

**Evaluating the effects of invasive brown bullhead catfish
(*Ameiurus nebulosus*) on kōura (freshwater crayfish,
Paranephrops planifrons) in Lake Rotoiti**

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Laura Beverley Francis



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This thesis is dedicated to Margaret Francis,
Tracey Wemyss and Margaret McQuarrie whom
passed away peacefully during my studies. Gone
but never forgotten.

Abstract

Brown bullhead catfish (*Ameiurus nebulosus*) are opportunistic carnivores native to North America and were first detected in Te Weta Bay, Lake Rotoiti, in March 2016. A cordon was placed across the bay to try and contain catfish, but they had already established populations elsewhere. Spread of catfish in the lake raised concern for resident populations of freshwater crayfish or kōura (*Paranephrops planifrons*), which are of ecological and cultural significance to Māori. Given the limited knowledge of the potential impacts of catfish on native biota, this thesis aims to evaluate the effects of catfish on kōura in Lake Rotoiti. To do this, Bay of Plenty Regional Council (BOPRC) routine fyke netting data was used to explore species trends and relationships. A habitat survey was also conducted using whakaweku (bracken fern bundles) and fyke nets, to generate data on species' habitat preferences and kōura metrics (e.g., sizes and sex ratios). In addition to fishing, kōura and catfish stomachs were dissected to determine diet. Potential food items of catfish were also collected for stable isotope analysis to estimate dietary overlap between catfish and kōura, and long-term resource acquisition.

Routine BOPRC fyke netting results indicated that kōura catch per unit effort (CPUE) has declined in Lake Rotoiti, with mean catch rates dropping from 10.6 kōura net⁻¹ night⁻¹ in 2016 to 4.2 kōura net⁻¹ night⁻¹ in 2018. Over the same period, catfish CPUE has increased in the lake, with the highest catch rates in Te Weta Bay, where mean catch rates have increased from 1.1 catfish net⁻¹ night⁻¹ in 2016 to 63.7 catfish net⁻¹ night⁻¹ in 2018. Catfish catch rates were negatively associated with catch rates of kōura ($r = -0.180$). Mean catfish density also had a significant effect on kōura catch rates, with significantly more kōura being caught at sites without catfish. The negative association between catfish and kōura could be due to catfish eating or competing with kōura, or their differing habitat preferences. Catfish were positively associated with sites that are weedy or muddy and kōura were negatively associated with muddy habitats and were positively associated with rocky habitats. Whakaweku set at shallow depths <1 m in the lake littoral zone were ineffective at catching kōura during the habitat survey.

Catfish diet consisted largely of chironomid larvae (Chironomidae), detritus, common bullies (*Gobiomorphus cotidianus*), and to a lesser extent kōura. Kōura

were found in 12% of large catfish (>200 mm fork length; FL) stomachs analysed and contributed 5% volumetrically to large catfish diet. Unfortunately, the contribution of kōura to catfish diet could not be established using stable isotopes because isotopic signatures of kōura and bullies were too close to differentiate. Kōura diet consisted primarily of animal remains (common bullies and invertebrates) and detritus. Stable isotopes of carbon and nitrogen revealed that diets of kōura and catfish overlapped, with kōura sharing more of their diet with catfish than vice versa, likely reflecting catfish's broad diet. This study suggests that catfish are responsible for the recent decline in kōura CPUE in Lake Rotoiti and that catfish are directly and indirectly affecting kōura through predation and competition for shared food resources.

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1 Chapter 1

General introduction

1.1 Brown bullhead catfish

The brown bullhead catfish (*Ameiurus nebulosus*) is a member of the Ictaluridae family, which originated from the brackish and freshwaters of North America (McDowall 1990). The native range of brown bullhead is east of the Rocky Mountains in southern Canada to central USA, with populations further establishing in eastern Canada (McDowall 1990). After subsequent introductions beyond their native ranges primarily for use as a game fish and in aquiculture, catfish can now be found on several continents including Europe, Asia, Middle East, South America, and some Pacific Islands (Hawaii and New Zealand) (Global Invasive Species Database 2018).

The brown bullhead is the only species of catfish in New Zealand, which established after 140 individuals were introduced for unknown reasons to Saint John's Lake in Auckland in 1877 (McDowall 1990; Hicks et al. 2010). As fish numbers multiplied, individuals were transported to Wellington and then Hokitika in 1885 to establish further populations (Barnes and Hicks 2003). Successive illegal introductions (both accidental and intentional) and movement through river networks (e.g. Waikato River and its tributaries) have aided their dispersal throughout New Zealand, with populations occurring throughout the North Island including the Waikato River system and Lake Taupo, isolated areas in the South Island (Barnes and Hicks 2003), and more recently lakes Rotoiti (Grayling 2017) and Rotorua (G. Ewert, BOPRC, pers. comm.) in the Bay of Plenty region (Figure 1-1). Invasion risk modelling has indicated that lakes in the Waikato and Bay of Plenty regions, and isolated locations in the South Island are at the greatest risk (probability >0.60) of catfish invasion. Lakes that are most at risk of invasion are warm watered lakes, particularly lowland lakes (Leathwick et al. 2016).

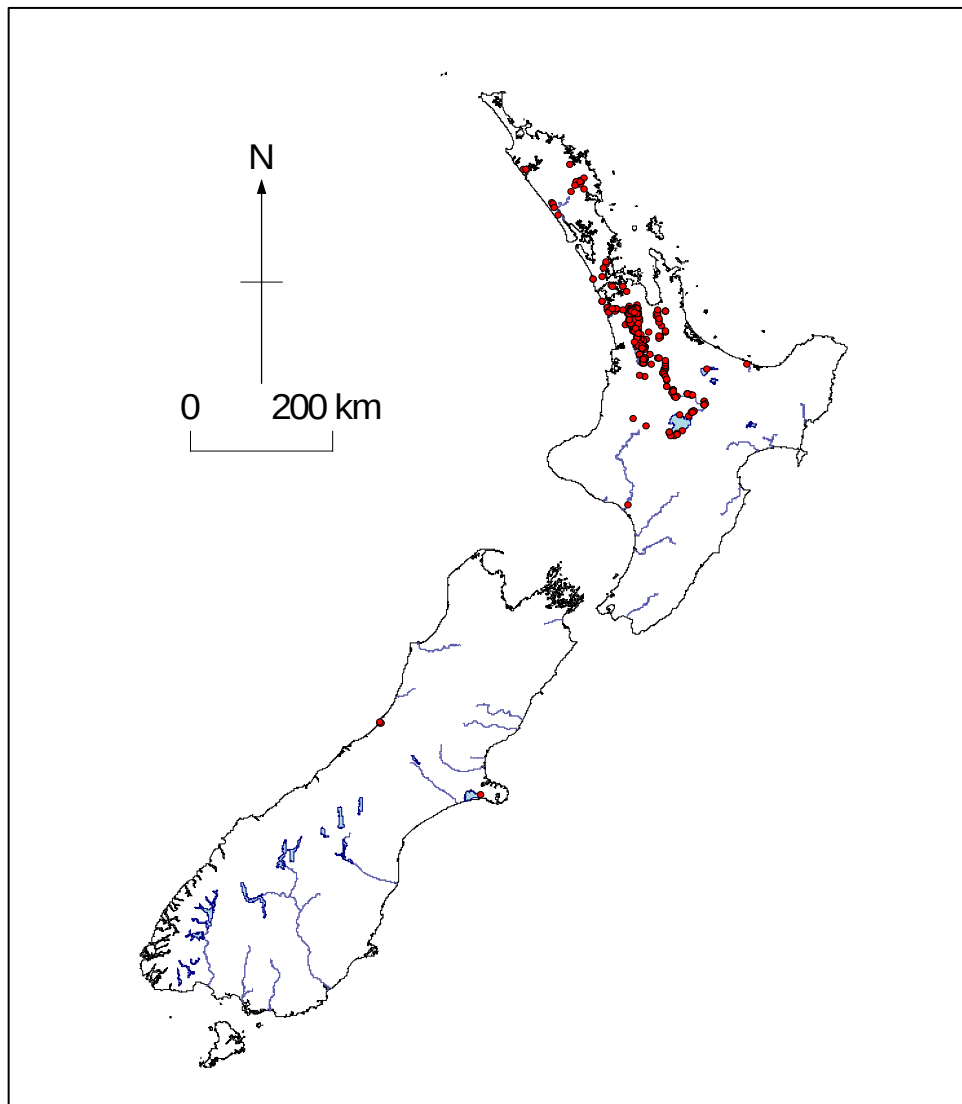


Figure 1-1. Distribution of the brown bullhead catfish in New Zealand, with the recent discovery catfish in the Bay of Plenty Region. Data points for catfish were obtained from the NZFFDB.

Catfish were confirmed present in Lake Rotoiti in March 2016 when a weed harvesting contactor observed two live catfish in Te Weta Bay and caught one. Two-weeks later, an incursion response began in Lake Rotoiti using fyke nets baited with sardines and mussels to capture catfish (Bay of Plenty Regional Council 2018a). In a one-year period (2016-17), 3,272 catfish were caught, with >98% of the catch being caught in Te Weta Bay (Grayling 2017). In an attempt to contain catfish in Te Weta Bay, a large net was used to cordon off the bay entrance in April 2017 (Figure 1-2). Catfish capture and removal using fyke netting continues at numerous sites around the lake, as well in neighbouring lakes to establish catfish presence. More recently, catfish were confirmed present in Lake Rotorua in December 2018 and were presumed to have entered via the Ohau Channel from

Lake Rotoiti. There is also potential for catfish to get into the Kaituna River and spread throughout its tributaries, but they have not been caught there to date.

Prior to catfish confirmation in Lake Rotoiti, the Bay of Plenty Regional Council (BOPRC) received numerous reports of catfish sightings. These included a live fish being presented to the Department of Conservation in 1993, after several juvenile catfish were observed falling out of a hollow-framed boat trailer in 1998 (Bay of Plenty Regional Council 2018a), a sighting of a presumed abandoned catfish nest on a sandy beach in 2003, and a body of a large 7-year old catfish washed up on the shores of Okawa Bay in January 2009 (Blair and Hicks 2009). Surveillance efforts following catfish sightings repeatedly failed to locate live catfish (Blair and Hicks 2009; Bay of Plenty Regional Council 2018a).



Figure 1-2. Catfish cordon installed in Te Weta Bay's entrance in April 2017 (photo: A. Pearson, University of Waikato.).

1.1.1 Effects of catfish

Globally, brown bullhead catfish have been reported to be having adverse unanticipated effects on native ecosystems (Froese and Pauly 2017) and have been associated with reductions in native biodiversity (Global Invasive Species Database 2018). Catfish have the ability to modify invertebrate communities, reduce water quality, and alter the internal nutrient status through excretion and the resuspension of sediments during feeding (Cline et al. 1994). For Lake Rotoiti, nutrient excretion by catfish has been estimated to contribute 0.6 to 11.7% of the internal phosphorus load and 2.3 to 28.9% to the internal nitrogen load (Hicks and Allan 2018).

Resuspension of bottom sediment increases nitrate and nitrogen concentrations in the water column, which can result in heightened lake productivity (Cline et al. 1994). Turbid waters caused by sediment resuspension can also lead to the collapse of submerged macrophytes in lakes, which can ultimately lead to algal dominance (van Vierssen and Prins 1985).

The flexible, carnivorous diets of catfish suggest there is likely dietary overlap between catfish and some native species, which can result in competition when catfish are at high densities (Barnes 1996). Catfish were found to have dietary overlap with eels in shallow Waikato lakes (Collier et al. 2018), and have been associated with negatively impacting eel populations and trout fisheries when at high densities (Hicks et al. 2010). Another way in which catfish can affect aquatic communities is through the direct consumption of native species (Scott and Crossman 1973; Barnes and Hicks 2003). By consuming native biota, catfish transform the movement of energy to the food chain creating novel food webs (Scott and Crossman 1973). Currently there is a lack of evidence on the environmental impacts caused by catfish (Global Invasive Species Database 2018).

1.1.2 Biology of the brown bullhead catfish

Catfish (Figure 1-3) are distinguished from other New Zealand fish by the presence of eight whisker-like barbels around the mouth along with their dorsal and pectoral fins, which have a strong, sharp spine (McDowall 1990). Catfish are thick-skinned fish with no scales and have a uniquely shaped broad, sloping, and dorso-ventrally flattened head (McDowall 1990). Adult catfish are dark brown to olive green in colour with lightly coloured sides. Smaller fish are typically similar in colour to adults, but can be a lighter green-gold colour (McDowall 1990).

Catfish occupy a vast range of habitats including lakes, rivers, constructed channels, and streams that are typically warm, sluggish, sandy, muddy, or weedy (Scott and Crossman 1973). In lakes, catfish prefer shallow depths spending most of their time in Lake Taupo at depths <10 m, often traveling to depths of between 0 and 17 m (Dedual 2002). They are also extremely tolerant and can survive for extended time periods out of water if their skin is kept moist (Collier and Grainger 2015). In their native range in America, catfish have been found to survive in low oxygen

conditions (>0.2 ppm) at temperatures of 36.1°C , with their critical temperature limits being between 0 and 38°C (Scott and Crossman 1973). They have also been reported to thrive in areas with contaminated sediments containing polycyclic hydrocarbons and heavy metals (Lesko et al. 1996). Catfish fecundity and size were all higher in the contaminated sites than in the control (Lesko et al. 1996). Increased fecundity in females was attributed to reduced competition for food resources and the lack of predators that were largely excluded from the degraded habitats. Catfish consumption by predators, including piscivorous fish, is restricted by their strong pectoral and dorsal spines, which can lock into an upright position upon attack (Scott and Crossman 1973).

Sexual maturity is typically reached in female catfish at ≥ 3 years when they are around 200-230 mm in length (Scott and Crossman 1973). Studies have reported female catfish having between 2,000-13,000 eggs in their ovaries (Scott and Crossman 1973), but Sinnott and Ringler (1987) found this number was lower with an average of 2,169 eggs (range 1,154-3,812 eggs). Fecundity is proportional to female size, with number of eggs per catfish increasing with increasing length (Sinnott and Ringler 1987). When it comes time to breed, male and female catfish form a pair bond and become territorial during the formation of the nest and laying of eggs (McDowall 1990). Spawning usually occurs in shallow depressions in muddy or sandy substrates averaging 48 cm depth (Blumer 1985) from September to December (McDowall 1990). Once the eggs are laid, males have the task of fanning and guarding the eggs, which is a crucial process as it takes approximately 6-9 days at 20.6 to 23.3°C for the eggs to hatch (Scott and Crossman 1973). Post-hatching of the eggs, male catfish and less so female catfish, continue to provide care for juvenile catfish for up to 19 days post-oviposition (Blumer 1985). This parental care for their young significantly increases the survival of their offspring (Blumer 1985). Full-grown catfish typically reach lengths of 200-300 mm, with some growing larger to around 500 mm in length and weighing up to 3 kg (Scott and Crossman 1973). There are reports of some catfish in New Zealand having reached lengths of 480 mm and weighing over 2 kg (McDowall 1990).

Catfish are nocturnal feeders that depend on their sense of smell and several taste sensors on their skin to locate food items in low water visibility (McDowall 1990). They can also track swimming prey using hydrodynamic and chemical signatures

left by fish in their wake, being able to judge the size and suitability of the prey items (Pohlmann et al. 2004). Although catfish are often referred to as opportunistic omnivores (Barnes and Hicks 2003), studies have found that catfish obtain more of their nutrition from animals than from detritus and algae (Collier et al. 2018); the latter thought to be inadvertently consumed during foraging for invertebrates and fish (Patchell 1977; Collier et al. 2018). Juvenile catfish have simpler diets than adults, comprising mostly cladocerans, amphipods, and chironomid larvae (McDowall 1990). Diets of small catfish (<150 mm fork length; FL) caught in Lake Taupo from weedy habitats contained mostly caddisfly larvae with smaller amounts of chironomids, cladocerans, and gastropods. Dragonfly larvae, fish, kōura, detritus, and plant material were absent from small catfish diet (Barnes and Hicks 2003). Diets of New Zealand adult catfish often consist of invertebrate larvae and molluscs (McDowall 1990), with lower quantities of kōura, worms, detritus, plant material, offal, fish, and fish eggs (Scott and Crossman 1973). In addition to catfish size, catfish diet can be dependent on habitat type (e.g., weedy vs. rocky; Barnes and Hicks 2003), likely because it affects food availability.



Figure 1-3. Large brown bullhead catfish caught in Lake Rotoiti (Photo: M. Dixon, NZ Fishing News).

1.2 Freshwater crayfish in New Zealand

New Zealand is home to two endemic species of freshwater crayfish belonging to the Parastacoidea superfamily, often referred to as kēwai or kōura by Māori, including the northern kōura (*Paranephrops planifrons*, White 1842) and the southern kōura (*P. zealandicus*, White 1842) (McDowall 2011). The northern kōura is the only species of freshwater crayfish in the North Island, with populations also located in the upper West Coast of the South Island (Figure 1-4). The southern kōura is restricted to the South Island with populations occurring on the eastern and southern parts of the mainland and Stewart Island (Chapman et al. 2011). There is evidence that kōura have been in New Zealand c.60 to 80 million years when it broke off from Gondwanaland, making these species among its earliest inhabitants (Kusabs 2017). Recently, there has been suggestion of a third cryptic species of kōura, occurring on the west coast of the South Island. DNA analysis revealed that it was more closely related to southern kōura than northern kōura and diverged sometime during mountain formation in the mid-Pliocene (Apte et al. 2007).

To Māori, kōura are a taonga (treasured) species, which traditionally acted as an important and prized dietary item, and an item of value that was traded with outsiders (McDowall 2011). Kōura currently sustain a limited number of recreational fisheries in New Zealand particularly where populations of kōura remain abundant in central North Island waterbodies, including the Te Arawa lakes (particularly lakes Okataina, Rotomā, Rotoiti, and Tarawera (Kusabs 2017), where Māori customary kōura fishing practices continue (Kusabs 2015).

In addition to being a culturally important species, kōura carry out crucial roles in aquatic environments and are regarded as a keystone species and ecosystem engineers where they occur in high numbers (Parkyn et al. 1997). Crayfish alter macroinvertebrate community structure by acting as shredders, sediment bioturbators, and predators (Parkyn et al. 1997; Parkyn et al. 2001). Kōura are also important food items for some native fish and bird species, being common prey items of eels (*Anguilla* spp.) (Hicks 1997) and shags (*Phalacrocoracidae* spp.) (Kusabs 2015). Their importance ecologically, their habitat requirements (e.g., oxygen concentrations $>5 \text{ mg L}^{-1}$), their preference for coarse substrates (Kusabs 2015), and cultural significance mean that freshwater crayfish are increasingly

being selected as an indicator species in aquatic ecosystems in New Zealand (Reynolds and Souty-Grosset 2011).

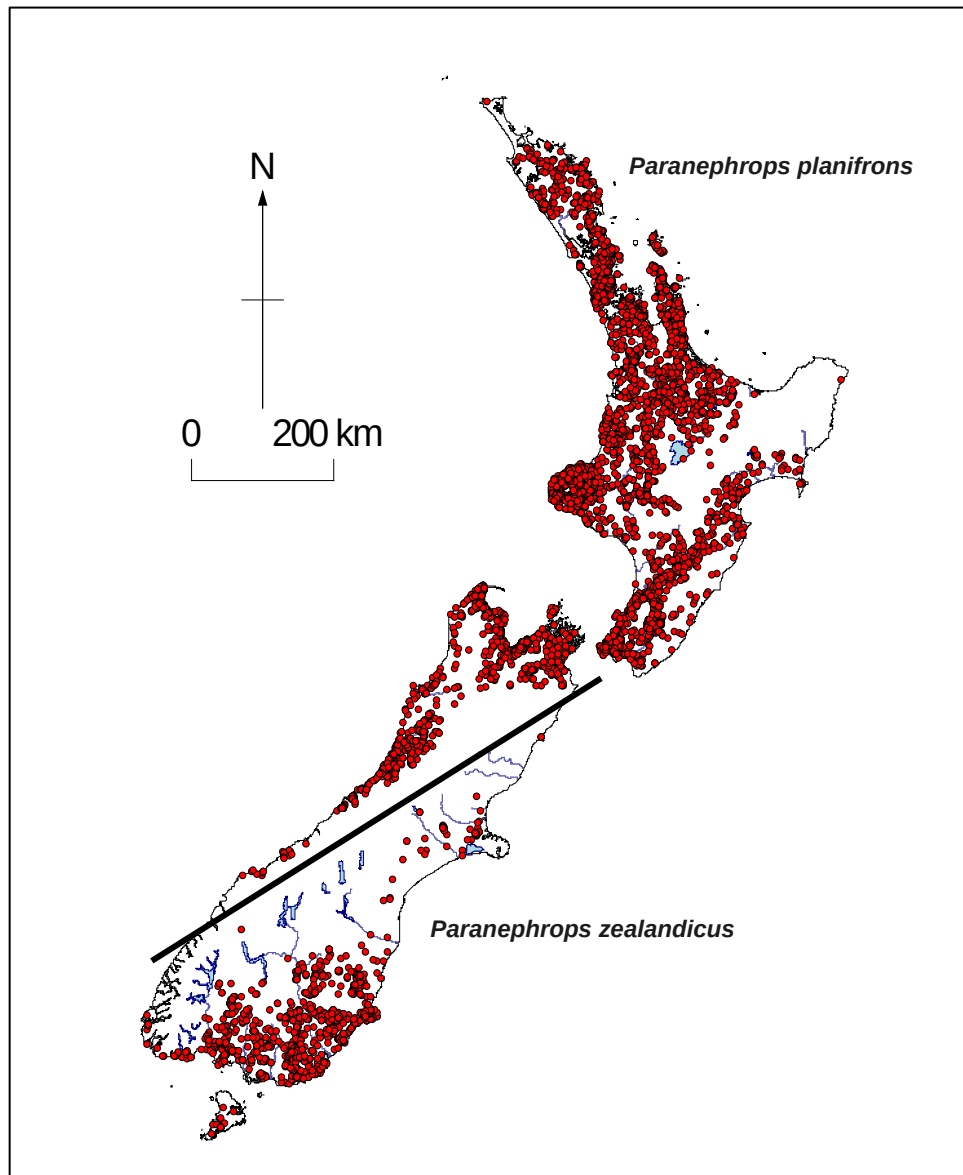


Figure 1-4. Distribution of kōura in New Zealand, with *Paranephrops planifrons* in the North Island and upper South Island and *P. zealandicus* in the South Island. Data points for *Paranephrops* spp. were obtained from the NZFFDB and the black line shows the approximate separation between both species.

1.2.1 Loss of kōura

Although kōura are not considered threatened in New Zealand (Grainger et al. 2014), anecdotal evidence suggests northern kōura numbers have declined since the early 1900s (Hiroa 1921; Dedual 2002; McDowall 2011). Kōura loss has been associated with fish (particularly trout, catfish, and native eels) and exotic macrophyte introductions along with the drainage and eutrophication of water

bodies owing to large-scale changes in land use (Parkyn et al. 2001; Kusabs and Quinn 2009; McDowall 2011; Kusabs et al. 2015a). Cannibalism, and reduced food and habitat availability (e.g. reductions in-stream wood) further affect freshwater crayfish abundance in New Zealand (Parkyn et al. 2001). Declines in kōura abundance upstream of the Waikato River have been linked to the transfer of elvers upstream of Lake Karāpiro, the introduction of non-native fish (particularly catfish), disease (reported local die out of kōura in Lake Waipapa in 1995), hydro-dam flow ramping, and deteriorations in habitat quality (Clearwater et al. 2014).

More recently, long-term monitoring of kōura populations in Lake Rotoiti between 2005 and 2016 has indicated kōura abundances and biomasses are in decline (Kusabs 2016). Reasons for the drop in kōura catch rates are unknown, but could be associated with the installation of the Ohau Channel diversion wall that may have altered physicochemical conditions, prolific exotic aquatic macrophyte growth, and increased predation by catfish (Kusabs 2016).

Countries outside of New Zealand are also reporting declines in freshwater crayfish abundance (Edsman et al. 2010; Füreder et al. 2010), for reasons including waterborne biocides and toxins, overharvesting and disease (Reynolds 2011). For example, transfer of North American freshwater crayfish species to Europe in the late 1900s has had disastrous consequences for local crayfish populations. North American crayfish were vectors of the crayfish plague (*Aphanomyces astaci*), resulting in widespread mortality of crayfish in Europe. The white-clawed crayfish (*Austropotamobius pallipes*) lost 70% of its population since the 1970s and is now classified as endangered on the IUCN Red List of Threatened Species (Peay and Füreder 2011). Additionally, the transfer and establishment of crayfish species beyond their native ranges has created novel food webs, altering predation and competition interactions (Degerman et al. 2007).

