught in nets to that extent. He reported that in the past you might experience some fin or tail damage to the fish from eel predation, but never every fish caught in the net eaten so only bones and skin remained. In 2024, the elder was required to retire two set nets because eels had tangled those nets so badly whilst scavenging the fish that they were ruined – this had never happened before. It was now difficult to leave a set net for patiki overnight without experiencing complete predation of caught fish by eels.

"*The eels are starving because they have started scavenging pātiki caught in a set net which they normally wouldn't do. Not to the extent they are doing now. It's a hundred times worse than normal. It's a significant change in eel behaviour. I'm sure its driven by the loss of their ability to source food elsewhere. The prey of the eel has gone*" (D. Brown pers. obs. 4 April 2024).

3.2 Elder perspectives on the efficacy of the Horomaka Kōhanga

Under the current conditions, the elder felt that the Kōhanga was too small and therefore unable to provide customary size eels for local needs.

The elder acknowledged in hindsight that the Kōhanga was not created large enough to protect a sufficient proportion of the eel stocks from commercial harvest. He recognises that the competition with commercial fishers and the current super-eutrophic state of the lake with its degraded food chain, has resulted in very few customary sized eels being available. The elder reports that stocks have deteriorated to a point that the catches of commercial fishers are also being affected. The challenge for the elder was how the lake could be restored, and a population of short-fin eels recovered enough to satisfy the tribe's customary need. The elder believed that the degradation of the customary eel fishery had already negatively impacted the culture and traditional knowledge system. He also recognised that he was one of the last Ngāi Tahu fishers who regularly fishes on Te Waihora, and that the historical customary economy was now taken over and dominated by non-Indigenous (*Pākeha*) commercial fishing interests.



(a) Number of eels by size

(b) Number of eels per net

(c) Weight of eels

Figure 2: Panel (a) Distance based sampling: Number of eels caught in each net, by size class (color), by distance from the Kōhanga boundary. The solid line shows the best model prediction for the mean abundance of eels per net at different distances from the Kōhanga boundary, calculated for the median environmental variables. Points are empirical data. The shaded region shows the standard error of the mean. Panels (b) and (c) additional point sampling of large eels using a 40mm escapement tube: b) Number of large eels caught per net and c) the weight of each larger eel. The dashed line in panel (c) shows the minimum customary size. A total of 26 customary sized eels were caught inside the Horomaka Kōhanga and 9 outside the Kōhanga during this sampling

"*Not being assigned commercial quota for short-fin eels by the government in the mid-1980s, because fishing did not make up 80% of my income, impacted me greatly. My commercial fishing rights financially supported my ability to engage in customary fishing. Commercial fishing paid for nets, petrol, and boats and allowed me to fish for my family. So I felt an immense loss of mana* [authority and prestige] *because I could no longer provide fish for my family or significant tribal events. Māori have been always prepared to share resources, but it seems every time we do that, we end up with nothing. Pākehā have taken our ability to fish off us. As a result, we have become strangers in our own land. It is now lonely out on the lake*" (D. Brown pers comm. 14 June 2023).

3.3 Influence of the customary protected area (Kōhanga) on eel abundance (field sampling results)

We observed higher abundances of eels within the Kōhanga across all size classes for the transect sampling (Fig. 2a). This was supported by the point sampling for larger eels, where there were more (t = 3.25, df = 51.037, p-value = 0.002) and heavier (t = 2.01, df = 260.94, p-value = 0.045) eels caught per net at locations inside than outside of the Kōhanga (Fig. 2b,c). In the transect data, the largest size class had a stronger decline across the border of the Kōhanga than other sizes. Model selection revealed that there were 10 models for the transect data within 2 AIC of each other. All of these included the following terms: lake height (H), lake height squared (H^2), temperature (T), eel size category (S), log of distance (D) and the interaction between the log of distance (D) and the largest size category (Table S1). Wind speed (W_s) was retained in 5 of the 10 best models, wind direction (W_d) and lunar illumination (I) were retained in four, the square of wind speed (W_s^2) in three, the interaction between distance and the third size class in two, and precipitation (P) in one.