1.2.2 The effects of catfish on kōura

The most important predators of kōura, in terms of affecting growth, behaviour, and abundance are predatory fish (Westman 1985), and catfish are no exception being established predators of kōura (e.g., Barnes and Hicks 2003). Catfish in Lake Taupo were found to increasingly feed on kōura at lengths >150 mm FL (Barnes and Hicks

2003), and are thought to be partially responsible for the decline or absence of kōura when in high densities in Waikato hydro-lakes (Clearwater et al. 2014). In addition to directly feeding on kōura, catfish may compete with freshwater crayfish for shelter and food resources (Barnes 1996). They may also modify habitat (Cline et al. 1994) and slow growth rates of kōura by reducing their activity rates, potentially leading to heightened mortality (Collier and Winterbourn 2000).

Currently, there are no overseas studies on the effects of *Ameiurus nebulosus* on freshwater crayfish species, but there are reports of other non-native catfish species consuming freshwater crayfish with varying consumptive effects. The invasive flathead catfish (*Pylodictis olivaris*) in Lake Mitchell, south Dakota, was found to primarily consume crayfish (*Orconectes* spp.), and included fish in their diet at around 400 mm (Lucchesi et al. 2017). Similarly, the invasive channel catfish was found to consume large numbers of crayfish in an Atlantic river, North Carolina, USA, accounting for 25% of catfish diet (Baumann and Kwak 2011). However, channel catfish in Coachella Canal in California were found to consume minimal amounts of crayfish, occurring in 3% of stomachs (Marsh 1981).

1.2.3 Biology of kōura

Kōura (Figure 1-5) have two prominent antennae on their head, which sit below the shorter antennules (Chapman et al. 2011). When bent directly back, the antennae extend beyond the fourth segment of the abdomen in *Paranephrops planifrons*, but only reaches a third of the abdomen in *P. zealandicus*. Kōura possess efficient thoracic limbs for walking, and have large chelipeds (arms with pincers) for defending themselves and to attack. *P. zealandicus* chelipeds are typically hairier than that of *P. planifrons* (Chapman and Lewis 1976).

Kōura occur in a range of freshwater habitats including lakes, reservoirs, ponds, swamps, and streams, on muddy and gravel substrates (Chapman et al. 2011). Kōura require shade during the day that sees them retreat to the depths to hide, often under rocks and in burrows or furrows in soft substrates. At night they become active and move to shallow depths to feed (Devcich 1979). Cobble-sized substrate acts as an important cover for kōura, providing refuge from predation and cannibalism (Stein 1977), and is often identified as the most important factor

affecting crayfish abundance (Capelli and Magnuson 1983; Kusabs et al. 2015b). In addition to habitat, freshwater crayfish require certain chemical and physical conditions, including suitable bottom dissolved oxygen levels, calcium concentrations, and water temperatures (Kusabs et al. 2015b). In Lake Rotoiti, Devcich (1979) found a strong correlation between kōura numbers and dissolved oxygen (DO) concentrations at 30 m and 50 m depths. When oxygen concentrations fell to $<5 \text{ mg L}^{-1}$ kōura abundances were considerably less, although they were still present in concentrations as low as 1.6 mg L^{-1} . Westman (1985) also found abundances of other crayfish species dropped when DO concentrations $<5 \text{ mg L}^{-1}$, due to avoidance of those low oxygen areas. Under laboratory conditions, Landman et al. (2005) calculated the dissolved oxygen (DO) LC_{50} (the level at which 50% of organisms die) for kōura at 0.77 mg L^{-1} (duration of 48 h at 17°C).

Calcium (Ca) is an essential element for crayfish survival and production, and can dictate crayfish presence and absence (Lodge and Hill 1994). Adequate calcium is important as it allows for the re-calcification or hardening of the crayfishes exoskeleton post moult (Vedia et al. 2017). Low calcium environments would result in crayfish being more vulnerable to predation and cannibalism, as well as limiting crayfish reproduction and survival (Stein 1977). A calcium concentration between $20\text{-}30 \text{ mg L}^{-1}$ is thought to be an ideal concentration for *P. zealandicus* survival and reproduction (Hammond et al. 2006), with a survival threshold of between 1 and 2.5 mg L^{-1} (Cairns and Yan 2009). However, kōura have been found in West Coast New Zealand streams with calcium concentrations as low as 0.9 mg L^{-1} (Olsson et al. 2006).

Water temperature is a very important factor, dictating kōura body temperature, metabolic activity, growth, and feeding regime (Verhoef and Austin 1999). Jones (1981) found the optimum mean daily temperature for kōura to be 19°C , with a mean critical limit of 31.9°C (Simons 1985). Kōura in Lake Rotoiti were found to be tolerant of temperatures up to 35°C (Devcich 1979), but prolonged periods of high temperatures could be detrimental to their survival (Kusabs 2015).

Sexual maturity of *P. planifrons* in the Te Arawa lakes is reached at around 2 years of age, with 50% of female kōura bearing eggs at 26.3 mm OCL (Kusabs 2015). The breeding period of kōura in Lake Rotoiti is continuous with berried (i.e., egg-

bearing) females being found throughout the year (Devcich 1979; Kusabs and Quinn 2009). Females from Bay of Plenty lakes had between 26 and 345 eggs (average 104 eggs), with female fecundity increasing with increasing size (Kusabs 2015). Most kōura in Lake Rotoiti breed during late autumn and carry their eggs over winter (Devcich 1979). Eggs develop into juveniles at around 3 weeks and attach themselves, post-hatching, onto the female's pleopods as they undergo development (Devcich 1979). There could also be a second kōura breeding season in the lake between spring and summer, with females carrying eggs from October to December and juvenile kōura being released between September and December (Devcich 1979). Once developed, juvenile kōura are released in the littoral zone where food and water temperatures are adequate (Devcich 1979).

In order to grow, kōura must shed their exoskeleton. In the first year of growth, juvenile kōura can moult nine times, followed by three times the second year and two times the following year (Parkyn et al. 2002). Kōura growth is typically faster in pasture streams than in native forest streams, with larger moult increments and more frequent moults occurring (Parkyn et al. 2002).

Kōura have varied omnivorous diets consisting of invertebrates, detritus, and plants (Chapman et al. 2011). Freshwater crayfish diet is influenced by land use and food availability, with leaf litter being the predominant food source in forested streams and invertebrates in pasture streams in the Waikato region (Parkyn et al. 2001). Although kōura diets are varied, animal protein contributes most to kōura growth, being commonly sourced from chironomids, aquatic snails, and mayflies (Parkyn et al. 2001). Kōura diet also changes with size, with larger crayfish consuming more plant material and less animal protein than juvenile crayfish (Whitmore et al. 2000).



Figure 1-5. Large female northern kōura (*P. planifrons*) caught in Lake Rotoiti.

1.3 Study objectives

Extensive studies exist on the effects of predatory fish on freshwater crayfish species (Stein 1977; Dorn and Mittelbach 1999; Englund and Krupa 2000; Usio and Townsend 2000; Nyström et al. 2006; Vedia et al. 2017), including some New Zealand studies on the effects of widespread introduced brown trout (*Salmo trutta*) on kōura populations (Usio and Townsend 2000; Olsson et al. 2006; Brown 2009; Kusabs et al. 2015b). However, only one study has tried to quantify the effects of introduced brown bullhead catfish and kōura by conducting a two-lake comparison with and without catfish, and likely under sampled the area where catfish and kōura are most likely to interact (depths <10 m; Kusabs and Taiaroa 2015). The current knowledge gap on catfish and kōura interactions, more specifically predation, is concerning given the current prevalence of catfish in New Zealand and their high potential to spread to other lakes in the Bay of Plenty and Waikato regions (Leathwick et al. 2016). Therefore, the primary aim of this thesis is to quantify the effects of catfish on kōura populations in Lake Rotoiti, a lake that has been recently invaded by catfish and that has high natural abundances of kōura (Kusabs 2015). Understanding what impact non-native catfish are having on kōura populations will help to establish whether an intervention is needed to sustain this culturally important resource.

To serve as a species monitoring tool and incorporate mātauranga Māori, whakaweku, a traditional kōura capture technique using bundles comprised of bracken fern (*Pteridium esculentum*) (Kusabs and Quinn 2009), was deployed at high and low catfish density sites to monitor kōura populations in Lake Rotoiti. This method has been used successfully on a number of different substrates, depths, and habitats, but has not yet been tested as a kōura capture technique in shallow lake littoral zones, where catfish and kōura are most likely to interact.

The main aims of this thesis are as follows:

1. Compare kōura numbers and sizes between high and low density catfish sites using fine-meshed fyke nets and whakaweku in Lake Rotoiti;
2. Determine if habitat variables and catfish densities can explain kōura and fish abundance in Lake Rotoiti;

3. Test the effectiveness of whakaweku as a kōura sampling method on lake shorelines, and as a potential refuge from catfish predation;
4. Identify the diets of catfish and kōura in Lake Rotoiti, based on stomach contents and stable isotope analysis of carbon and nitrogen;
5. Determine if catfish and kōura have any dietary overlap using stomach contents and stable isotopes of carbon and nitrogen; and
6. Establish the relationship between catfish gape size and fish length for fresh and frozen fish, so in future, sizes of food items found in catfish guts can be related back to the gape size of fish.

1.4 Thesis overview

Aside from the introduction, there are four remaining chapters in this thesis. Chapter 2 introduces the study area and sites. Chapter 3 examines the influence of habitat variables and catfish densities on kōura and native fish abundances in Lake Rotoiti. In addition, it addresses the effectiveness of whakaweku as a kōura capture technique in shallow lake habitats and as a refuge from catfish predation. Chapter 4 uses stable isotopes and stomach contents to (i) identify the diet of different-sized catfish and kōura in Lake Rotoiti, (ii) establish the contribution of kōura to the diet of catfish, and (iii) determine the degree of dietary overlap between catfish and kōura. A gape-size for catfish length regression was calculated for fresh and frozen catfish so catfish gape size can be calculated from catfish length and then related to feeding habits. Chapters 3 and 4 are in journal article format for submission to the New Zealand Journal of Marine and Freshwater Research. Chapter 3 was submitted on 8 February 2019 and chapter 4 will be submitted in the near future. The final chapter, Chapter 5, will summarise the main findings of chapters 3-4 and provides recommendations for the management of kōura populations in Lake Rotoiti with the recent catfish incursion.

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2 Chapter 2

Study area

2.1 Lake Rotoiti

Lake Rotoiti (38.039895°S, 176.345803°E; Figure 2-1) is one of 12 major lakes in the Bay of Plenty Region that are collectively known as the Te Arawa lakes (Kusabs et al. 2015b), and is situated about 278 m a.s.l. on the Central Volcanic Plateau, North Island, New Zealand (von Westernhagen 2010). The lake was formed c. 8.5 to 9 thousand years ago when river valleys became dammed with lava following a volcanic eruption (Lowe and Green 1987). The basin of Lake Rotoiti is unusually long and narrow compared to other lakes in the district (Fish 1975), and consists of two distinct basins including a shallow western basin (maximum depth 25 m) and a deep eastern basin, separated by a narrow constriction (von Westernhagen 2010).

The lake is deep (maximum depth 124 m, average depth 32 m; Figure 2-2), large (surface area 34.6 km²), warm, mesotrophic, and monomictic (von Westernhagen 2010). For 9 months of the year, the lake is stratified and mixes once in late autumn before stratifying again in the spring (Kusabs and Quinn 2009). Rotoiti receives multiple geothermal inputs, with the Tikitere geothermal field being the main input (Environment Bay of Plenty 2009). Approximately 80% of the main inflow into Lake Rotoiti comes from Lake Rotorua through the Ohau Channel which flows into the western basin. The sole outflow of the lake is the Kaituna River through the Okere Inlet (Kusabs and Quinn 2009). Currently, 24% of the surrounding catchment area is used for agriculture, 43% is forest, and 1% is urban (Bruesewitz et al. 2011).

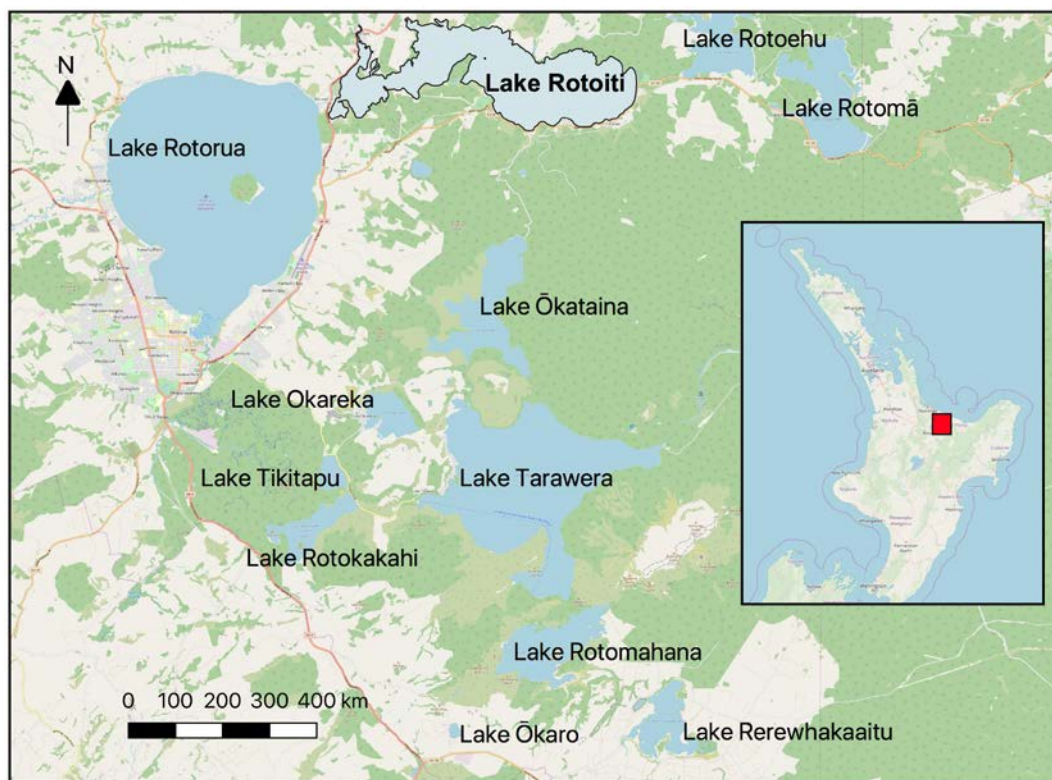


Figure 2-1. Location of the Te Arawa lakes including Lake Rotoiti in the Bay of Plenty region, North Island, New Zealand.

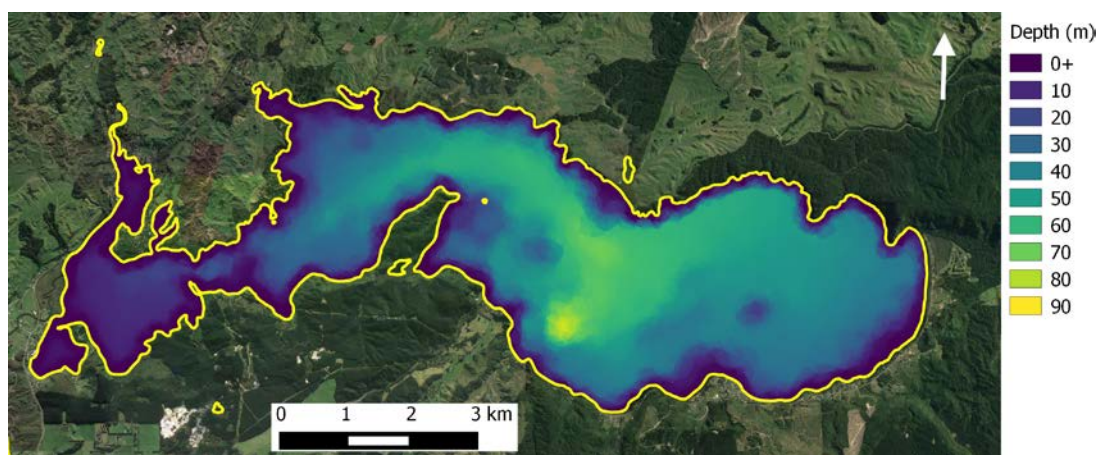


Figure 2-2. Bathymetry of Lake Rotoiti. Source data Waikato Coastal Marine Group. Data is interpolated to a 5 m grid. Map supplied by M. Allan, University of Waikato.

2.1.1 Lake water quality

Water quality in Lake Rotoiti has gradually deteriorated since the 1950s (Burns et al. 1997), coinciding with changes in catchment land use. In the warmer months, the lake experiences cyanobacteria blooms (Burger et al. 2007) and deoxygenation in its bottom waters during periods of stratification (Hamilton et al. 2004). When the lake is stratified, about 20 t of phosphorus and 50 t of nitrogen are mobilised to

the water column from the bottom sediments (Hamilton et al. 2004). To improve water quality in Lake Rotoiti, the Ohau Diversion Wall (1,275 m long; Figure 2-3) was installed to divert nutrient-rich water exiting Lake Rotorua through the Ohau Channel, away from Lake Rotoiti (Gillies et al. 2010). Construction of the wall took roughly a year starting in June 2007, being completed in July 2008. The wall is estimated to prevent 180 t of nitrogen and 50 t of phosphorus from entering the lake each year, and was expected to improve water quality within five years (Gillies et al. 2010). Further attempts to improve lake water quality have seen the Bay of Plenty Regional Council (BOPRC) remove large quantities of exotic macrophytes, including hornwort (*Ceratophyllum demersum*) from the lakebed using a weed harvester (S. Grayling, BOPRC, pers. comm.). Alum dosing of the Utuhina and Puarenga streams flowing into Lake Rotorua, may have also reduced phosphorus concentrations (Environment Bay of Plenty 2009). Recent water quality results are showing gradual improvement in the condition of Lake Rotoiti, with the lake shifting from a eutrophic state (average TLI score of 4 from 2004 to 2006) to a mesotrophic state (average TLI score of 3.5 from 2014 to 2016; Land Air Water Aotearoa 2016).



Figure 2-3. Aerial view of the Ohau Channel diversion wall that diverts water from Lake Rotorua towards the Kaituna River outflow (Hamilton et al. 2018).

2.1.2 Fish

Lake Rotoiti is home to three species of native fish including kōaro, common bullies (*Gobiomorphus cotidianus*), and common smelt (*Retropinna retropinna*) (Kusabs and Quinn 2009). Although common smelt are native to New Zealand, they were introduced to the lake to provide an alternative food source to kōaro for trout (McDowall 2011). Longfin eels (*Anguilla dieffenbachii*) are also present in Lake Rototiti but are found in very low densities (Martin et al. 2007). In addition to native fish species, Lake Rotoiti has five species of non-native fish including rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), catfish, gambusia (*Gambusia affinis*), and goldfish (*Carassius auratus*). Brown trout and rainbow trout were introduced to the catchment in 1888 and 1889, respectively (Kusabs and Quinn 2009). Catfish were confirmed present in Lake Rotoiti in March 2016 (Bay of Plenty Regional Council 2018a).

2.1.3 Macrophytes

There are four main species of exotic macrophytes in Lake Rotoiti, including Canadian pondweed (*Elodea canadensis*), egeria (*Egeria densa*), Lagarosiphon (*Lagarosiphon major*), and hornwort (Lakes Water Quality Society 2017). The introduction and establishment of hornwort in the 1970s has been particularly problematic for lake managers and general lake health, and has been implicated with the loss of native flora in Lake Rotoiti over the past half century (Lakes Water Quality Society 2017). A flora survey by Coffey and Clayton (1988) recorded a number of macrophyte species present in Lake Rotoiti between 1965 and 1985 (Table 2-1), but what species remain and their distributions are unknown.

Table 2-1. Aquatic plant species recorded present and their status in Lake Rotoiti in between 1969 and 1985 (Coffey and Clayton 1988).

Common and scientific name	Status
<u>Tall Growing macrophytes</u>	
Hornwort (<i>Ceratophyllum demersum</i> L.)	Introduced
Blunt pondweed (<i>Potamogeton ochreatus</i> Raoul)	Native
Lagarosiphon (<i>Lagarosiphon major</i> Ridley)	Introduced
Curly leaved pondweed (<i>Potamogeton crispus</i> L.)	Introduced
Red pondweed (<i>Potamogeton cheesemanii</i> A. Benn.)	Native
Canadian pondweed (<i>Elodea canadensis</i> Michx.)	Introduced
Water milfoil (<i>Myriophyllum triphyllum</i> Orchard)	Native
Common water milfoil (<i>Myriophyllum propinquum</i> A. Cunn)	Native
Stonewort (<i>Chara corallina</i> Klein)	Native
Nitella hookeri A. Br.	Native
<u>Low-mound community</u>	
Small mudmat (<i>Glossostigma elatinoides</i> Benth.)	Native
Zealandia chain sword (<i>Lilaeopsis lacustris</i> Hill)	Native
Mudwort (<i>Limosella lineata</i> Gluck)	Native
Waterwort (<i>Elatine gratioloides</i> A. Cunn.)	Native
Elatine sp.	Native
Quillwort (<i>Isoetes kirkii</i> A. Braun)	Native
Mud buttercup (<i>Ranunculus limosella</i> F. Muell)	Native
Eleocharis pusilla R. Braun	Native
Bladderwort (<i>Utricularia protrusa</i> F. Hook)	Native
Triglochin (<i>Triglochin striata</i> Ruiz)	Native
Horses' mane weed (<i>Ruppia polycarpa</i> R. Mason)	Native
Stonewort (<i>Nitella pseudoflabellata</i> A. Braun)	Native
Glossostigma submersum Petrie	Native

2.2 Study sites

Six sites were selected around the western end of Lake Rotoiti (Te Weta Bay, Southern Shoreline, Okere Inlet, Otaramarae, Okawa Bay, and Te Arero Bay; Figure 2-4) for this study, based on their similarities including bathymetry, proximity to one another, dominant substrate type, and catfish density. Descriptions of each of the sites follow.

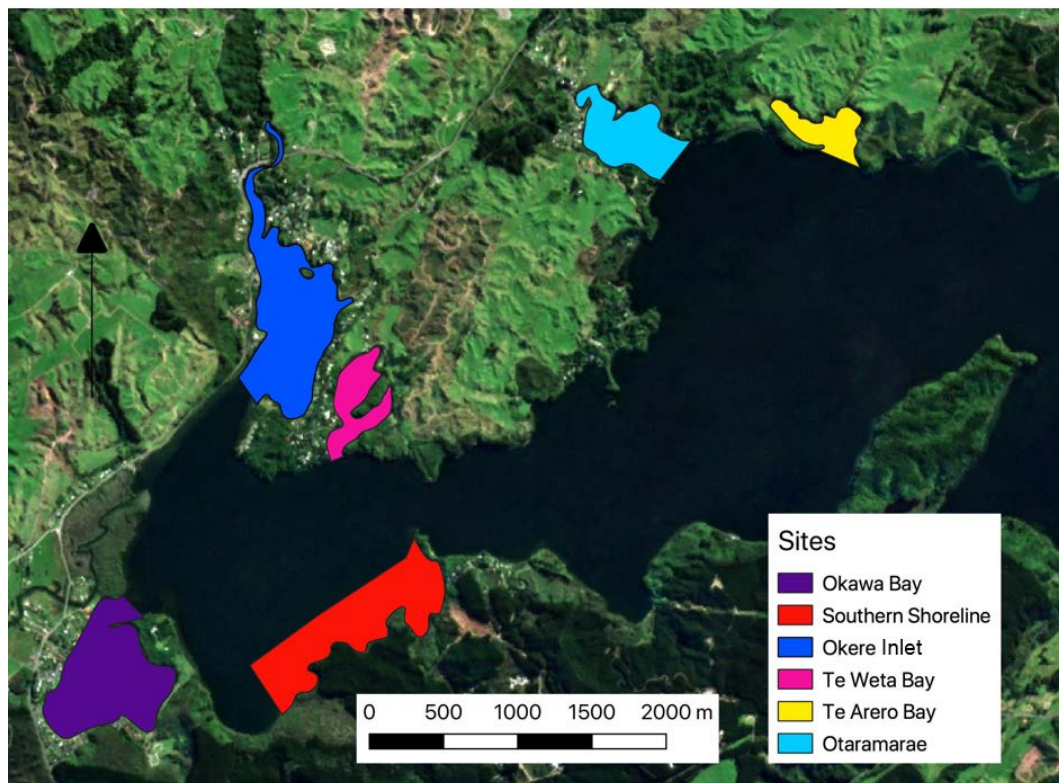


Figure 2-4. Locations of the six study sites at the western end of Lake Rotoiti.

2.2.1 Te Weta Bay

Te Weta Bay is located to the north west of Lake Rotoiti (38.032768°S, 176.352794°E; Figure 2-5) and is the site to have the most catfish caught to date. The bay is largely shallow (<6 m deep), reaching depths of up to 10 m at its entrance (G. Ewert, BOPRC, pers. comm.). There are several stands of dense exotic macrophytes in the bay, and it experiences problems with excessive filamentous algae growth and cyanobacteria blooms in summer. Te Weta Bay also hosts stands of great spike rush (*Eleocharis sphacelata*) and raupō (*Typha orientalis*) along its shorelines. The dominant substrate type is silt, with small localised areas of sand and rocks at the entrance to the bay (G. Ewert, BOPRC, pers. comm.). Silt in Te Weta Bay could have originated from erosion from the surrounding hills. The predominant land use is low-density housing, farming and forestry.



Figure 2-5. Photo images of Te Weta Bay, A. typical emergent vegetation in Te Weta Bay; B. macrophyte beds in Te Weta Bay (Photos: A. Pearson, University of Waikato).

2.2.2 Southern Shoreline

Southern Shoreline is a geothermally active site located on the southern shores of Lake Rotoiti (38.042243°S, 176.357657°E; Figure 2-6), and was the second site found to have catfish after Te Weta Bay (G. Ewert, BOPRC, pers. comm.). The shallows are predominately weedy, shallow, and rocky (mostly bedrock), with a thin coverage of gravely sand. There are also some steep drop-offs in places. The site has several stands of emergent great spike rush and raupō, which is where catfish were first caught in the area (G. Ewert, BOPRC, pers. comm.). The surrounding land use is predominately exotic and native forestry.



Figure 2-6. Photo images of the Southern Shoreline site, A. close up of vegetation; B. vegetation of the Southern Shoreline consists of predominantly radiata pine and mānuka scrub (Photos: A. Pearson, University of Waikato).

2.2.3 Okere Inlet

Okere Inlet is located in the far north western end of Lake Rotoiti ($38.029692^{\circ}\text{S}$, $176.347429^{\circ}\text{E}$; Figure 2-7). The site is shallow, weedy, and reasonably sandy, with some rocky outcrops (G. Ewert, BOPRC, pers. comm.). There are several large stands of raupō around the entrance of Okere Inlet, which is where the majority of catfish have been caught. The inlet receives large volumes of nutrient rich water from Lake Rotorua because of the diversion wall, and is connected to the sole outlet for the lake, the Kaituna River (Hamilton et al. 2018). The dominant surrounding land-use is low-density housing, tourism (rafting down the Kaituna River) and native vegetation.



Figure 2-7. Photo images of Okere Inlet. A. close up of vegetation; B. Okere Inlet entrance (Photos: A. Pearson, University of Waikato).

2.2.4 Otaramarae

Otaramarae is located to the north east of Lake Rotoiti ($38.014734^{\circ}\text{S}$, $176.373263^{\circ}\text{E}$; Figure 2-8). Although catfish have been caught at the site, it's only in recent times that catches are increasing. The bay is shallow with dense stands of hornwort. Lake bed substrate is composed of sand around the edges, with areas of silt. There are some isolated stands of emergent vegetation around the lake edges (G. Ewert, BOPRC, pers. comm.). The predominant surrounding land use is low-density housing and farming.

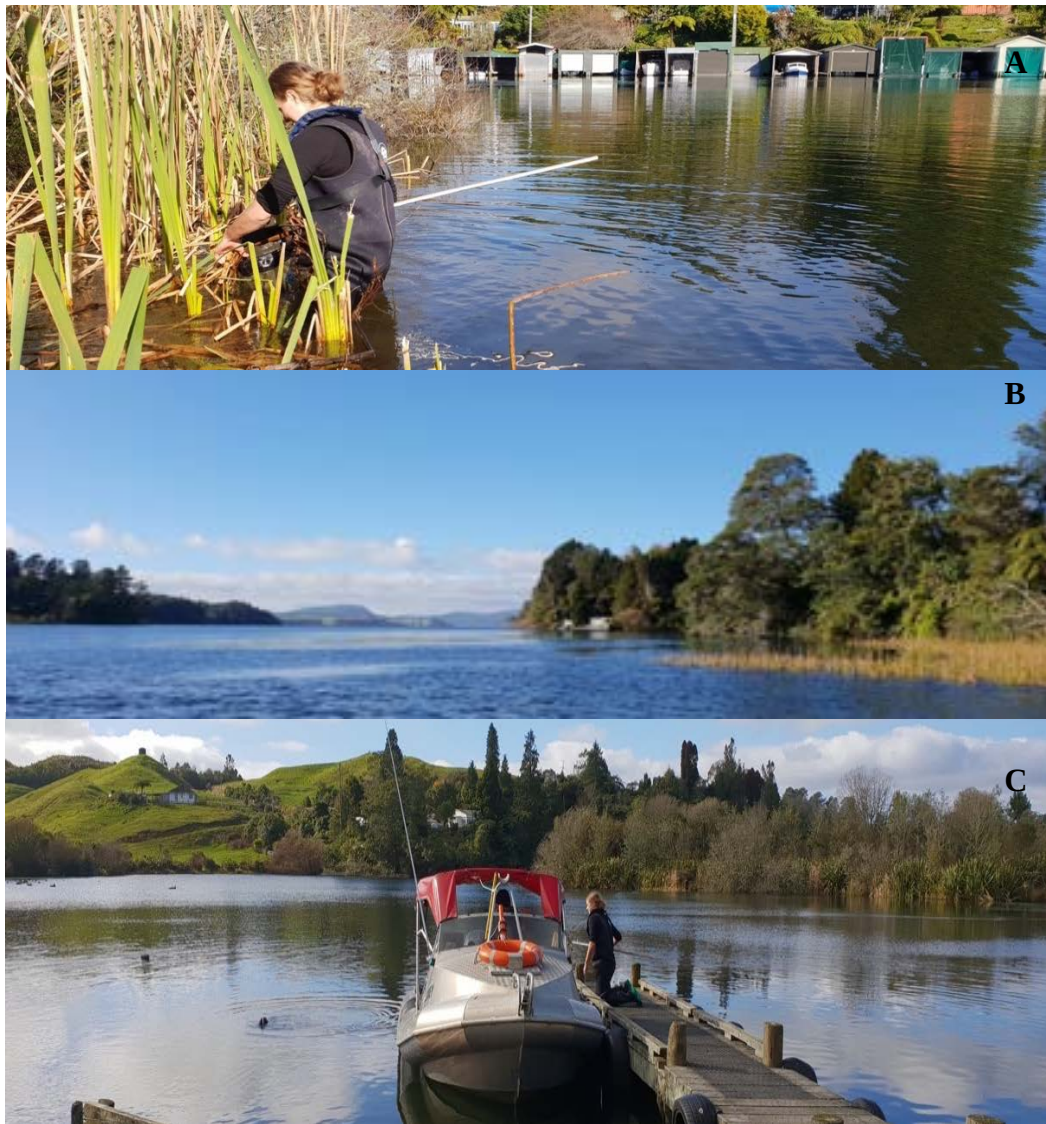


Figure 2-8. Photo images of Otaramarae. A. close up of emergent vegetation where catfish have been caught; B. entrance to Otaramarae looking towards the main body of the lake; C. Otaramarae boat ramp (Photos: A. Pearson, University of Waikato).

2.2.5 Okawa Bay

Okawa Bay is located to the south west of Lake Rotoiti ($38.049295^{\circ}\text{S}$, $176.334870^{\circ}\text{E}$; Figure 2-9). The bay is very shallow and sandy around the edges, with some stands of emergent vegetation. The bay has no rocky outcrops (G. Ewert, BOPRC, pers. comm.). In the summer, Okawa Bay experiences blooms of blue-green algae (i.e., Cyanobacteria) (Environment Bay of Plenty 2009). The lake is also sprayed with diquat herbicide in summer to kill off aquatic macrophytes. The land use surrounding the bay is predominately low-density housing, with areas of native and exotic forest.



Figure 2-9. Photo images of Okawa Bay. A. close up of vegetation; B. looking south at Okawa Bay (Photos: A. Pearson, University of Waikato).

2.2.6 Te Arero Bay

Te Arero Bay is located to the north east of Lake Rotoiti ($38.014193^{\circ}\text{S}$, $176.389174^{\circ}\text{E}$; Figure 2-10), and has not had a catfish caught in the bay to date. Te Arero Bay is a relatively deep, weedy, and sandy, with isolated areas of rock and silt (G. Ewert, BOPRC, pers. comm.). The bay hosts no stands of emergent vegetation, but has wetlands of ecological significance. Te Arero Bay is covered largely in native forest except for some small areas cleared for sheep and beef farming and has no housing or commercial forestry.



Figure 2-10. Photo images of Te Arero Bay. A. western shoreline of Te Arero Bay; B. close up of typical mudstone cliffs, with lake side vegetation (Photos: A. Pearson, University of Waikato)

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3 Chapter 3

***Relationship between invasive brown bullhead catfish and native fish and kōura abundance in Lake Rotoiti*¹**

3.1 Abstract

Catch rates of kōura (freshwater crayfish, *Paranephrops planifrons*) have declined significantly in Lake Rotoiti over the last decade and we conclude that brown bullhead catfish (*Ameiurus nebulosus*) are primarily responsible. The brown bullhead catfish is a predator and scavenger that is native to North America, and was confirmed to be present in Lake Rotoiti in 2016. To assess the effects of catfish on kōura and native fish populations in the lake, routine fyke netting data generated by the Bay of Plenty Regional Council (BOPRC) since March 2016 was used. Kōura mean catch per unit effort (CPUE) has declined in Lake Rotoiti since the initiation of fyke netting, with mean catch rates dropping from 10.6 kōura net⁻¹ night⁻¹ in 2016 to 4.2 kōura net⁻¹ night⁻¹ in 2018. Over the same period, mean catfish CPUE has increased, with the highest catch rates in Te Weta Bay, where mean catch rates have increased from 1.1 catfish net⁻¹ night⁻¹ in 2016 to 63.7 catfish net⁻¹ night⁻¹ in 2018. Routine fyke netting data revealed that catfish CPUE was negatively associated with kōura catch per unit effort ($r = -0.180$). Mean catfish density also had a significant effect on kōura catch rates, with significantly more kōura being caught at sites without catfish. The negative association between catfish and kōura could be due to catfish eating or competing with kōura, or their differing habitat preferences. Additionally, fine-meshed fyke nets and whakaweku (bracken fern bundles) were used to obtain data on kōura population metrics (e.g., sizes and sex ratios) and species habitat preferences. Catfish were positively associated with weedy or muddy habitats and kōura were negatively associated with muddy habitats and were positively associated with rocky habitats.

¹ Francis LB, Hicks BJ, Kusabs IA (2019). Submitted. Relationship between invasive brown bullhead catfish and native fish and kōura abundance in Lake Rotoiti. New Zealand Journal of Marine and Freshwater Research.

3.2 Introduction

Monitoring of kōura (*Paranephrops planifrons*) populations in Lake Rotoiti from 2005 to 2016 found that kōura catch rates and biomasses are in decline, with a 24% reduction in kōura catch rates from 2014 to 2016 (Kusabs 2016). Invasion of brown bullhead catfish (*Ameiurus nebulosus*), prolific invasive macrophyte growth, and physicochemical changes in the lake could be potential causes (Kusabs 2016). Other studies have identified physicochemical conditions, the presence of predatory fish, food supply, and refuge availability, as important factors affecting freshwater crayfish abundances and size-class distributions (Lodge and Hill 1994; Kershner and Lodge 1995; Usio and Townsend 2000; Nyström et al. 2006; Kusabs 2015).

Internationally, fish are important predators of crayfish and also affect their growth, behaviour, and abundance (Westman 1985). In New Zealand, introduced fish species known to prey on kōura include trout, perch (*Perca fluviatilis*), and brown bullhead catfish (Parkyn and Kusabs 2007). Until recently, the Te Arawa lakes in the Rotorua region have remained comparatively free of introduced fish, with only rainbow trout (*Oncorhynchus mykiss*), which are stocked by Fish and Game New Zealand for recreational purposes, naturalised brown trout (*Salmo trutta*) (Kusabs et al. 2015a), gambusia (*Gambusia affinis*), and goldfish (*Carassius auratus*). The impact of trout on kōura populations in lakes appears to be comparatively low compared to lotic waters. Diets of rainbow trout (>200 mm fork length; FL) in central North Island lakes were found to primarily consist of common smelt (*Retropinna retropinna*), with kōura, common bully (*Gobiomorphus cotidianus*), and kōaro (*Galaxias brevipinnis*) being infrequent items (Blair et al. 2012). Kusabs et al. (2015a) found that relative trout abundance was unrelated to kōura size or abundances in the Te Arawa lakes, suggesting that the impacts of trout on kōura population structures are not significant. Eels (*Anguilla* spp.) are the only native freshwater fish that are capable of exerting significant predation pressure on kōura. For example, in Waikato streams, 22-25% of longfin eel (*Anguilla dieffenbachii*) stomachs contained kōura (Hicks 1997), suggesting kōura were an important component of their diet. However, longfin and shortfin eel (*Anguilla australis*) densities are low in Lake Rotoiti due to the distance inland and difficulty in migrating upstream past the Okere Falls (Martin et al. 2007). Therefore, it is likely that fish predation has not been a significant influence on Lake Rotoiti kōura prior to the invasion of catfish.

Catfish eat kōura, comprising up to 64% of dietary items in the stomachs of large catfish (>250 mm FL) from rocky habitats in Lake Taupo (Barnes and Hicks 2003). Negative correlations of kōura abundance in relation to catfish density have also been observed in Waikato River hydro lakes (Clearwater et al. 2014). Kusabs and Taiaroa (2015) compared a high-density catfish lake (Lake Taupo) and a lake with no catfish, and hypothesised that catfish in combination with exotic macrophytes likely excluded kōura from the littoral zones of Lake Taupo (Kusabs and Taiaroa 2015). In addition to kōura, catfish also consume varying quantities of fish. In shallow Waikato lakes, common bullies comprised 47% of catfish diet (Collier et al. 2018). Lake Rotoiti has resident populations of native common bullies, common smelt and kōaro, which could all be potential food items of catfish due to their small size.

Habitat complexity provides refugia from predation for crayfish, with several studies finding a positive relationship between crayfish abundance or crayfish survival and increasing particle size and abundance (Stein and Magnuson 1976; Lodge and Hill 1994; Nyström et al. 2006; Ramberg-Pihl et al. 2017). Cobble-sized substrates are frequently identified as the most important factor explaining crayfish abundance in lakes (Capelli and Magnuson 1983; Lodge and Hill 1994; Johnsen and Taugbøl 2008; Kusabs et al. 2015a; Ramberg-Pihl et al. 2017), suggesting they provide shelter from predation and cannibalism of juveniles, post-moult soft-shelled individuals, and egg-bearing females (Stein 1977; DiDonato and Lodge 1993). In the Te Arawa lakes, the substrate is of volcanic origin and is composed of fine material (<1 mm in diameter) consisting of predominately silt, mud and sand, with small localised areas of cobble (Kusabs et al. 2015a), suggesting that preferred kōura habitat in the lake is minimal.

Crayfish abundance has been negatively associated with exotic macrophyte cover, although the effects are not well studied. The littoral zone of Lake Rotoiti is largely covered by four species of exotic macrophytes including Canadian pondweed (*Elodea canadensis*), egeria (*Egeria densa*), lagarosiphon (*Lagarosiphon major*), and hornwort (*Ceratophyllum demersum*). Dense stands of Canadian pond weed in Lake Rotoiti are thought to hinder kōura movement, influence food availability and sediment characteristics, but may also provide refuge from predation (Kusabs 2015). A study on the effects of Canadian pond weed on the distribution of noble

crayfish (*Astacus astacus*) in Lake Steinsfjorden, Norway, found that crayfish were virtually excluded from the shallow littoral zone where the weed had established (Hessen et al. 2004). Another study conducted in central North Hampshire, USA, also observed a negative relationship between northern crayfish (*Orconectes virilis*) abundance and macrophyte cover (Ramberg-Pihl et al. 2017).

Bracken fern (*Pteridium esculentum*) bundles, or whakaweku, are a traditional tool used by Te Arawa and Tūwharetoa iwi to capture kōura. Whakaweku have been shown to be a superior kōura capture technique over conventional methods, because they capture kōura from all size classes and both genders (Kusabs 2015). They are also routinely used to monitor kōura populations in Lake Rotoiti and other Te Arawa lakes (Kusabs 2015). In addition to monitoring kōura populations, whakaweku can be used to monitor small fish (e.g. common bullies) and other invertebrates (e.g., dragonfly larvae) (Kusabs 2015; Kusabs et al. 2018).

Whakaweku bundles consist of about 10-12 bracken fern fronds bound together at the stems using plastic cable ties. In lakes, multiple whakaweku are typically set along a tāuhu (rope line) to form a tau kōura that can be set over a range of depths (3-34 m; Kusabs and Quinn 2009; Kusabs et al. 2015a). Once deployed, tau kōura are left in place for at least 2 weeks to allow colonisation by kōura and fish (Kusabs et al. 2018), but they can also be left deployed for up to 6 months in eutrophic lakes and >2 years in oligotrophic lakes, before they start to deteriorate (Kusabs and Quinn 2009; Kusabs et al. 2015a). Upon retrieval, kōura are shaken from the whakaweku into a landing net or kōrapa for processing. This technique has proven highly effective in surveying kōura from below the littoral zone, but they have yet to be tested in shallow littoral zones in the presence of submerged macrophytes. The effectiveness of whakaweku in capturing kōura in the Te Arawa lakes may be related to the lack of preferred cobble habitat (Devcich 1979), with whakaweku providing habitat and additional foraging areas (Kusabs and Quinn 2009). Their persistence and low-cost construction make whakaweku a potential tool for mitigating catfish predation of kōura in fine particulate sediment lakes such as Lake Rotoiti.

3.3 Aims and objectives

Brown bullhead catfish were confirmed present in Lake Rotoiti in March 2016 and in neighbouring Lake Rotorua in December 2018, with the potential to spread to the Kaituna River catchment. The main objective of this chapter was to determine if kōura and native fish populations were affected by the establishment of catfish in Lake Rotoiti, and to ascertain whether habitat composition played a role in determining kōura and fish distributions within the lake. This was approached by (i) comparing fyke net catches of kōura and native fish at low and high catfish densities, (ii) examining the size-class distribution of kōura, and (iii) observing the effects of habitat on kōura capture rates. The Bay of Plenty Regional Council (BOPRC) has been conducting an extensive fyke netting programme throughout the lake to systematically remove catfish since March 2016, generating a spatial and temporal dataset of fish and kōura abundance. This dataset was analysed to determine if an inverse catch per unit effort (CPUE) relationship between catfish and kōura existed. Such a relationship could indicate interactions such as predation or interspecific competition between the two species.

A netting survey independent of the BOPRC programme employing both whakaweku and fyke nets was also conducted in order to collect kōura size-class data, and determine the effectiveness of whakaweku in the shallow littoral zone of the lake. Examination of this data would help determine if sites with lower catch rates of kōura were missing smaller size-classes of kōura, due to size-selective predation by catfish. The independent netting survey also allowed for localised habitat around the whakaweku and fyke to be characterised in more detail, in order to identify potential effects of habitat on fish and kōura capture rates. A secondary objective of this study was to investigate whether kōura would utilise the structure of whakaweku on the lake shorelines as refugia from catfish predation or competition. To test this hypothesis, two tank trials employing cobble structure and whakaweku were conducted to evaluate their effectiveness in mediating catfish and kōura interactions.

3.4 Methods

3.4.1 Study area

Lake Rotoiti (38.039895°S, 176.345803°E) sits at 278 m a.s.l. on the Central Volcanic Plateau, North Island, New Zealand (von Westernhagen 2010), and is one of many lakes, collectively known as the Te Arawa lakes, in the Bay of Plenty region (Kusabs et al. 2015b). The lake is large (3460 ha) and deep (average depth 32 m, maximum depth 124 m), and consists of a shallow western basin (maximum depth 25 m) and a deeper eastern basin. For 9 months of the year, the lake is stratified and mixes once in late autumn (Kusabs and Quinn 2009).

To compare kōura and fish abundances with varying densities of catfish, BOPRC fyke-netting data was used, which encompassed the whole of Lake Rotoiti (Figure 3-1). In addition, six sites at the western end of Lake Rotoiti (Te Weta Bay, Okere Inlet, Otaramarae, Te Arero Bay, Okawa Bay, and Southern Shoreline) where chosen to investigate kōura population metrics and species habitat preferences.

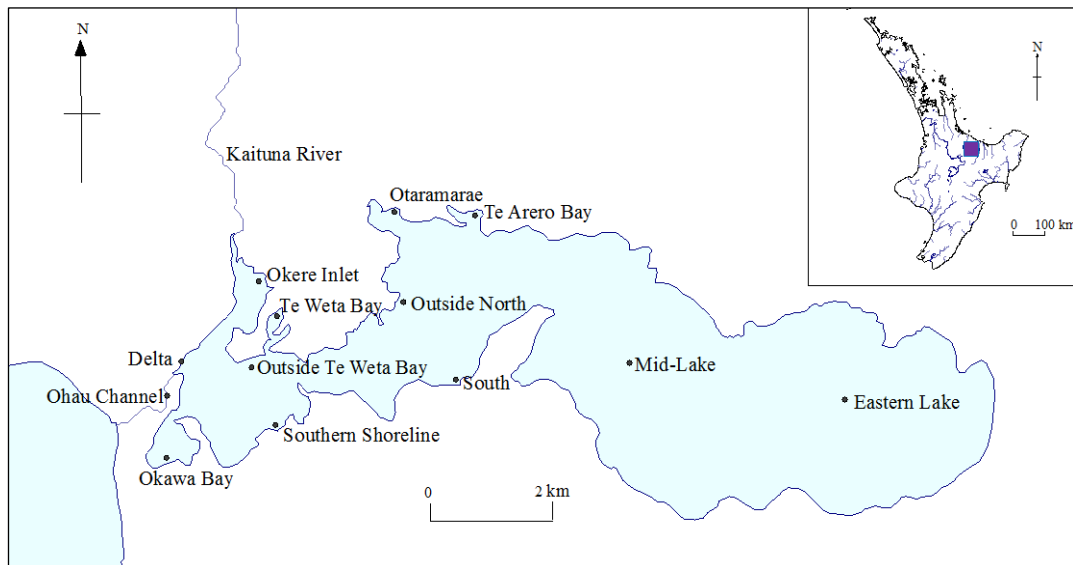


Figure 3-1. Location of the six main study sites and additional sites encompassing the whole of Lake Rotoiti.

3.4.2 Routine catfish monitoring

Fyke nets (n net nights = 6954) were set in Lake Rotoiti between 29 March 2016 and 27 September 2018 by the BOPRC, as part of their catfish eradication programme. The nets used were a mixture of fine (mesh size 4 mm, n = 4471) and coarse meshed (mesh size 6 mm, n = 2483), which were either unchoked (n = 3385) or choked (n = 3569; Table 3-1). The purpose of the added plastic mesh choke was to avoid unwanted by-catch, particularly of waterfowl such as the threatened dabchick or weweia (*Poliocephalus rufopectus*). The choke was a square of plastic mesh with an 85-mm by 85-mm opening (Figure 3-2). In 2016, a majority of fyke nets used were coarse-meshed, resulting in smaller fish such as bullies and smelt not being captured. Fyke nets were single-winged, with two internal throats to prevent fish escaping, and a 600-mm high D hoop at the front. In each net, one 106-g tin of sardines in soya bean oil and one or two crushed green-lipped mussels (*Perna canaliculus*) were used as bait. The contents of the sardine tins were not emptied into the nets, instead several holes (~8 per side) were punched into both sides of the tins. Bait was not reused in subsequent nets. Fyke nets were typically set in the shallow water (<7 m deep) for about 24 h. Catfish caught by netting were measured or averaged to a size range of <150 mm FL. Kōura and other fish were counted but not measured. Catfish were removed from the lake, but kōura and other fish species were returned to the lake.

Table 3-1. Number of coarse and fine mesh, choked and unchoked nets set during each season (3-monthly periods) from 2016 to 2018 in Lake Rotoiti.

Year	Season	Coarse mesh		Fine mesh	
		Unchoked	Choked	Unchoked	Choked
2016	Spring	402		44	
	Summer	75		155	
	Autumn	514			
	Winter	253			
2017	Spring	190	75	233	206
	Summer	235	53	405	141
	Autumn	105	95	228	249
	Winter	89	60	179	180
2018	Spring			52	506
	Summer	29	31	118	221
	Autumn	16	188	12	995
	Winter		73	51	496
N net nights		1908	575	1477	2994

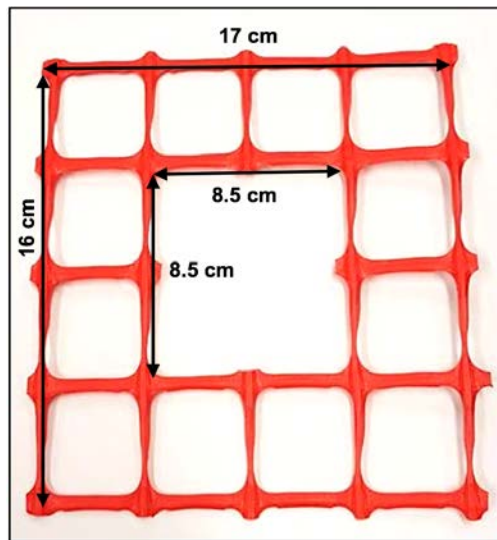


Figure 3-2. Plastic mesh choke placed at the entrance of the net to reduce by-catch of dabchicks in fyke nets.