3.4 Population model

Using the population model, we show the impact that spillover across the border of the Kōhanga can have (Fig. S5). We find that the strongest impact on population sizes is due to growth rate, and that a slow growth rate limits the effectiveness of other actions. Compared to a medium growth rate of 2.5cm/yr and the baseline scenario, an increase of the growth rate by 1cm/yr (increasing customary eel densities by 149% inside the Kōhanga and 347% outside) would be more effective than doubling the size of the Kōhanga (which increases customary populations by just 60% inside and decreases them by 66% outside).

For a given growth rate, halving the annual commercial quota has the biggest impact on the density of customary-sized eels both inside and outside of the Kōhanga. Doubling the size of the Kōhanga also increases the density of customary-sized eels inside the Kōhanga, however the fishing pressure on the remaining part of the lake at low and medium growth rates eventually reaches 90%, the point at which we capped commercial fishing and the commercial take cannot reach the quota. Imposing a slot fishery has very little benefit and ultimately results in a lower density of customary-sized eels than the baseline scenario, because stronger fishing pressure on smaller eels decreases the number of eels surviving to reach customary size (Fig. 3). At the lowest growth rate, a slot fishery has no impact whatsoever because no individuals make it to customary size outside the Kōhanga, so they cannot be fished in either scenario.

Note that all of these results are contingent on spillover from the Kōhanga to the rest of the lake. If the Kōhanga boundary was an impermeable barrier then all scenarios converge to the same density of customary-sized eels inside of the Kōhanga for a given growth rate (54.5 eels/km^2, 409 eels/km^2 and 627 eels/km^2 for low, medium and high growth rates respectively) (Fig. S5). This also demonstrates the importance of spillover from the Kōhanga for maintaining commercial fishing. Many more scenarios are unsustainable for commercial fishing (reaching a fishing pressure of 90%) if spillover is prevented (Fig. S6).

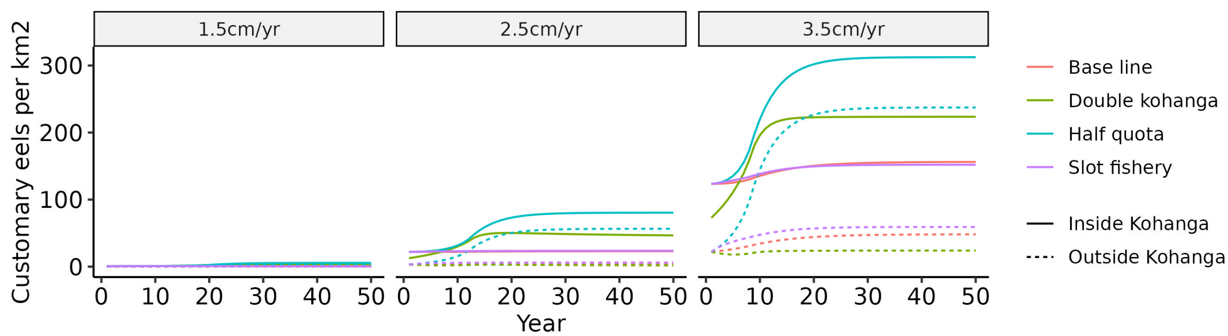
4 Discussion

Combining observations by a Ngāi Tahu elder and customary fisher, field sampling, and simulation models, we find that customary-sized eels have nearly disappeared from Te Waihora in recent years, and that the Kōhanga alone is insufficient to reverse this trend. Earlier reports suggested that eel populations, including large eels, were stable or improving in Te Waihora (Beentjes and Dunn, 2014; P. G. Jellyman, Crow, and Sinton, 2017; D. J. Jellyman, 2001), but the most recent of these reports is nearly a decade old and customary observations are that conditions have worsened noticeably since then. While our data are not directly comparable to the previous reports—due to differences in gear and sampling approaches used by customary fishers Don and Les Brown—our findings show a population increasingly skewed toward smaller individuals compared to the earlier reports (e.g. P. G. Jellyman, Crow, and Sinton, 2017). Combined with our simulation results, this suggests that recruitment is not the problem, but that either growth rate or survival have declined below the point where the current fishing pressure is sustainable.