3.4.3 Habitat survey using whakaweku and fyke nets

To analyse habitat-specific catch rates and the length frequency of kōura caught by fyke netting, baited fine-meshed fyke nets (n net nights = 292) that were either choked (n = 211) or unchoked (n = 81) were set at six sites at the western end of Lake Rotoiti, between 28 August and 12 September 2018. Sites included Te Weta Bay, Okere Inlet, Otaramarae, Te Arero Bay, Okawa Bay, and Southern Shoreline (Figure 3-3). Sites had differing numbers of nets in order to obtain a large enough kōura sample size. All fykes were baited with crushed mussels and a tin of sardines, and were set in the shallow water (<7 m deep) for about 24 h.

Whakaweku (Figure 3-4) were constructed of 10-12 fronds of freshly cut, mature woody bracken fern that were held together at the base with two cable ties, as used by Kusabs et al. (2015a). To set the whakaweku, braided nylon rope (1.5 m x 7 mm) was tied around the base of the stems between the cable ties, and attached by a shark clip to a 6-kg concrete Firth Gobi block as an anchor. A float was attached to the end of the nylon rope to aid retrieval.

Ten whakaweku were set in Te Weta Bay, a high catfish density site, and 10 in Otaramarae (Figure 3-5), a low catfish density site, at depths of between 0.5 and 1 m. Whakaweku were not deployed in areas of dense weed, as it can smother the bundles making retrieval difficult. In order to maximise the comparability of kōura

CPUE between sites, whakaweku were only set on sandy substrates, as habitat strongly influences kōura catch rates (i.e., Devcich 1979; Kusabs et al. 2015a). Sandy sheltered bays were not common at the study sites, therefore whakaweku were placed in close proximity to one another, between 6 and 25 m apart.

Whakaweku were left for 1 month before their first collection, and were then reset a further two times, 3 and 5 months after their initial deployment. On retrieval, a kōrapa (landing net) was slid under the whakaweku to collect invertebrates and fish. The whakaweku was shaken vigorously to dislodge its contents onto the kōrapa for counting and measurement.

Numbers of fish and invertebrates (i.e., kōura, dragonfly larvae, damselfly larvae, and snails) were recorded for whakaweku catches. For fyke net catches, only fish and kōura were recorded, as smaller invertebrates were not captured. Catfish fork length, kōura orbital-carapace length (OCL), and sex, were recorded from captures between 28 August 2018 and 12 September 2018. All species, except catfish, were released after counts were made. Catfish were euthanised as per Biosecurity Act 1993, Sections 52 & 53 requirements.

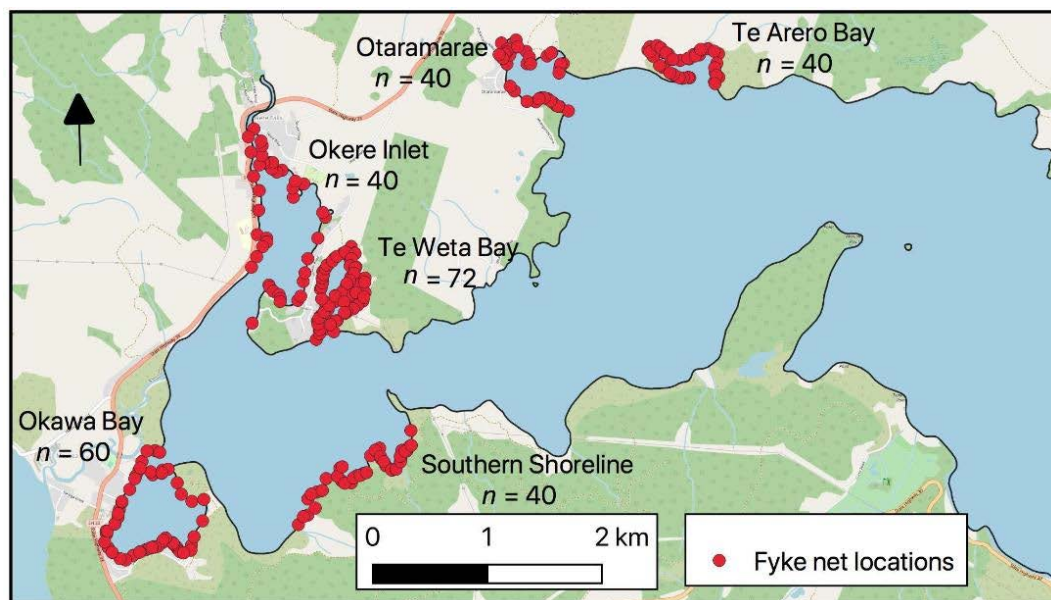


Figure 3-3. Location and number of fine-meshed fyke nets (n net nights = 292) set at the six study sites between 28 August and 12 September 2018 used for the habitat survey.



Figure 3-4. Photos of conditioned whakaweku (fern bundle). A. deployed whakaweku in the shallows (Photo: D. Bach, Te Arawa Lakes Trust); B. whakaweku on a kōrapa (landing net); C. whakaweku sitting on the bank with a Gobi block and a float attached.

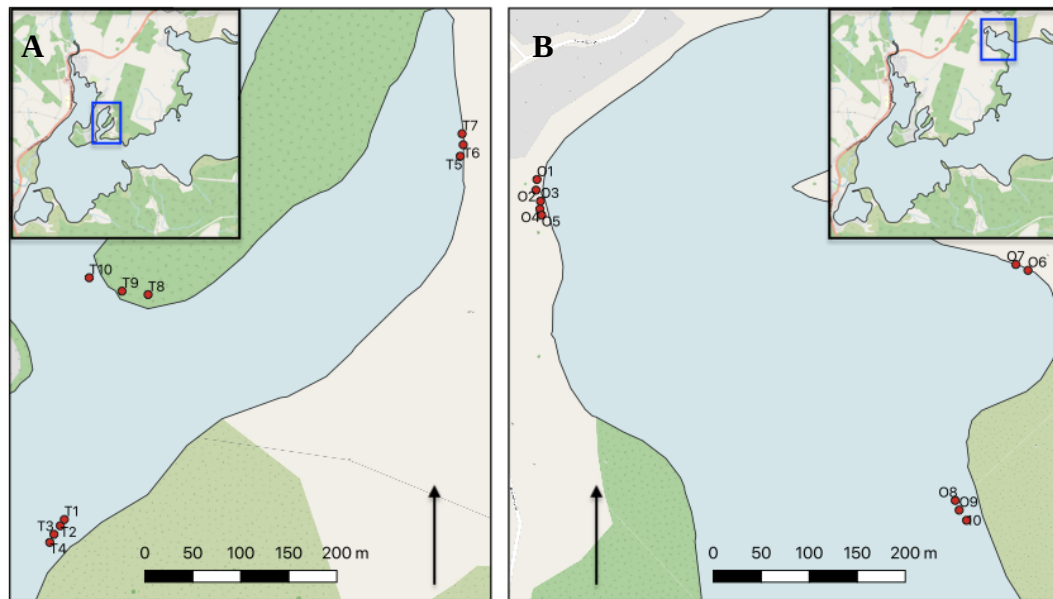


Figure 3-5. Location of whakaweku set in A. Te Weta Bay ($n = 10$) and B. Otaramarae ($n = 10$) in Lake Rotoiti.

3.4.4 Habitat characteristics

During the habitat survey, habitat in the vicinity of the fyke net or whakaweku was assessed to determine whether habitat characteristics had an observable effect on kōura and fish catch rates. This included dominant substrate type, macrophyte

density, and in-lake vegetation. The dominant substrate type directly under the fyke net or whakaweku was determined by pushing a long stick into the ground to gauge compactness, followed by a visual assessment to determine rough particle size. The presence of exotic macrophytes around the entrance to the net or distance to the whakaweku was noted. Aquatic macrophytes were classified as present when the macrophyte bed covered the entrance to the net, or absent when macrophytes were sparse or not in close proximity to the net. In-lake vegetation was classified as present when submerged vegetation was in close proximity (<3 m) to the fyke net or whakaweku.

3.4.5 Water characteristics

Water characteristics including dissolved oxygen, temperature, and pH, were measured on five occasions during the independent netting survey between 7 June 2018 and 8 October 2018. Measurements were made using YSI digital multimeters and a hand-held pH meter from approximately 20 cm below the surface. For the sites with whakaweku, water temperature was recorded every 15 minutes using a HOBO MX2202 temperature logger attached to a length of rope on to the same Gobi block as the whakaweku, with a float attached to keep it suspended approximately 30 cm from the lake bed.

3.4.6 Tank trial to assess the effectiveness of whakaweku in mediating kōura predation by catfish

Kōura ($n = 136$, OCL range 5.5-26.0 mm) were obtained from lakes Rotoiti and Rotorua using fine-meshed fyke nets and whakaweku, with permission from the Te Arawa Lakes Trust and the Komiti Whakahaere. Kōura <26.0 mm OCL were selected for the experiments as it was assumed that they would be the most vulnerable to predation by catfish, and the size most likely to be encountered in lake shorelines where catfish and kōura co-exist.

Catfish were collected using overnight fyke netting from University of Waikato campus lakes on 1 June 2018. Catfish >200 mm were retained for trials ($n = 16$, fork length range 216-267 mm), as Barnes (1996) found catfish >200 mm FL contained a greater proportion of kōura in their stomachs, suggesting they would be

capable of consuming kōura. Catfish were held for at least 1 week prior to the trials starting to allow for acclimation.

Tank trials were run using four 1,425-L concrete tanks (1.85-m diameter x 0.53-m high). Strips of polyethylene plastic (40-cm wide x 0.2-cm thick) were placed over the rim of the tank and secured using duct tape to prevent the kōura from escaping. Tanks were supplied with a continuous flow of oxygen and dechlorinated tap water. The water level of the tanks was moderated to ~0.3 m high to give a volume of 810 L, controlled with rotatable overflow pipes. Each tank had a fitted lid, consisting of a metal frame with two layers of white and green shade cloth. Tank water temperature was recorded every 15 minutes using HOBO MX2202 loggers.

Before placing kōura into the allocated tank, they were measured to the nearest 0.1 mm for orbital-carapace length (OCL; Figure 3-6), sex was determined, and the number of pincers was recorded. For the first experiment (experiment one), kōura weights and the number of legs were also recorded. Catfish were measured for fork length and weighed to the nearest 1.0 g. Catfish were not reused in subsequent trials in order to avoid any learned behaviour from previous trials. Kōura were reused in successive trials to minimise the number required.



Figure 3-6. Measuring kōura orbital-carapace length (OCL) using digital callipers (Photo: A. Pearson, University of Waikato).

3.4.6.1 Experiment one

Experiment one consisted of four treatments comprising (i) cobbles with catfish, (ii) cobbles without catfish, (iii) whakaweku with catfish, and (iv) whakaweku without catfish (Figure 3-7). Each of the tanks had 20 kōura (equivalent of 7.4 kōura m⁻²), and catfish tanks each contained three catfish. The experiments ran for 2

weeks beginning 2 July 2018. Catfish and kōura were fed bloodworms (tubificids) every 2 days.

A total of 40 cobbles were placed in each tank of mean diameter 81.4 (± 13.1 mm, 1 SD), in a double layer to provide crevices for kōura refuge. For the treatments with whakaweku, seven fronds of 1-day-old fern were bundled together, then submerged to condition for 2 days, before being placed on top of the cobble pile. All tanks were equipped with a polyethylene pipe (630 mm x 100 mm) for catfish refuge. Mean water temperature (± 1 SD) in the tanks was $10.3 \pm 2.5^\circ\text{C}$ and the temperature range was $4.2\text{-}15.4^\circ\text{C}$.



Figure 3-7. Images of the tank setup during experiment one. A. tank setup showing the cobble only treatment; B. tank setup showing the cobble + whakaweku treatment.

3.4.6.2 Experiment two

Experiment two consisted of four treatments including (i) no whakaweku with catfish, (ii) no whakaweku and no catfish, (iii) whakaweku with catfish, and (iv) whakaweku without catfish. Each of the tanks contained 10 kōura (equivalent of 3.7 kōura m^{-2}), and three catfish. The experiments ran for 3 days starting on 15 October 2018. Catfish were starved for 6 days (last fed on the 8 October 2018) leading up to the experiment and placed in an outdoor tank 2 days before the experiment to acclimatise. No food was added to the tanks due to the short duration of the experiment. Mean water temperature (± 1 SD) in the tanks was $15.3 \pm 1.2^\circ\text{C}$ and the temperature range was $12.3\text{-}23.6^\circ\text{C}$.

3.4.7 Data analysis

Effects of net type (i.e., fine or coarse-meshed, choked or unchoked entrance) on species catch rates was analysed using a two-way ANOVA. If there was no significant interaction in catch rates between mesh size and choke status, a one-way ANOVA of catch rate for each main effect was used to determine where there are differences in catch rates. Catfish length frequencies in Te Weta Bay were analysed to determine if the removal of large catfish (>200 mm FL) differed between 2016-2017 and 2018 with a one-way ANOVA.

The effects of catfish density and time on kōura and fish catch rates in unchoked fine-meshed fyke nets, was analysed using a two-way ANOVA. To test for relationships between species catch rates for the different netting combinations, a Shapiro–Wilk’s test was performed in Statistica (version 13.2) to test for normality and a Levene’s test for the homogeneity of variances. Because the data was found to be non-parametric, species catch rates were analysed using Spearman rank-order correlation to determine the association between the different species for net combinations. The seasonal effects on species catch rates was analysed using one-way ANOVAs.

Species catch rates in fine-meshed fyke nets set between 28 August and 12 October 2018 were compared against habitat characteristics using a two-way ANOVA. Differences in kōura and fish catch rates between sites and methods was explored using one-way ANOVAs in R. Unless otherwise stated, all analyses were performed in R statistical software version 3.4.1; $\alpha = 0.05$ was used as the critical P value.

3.5 Results

3.5.1 Routine catfish monitoring

3.5.1.1 Effects of mesh size and net chokes on species' catches

Mean catch per unit effort (CPUE) for each of the netting combinations (i.e., coarse and fine-meshed nets with choked and unchoked entrances) were compared for fish species and kōura. Not all species had the same number of observations, due to some smaller fish species not being recorded at the start of the netting programme. Mesh type and choking status had a significant effect on the catch rates of bullies, kōura, goldfish, and kōaro (Table 3-2). Fine-meshed unchoked nets caught the highest numbers of fish and kōura (mean all species combined 224.6 individuals net⁻¹ night⁻¹), while the least amount were caught in coarse-meshed choked nets (mean all species combined 14.2 individuals net⁻¹ night⁻¹). Coarse-meshed fyke nets caught significantly more longfin eels (ANOVA $P < 0.05$; Table 3-3), and significantly fewer bullies, kōura, goldfish, catfish, smelt, and kōaro, than fine-meshed fyke nets. Coarse-meshed fyke nets had similar mean catches of trout as fine-meshed fyke nets. Choked nets caught significantly fewer bullies, kōura, and goldfish (ANOVA $P < 0.001$), and significantly more longfin eels (ANOVA $P < 0.05$). Choking did not have an effect on the mean CPUE of catfish, smelt, trout, or kōaro (ANOVA $P > 0.05$).

Table 3-2. Mean catch per unit effort (CPUE) and the total number of net-nights for kōura and fish caught in fyke nets set in Lake Rotoiti between March 2016 and April 2018. Total number of observations refers to the number of fyke nets, which we have species catch data for. P values refer to the interaction term of a two-way ANOVA for coarse or fine mesh size and choked or unchoked entrance. Significant values ($P < 0.05$) are marked in bold.

Species	CPUE (mean number net ⁻¹ nigh ⁻¹)				Number of net-nights	<i>P</i> value
	Coarse mesh		Fine mesh			
	Unchoked	Choked	Unchoked	Choked		
Bullies	10.2	6.9	165.9	96.0	6954	<0.001
Kōura	2.9	2.7	6.6	3.3	6933	<0.001
Goldfish	1.9	1.0	18.0	9.5	6933	<0.001
Smelt	1.8	0.6	26.7	26.0	6933	0.966
Catfish	0.5	2.9	7.2	9.6	6681	1.000
Trout	0.021	0.019	0.055	0.012	6649	0.249
Kōaro	0.048	0.026	0.173	0.267	6553	0.029
Longfin eel	0.017	0.024	0.007	0.016	5807	0.745

Table 3-3. Mean catch per unit effort (CPUE) for kōura and fish in fyke nets set in Lake Rotoiti between March 2016 and April 2018 using fine-meshed and coarse-meshed nets, unchoked and choked nets with *P* values. Significant values (*P* < 0.05) are marked in bold.

Species	CPUE (mean number net ⁻¹ night ⁻¹)					
	Mesh type		<i>P</i>	Choking status		<i>P</i> value
	Coarse mesh	Fine mesh		Unchoked	Choked	
Bullies	9.3	119.1	<0.001	87.3	81.7	<0.001
Kōura	2.8	4.4	<0.001	4.6	3.2	<0.001
Goldfish	1.6	12.3	<0.001	9.6	8.1	<0.001
Catfish	1.1	8.8	<0.001	3.4	8.5	0.209
Smelt	1.3	26.2	<0.001	18.2	21.9	0.870
Kōaro	0.043	0.236	<0.001	0.103	0.228	0.170
Trout	0.021	0.026	0.453	0.036	0.013	0.204
Longfin eel	0.019	0.013	0.010	0.013	0.017	0.029

3.5.1.2 Kōura and fish catch rates with site and time and the effects of catfish

Catch rates of fish and kōura in choked and unchoked fine-meshed fyke nets set between 2016 and 2018 were grouped by catfish density (i.e., high, medium, low density, or no catfish) and year, to observe CPUE trends and to determine if catfish had an association with species' catch rates. Mean species catch rates in fine-meshed fyke nets by site and year can be found in Appendix 1. Due to differences in catch rates between coarse and fine-meshed fyke nets (Table 3-4), only fine-meshed fyke nets (*n* net nights = 4471) were used for this analysis. Choked nets were also included in the analysis as differences in species CPUE between choked and unchoked fyke nets was less than that of mesh size. Catfish CPUE has increased in Lake Rotoiti over the past three years, most notably in Te Weta Bay, where catch rates have increased from 1.1 ± 2.3 (mean $\pm$ 1 SD) in 2016 to 63.7 ± 248.1 in 2018 (Table 3-5). The number of sites where catfish were detected also increased. Considering all net types, catfish were found at six sites 2016 and 11 sites in 2018, showing a range expansion (Figure 3-8). Kōura CPUE has declined significantly (ANOVA *P* < 0.001) in Lake Rotoiti over the same period, including the sites without catfish (Table 3-5). Across all sites, kōura catch rates declined from 10.6 kōura net⁻¹ night⁻¹ in 2016, to 5.4 kōura net⁻¹ night⁻¹ in 2017 and 3.2 kōura net⁻¹ night⁻¹ in 2018. Kōura CPUE was negatively associated with catfish CPUE, with the highest kōura CPUE at the sites without catfish. Bully and goldfish catch rates were positively associated with catfish, while kōaro, smelt and longfin eel catch rates were negatively associated with catfish.

Table 3-4. Mean catfish catch per unit effort (CPUE) for all sites in Lake Rotoiti for all netting years combined, 2016, 2017 and 2018 netting years, using choked and unchoked and fine and coarse meshed fyke nets, and their allocated catfish density class. Number of nets refers to the total number of fine-meshed fyke nets set between 2016 and 2018. 1 SD in brackets. * Only one fine-meshed fyke net was set in the Ohau Channel in 2017.

Catfish density	Site	CPUE (catfish net ⁻¹ night ⁻¹)				<i>n</i> nets
		All years	2016	2017	2018	
High	Te Weta Bay	15.58 (119.89)	1.10 (2.29)	3.49 (39.53)	63.70 (248.08)	2078
Medium	Okere Inlet	5.93 (28.57)	0.04 (0.23)	0.10 (0.36)	17.48 (47.26)	863
	Outside Te Weta Bay	2.12 (10.47)	0.10 (0.50)	0.05 (0.26)	11.37 (22.45)	524
Low	Ohau Channel	1.69 (6.61)	0	0*	1.75 (6.72)	913
	Outside North	1.26 (6.98)	0.07 (0.34)	0.03 (0.21)	3.07 (10.79)	447
	Okawa Bay	0.96 (5.04)	0	0.05 (0.25)	2.12 (7.43)	477
	Southern Shoreline	0.84 (4.46)	0.02 (0.15)	0.07 (0.27)	2.26 (7.27)	622
	Delta	0.50 (1.98)	0	0	0.64 (2.22)	300
	Otaramarae	0.05 (0.31)	0.01 (0.10)	0.01 (0.10)	0.15 (0.51)	278
	Mid-Lake	0.05 (0.27)	0	0	0.13 (0.43)	156
	South	0.02 (0.18)	0	0	0.17 (0.58)	122
None	Eastern Lake	0	0	0	0	56
	Te Arero Bay	0	0	0	0	118

Table 3-5. Mean kōura and fish catch per unit effort (CPUE) and the total number of unchoked and choked fine-meshed fyke nets set in Lake Rotoiti between 2016 and 2018. Two-way ANOVA *P* for catfish density, year and the interaction between catfish density and year. Significant values (*P* < 0.05) are marked in bold.

Catfish density	Year	CPUE (mean number net ⁻¹ night ⁻¹)								<i>n</i> nets
		Catfish	Kōura	Bullies	Goldfish	Smelt	Kōaro	Trout	Longfin eel	
High	2016	0.94	4.8	145.4	6.5	1.1	0	0.014	0	71
	2017	4.82	2.3	204.4	18.8	9.4	0.03	0.005	0.001	776
	2018	65.27	0.9	106.6	19.9	3.6	0.2	0.01	0	407
Medium	2016	0	13.5	137.7	15.8	13.9	0	0	0.023	44
	2017	0.07	8.6	108.5	18.4	19.9	0.29	0.053	0.014	435
	2018	16.66	6.3	115.7	14.7	42.4	0.21	0.012	0.038	346
Low	2016	0	14.2	75.8	6.2	6.7	0	0	0.014	71
	2017	0.04	6.5	121.2	12.3	39.3	0.25	0.101	0.007	587
	2018	1.85	2.9	88.3	5.9	36.7	0.30	0.014	0.019	1627
None	2016	0	12.3	44.9	1.4	13.7	0	0	0	13
	2017	0	18.8	78.0	13.1	13.3	3.48	0	0	23
	2018	0	7.1	61.5	8.3	7.1	0.63	0	0.014	71
<i>P</i> catfish density		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.730	<0.001	
<i>P</i> year		<0.001	<0.001	<0.001	0.008	0.388	0.036	0.170	0.018	
<i>P</i> interaction		<0.001	<0.001	<0.001	<0.001	0.598	0.005	0.730	0.308	

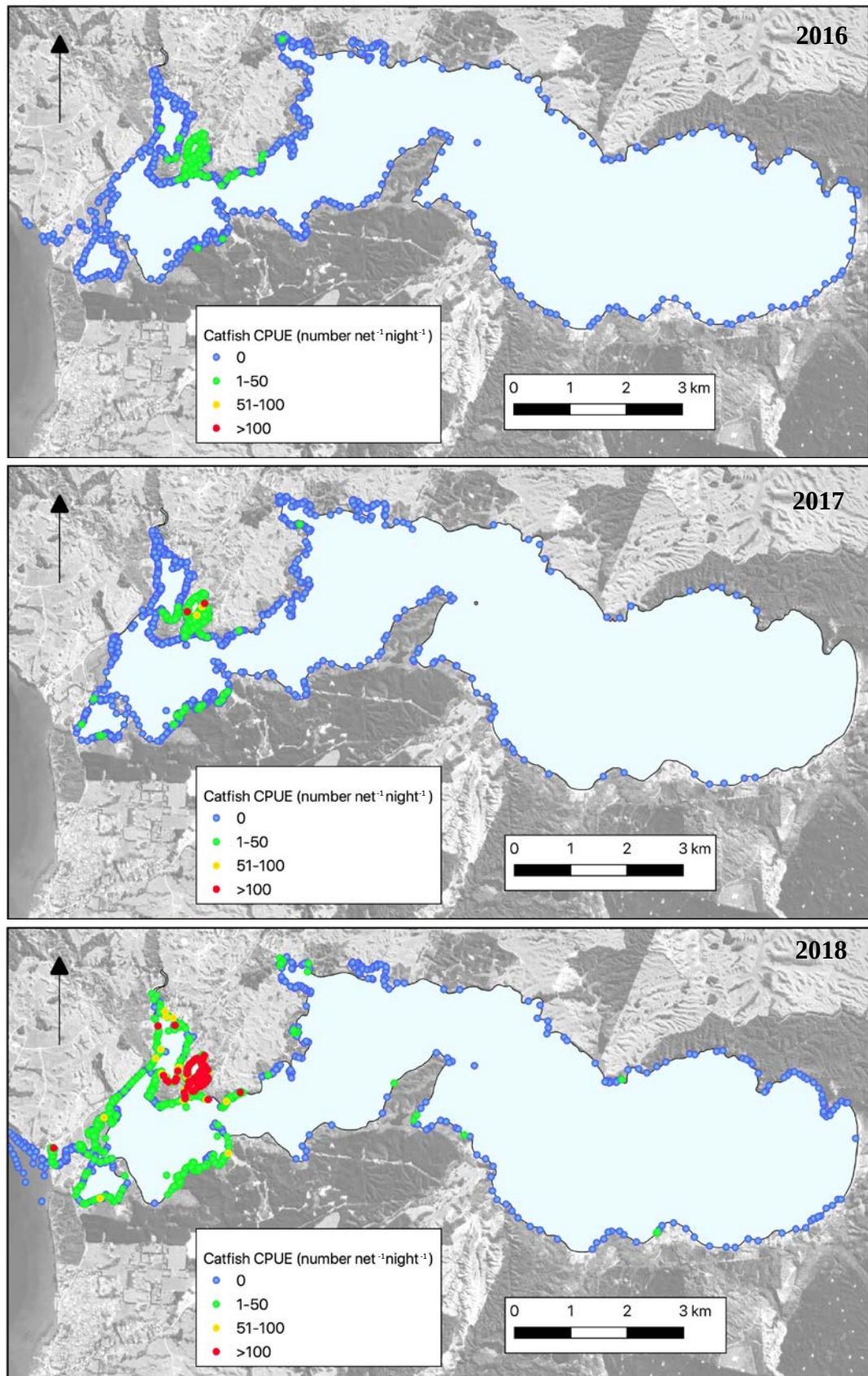


Figure 3-8. Catfish catch rates (number net⁻¹ night⁻¹) for all net types set in Lake Rotoiti between 2016-18 during routine monitoring for catfish.

3.5.1.3 Relationship between catfish, native fish and kōura catch rates

Fyke netting CPUE of catfish, bullies, kōura, kōaro, goldfish, longfin eel, smelt and trout were compared against each other to establish relationships between species for choked and unchoked fine-meshed fyke nets (Table 3-6). Catches of longfin eels and trout were too low to make any meaningful comparisons, with >98% of catches being zero. Kōura CPUE was negatively associated with catfish ($r = -0.180$), with the most negative significant relationship of any species. Kōura were also positively associated with catches of goldfish, kōaro, smelt and bullies. Catfish CPUE was positively associated with bully and goldfish catches and negatively associated with catches of smelt. Catfish CPUE had no effect on kōaro catches. Season had a significant effect on catch rates of all species excluding trout (Table 3-7), with the lowest catch rates occurring in the spring for catfish and winter for kōura.

Table 3-6. Spearman rank order correlations for species' catch rates in choked and unchoked fine-meshed fyke nets. Significant correlations ($P < 0.05$) are marked in bold.

Species	Catfish	Bullies	Kōura	Kōaro	Goldfish	Smelt
Catfish	1.000	0.116	-0.180	0.010	0.257	-0.133
Bullies	0.116	1.000	0.060	-0.030	0.485	0.246
Kōura	-0.180	0.060	1.000	0.101	0.106	0.111
Kōaro	0.010	-0.030	0.101	1.000	0.008	0.054
Goldfish	0.257	0.485	0.106	0.008	1.000	0.108
Smelt	-0.133	0.246	0.111	0.054	0.108	1.000

Table 3-7. Mean seasonal fish and kōura catch per unit effort (CPUE) in Lake Rotoiti using all fyke nets types, with the number of observations for each species and associated P values comparing CPUE between seasons. Significant values ($P < 0.05$) are marked in bold.

Species	CPUE (mean number net ⁻¹ night ⁻¹)				Number of observations	P value
	Autumn	Winter	Spring	Summer		
Bullies	49.2	48.4	126.8	136.4	6553	<0.001
Smelt	21.3	16.8	31.4	12.3	5807	0.044
Catfish	8.2	4.9	2.0	8.1	6954	0.014
Goldfish	5.9	6.4	9.6	15.0	6649	<0.001
Kōura	3.1	2.9	3.2	6.7	6681	<0.001
Kōaro	0.193	0.384	0.099	0.001	6933	<0.001
Trout	0.040	0.017	0.019	0.011	6933	0.456
Longfin eel	0.022	0.007	0.010	0.017	6933	0.001

3.5.1.4 Catfish length frequencies in Te Weta Bay

Lengths of catfish from Te Weta Bay between May 2016 and September 2018, shows that successful recruitment of juveniles occurred in the lake during this time (Figure 3-9). This was particularly apparent in February 2018, where the number of

juveniles caught were higher than the same time period, the previous year. Large catfish (>200 mm FL) appeared to be absent from Te Weta Bay from January and July 2017, and from February 2018 on; however, the number of large catfish caught during 2016-17 and 2018 years was not significantly different.

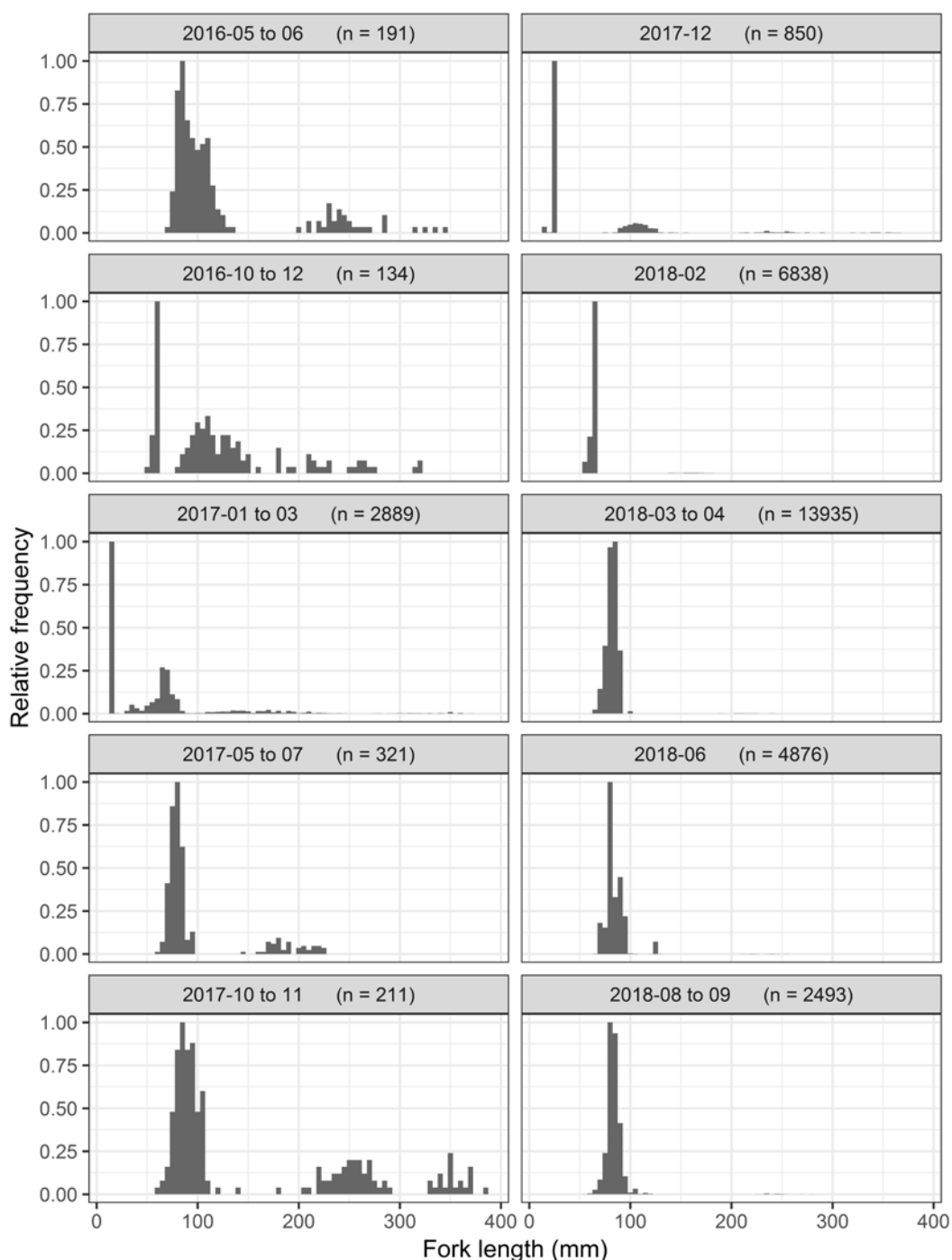


Figure 3-9. Length frequencies of catfish (n catfish = 32,738) caught in Te Weta Bay between March 2016 and September 2018 by fyke netting (n net nights = 5,812). Relative frequency scales are normalised the modal length to 1.

3.5.2 Habitat survey using whakaweku and fyke nets

3.5.2.1 Water characteristics

Mean oxygen saturation across the sites was $98.0 \pm 12.6\%$ (mean $\pm$ 1 SD), and site means ranged between 93.3-103.4% (Table 3-8). Mean water temperatures ranged between 11.4-13.7°C, and median water pH values were 7.3 and 7.4. Mean water temperatures in Otaramarae and Te Weta Bay were 11.5°C in winter, reaching a maximum daily temperature of 15.3°C in May and October 2018.

Table 3-8. Mean dissolved oxygen concentrations, water temperatures (1 SD in brackets), and median pH values for the six study sites in Lake Rotoiti. Spot measurements were taken between 7 June 2018 and 8 October 2018 at the time of sampling.

Site	Mean dissolved oxygen (%)	Mean dissolved oxygen (mg L ⁻¹)	Mean temperature (°C)	Median pH
Okawa Bay	96.8 (5.1)	10.5 (0.6)	11.4 (0.3)	7.3
Okere Inlet	98.6 (0.8)	10.6 (0.2)	12.1 (0.5)	7.3
Otaramarae	95.0 (12.4)	9.9 (1.3)	13.1 (1.1)	7.4
Southern Shoreline	100.8 (8.1)	10.6 (0.8)	13.7 (1.5)	7.3
Te Arero Bay	93.2 (5.7)	9.8 (0.5)	12.7 (1.1)	7.4
Te Weta Bay	103.4 (6.3)	10.9 (0.4)	12.7 (1.3)	7.3

3.5.2.2 Effects of habitat on kōura and fish catch rates in fyke nets

Fine-meshed fyke nets were set in the habitat survey between 28 August and 12 September 2018. For this survey, choking of fine-meshed fyke nets did not have a significant effect on kōura CPUE, therefore, netting data for choked and unchoked nets was combined. Substrate was the only habitat variable to have a significant effect on kōura CPUE (ANOVA $P < 0.001$; Table 3-9). Mean kōura catch rates ranged from 1.42 kōura net⁻¹ night⁻¹ on mud substrates to 9.16 kōura net⁻¹ night⁻¹ on broken rock substrates (Figure 3-10). Bedrock, sand, and silt, had similar mean catch rates. The presence of macrophyte beds around the entrance to the net (Table 3-10) and in-lake vegetation and wood, did not have a significant effect on the number of kōura caught.

The effects of substrate and dense macrophyte beds around the entrance of the net on fish catch rates (excluding trout and longfin eels) were also examined. CPUE of catfish and goldfish were highest on mud, while bully and smelt catches were highest on sand, and kōaro catches were highest on silt. Significantly more catfish

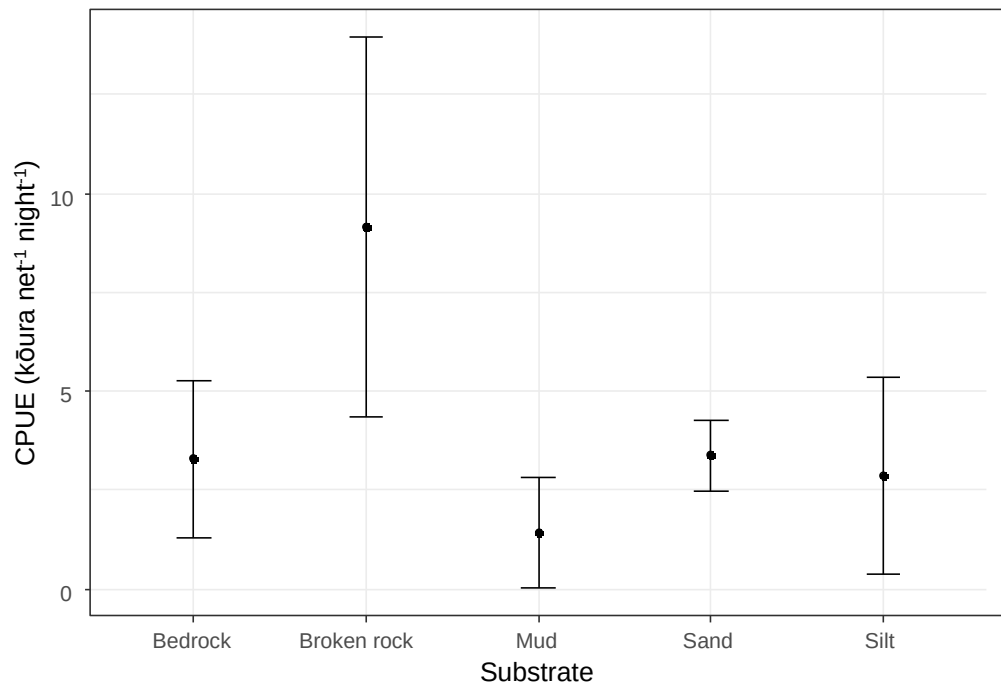
and goldfish were caught at sites with dense macrophyte beds than those without. Fewer bullies were caught at sites with dense aquatic macrophyte beds, while catches of smelt and kōaro were not significantly different between sites.

Table 3-9. Mean fish and kōura catch per unit effort (CPUE) on the different substrate types, using unchoked and choked fine-meshed fyke nets. 1 SD in brackets. Two-way ANOVA *P* for substrate, choked entry, and the interaction between substrate and choked entry are given. Significant values (*P* < 0.05) are marked in bold

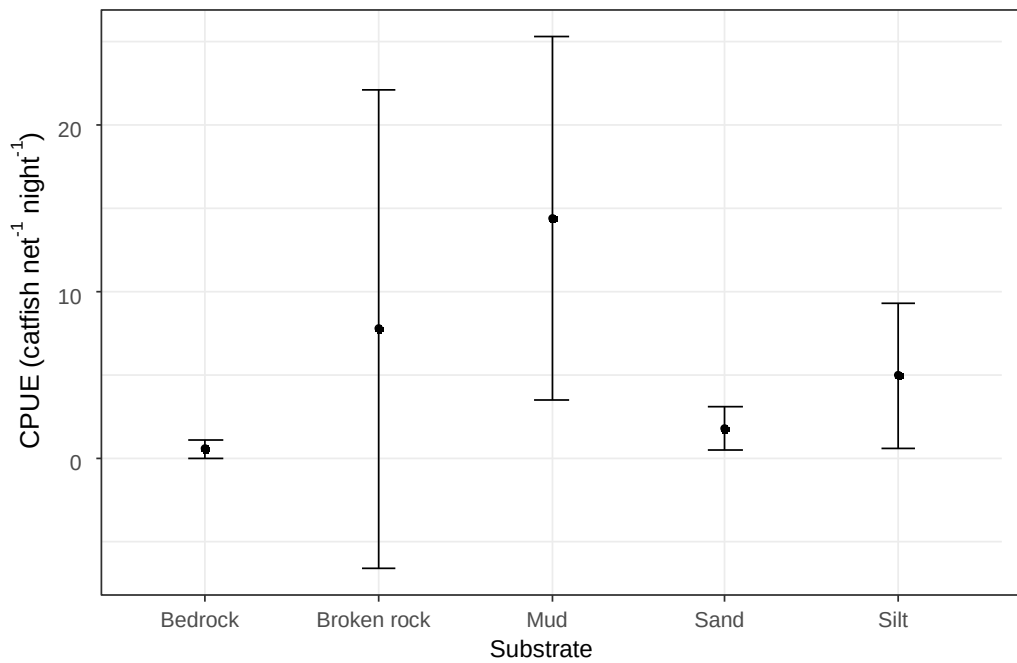
Substrate type	CPUE (mean number net ⁻¹ night ⁻¹)						<i>n</i> nets
	Kōura	Catfish	Goldfish	Bullies	Smelt	Kōaro	
Broken rock	9.2 (10.0)	7.7 (29.9)	7.8 (8.4)	59.3 (73.3)	7.3 (18.7)	0.105 (0.315)	19
Sand	3.4 (5.9)	1.77 (9.0)	13.4 (15.9)	153.9 (155.2)	79.0 (537.6)	0.301 (0.684)	173
Bedrock	3.3 (3.9)	0.5 (1.0)	6.9 (8.6)	90.6 (67.6)	34.4 (51.6)	0.059 (0.243)	17
Silt	2.9 (6.7)	4.9 (11.7)	16.3 (13.1)	139.5 (125.5)	18.2 (28.7)	0.600 (0.968)	30
Mud	1.4 (5.1)	14.4 (39.6)	20.4 (15.4)	120.9 (96.2)	14.6 (40.9)	0.226 (0.505)	53
<i>P</i> substrate	< 0.001	0.002	0.002	0.020	0.809	0.031	
<i>P</i> choked	0.773	0.968	0.448	0.030	0.059	0.964	
<i>P</i> interaction	0.466	0.182	0.6115	0.470	0.762	0.524	

Table 3-10. Mean fish and kōura catch per unit effort (CPUE) with and without dense macrophyte beds around the entrance to the net, using unchoked and choked fine-meshed fyke nets. 1 SD in brackets. Two-way ANOVA *P* for the presence of aquatic macrophytes, choked entry and the interaction between the presence of aquatic macrophytes and choked entry are given. Significant values (*P* < 0.05) are marked in bold.

Macrophyte density	CPUE (mean number net ⁻¹ night ⁻¹)						<i>n</i> nets
	Kōura	Catfish	Goldfish	Bullies	Smelt	Kōaro	
None/low	3.2 (5.4)	1.0 (4.4)	11.1 (14.4)	165.6 (157.0)	86.3 (547.8)	0.331 (0.758)	166
High	3.5 (7.3)	9.6 (30.2)	18.3 (15.2)	98.3 (92.6)	11.1 (42.7)	0.238 (0.513)	126
<i>P</i> macrophytes	0.554	<0.001	0.003	<0.001	0.050	0.990	
<i>P</i> choked or unchoked	0.910	0.990	0.918	0.029	0.023	0.677	
<i>P</i> interaction	0.629	0.752	0.351	0.167	0.189	0.449	



A. Kōura



B. Catfish

Figure 3-10. Mean catch per unit effort (CPUE) of A. *kōura* ($n = 976$) and B. catfish ($n = 1375$), caught in Lake Rotoiti by fyke netting over five different substrates between 28 August and 12 September. Error bars are 95% confidence intervals

3.5.2.3 Whakaweku catch rates

Water levels in Okawa Bay, Lake Rotoiti, varied between 279.0 and 279.3 m during the period of whakaweku deployment (Bay of Plenty Regional Council 2018b), meaning whakaweku were always submerged as they were set at depths between 0.5 and 1.0 m. Whakaweku caught a wide range of fish and invertebrate species, including dragonfly larvae, bullies, snails, kōaro, damselflies, gambusia (*Gambusia affinis*), goldfish, and kōura. Numbers of dragonflies, damselflies, and goldfish, were significantly higher (ANOVA $P < 0.05$) in Otaramarae than in Te Weta Bay, with no significant difference in the numbers of bullies, snails, kōaro, gambusia, and kōura between sites (Table 3-11). The effects of habitat and catfish densities on kōura whakaweku catches were not analysed, as too few kōura ($n = 21$) were caught over the sampling period to produce meaningful results. During sampling, two of the whakaweku set in Otaramarae were stolen and another tampered with.

Table 3-11. Whakaweku catch rates (whakaweku⁻¹) for three sampling occasions in A. Te Weta Bay and B. Otaramarae, showing the number of whakaweku, total number of individuals caught (n), mean catch per unit effort (CPUE), and CPUE ranges. 1 SD in brackets.

A. Te Weta Bay

Species	7 Jun-18			8 Aug-18			8 Oct-18		
	n	Mean CPUE	CPUE range	n	Mean CPUE	CPUE range	n	Mean CPUE	CPUE range
Snails	46	4.6 (2.5)	0-10	149	14.9 (8.9)	0-30	155	15.5 (6.9)	10-30
Bullies	30	3.0 (1.8)	1-5	75	7.5 (3.4)	3-13	136	13.6 (7.7)	5-25
Dragonfly	0	0	0	16	1.6 (3.0)	0-10	16	1.6 (1.4)	0-4
Kōaro	0	0	0	1	0.1 (0.3)	0-1	0	0	0
Damselflies	0	0	0	1	0.1 (0.3)	0-1	1	0.1 (0.3)	0-1
Gambusia	0	0	0	4	0.4 (0.7)	0-2	0	0	0
Kōura	0	0	0	5	0.5 (1.3)	0-4	0	0	0
Goldfish	0	0	0	0	0	0	0	0	0
<i>N</i> whakaweku	10			10			10		

B. Otaramarae

Species	7 Jun-18			8 Aug-18			8 Sep-18		
	n	Mean CPUE	CPUE range	n	Mean CPUE	CPUE range	n	Mean CPUE	CPUE range
Snails	23	2.3 (3.5)	0-10	55	6.1 (1.6)	0-10	221	27.6 (44.7)	1-100
Bullies	99	9.9 (8.8)	0-30	99	11.0 (9.0)	0-25	126	15.8 (8.2)	7-27
Dragonfly	35	3.5 (3.7)	0-10	110	12.2 (9.2)	2-26	29	3.6 (2.2)	1-7
Kōaro	1	0.1 (0.3)	0-1	0	0	0	0	0	0
Damselflies	0	0	0	6	0.7 (1.3)	0-4	20	2.5 (2.5)	0-7
Gambusia	0	0	0	0	0	0	0	0	0
Kōura	2	0.2 (0.4)	0-1	10	1.1 (1.3)	0-3	4	0.5 (0.8)	0-2
Goldfish	0	0	0	2	0.2 (0.4)	0-1	0	0	0
<i>N</i> whakaweku	10			9			8		

3.5.3 Kōura population metrics

Fyke nets caught 976 kōura over the 15-day sampling period across the six study sites (29 August to 12 September 2018). Mean CPUE ranged from 0.52 kōura net⁻¹ night⁻¹ in Okawa Bay to 8.28 kōura net⁻¹ night⁻¹ in Te Arero Bay (Table 3-12). In comparison to baited fyke nets, whakaweku caught far fewer kōura (21 individuals over a 5-month period; Table 3-13). Otaramarae had the highest kōura CPUE of the two sites (0.89 kōura whakaweku⁻¹), and kōura were captured on all three sampling occasions. Whakaweku set in Te Weta Bay caught kōura on only one occasion, during the August sampling period. For both sites, kōura catches using whakaweku peaked at 3-months soak time.

Site-specific mean kōura OCLs during the 15-day period ranged from 30.4 mm in Otaramarae to 39.2 mm in Okawa Bay, with kōura caught in Okawa Bay being significantly larger (ANOVA $P < 0.001$) than the other sites (Figure 3-11). Kōura caught using fyke nets ranged from 13.4 mm to 53.5 mm OCL, with the smallest kōura been caught in Te Arero Bay and largest on the Southern Shoreline. In comparison to fyke nets, kōura caught using whakaweku were significantly smaller (ANOVA $P < 0.001$), with a mean OCL of 15.0 mm. Sizes of the kōura caught in whakaweku ranged from 11.0 to 31.0 mm OCL, with the smallest and largest kōura caught in Otaramarae.

Fyke nets caught more males than females across all sites, with a male to female ratio of 3.5:1 ($n = 976$). The lowest proportion of females were in Te Weta Bay where 11.8% of the catch was female, while the highest proportion (26.9%) of females occurred in Te Arero Bay. Of the females caught using fyke nets, approximately half were in berry. The highest proportion of berried females were caught in Otaramarae, with 53.7% of all females in berry. In comparison, whakaweku male to female ratio was 1:1 ($n = 21$). All females caught in the whakaweku were not in berry.

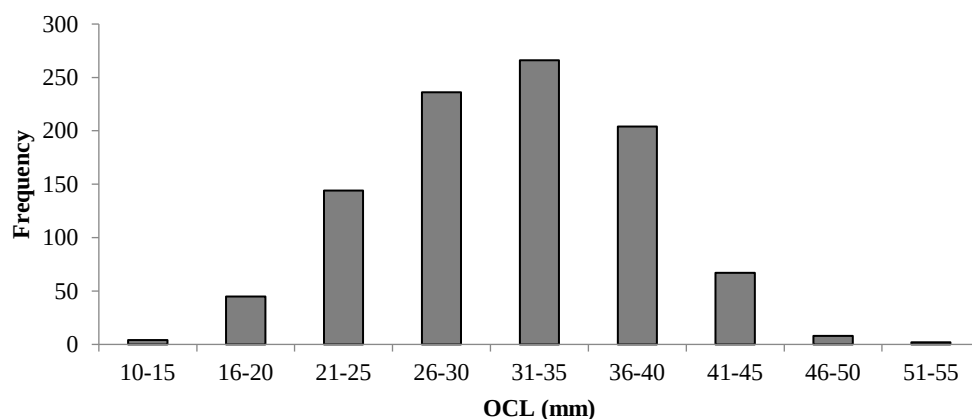
Table 3-12. Fine-meshed fyke netting data from the habitat survey sampled between 29 August and 12 September 2018, showing the total number of nets set, the percentage of nets that are choked, number of kōura, mean CPUE, mean OCL, OCL range, percentage of female kōura, percentage of female kōura in berry and the percentage of females with juveniles. 1 SD in brackets. Two-way ANOVA *P* value for interaction between OCL x site <0.001.