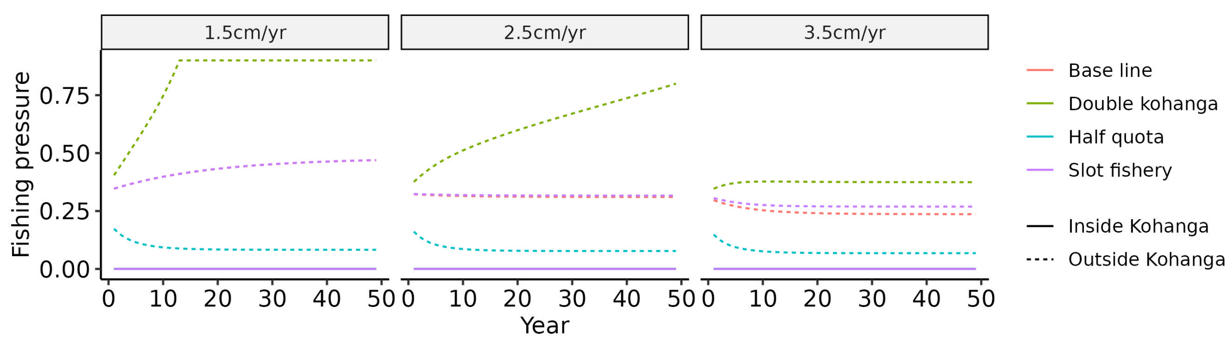
Although the government of New Zealand has legislative obligations to support Māori non-commercial fishing interests (*Fisheries Act* 1996; *Treaty of Waitangi (Fisheries Claims) Settlement Act* 1992), multiple barriers remain to restoring customary eel populations. Our model results suggest that reducing commercial harvest and/or expanding the Kōhanga would help increase customary-sized eel abundance. However, the effectiveness of these actions depends strongly on growth rate, which was the most influential driver in our simulations and is more difficult to manage directly.

Eel growth in Te Waihora is highly variable (6.3-93mm/yr for short-fin eels) and is strongly driven by food resources (D. J. Jellyman, 2001; Graynoth and D. J. Jellyman, 2002). Major shifts in the lake's ecology, including collapse of the macrophyte beds in the 1960s, led to changes in eel diets (Kelly and D. J. Jellyman, 2007). In particular, eels switched to piscivory at a smaller size due to a lack of invertebrate prey, which accelerated their growth (Ryan, 1986; Kelly and D. J. Jellyman, 2007; D. J. Jellyman, 2001). Common bullies (*Gobiomorphus cotidianus*), the predominant prey for piscivorous eels, recently comprised nearly 45% of the lake's fish biomass (Glova and Sagar, 2000; D. J. Jellyman, 2012). However, recent observations by the Indigenous elder D. Brown suggest that cockabullies are now largely absent, and that eels are displaying abnormal scavenging behaviour, causing unprecedented net and fish damage. These changes suggest a collapse in the food web, and our simulations show that low growth rates — driven by such food limitation — lead to very low densities of customary-sized eels, regardless of, but exacerbated by, fishing pressure. Continued decline will not only render customary fishing unviable but may also jeopardize the long-term sustainability of the commercial fishery.

Despite policy commitments to involve tangata tiaki in fisheries management, efforts to improve customary eel populations face significant spatial, temporal, and institutional mismatches (G. S. Cumming,



(a) Model predictions of eel density



(b) Model predictions of fishing pressure

Figure 3: Model predictions of customary sized eel density (number of eels per km^2) (panel a) and fishing pressure (panel b) across different scenarios (line colours) and growth rates (panels) both inside (solid line) and outside (dashed line) of the Kōhanga. Fishing pressure measures the proportion of the fishable eel population that is commercially harvested per year, and is the pressure that is required to meet the quota (50 tonnes per year, or 25 tonnes per year for the Half quota scenario). Fishing pressure within the Kōhanga is always zero. We capped fishing pressure at 90%, meaning that beyond this point the commercial harvest drops below the quota. We show model results for 50 years after a change is made from 32% fishing pressure and a Kōhanga of $25km^2$, which corresponds to the baseline scenario with medium growth rate.