Site	Catfish density	Total number of nets set	Percentage of nets choked (%)	Number of kōura	Mean CPUE (number net ⁻¹ night ⁻¹)	Mean OCL (mm)	OCL range (mm)	Percent female (%)	Percent soft (%)	Percentage of females in berry (%)	Percentage of females with juveniles (%)
Te Arero Bay	None	40	82.5	331	8.3 (8.5)	31.5 (6.4)	13.4-46.0	26.9	5.1	55.1	1.1
Okere Inlet	Medium	40	65	235	5.9 (7.4)	31.3 (6.2)	15.0-45.0	18.3	5.1	46.5	0
Southern Shoreline	Low	40	65	166	4.3 (7.2)	31.8 (6.1)	17.0-53.5	19.3	4.2	40.6	3.1
Otaramarae	Low	40	80	162	4.1 (7.3)	30.4 (7.0)	14.0-45.0	25.3	4.9	53.7	0
Te Weta Bay	High	72	66.7	51	0.7 (2.0)	30.7 (6.5)	19.0-45.0	11.8	2	33.3	0
Okawa Bay	Low	60	76.7	31	0.5 (1.2)	39.2 (7.8)	23.0-52.0	12.9	3.2	50	0

Table 3-13. Whakaweku kōura catches at Te Weta Bay and Otaramarae on three sampling occasions. 1 SD in brackets.

Site	Catfish density	Sampling occasion in 2018	Number of whakaweku	Number of kōura	Mean kōura (whakaweku ⁻¹)	Mean OCL (mm)	OCL range (mm)	Percent female (%)	Percentage of females in berry (%)
Te Weta Bay	High	7-Jun	10	0	0				
		8-Aug	10	5	0.50	14.9 (2.7)	12.0-18.0	56	0
		8-Oct	10	0	0				
Otaramarae	Low	7-Jun	10	2	0.20	12.0 (0.1)	11.3-12.7	50	0
		8-Aug	9	10	1.11	15.3 (5.9)	11.0-31.0	60	0
		8-Oct	8	4	0.50	15.8 (2.5)	13.0-19.0	25	0

A. Length frequency of kōura ($n = 976$) caught in fine-meshed fyke nets (n net nights = 292) at six sites.



B. Length frequency of kōura ($n = 21$) caught in whakaweku at two sites ($n = 57$ whakaweku hauls).

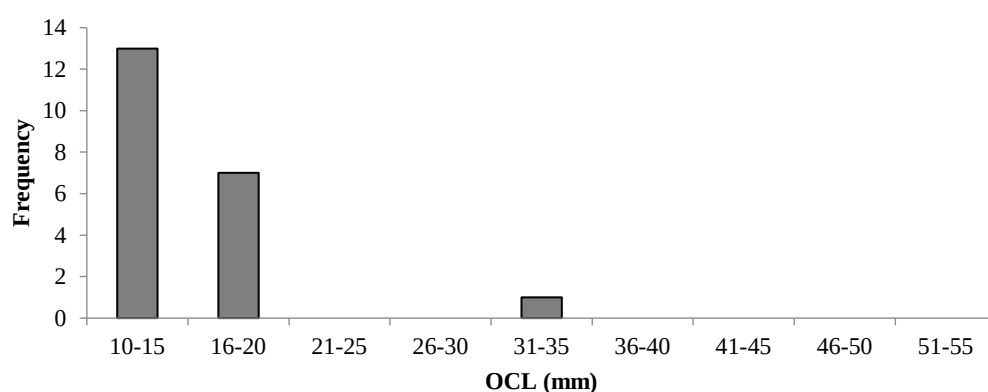


Figure 3-11. Length frequency of kōura caught in A. fine-meshed fyke nets set between August 28 and September 12, 2018 and B. whakaweku (fern bundles) set in Te Weta Bay and Te Karaka Bay, Lake Rotoiti between May and October 2018.

3.5.4 Effectiveness of whakaweku at reducing kōura predation

3.5.4.1 Experiment one

Overall kōura mortality was low (10%); of the 80 kōura used in experiment one, 72 remained at the end of the experiment, with two kōura lost from each tank. Kōura missing from the treatments without catfish were found to have died through cannibalism or illness, rather than predation. Kōura missing from the catfish treatments were not recovered, but catfish stomachs were dissected after the experiment, revealing empty stomachs with only hard remains of fish (e.g., vertebrae and otoliths) from feeding prior to capture. All catfish stomachs were

devoid of kōura and bloodworm remains. Mean kōura OCL at the start of experiment one was 15.6 ($\pm$ 4.9, SD) mm, with a size range of 5.5-25.3 mm (Table 3-14). Mean number of pincers, legs and kōura weights were similar at the start and end of the experiment. Kōura in the tanks were observed using the whakaweku and cobbles when provided, regardless of catfish presence.

Table 3-14. Mean kōura OCLs, OCL ranges, mean number of pincers, mean number of legs, mean weights, and gender ratios at the start and finish of Experiment one. 1SD in brackets.

Experiment	Mean OCL (mm)	OCL range (mm)	Mean number of pincers	Mean number of legs	Mean kōura weights (g)	Gender ratios (unknown :male: female)
Start	15.6 (4.9)	5.5–25.3	1.7 (0.4)	7.3 (0.9)	3.8 (2.8)	20:34:26
Finish	16.2 (4.2)	10.0–25.5	1.7 (0.4)	7.2 (1.1)	4.1 (2.9)	1:37:34

3.5.4.2 Experiment two

There was no kōura mortality during experiment two; all 40 kōura at the start of the experiment were present 3 days later at the end. Mean kōura size was 19.2 ($\pm$ 1.1, SD) mm OCL, with a size range of 14.0-26.0 mm OCL. All of the kōura had two pincers. The sex ratios of the kōura were 26:14 male: female. Kōura in the tanks could be observed raising their chelae in response to the catfish, and even attacked catfish nipping their tails and whiskers when they approached (Figure 3-12).



Figure 3-12. A kōura raising its chelae in response to catfish.

3.6 Discussion

The objective of this study was to understand the effects of catfish on kōura and native fish species, and to determine the effects of habitat on species' catch rates. This was approached by (i) analysing routine catfish fyke-net monitoring data for 2016-18 for trends in catch rates, and (ii) a habitat survey for kōura with fine-meshed fyke netting between 29 August and 12 September 2018. The habitat survey was conducted at sites with varying densities of catfish to obtain data on species catch rates, habitat types, and kōura metrics (e.g., sizes and sex ratios). Whakaweku (bundles of bracken fern) were also deployed at a high and low catfish density site, to enable further comparisons of kōura metrics. Lastly, a series of tank trials were performed to determine if whakaweku could be deployed in habitats where catfish and kōura co-exist to minimise predation.

3.6.1 Effects of mesh size and choked entrances on species catch rates

More fish and kōura were caught in fine-meshed fyke nets than in coarse-meshed nets. The lower catch rates in coarse-meshed nets can be attributed to smaller individuals escaping through the larger mesh. Choking of the nets also had an effect on the capture rates of bullies, goldfish, longfin eels, and kōura, with fewer individuals caught in choked nets. Choking did not have a significant effect on catfish catch rates. Chokes or by-catch reduction devices are often added to fishing gear to avoid the unwanted capture of non-target species (Broadhurst 2000). In this case, the addition of the choke was to avoid the capture of dabchicks, but adding the choke also reduced the catch rate of some fish species and kōura. It is not uncommon for chokes to lower the capture rates of targeted species in nets. For example, the addition of otter guards to eel fyke nets in Danish rivers significantly reduced legal sized eel and salmonid catch rates by 30% and 53-55%, respectively (Koed and Dieperink 2001). Unfortunately, chokes have not made a difference to dabchick by-catch and other solutions are being investigated (G. Ewart, BOPRC, pers. comm.).

3.6.2 Kōura and catfish catch rates

Data from fine-meshed fyke netting shows that mean catfish CPUE has increased in Lake Rotoiti between 2016 and 2018. The highest catch rates were in Te Weta

Bay, where mean catch rates have increased from 1.1 catfish net⁻¹ night⁻¹ in 2016 to 63.7 catfish net⁻¹ night⁻¹ in 2018. The number of sites where catfish have been detected has also increased from six sites in 2016 to 11 sites in 2018, encompassing the whole of the western end of the lake. Catfish catch rates in 2018 from Te Weta Bay were higher than in 2012-13 summer from Waihi, Motuoapa and Whakaipo Bay in Lake Taupo using unbaited fyke nets, which had a mean CPUE of 35.6 catfish net⁻¹ night⁻¹ (n net nights = 74; Department of Conservation 2013). Comparisons are somewhat compromised by the use of baits in Lake Rotoiti fyke nets, because bait increased catch rates of catfish and eels 6-fold in Waikato drains (ANOVA $P = 0.036$; Bannon 2001). Catfish expansion in Lake Rotoiti is largely inevitable, with the size, range, and density of catfish likely to increase into the future (Hicks and Allan 2018). This is because the lake has abundant food resources (e.g., kōura and bullies) and has adequate catfish habitat, including dense stands of aquatic macrophytes, some rocky outcrops (Barnes 1996), large areas that are <6 m depth (Hicks and Allan 2018), and a number of sheltered bays.

Following catfish detection in 2016, mean kōura catch rates have declined in Lake Rotoiti from 10.6 kōura net⁻¹ night⁻¹ in 2016 to 4.2 kōura net⁻¹ night⁻¹ in 2018. This is consistent with long-term monitoring over the last decade (Kusabs and Taiaroa 2015). Potential factors causing kōura decline were identified as catfish, changes in physicochemical conditions following the installation of the Ohau Channel diversion wall in July 2008, and prolific macrophyte growth (Kusabs and Taiaroa 2015). Catfish are most likely to affect kōura abundance in littoral habitats (<10 m deep) where both catfish and kōura co-occur (Kusabs and Taiaroa 2015). The Ohau Channel diversion wall was installed to direct nutrient-rich water from Lake Rotorua into Okere Inlet and down the Kaituna River rather than into the deep basins of Lake Rotoiti (Kusabs 2016).

The installation of the Ohau Channel diversion wall could have influenced kōura catch rates in a number of ways. When the wall was installed, water clarity greatly improved in both Lake Rotoiti and Lake Rotorua, lowering primary production in Lake Rotoiti and potentially reducing the food availability for kōura (Kusabs 2016). Increased water clarity may have also facilitated the spread of invasive macrophytes in the lake (Kusabs 2016), which could exclude kōura from the littoral zone (Hessen et al. 2004). In addition, redirecting the water could have minimised underflow to

the western end of Lake Rotoiti during periods of stratification, potentially reducing mixing and dissolved oxygen dispersion during these times (I. Kusabs, Ian Kusabs and Associates and C. McBride, University of Waikato, pers. comm.).

3.6.3 Relationship between catfish, fish and kōura catch rates

Kōura CPUE was negatively correlated with catfish CPUE, suggesting that catfish reduced or competitively excluded kōura from some of the lakes littoral zones through predation or competition. Habitat preferences of catfish also differ to those of kōura, and may be contributing to the negative relationship. Catfish typically prefer shallow depths (<12 m), and habitats that are muddy or weedy (Scott and Crossman 1973). Data from this study supports this, with significantly more catfish caught on muddy substrates and sites with dense aquatic macrophytes. In contrast, kōura have been positively associated with rocky habitats and deeper waters (Devcich 1979), and negatively associated with weedy (Hessen et al. 2004) and muddy habitats (Devcich 1979). Similar relationships were observed in this study, with broken rock substrates resulting in higher catch rates of kōura than nets set over sand, silt, mud and bedrock. Catch rates of goldfish and catfish were positively correlated, with goldfish having similar habitat preferences to catfish of muddy and weedy habitats (Collier and Grainger 2015).

3.6.4 Comparison of kōura size between sites

Okawa Bay had the largest kōura OCL (mean 39.2 mm, minimum 23.0 mm) of the sites, mostly because no juveniles were caught there. A possible reason why no juveniles were caught in Okawa Bay is because the bay has limited structural habitat (e.g., wood and cobbles). Large kōura are likely to dominate the limited habitat in the bay (personal observation) and could be excluding juveniles, making them vulnerable to predation (Bergman and Moore 2003; Stewart and Tabak 2011). Sizes of kōura at the other five sites were similar, with mean OCLs ranging from 30.4 mm in Otaramarae, to 31.8 mm on the Southern Shoreline. Compared to fyke nets, whakaweku caught smaller kōura, and sizes of kōura were not different between the sites.

3.6.5 Evaluation of whakaweku and baited fine-meshed fyke nets as kōura capture techniques in lake littoral zones

Assessing kōura abundances and size structures can be difficult, due to the lack of representative sampling methods (Rabeni et al. 2008; Kusabs and Quinn 2009). In this study, we used two different methods to sample kōura populations in Lake Rotoiti, including baited fyke nets and whakaweku. When any capture method is used, the general assumption is that it accurately depicts the population size and characteristics (e.g., sex ratios, size classes, berried females; Rabeni et al. 2008). It is also important to understand the technique's limitations (Rabeni et al. 2008). Fishing of Lake Rotoiti found baited fine-meshed fyke nets were biased towards the capture of larger individuals and male kōura. Other studies have also found baited traps to be biased towards the capture of males (Devcich 1979; Capelli and Magnuson 1983), with one study in Lake Rotoiti catching male to females at a ratio of 2.1:1 (n kōura = 4207; Devcich 1979). Selectivity towards larger individuals could be due to the dominance hierarchy in kōura, where larger individuals are more dominant, increasing their chances of winning agonistic encounters, gaining access to high quality habitat, food, and space (Bergman and Moore 2003; Stewart and Tabak 2011). Males are also typically more aggressive than females (Bruski and Dunham 1987).

Whakaweku caught an even sex ratio of kōura (10:11 male to females, M:F), compared to baited fyke nets that were biased towards the capture of male kōura (761:215 M:F). Whakaweku sex ratios were similar to what tau kōura set in Lake Rotoiti caught (817:647 M:F; Kusabs 2015). Whakaweku also caught significantly smaller individuals (ANOVA $P < 0.001$) than baited fyke nets. Higher catch rates of juvenile kōura are likely because most of the juvenile population permanently resides in the shallows; and their sensitivity to light (>150-205 lux) makes them seek out shelter (Devcich 1979). Additionally, only 10-20% of the adult population occupy the shallows with most living in the depths, which may explain the lower catch rates of larger kōura in the whakaweku (Devcich 1979). Adult kōura move into the shallows at night to feed (Devcich 1979), which is presumably when they enter the baited fyke nets to gain shelter or food.

It is unclear why whakaweku caught so few kōura given the long soak time of 5 months and their success in deeper water (3-20 m; Kusabs and Quinn 2009). We

hypothesised that it would take >2 weeks for kōura to colonise the whakaweku, as it takes time for kōura to locate whakaweku and for invertebrate species to colonise them (Kusabs et al. 2018). In our study, kōura numbers peaked after a 3-month soak time, and the highest mean kōura CPUE was low (1.89 ± 1.27 , SD kōura whakaweku⁻¹) compared to the mean CPUE of 25.5 to 96.7 kōura whakaweku⁻¹ recorded by Kusabs and Quinn (2009) for tau kōura. Cooler water temperatures over the June–October period were a potential influence, as kōura activity and trapping rates are often reduced during cold water periods (Momot and Gowing 1972). For example, Momot and Gowing (1972) trapped more crayfish (*Orconectes virilis*) in Marl Lakes, USA, in summer than in autumn, and when temperatures were <10°C crayfish activity reduced rapidly. Abundances of other crayfish species (*Pacifastacus leniusculus*) have also been related to water temperatures, with catch rates peaking at 18–21°C (Usio et al. 2006). This theory is supported by fyke net CPUE analysis where season was found to be a predictor of kōura trapping rates in routine monitoring, with catch rates in summer being double of that in any other season. The optimum water temperature for kōura is 19°C (Jones 1981). Water temperatures in May 2018 (late autumn) when the whakaweku were deployed averaged 14.3°C and 14.7°C in Otaramarae and Te Weta Bay, respectively, but dropped in winter to mean temperatures of 11.5°C and 11.6°C, respectively. Water temperatures can also influence lake stratification, which affects bottom dissolved oxygen concentrations and the distribution of kōura. In summer, kōura in Lake Rotoiti occupied depths of 5–10 m, which may contribute to the higher summer catch rates (Devcich 1979). When the thermocline broke down in late autumn, kōura re-dispersed to depths of up to 50 m (Devcich 1979).

There is an abundance of structural habitat along the lake shorelines of Te Weta Bay and Otaramarae, mainly in-lake vegetation, macrophyte beds, root wads, and fallen trees. Although there was no statistical relationship between in-lake vegetation and wood, and kōura abundance, such bodies provide structural complexity and have been closely associated with kōura abundances in streams (Jowett et al. 2008). The abundance of habitat complexity in the lake littoral zone may make the whakaweku less attractive to kōura. In contrast, at depth, habitat complexity is reduced with only soft mud and the occasional rocky outcrop available (Devcich 1979). Whakaweku set as a tau kōura (i.e., attached to a rope line) at these depths perform better than in the littoral zone. For example, a tau

kōura set at 11-16 m depth just outside Te Weta Bay, when sampled in April, July and November 2009, produced mean kōura catches of 32.4, 21.9, 10.9 kōura whakaweku⁻¹, respectively (Kusabs et al. 2015a). More recently, however, the same tau kōura caught 3.1 kōura whakaweku⁻¹ in August and 4.9 whakaweku⁻¹ in November 2018 (I. Kusabs, Ian Kusabs and Associates, pers. comm.). Tau kōura also work well on bedrock. A tau kōura set in Okere Inlet at 3-6 m depth on bedrock had a mean catch rate of 33.8 kōura whakaweku⁻¹ in August and 28.7 kōura whakaweku⁻¹ in November 2018 (I. Kusabs, Ian Kusabs and Associates, pers. comm.). The higher kōura catch rates in these deeper waters and less structurally complex habitats may be because the whakaweku provide a form of structural complexity in areas with little available habitat (Kusabs et al. 2018).

3.6.6 Effectiveness of whakaweku at remediating kōura predation

There was little evidence to suggest that catfish had consumed kōura in either of the tank experiments. In experiment one, the lack of kōura predation by catfish was attributed to the presence of cobbles in all tanks providing sufficient refuge to avoid predation. A refuge experiment conducted in tanks that compared the effectiveness of cobbles and gravel as shelter for juvenile kōura found that survival was highest in cobble substrates, regardless of catfish presence, with kōura survival rates of $95 \pm 6\%$ (mean ± 1 SD) (Clearwater et al. 2018). Other studies have also found that cobbles are the most important factor relating to kōura abundance, providing effective refuge from predators and cannibalism (Capelli and Magnuson 1983; Lodge and Hill 1994; Johnsen and Taugbøl 2008; Kusabs et al. 2015a; Ramberg-Pihl et al. 2017). Because of the effectiveness of cobbles at providing shelter, cobbles were not used in the tanks for our second experiment. However, still no kōura were consumed by catfish, even in the absence of whakaweku (i.e., no habitat) with catfish treatment. This result was unexpected, given catfish were observed coming in contact with the kōura on multiple occasions (personal observation).

Mean kōura size used in the experiments was 16.6 mm OCL (OCL range 5.5–26.0 mm). These sizes were larger than juvenile kōura used by Clearwater *et al.* (2018), which had a mean size of $3.9 (\pm 0.3, \text{SD})$ mm OCL. Juvenile crayfish are more vulnerable to predatory fish consumption because of their small size, softer

exoskeletons, with their vulnerability decreasing with size due to the gape limitations of these predators (DiDonato and Lodge 1993). The larger crayfish used in the experiments were also observed displaying effective defensive behaviour. Threat displays are used by kōura as an anti-predator response when a predator is physically near (Shave et al. 1994).

Catfish used in the current experiments had a mean size of 230 mm FL, and were the same size or larger than the catfish from Lake Taupo that had consumed kōura (>150 mm FL; Barnes 1996). As the kōura used in this experiment were within the size range that catfish were capable of consuming, we conclude that kōura aggression towards catfish and the naivety of the catfish towards kōura reduced predation. Catfish used in the experiments had not encountered kōura before the tank trials. Catfish may have also been too stressed to feed.

Although there was no evidence of kōura predation in the treatments, kōura were still observed actively seeking out and utilising the whakaweku and cobble habitat when provided. In other experimental studies, utilisation of cobble and other habitats by crayfish is a common response to predatory fish to avoid predation (Blake and Heart 1993). Whakaweku in the tanks gave kōura a structured habitat that they utilize in the same way that they use natural refugia (Kusabs and Quinn 2009). When deployed, whakaweku can last up to 6 months in eutrophic lakes and 2 years in oligotrophic lakes, they are easy and cheap to construct, and can be set at any depth (>0.2 m; Kusabs and Quinn 2009; Kusabs et al. 2018). These factors make whakaweku an effective sampling tool, and a means to add additional habitat where it is lacking (e.g., on sandy or muddy substrates or bedrock). However, it is possible for catfish to also utilise the whakaweku, as was observed during the tank trials. During the seasonal sampling of the tau kōura on the 15 November, 2018 a small catfish (97 mm FL) was also found in a bundle at 13.3 m depth; suggesting that catfish utilisation of the bundles, could pose a threat to the fish and kōura inside (I. Kusabs, Ian Kusabs and Associates, pers. comm.).

3.7 Conclusion

Kōura catch rates have significantly declined in Lake Rotoiti over the last decade (Kusabs 2016), and we conclude that brown bullhead catfish are primarily

responsible. Other factors that could have led to the decline of kōura are the spread of exotic macrophytes and changes in physicochemical conditions. In our study, catfish were the only species to be negatively correlated with kōura abundance. The inverse relationship between catfish and kōura was thought to be due to direct consumption of kōura, and competitive exclusion from the littoral zone. Habitat preferences could have contributed to the inverse relationship between catfish and kōura, but declining kōura catch rates in Te Weta Bay as catfish numbers increased from 2016 to 2018 suggest that the impact of catfish is real. Habitat does influence kōura catch rates, which were highest on broken rock substrates, while catfish were associated with mud substrates and macrophytes. Kōaro abundances were not negatively correlated with catfish, suggesting they may not be potential prey items of catfish. Further research is needed to observe the effects of exotic macrophytes and physicochemical changes on kōura in the lake.

Whakaweku were unsuccessful at catching kōura in the littoral zones at depths <1 m in Lake Rotoiti, which was attributed to reduced autumn catch rates, abundant alternative habitat along the lake shoreline, and the fact that the majority of the adult kōura population lives at 3-20 m depth. Although whakaweku caught few kōura in shallow depths in the littoral zone, kōura used whakaweku in experimental trials. It is possible that kōura would use whakaweku in the deeper littoral zone, but the extensive macrophyte growth makes this very difficult to test.

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4 Chapter 4

*Catfish consumption of kōura in Lake Rotoiti and competition for shared food resources*²

4.1 Abstract

Invasive brown bullhead catfish (*Ameiurus nebulosus*) were first discovered in Lake Rotoiti in the Bay of Plenty region in March 2016. The presence of catfish in the lake is concerning given the carnivorous and opportunistic feeding habits of catfish as well as the lake's resident populations of freshwater crayfish or kōura (*Paranephrops planifrons*) and kōaro (*Galaxias brevipinnis*), which have ecological and cultural significance to Māori. Previous studies have demonstrated that kōura are important prey items of catfish, and kōaro could be important food items of catfish due to their small size. In this study, we assessed the threat that catfish pose to kōura and native fish species in Lake Rotoiti by analysing catfish and kōura stomach contents, in combination with stable isotope analysis to determine resource acquisition and dietary overlap. Catfish diet consisted largely of chironomid larvae (Chironomidae), detritus, common bullies (*Gobiomorphus cotidianus*), and to a lesser extent kōura. Kōura were found in 12% of large catfish stomachs (>200 mm fork length; FL) analysed, and contributed 5% volumetrically to large catfish diet. This suggests that the effects of catfish on kōura will likely increase in the future, as the number of adult catfish increases in the lake. Diets of kōura consisted primarily of animal remains (common bullies and invertebrates) and detritus. Stable isotopes of carbon and nitrogen revealed that diets of kōura and catfish overlapped, with kōura sharing between 30-90% of their niche space with catfish, and catfish sharing between 12-79% of their niche space with kōura. This research determined that catfish can directly and indirectly affect kōura through consumption and competition for shared food resources.

² Francis LB and Hicks BJ. In preparation. Catfish consumption of kōura in Lake Rotoiti and competition for shared food resources. New Zealand Journal of Marine and Freshwater Research.

4.2 Introduction

Determination of animal diet and its trophic position in the food web has traditionally been based on stomach contents. Although stomach contents of an animal provides useful dietary information, it only provides a glimpse at what the organism has eaten over the last one to two days and is subject to human error (Mann and Orr 1969). Dietary items in the animal's gut are often difficult to identify due to food items undergoing digestion (Gannon 1976). Items of small size such as invertebrates and organic matter can also be difficult to accurately identify and count, and are therefore, potentially misrepresented. The more recent development and use of stable isotope analysis (SIA) has provided ecologists with another means to trace flows of organic carbon and nitrogen through food webs, and is a major advancement on traditional methods as it provides long-term integrated dietary information, reducing temporal bias (Post 2002).

Isotopes (both stable and radioactive) are atoms of the same element that differ in their atomic masses due to having different numbers of neutrons (Ehleringer and Rundel 1988; Krigbaum 2008). Slight differences in mass gives each isotope a unique set of physical properties, which results in their variation or fractionation in natural systems, with a tendency to favour the lighter isotope (Ehleringer and Rundel 1988; Krigbaum 2008). It is this variation (i.e., the proportion of heavier to lighter isotope) that SIA is concerned with, as each organism holds a unique isotopic signature that can be measured and used for identification purposes (Krigbaum 2008). Stable isotopes frequently used in ecology include isotopes of carbon and nitrogen (Rounick and Winterbourn 1986). Carbon has two stable isotopes consisting of ^{12}C and ^{13}C , with natural abundances of 98.89 and 1.11 atom %, respectively. Similarly, nitrogen has two stable isotopes consisting of ^{14}N and ^{15}N , with natural abundances of 99.63 and 0.37 atom %, respectively (Ehleringer and Rundel 1988). To express the ratio of the heavier isotope to the lighter isotope (e.g., $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$) the standard notation δ (delta) is used, which compares the sample against a known standard material giving a value in parts per mil or parts per thousand (‰) (Krigbaum 2008).

Isotopic signatures of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ of basal resources and consumers can be used to indicate an organism's relative positioning in a food web, enabling inferences to be made about trophic structure and diet (Elsdon et al. 2010). Values of $\delta^{13}\text{C}$ vary

among basal resources due to the photosynthetic pathway and the carbon source (e.g., CO₂ in air and HCO₃⁻ in water) used (Ehleringer and Rundel 1988; Krigbaum 2008), but change little among trophic transfers making them good indicators of important organic carbon sources for animal nutrition (DeNiro and Epstein 1978). In comparison, nitrogen is preferentially incorporated into the tissues of the animal relative to its diet, resulting in an orderly enrichment of the heavier ¹⁵N isotope with each trophic level increase (DeNiro and Epstein 1981). The systematic enrichment of ¹⁵N with each trophic level can be used as an indicator of an organisms' positioning in a food web and is referred to as a trophic shift (Focken & Becker, 1998; Kelly, 2000). With each trophic shift, organisms theoretically become consistently enriched with a >3‰ increase in δ¹⁵N (DeNiro and Epstein 1981) and a 0-1‰ increase in δ¹³C (DeNiro and Epstein 1978), compared to their food source, although increases are not always consistent (McCutchan et al. 2003). Variations in isotope ratios arise from differences in animal diet, differential digestion rates (McCutchan et al. 2003), discrimination of particular enzymes, and preferences for certain isotopic species (Ehleringer and Rundel 1988; Focken and Becker 1998; Birchall et al. 2005).

Stable isotope plots provide a useful tool to show ecological responses to anthropogenic impacts, including pest fish introductions (Pilger et al. 2010; Collier et al. 2018). Isotopes of carbon and nitrogen can be used to show if a species diet is being restricted and can identify if there is potential competition over a shared food resource (Pilger et al. 2010; Collier et al. 2018). Brown bullhead catfish (*Ameiurus nebulosus*) is an invasive fish from North America, which was confirmed present in Lake Rotoiti in the Bay of Plenty region in 2016 (Bay of Plenty Regional Council 2018a). There are several negative impacts associated with the fish; two of which are the formation of novel food webs (Scott and Crossman 1973; Collier et al. 2018), and the consumption of indigenous biota (Barnes 1996).

Catfish are opportunistic feeders that consume a wide variety of food types and have been implicated with sharing a similar trophic niche with native eels (*Anguilla* spp.) (Collier et al. 2018). Catfish are also renowned for consuming large amounts of small native fish such as common bullies (*Gobiomorphus cotidianus*) (Collier et al. 2018), and consume a number of invertebrates, ranging from small (e.g., chironomids) to large (e.g., kōura) size (Barnes 1996; Barnes and Hicks 2003).

Investigation into the consumption of freshwater crayfish or kōura (*Paranephrops planifrons*) and native fish species by catfish and dietary overlap is of particular interest in this current study, as kōura and kōaro (*Galaxias brevipinnis*) are taonga to the local iwi and the effects of catfish on native species are yet to be quantified for the lake.

4.3 Aims and objectives

The main aim of this chapter is to determine whether catfish pose a significant threat to kōura and native fish species in Lake Rotoiti through predation or competition for shared food resources. This was approached by (i) analysing catfish and kōura gut contents in combination with stable isotopes to quantify patterns of resource use over time, (ii) determining the degree of dietary overlap between catfish, kōura, goldfish and bullies, and (iii) observing if catfish diet changes with increasing size. The secondary objective of this study was to create a gape-length equation for fresh and frozen catfish, so catfish length could be used to predict gape size. Although not in the scope in this study, gape size can be used to make inferences about a fish's feeding habitats, by relating gape size to the number and size of prey consumed (e.g., Boubée and Ward 1997).

4.4 Methods

4.4.1 Study area

Lake Rotoiti (38.039895°S, 176.345803°E; Figure 4-1) is one of 12 major lakes in the Bay of Plenty Region, collectively known as the Te Arawa lakes (Kusabs et al. 2015b), situated about 278 m a.s.l on the Central Volcanic Plateau, North Island, New Zealand (von Westernhagen 2010). Lake Rotoiti is deep (maximum depth 124 m, average depth 32 m), large (surface area 34.6 km²), warm, monomictic, and mesotrophic (von Westernhagen 2010). The lake stratifies for nine months of the year, mixing in late autumn (Kusabs and Quinn 2009). Currently, 24% of the catchment area of Lake Rotoiti is used for agriculture, 43% is forest, and 1% is urban (Bruesewitz et al. 2011).

Six sites were chosen at the western end of Lake Rotoiti (Okawa Bay, Southern Shoreline, Te Weta Bay, Okere Inlet, Otaramarae, and Te Arero Bay; Figure 4-1) for dietary analyses based on catfish densities.

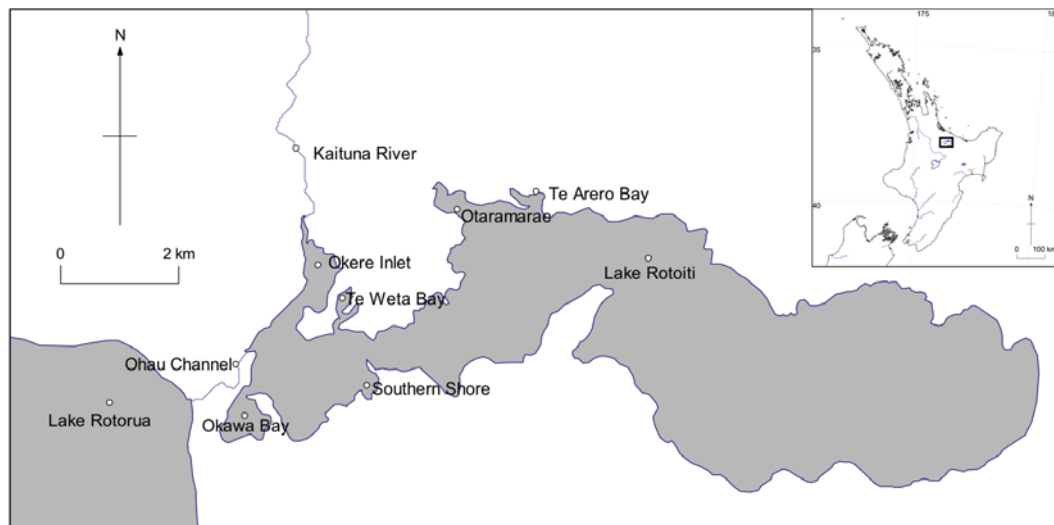


Figure 4-1. Location of Lake Rotoiti in the Bay of Plenty region and the six study sites.

4.4.2 Field sample collection

Samples were collected from the six sites around Lake Rotoiti from 15 April 2016 to 25 October 2018. Potential catfish food items including common smelt (*Retropinna retropinna*), common bullies, goldfish (*Carassius auratus*), gambusia (*Gambusia affinis*), kōura, dragonfly larvae (*Hemicordulia australiae*), damselfly larvae (*Xanthocnemis zealandica*), chironomid larvae (Chironomidae), oligochaetes, snails (*Physa* spp.), water boatmen (*Corixidae sigara*), zooplankton, phytoplankton, seston, terrestrial vegetation, coarse particulate organic matter (CPOM), periphyton and submerged macrophytes were collected during 2018 for stable isotope analysis. Catfish and other potential predators of kōura including rainbow trout (*Oncorhynchus mykiss*) and longfin eels (*Anguilla dieffenbachii*) were also collected for analysis. Trout flesh was obtained from local fisherman and clips of longfin eel fin were collected from BOPRC fyke net catches. Longfin eel fin clips are very similar isotopically to longfin muscle tissue, and offer a non-destructive alternative (Smith et al. In preparation).

Fish and kōura were caught using baited fyke nets set overnight. Upon capture, fish and kōura were immediately placed on ice and frozen for later analysis. Snails, dragonfly larvae, and water boatmen were obtained from the lake's littoral zone by opportunistically sweep-netting vegetation. Sweep-net samples were washed in a sieve bucket before being bagged by site and placed on ice. In addition to collecting invertebrates, left-over plant material obtained from sweep netting was used as CPOM (fragment size >500 µm). Samples of damselfly larvae were obtained from the whakaweku set in shallow waters (<1 m). A Ponar grab sampler or a coarse-mesh sieve was used to collect oligochaetes and chironomid larvae. Material collected in the Ponar grab was washed in a sieve bucket before being placed on ice for separation back in the lab. Sorted invertebrates were placed in plastic bags and frozen until analysis.

Samples of zooplankton and phytoplankton were collected using a 40-µm mesh plankton tow net in winter and a 25-µm mesh net in summer. The net was towed horizontally for 9 m in the littoral zone three times and samples were pooled for each site. Any organic material larger than zooplankton caught in the net was manually removed. The resulting sample was poured into a polypropylene bottle, before being stored on ice for later separation in the lab. Vegetation samples were

obtained by picking off the actively growing tips of macrophytes, and taking the leaves off common terrestrial plants. Aquatic samples were shaken vigorously in the lake to remove epiphytic algae before being bagged by species and placed on ice. To obtain a sample of periphyton, rocks were scraped using a spoon. The resulting material was bagged and immediately placed on ice.

4.4.3 Catfish and kōura stomach contents analysis

Catfish ($n = 238$, fork length range 51-365 mm) were collected for analysis from the BOPRC freezers that had been caught from various sites around Lake Rotoiti between 15 April 2016 and 25 October 2018 (Table 4-1). Catfish were thawed out overnight or placed in a warm water bath for several hours. Each catfish was weighed to the nearest 0.1 g and had its fork length (snout to tail fork) measured to the nearest 0.01 mm and classified into one of three class sizes (small <100 mm, medium 100-200 mm and large >200 mm), before removing its gut. For the first 100 catfish, only the stomach was removed for analysis. However, it was thought that important dietary information was being missed. As such, in subsequent dissections, the oesophagus, stomach, and lower intestines were removed from the animal. Stomachs were stored in labelled vials containing 75% ethanol for later analysis. Kōura ($n = 28$, OCL range 21.1–31.7 mm) were also collected for analysis from the six main study sites between 13 June and 31 August 2018 (Table 4-2). Kōura were thawed overnight to enable stomach and flesh extraction. Each kōura was weighed to the nearest 0.1 g, had its gender recorded, and orbital-carapace length (OCL) measured to the nearest millimetre, before having its stomach removed and placed in ethanol.

Prior to stomach contents analysis, the fullness of each catfish or kōura gut was estimated as empty, trace, half full, full, and distended, before being cut open using a scalpel blade. For catfish, the contents of the stomach and intestines were flushed out with tap water into a 100- μ m mesh sieve and transferred onto a white square plastic tray (11.5 cm x 11.5 cm). Using a dissection microscope at 10 x magnification, stomach items were identified and recorded to the lowest possible taxa. Two separate methods were used to estimate the contribution of different food items to the diet of catfish diet. Firstly, the occurrence method was used that counts the number of times a species occurs in the catfish's stomach. Secondly, the

displacement method was used to obtain the contribution of each food group (kōura, dipterans, fish, detritus, unidentified animal matter and other invertebrates) to catfish diet. Food items were separated into food groups and placed on mesh sieves to remove excess water, before being placed in a measuring cylinder to record water displacement. Water displacement by each food group was divided by the combined water displacement to give a percentage contribution for each food group.

Kōura gut contents were washed out onto a clear, circular petri dish (8.5 cm diameter), which was placed on top of a white square plastic tray (11.5 cm x 11.5 cm), with a 1 cm x 1 cm grid pattern. Using a dissection microscope, items were identified and percentage cover was estimated in 10 randomly selected grid squares (1 cm x 1 cm). Food items were identified to the lowest possible taxon practicable.

Table 4-1. Number of small, medium and large catfish stomachs analysed from April 2016 to October 2018. Catfish used in the analysis were collected from Ohau Channel and Delta, Okawa Bay, Okere Inlet, Otaramarae, outside Te Weta Bay, Southern Shoreline and Te Weta Bay.

Site	Catfish size class			<i>n</i> stomachs
	Small (<100 mm)	Medium (100-200 mm)	Large (>200 mm)	
Ohau Channel and Delta	6			6
Okawa Bay	9	5	7	21
Okere Inlet	7	14	10	31
Otaramarae	5	5	2	12
Outside Te Weta Bay			3	3
Southern Shoreline	14	16	7	37
Te Weta Bay	40	33	55	128
<i>N</i> stomachs	81	73	84	238

Table 4-2. Numbers, OCL ranges, weight ranges and gender ratios of kōura (*n* = 28) collected from the six study sites in Lake Rotoiti for gut contents and stable analysis.

Site	Number of kōura	OCL range (mm)	Weight range (g)	Gender ratios (m: f)
Okawa Bay	2	21.6-30.0	7.2-19.4	2: 0
Okere Inlet	5	21.9-27.4	6.8-15.3	4: 1
Otaramarae	5	23.9-31.7	14.1-24.1	3: 2
Southern Shoreline	5	24.8-30.9	10.1-19.8	3: 2
Te Arero Bay	5	22.1-29.6	6.8-16.9	3: 2
Te Weta Bay	6	21.1-29.7	6.8-17.0	5: 1
Summary	28	21.1-31.7	6.8-24.1	20:8

4.4.4 Isotope analysis

Stable isotope analyses were performed at the University of Waikato Stable Isotope Unit using a fully automated Europa Scientific continuous flow 20/20 mass spectrometer. Stable isotope values of carbon ($^{13}\text{C}/^{12}\text{C}$) and nitrogen ($^{15}\text{N}/^{14}\text{N}$) were given as δ values (Equation 1), which were expressed against the reference standard leucine, which was calibrated against Pee Dee Belemnite for $\delta^{13}\text{C}$, and nitrogen in air for $\delta^{15}\text{N}$. Precision of the analyser was approximately 0.3‰ for $\delta^{13}\text{C}$ and 0.5‰ for $\delta^{15}\text{N}$.

Equation 1:

$$\delta^{13}\text{C} \text{ or } \delta^{15}\text{N} = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 1000$$

R is the ratio of $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$ of the sample or standard

Fish and crayfish were measured to the nearest 1 mm for either fork length or orbital-carapace length (OCL), weighed to the nearest 0.1 g, and sex determined if possible. Plugs of white muscle tissue were taken from below the dorsal fin in larger fish, and from both sides in smelt and bullies, as white muscle was shown to be less isotopically variable than other tissues (Pinnegar and Polunin 1999). Muscle tissue was examined for skin or scales and bones, which were removed before samples were dried and ground. For crayfish, samples of white abdominal muscle were taken from the tail region. All fish and crayfish were analysed individually, where the size (>2 mg) of the sample permitted. The smallest fish species, gambusia, were decapitated, and gut tracts were removed.

Invertebrates were sorted into taxonomic groups, and when necessary, individuals were pooled to produce a sufficient sample for analysis. Snails were removed from their shells prior to analysis, to avoid carbonate contamination (Carabel et al. 2006). The guts of dragonfly larvae and damselfly larvae were removed before being dried. All animal samples were dried at 50°C for 48 h and subsequently ground.

Winter phytoplankton and zooplankton samples were poured through a 100- μm sieve in the lab in an attempt to separate out the larger zooplankton from the phytoplankton. A small mesh size was used as the samples were lacking larger crustaceans, and contained smaller zooplankton species (I. Duggan, University of Waikato, pers. comm.). Autumn seston samples were analysed whole as there were

few zooplankton. The resulting samples were dried at 50°C for 48 h and subsequently ground for analysis.

Tips of macrophytes were thoroughly cleaned of algae before drying. All samples were washed with deionized water several times before being dried in aluminium cups at 50°C for 48 h. Coarse particulate organic matter was cleaned using tap water and sorted of stones and large debris. The remaining fraction was dried at 50°C for 72 h and subsequently ground. Terrestrial leaves were cut up and dried at 50°C for 72 h. The singular periphyton sample was checked for small gravel and foreign vegetation, before being dried at 50°C for 48 h. Samples were ground using a mortar and pestle or a ball mill, which was either wiped with ethanol or washed and dried between samples. For stable isotope analysis, between 2 mg and 7.5 mg of sample was weighed to the nearest 0.01 mg in aluminium cups.

4.4.5 Gape-length relationship in catfish

Fresh catfish ($n = 63$, fork length range 75-372 mm) were collected from various locations in the Waikato and Bay of Plenty regions including the University of Waikato campus lakes and lakes Rotorua and Rotoiti over a 4-month time period from 26 January to 12 April 2018. Fresh catfish were obtained using various methods, including the university's electrofishing boat, course mesh fyke nets, and an electrofishing backpack (EFM200). Upon being captured, catfish were euthanised using benzocaine and stored at 4°C for analysis. Frozen catfish ($n = 65$, fork length range 51-355 mm) were obtained from BOPRC freezers, which were caught from Lake Rotoiti between 27 January 2017 and 22 February 2018.

Measurements of mouth gape were taken on freshly euthanised and previously frozen catfish, to see what effect freezing of the fish had on gape size. Prior to measurements being taken, frozen catfish were thawed overnight. To measure gape size, a gape tool (Figure 4-2) was made by University of Waikato workshop staff, which consisted of a hand-held aluminium cone-shaped device with millimetre increments ranging from 2 to 60 mm. The tool was based on the gape tool developed by National Institute of Water and Atmospheric Research (NIWA) staff in Hamilton. To measure catfish gape size, the tool was inserted into the fish's mouth and pushed back towards the gill arches until its lips were firmly around the tool,

being careful not to touch the back of the fish's mouth. Measurements of gape were taken when the gape tool could not move further into the mouth without applying excessive force. This was to avoid extending the fish's mouth opening beyond what is naturally achievable. Two gape measurements were taken, including one from the top of the lip and the other from the side of the mouth to the nearest millimetre. Other catfish measurements taken included weight, which was measured using calibrated scales to the nearest gram, and fork length (snout to fork in tail) using a measuring board to the nearest millimetre.



Figure 4-2. Gape tool used to measure catfish gape height and gape width in fresh and frozen catfish.

4.4.6 Statistical analyses

Differences in stable isotope results across sites were analysed by comparing $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values for bullies, smelt, kōura and catfish using a one-way ANOVA. To determine if different sized catfish consumed different foods the mean contribution of each food group (e.g., chironomids and fish) to catfish diet was analysed by catfish size class using a one-way ANOVA. Niche overlap between bullies, goldfish, catfish and kōura in Te Weta Bay was estimated using R package nicheROVER (Swanson et al. 2015).

Individual and combined gape-length relationships of fresh and frozen catfish, were analysed using linear regression models of gape height and gape width as dependent variables, against fork length as the independent variable. Summary statistics including the Y intercept, line slope, degrees of freedom, and the adjusted R^2 value were calculated. To evaluate whether separate regression models were justified for fresh and frozen catfish, analysis of covariance (ANCOVA) was used to test the equality of the two slopes and the equality of the Y intercepts. All analyses were performed in R statistical software version 3.4.1; $\alpha = 0.05$ was used as the critical P value.

4.5 Results

4.5.1 Catfish stomach contents analysis

The guts of 238 catfish caught between April 2016 and October 2018 from the main six study sites and two additional sites were analysed for diet. Very few catfish had empty stomachs or gastrointestinal tracts with 12% of all catfish being fully empty, followed by 29% being almost empty with trace remains (Table 4-3).

Table 4-3. The number of small, medium, and large catfish stomachs and the combined percentage of stomachs that are empty, have trace remains, are half full, full, and distended.

Stomach fullness	Catfish size class			Overall percentage
	Small (<100 mm)	Medium (100-200 mm)	Large (>200 mm)	
Empty	11	7	11	12%
Trace remains	29	17	22	29%
Half full	20	6	25	21%
Full	17	17	17	21%
Distended	7	23	9	16%
Number of stomachs analysed	84	70	84	

Catfish diets were highly diverse and contained 29 different food items of animal and plant origin. Food items that were found in less than a combined 10% of catfish size classes were omitted (Table 4-4). These included, from highest to lowest importance, fingernail clams, other terrestrial invertebrates, ticks and mites, gambusia, *Oxyethira* larvae, Lymnaeidae snails, Coleoptera larvae, smelt, goldfish, amphipods, chironomid adults, *Potamopyrgus* snails, free-living caddisfly and stony-cased caddisfly.

Small catfish (<100 mm FL) consumed significantly more (ANOVA $P < 0.001$) chironomids than any other size class, with chironomids being the most abundant food item in small catfish guts being found in 77% of stomachs. Guts of small catfish also contained similar amounts of detritus, chironomid pupae, purse caddis larvae (*Paroxyethira hendersoni*), unidentified animal material, and unidentified insects. Volumetrically, chironomid larvae contributed the most to small catfish diet (48%), followed by other invertebrates, and unidentified animal matter (Table 4-5). Fewer small catfish contained Odonata (i.e., damselflies and dragonflies), common bully, snails, unidentified fish, oligochaetes, Hemiptera and isopods than the larger

size classes, and kōura were absent from small catfish diet. Of the size classes, small catfish had the highest occurrence of zooplankton in their stomachs.

Chironomid larvae, detritus, Odonata, and common bullies were the most commonly found items in medium (100-200 mm FL) sized catfish guts. Consumption of fish was significantly (ANOVA $P < 0.001$) higher in medium sized catfish than the other size classes, with ~46% of their diets by volume coming from fish. Medium catfish stomachs also contained the most Odonata and unidentified fish of the catfish size classes, being found in 46% and 32% of stomachs, respectively. Volumetrically, medium sized catfish stomachs contained significantly (ANOVA $P < 0.001$) less detritus than the other size classes, with an average contribution of 9%. No kōura remains were found in medium sized catfish stomachs.

Large catfish (>200 mm FL) diet consisted of largely detritus and chironomid larvae, which were found in 80% and 66% of stomachs respectively, with lesser equal amounts of chironomid pupa, unidentified animal material and Odonata. Volumetrically, detritus and chironomid larvae contributed the most to large catfish diet. Large catfish stomachs had the highest occurrence of detritus in their stomachs of the size classes and contained the greatest volume of other invertebrates. Furthermore, they were the only size class to contain kōura, with 12% of large stomachs containing kōura (i.e., 9 out of 73 full catfish stomachs contained kōura), contributing an average of 5% to large catfish diet. Catfish that contained kōura were all >240 mm in fork length and were caught in Te Weta Bay.

Table 4-4. The average percentage occurrence of small, medium and large catfish stomachs containing one or more food items. Food items with combined percentages of <10% were omitted. Catfish were all caught from Lake Rotoiti between April 2016 and October 2018.

Food items	Percentage occurrence of food items in catfish size classes		
	Small (<100 mm)	Medium (100-200 mm)	Large (>200 mm)
Chironomid larvae	77	68	66
Detritus	36	57	79
Chironomid pupae	34	33	30
Purse caddis larvae	24	16	16
Unidentified animal flesh	23	13	26
Unidentified insect	20	19	10
Odonata	15	46	32
Zooplankton	8	3	1
Common bully	5	44	15
<i>Physa</i> snail	5	14	21
Unidentified fish	4	32	15
Oligochaetes	4	10	12
Hemiptera	4	8	4
Isopod	1	10	3
Kōura	-	-	12

Table 4-5. The average volumetric percentage contribution of fish, detritus, kōura other invertebrates, chironomids, and unidentified animal matter to small, medium and large catfish diet. One-way ANOVA *P* values indicate whether there is a significant difference between size classes. Total combined displaced volumes for each size class and 95% confidence intervals are given.