D. H. M. Cumming, and Redman, 2006). The spatial scale of the Kōhanga does not align with the ecological needs of the eel population. While it offers some protection, eel abundance declines near its boundaries, particularly for the largest size classes. This suggests that spillover benefits to commercial fisheries are occurring, but at the expense of customary stocks within the Kōhanga. Our simulations confirm that spillover can lead to source-sink dynamics where customary protection inadvertently subsidizes commercial harvest (Fig. S5).

Further compounding this, eels are migratory and must pass through areas outside the Kōhanga to reach the sea, including zones of active commercial fishing. The lake is manually opened to the sea, and if the timing misaligns with migration cues, it can drastically impact spawning success and recruitment (Meijer et al., 2024; Graynoth and D. J. Jellyman, 2002). These life history traits expose eels the jurisdiction of multiple agencies and institutions at different life stages and locations—including the Department of Conservation, Ministry for Primary Industries, district councils, and *rūnanga*|tribal councils (Williams et al., 2017)—fragmenting knowledge, responsibility, and decision-making and creating institutional mismatches (Epstein et al., 2015; Maciejewski et al., 2015).

In addition to these structural mismatches, there are functional–conceptual mismatches arising from divergent worldviews, values, and governance priorities (Bataille, Malinen, Yletyinen, et al., 2021). While tangata tiaki hold constitutional rights to practice customary management, they are often treated as one of many stakeholders, and their rights and values are subordinate to the Crown's colonialist laws and views (Lyver, Timoti, Davis, et al., 2019). This power asymmetry means that short-term economic priorities often override both scientific and traditional knowledge, perpetuating delays and degradation of the lake (Jenkins, 2023). The burden of this degradation falls disproportionately on Ngāi Tahu, eroding food security, cultural identity, and intergenerational knowledge transfer (Bataille, Malinen, and Lyver, 2023).

Restoring and sustaining customary-sized eel populations will require customary management with power and influence well beyond the borders of the lake. There is a need to address and account for ecological flows and connectivity in management, not just for eels (Herse et al., 2020). An effective solution must recognize the wide spatial and temporal scales relevant at Te Waihora (Jenkins, 2023) and the core values, world views and aspirations of diverse stakeholder groups (Bataille, Malinen, and Lyver, 2023). The benefits of restoration would go far beyond eels. Greater eel abundance would support commercial and recreational users, while strengthening cultural practices linked to mahinga kai. For Ngāi Tahu, food gathering is not just subsistence, but a foundation for relationship-building, kinship, identity, and knowledge transfer (Bataille, Malinen, Yletyinen, et al., 2021). The loss of eels jeopardizes knowledge transfer to *rangitahi*|young people because "there is no point taking [them] out to be unsuccessful and demoralized" (D. Brown, pers. comm.). It also undermines community ties when there are no eels to share with community members (Bodwitch et al., 2022). Without management that aligns with social, ecological, and cultural scales, we risk cultural heritage and knowledge erosion, which may not be easily restored and may feed back to further prevent restoration of the lake ecosystem (Lyver, Timoti, Davis, et al., 2019).

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6 Conflict of interest

D. Brown and L. Brown are customary fishers on Te Waihora.

7 Author contributions

All authors contributed to the study design and development of methods. D. Brown, L. Brown, and K. Trought conducted all fieldwork. P.O'B. Lyver conducted and analysed the interviews with D. Brown, and co-ordinated the project and funding. N.J. Scott convening the Ngāi Tahu Advisory Committee and provided fisheries information for the model. K.L. Wootton led the statistical analysis and simulation modeling, with support from J. Tylianakis and A.M. Gormley. K.L. Wootton also led the writing of the manuscript, with contributions from P.O'B. Lyver, and all authors participated in reviewing and revising the manuscript. This study was a collaboration between Ngāi Tahu customary fishers of Te Waihora and scientists (all of whom are authors) and was conceived, designed, and executed together. We sought additional advice and guidance throughout the project from the Ngāi Tahu Advisory Committee which is made up of *mahinga kai*|traditional food gathering practitioners from around the South Island.