Food group	Volumetric contribution of food items in catfish size classes						<i>P</i> value
	Small (<100 mm)		Medium (100-200 mm)		Large (>200 mm)		
	Mean	CI	Mean	CI	Mean	CI	
Chironomids	48.1	9.3	22.7	8.8	22.2	7.6	<0.001
Non-kōura invertebrates	17.9	6.1	16.4	6.5	18.9	7.2	0.87
Unidentified animal flesh	16.6	8.1	6.4	5.3	18.3	7.9	0.06
Detritus	11.0	5.1	8.7	5.7	25.9	8.7	<0.001
Fish	7.3	5.8	45.7	11.3	9.9	6.1	<0.001
Kōura	0		0		4.9	4.3	0.009
Total volume (mL)	15.9		138.5		167.9		

4.5.2 Kōura stomach contents analysis

The guts of 28 kōura (mean OCL $\pm$ SD 26.1 ± 3.0 mm, OCL range 21.1–31.7 mm) caught between June and August 2018 were analysed for diet. None of the stomachs analysed were empty and 7% had trace remains (Table 4-6). Animal material was the most abundant food group in kōura guts, followed by detritus, unidentified matter, and inorganic matter. Inorganic matter comprised <1% of kōura diet (Table 4-7). Zooplankton and phytoplankton were also present in kōura guts but were removed during the sieving process that retained items >100 μ m.

Fish was the most abundant food item in kōura guts, occurring in 100% of stomachs analysed, contributing to >50% of their diets volumetrically. Common bullies were the main fish species in their stomachs based on the characteristic spotting pattern on the bullies' skin (personal observation). Invertebrates were the second most common item in kōura guts, occurring in 96% stomachs, but contributed only 11% to overall kōura diet. Invertebrates comprised chironomid larvae and pupae, kōura exoskeleton, oligochaetes, dipteran larvae, purse caddis larvae, daphnids, and fragments of wings and mouth parts of unidentified insects. The presence of kōura exoskeleton in kōura guts was confirmed by an unidentified invertebrate sample, which was sent to the Waikato DNA Sequencing Facility. Results indicated that the DNA sequence was 98-100% similar to *Paranephrops planifrons*.

Terrestrial organic matter occurred in 93% of kōura stomachs and consisted of leaves, sticks, and possible raupō fragments. Terrestrial organic matter had the second overall highest contribution to kōura diet (23%). Aquatic macrophytes and unidentified animal flesh was also abundant in kōura stomachs, being found in 71% and 46% of stomachs respectively, but only contributed ~4% volumetrically to overall diet. Filamentous algae, oligochaetes, inorganic matter, and unidentified matter were less common in kōura guts, and contributed the least overall to kōura diet.

Table 4-6. The number and percentage of kōura stomachs analysed ($n = 28$) that are empty, have trace remains, were half full, full or distended.

Gut fullness	Number of stomachs	Percentage of stomachs (%)
Empty	0	0
Trace remains	2	7
Half full	3	11
Full	16	57
Distended	7	25

Table 4-7. Occurrence of the different food items in kōura guts, including the number and percentage of individuals containing each food subgroup, and the average percentage contribution of each subgroup to kōura diet.

Food groups	Subgroups	Number of individuals	Percentage of individuals (%)	Average volumetric contribution (%)
Animal material	Fish	28	100.0	52.4
	Invertebrate	26	92.9	11.1
	Animal flesh	13	46.4	3.8
	Unidentified animal matter	2	7.1	0.5
	Oligochaetes	1	3.6	1.2
Detritus	Terrestrial matter	26	92.9	22.9
	Aquatic macrophytes	20	71.4	4.1
	Filamentous algae	6	21.4	0.1
Unidentified matter		3	10.7	2.2
Inorganic matter		1	3.6	0.1

4.5.3 Stable isotopes

To test whether isotope results for food items could be combined across sites, values of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ were compared for bullies, smelt, catfish, and kōura. $\delta^{15}\text{N}$ values were significantly different between sites for all species (Table 4-8; Figure 4-3). $\delta^{13}\text{C}$ values were also significantly different between sites for catfish and bullies, but not for smelt or kōura. Because of the difference in $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values between sites, the isotope data was not combined across sites for the main analysis of catfish and kōura diet. Instead, Te Weta Bay, which had the most samples, was analysed separately with the addition of a few important species (e.g., chironomids and damselfly larvae), which we were unable to locate at the site. Some items were

difficult to collect across sites (e.g., rainbow trout and longfin eels), as such, a combined site stable isotope plot was necessary to make inferences about the diet of other fish species.

Table 4-8. Mean A. $\delta^{15}\text{N}$ and B. $\delta^{13}\text{C}$ values for catfish, bullies, smelt, and catfish, including sample sizes (n) and confidence intervals for the different study sites ($n = 6$). One-way ANOVA P values indicate whether there is a significant difference between sites.

A. $\delta^{15}\text{N}$ values (‰)

Site	Species							
	Catfish		Bullies		Smelt		Kōura	
	n	Mean	n	Mean	n	Mean	n	Mean
Okawa Bay	12	9.18	5	8.85	2	10.20	2	9.20
Okere Inlet	16	10.03	5	9.47	5	11.00	5	9.34
Otaramarae	12	9.63	5	9.04	3	11.90	5	8.02
Southern Shoreline	14	8.11	5	6.52	5	10.50	5	5.81
Te Arero Bay	0		5	8.62	4	11.40	5	8.60
Te Weta Bay	122	8.41	5	7.69	5	10.50	6	8.26
P value	<0.001		0.041		0.020		0.001	

B. $\delta^{13}\text{C}$ values (‰)

Site	Species							
	Catfish		Bullies		Smelt		Kōura	
	n	Mean	n	Mean	n	Mean	n	Mean
Okawa Bay	12	-15.00	5	-16.20	2	-17.60	2	-19.60
Okere Inlet	16	-17.00	5	-16.80	5	-19.30	5	-15.10
Otaramarae	12	-17.10	5	-18.80	3	-19.90	5	-18.50
Southern Shoreline	14	-17.20	5	-20.10	5	-18.80	5	-18.40
Te Arero Bay	0		5	-18.60	4	-19.10	5	-16.80
Te Weta Bay	122	-14.40	5	-18.70	5	-17.30	6	-17.70
P value	<0.001		0.029		0.055		0.156	

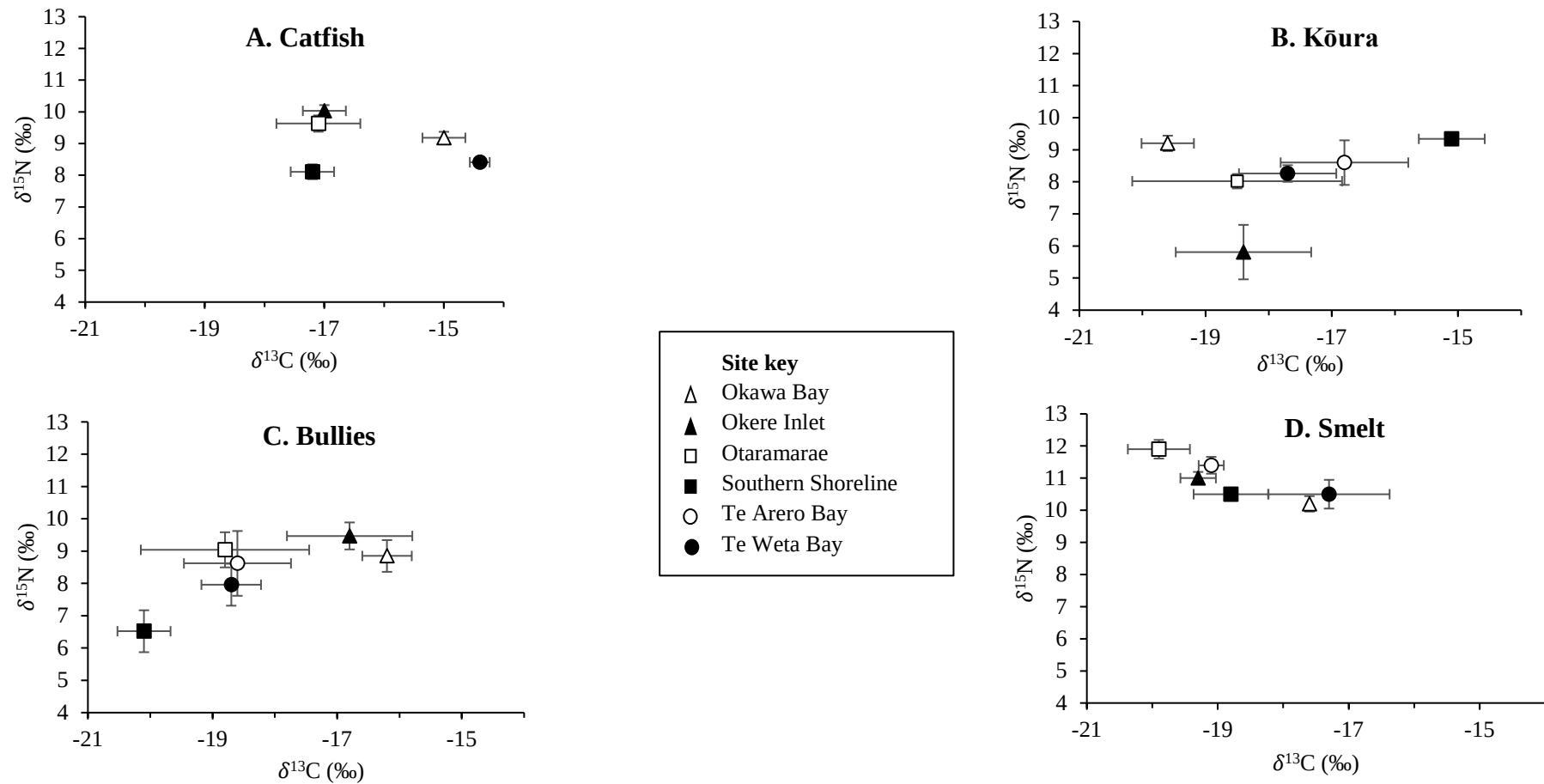


Figure 4-3. Mean stable isotope ratio plots of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ with 1 SE bars for A. catfish (all size classes), B. kōura, C. bullies and D. smelt at the six study sites in Lake Rotoiti. Note that no catfish we caught in Te Arero Bay.

4.5.3.1 Complete food web

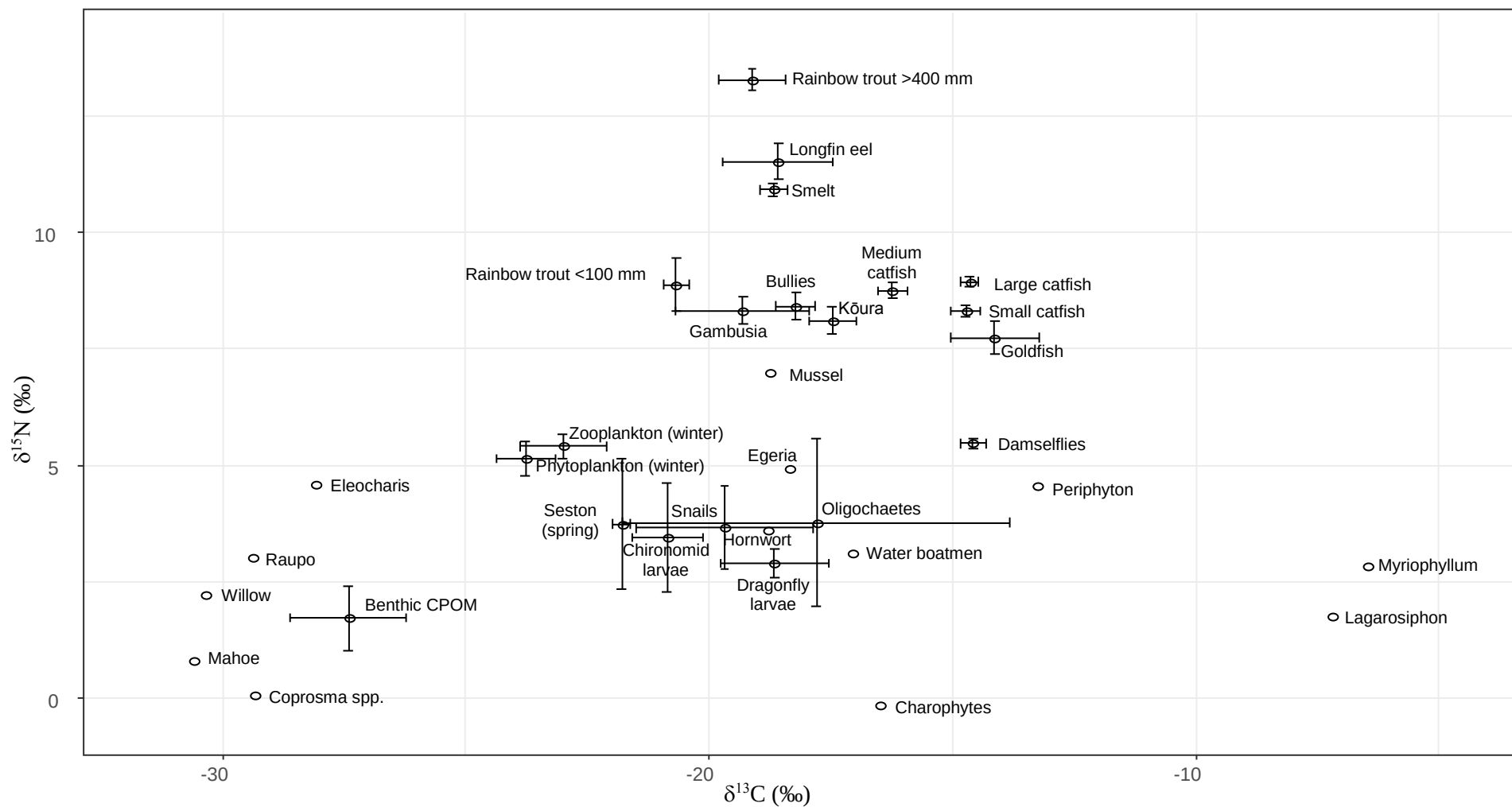
A total of 340 samples of fish, invertebrates (including kōura), seston, coarse particulate organic matter (CPOM), terrestrial plants and macrophytes were collected from six sites in Lake Rotoiti for stable isotope analysis between April 2016 and November 2018. Inter-site variability and more than 2-year sample collection time has undoubtedly introduced variation in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. However, catfish were the only species that were sampled more than 1 year ago and exhibit little variation between sites with small standard error bars (Figure 4-4), likely due to the large sample size ($n = 122$) and little dietary change over time (Collier et al. 2018). Isotopic values for sample types ranged between -1.51 and 13.51‰ for $\delta^{15}\text{N}$ and -30.59 and -6.48‰ for $\delta^{13}\text{C}$. Isotope results by site can be found in Appendix 2.

Terrestrial plants and aquatic macrophytes including *Coprosma* spp., māhoe (*Melicytus ramiflorus*), willow (*Salix fragilis*), raupō (*Typha orientalis*) and elocharis (*Eleocharis palustris*) were the most depleted in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, and based on their isotopic distance from consumers, did not likely contribute to invertebrate or fish diet. Charophytes, *Myriophyllum* spp. and lagarosiphon (*Lagarosiphon major*) were also depleted in $\delta^{15}\text{N}$ but were enriched in $\delta^{13}\text{C}$, indicating possibly a different photosynthetic pathway or carbon source. Of the plants examined, charophytes, egeria (*Egeria densa*), hornwort (*Ceratophyllum demersum*) and periphyton appear to be important food items for fish and invertebrate species based on their position close to consumers.

A number of insects, plants and seston including dragonfly larvae, oligochaetes, snails, water boatmen, chironomids, damselflies, zooplankton, phytoplankton, hornwort, egeria and periphyton shared a similar position in the food web ($\delta^{15}\text{N}$ 0.7 to 6.7‰ and $\delta^{13}\text{C}$ -11.4 to -26.5‰). The positioning of these species and the expected trophic increase (i.e., ~2.3‰ increase in $\delta^{15}\text{N}$ and a 0-1‰ increase in $\delta^{13}\text{C}$, compared to their food source; McCutchan et al. 2003) suggested they were of importance to small fish and kōura diet. The large standard deviation bars for seston, chironomid larvae, snails and bullies suggested isotopic values were variable between sites or samples. Isotopic values of zooplankton, phytoplankton and seston collected during winter and spring are close together.

Bullies, gambusia, kōura and goldfish had a similar trophic position as shown by their similar carbon and nitrogen values. Medium, large, and small sized catfish also shared similar trophic positioning, indicating that catfish diet did not change much with size. Large catfish had the highest $\delta^{15}\text{N}$ values of the size classes, but shared a similar $\delta^{13}\text{C}$ signature to small catfish. Medium sized catfish had lower $\delta^{13}\text{C}$ values. The close positioning of kōura to catfish in the food web indicates there could be some dietary overlap between both species

Isotopic values for large rainbow trout (>400 mm FL) were very different to that of small rainbow trout, suggesting they had different diets. Large rainbow trout were the most enriched in $\delta^{15}\text{N}$ relative to other taxa, and appeared to be eating smelt, gambusia, kōura and bullies. This could be similar to what longfin eels were consuming, with the exception of smelt. Small rainbow trout (<100 mm FL) shared a similar trophic niche to gambusia and bullies.



97 Figure 4-4. Stable isotope plot of organisms collected from six sites in Lake Rotoiti; error bars are 1 SE.

4.5.3.2 Catfish and kōura diet

A total of 169 samples of catfish and their potential prey items were collected for stable isotope analysis from Te Weta Bay between April 2016 and September 2018. Additional missing values from other sites were used in the analysis for chironomids ($n = 3$), damselflies ($n = 5$), and water boatmen ($n = 1$). To determine what was contributing to the nutrition of small, medium, and large catfish and kōura, the assumed trophic increase of 0.4‰ for $\delta^{13}\text{C}$ and a 2.3‰ $\delta^{15}\text{N}$ for aquatic animals was deducted from their carbon and nitrogen values based on McCutchan et al. (2003). The aim of the correction is to correct for trophic enrichment so that consumers should overlap more closely with their food sources (Phillips 2012). For a mixing model to be accurate, the trophically-corrected consumer isotope values should fall within the space defined in the polygon (dashed line), which is formed around the end members (i.e., food sources at the outer most edges) to be considered part of their diet (Phillips 2012).

Catfish appear to have 3 main groups of end members including invertebrates, smelt, and periphyton, which are all of aquatic origin (Figure 4-5). There is a large spread in the end members with values ranging from -21.8 to -13.3‰ for $\delta^{13}\text{C}$, and between 1.96 to 10.6‰ for $\delta^{15}\text{N}$, which is larger than expected (McCutchan et al. 2003), implying important food groups could be missing. Damselflies appear to be the most important to catfish diet based on their close proximity, and its positioning overlaps with small catfish. Goldfish are also in close proximity to catfish indicating a shared food resource. Several invertebrates appear to contribute to catfish diet, including snails, dragonfly larvae and chironomid larvae. Although hornwort and egeria are in the polygon, they are not below catfish, implying they are not important carbon sources. Isotopic signatures of bullies and kōura are largely indistinguishable, making it hard to determine the relative importance of kōura or bullies to catfish diet. *Gambusia* also fall within the polygon, suggesting they could be consumed by catfish.

Kōura have 3 main end members including bullies, periphyton, and seston which are all of aquatic origin (Figure 4-6). There are no food groups in immediate proximity to kōura, indicating that there are missing food items. Of the items sampled, egeria, bullies and damselflies are likely of the most importance to kōura

diet. Hornwort is the only other plant that appears to be part of kōura diet. Invertebrates particularly dragonfly larvae and chironomid larvae appear to be contributing to kōura nutrition.

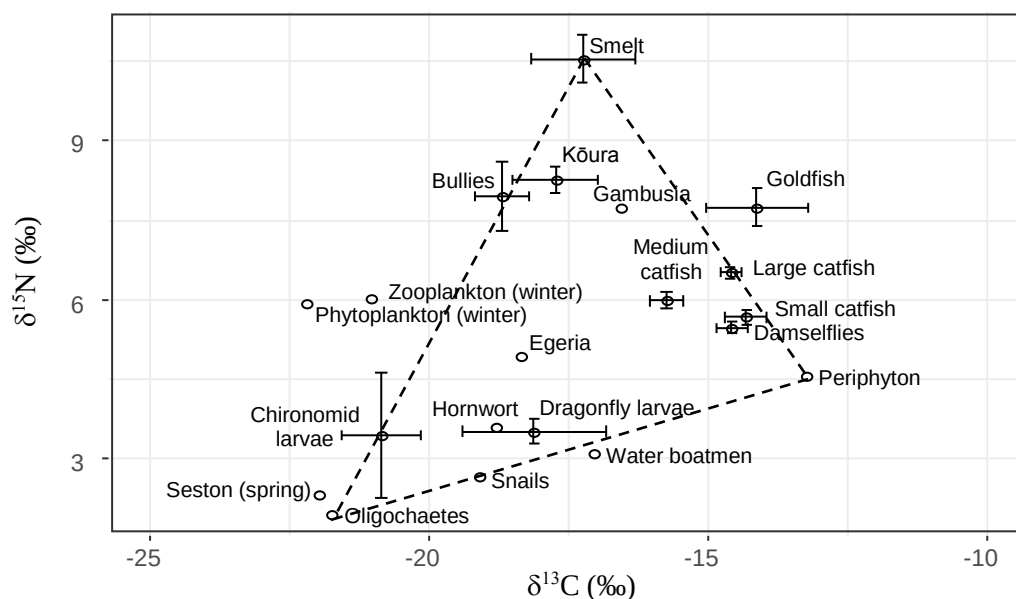


Figure 4-5. Dual isotope plot for catfish diet in Te Weta Bay, with 1SE bars. Presumed trophic enrichment has been subtracted from catfish values.

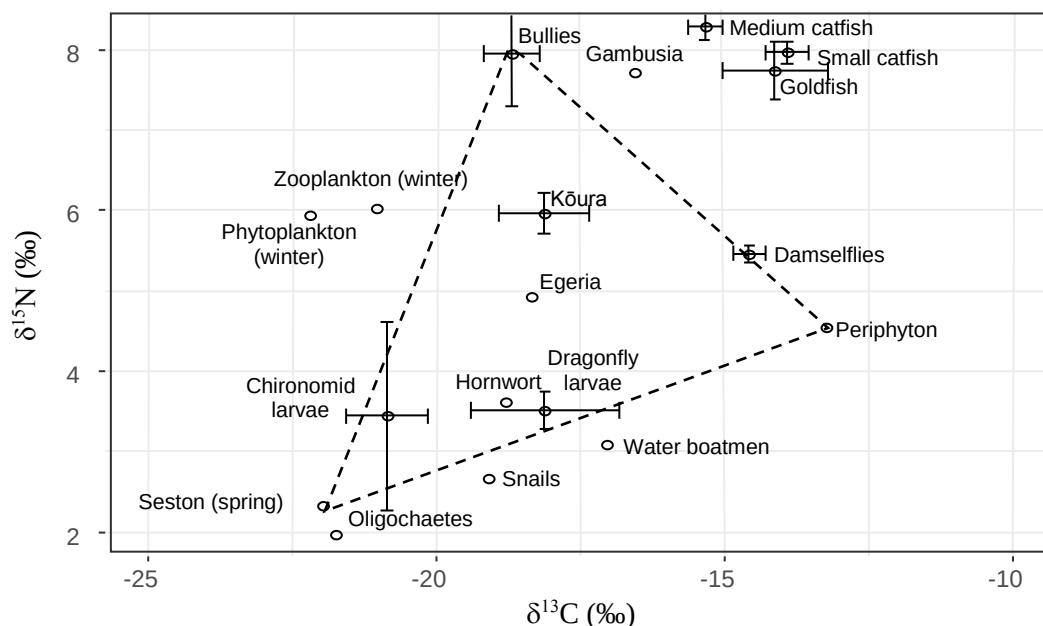


Figure 4-6. Dual isotope plot for kōura diet in Te Weta Bay, with 1SE bars. Presumed trophic enrichment has been subtracted from kōura values.

4.5.4 Dietary overlap

Values of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ for bullies, catfish, goldfish and kōura from Te Weta Bay (Table 4-9) were analysed using nicheROVER programme in R to estimate 95% niche regions of each species. Results indicated that catfish and kōura diet overlapped, with kōura occupying a greater proportion of catfish niche space than contrary. Kōura shared between 30-90% of niche space with catfish, whereas, catfish shared between 12-79% of their niche space with kōura, suggesting that catfish ate similar things to kōura, but had a broader diet (Table 4-10; Figure 4-7). Catfish also shared a large proportion of their niche space with goldfish and vice versa, implying they consume similar things. There was little dietary overlap between catfish and bullies.

Table 4-9. Mean $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values for bullies, catfish, goldfish, and kōura caught in Te Weta Bay, showing the number of samples, with 1SD.

Species	$\delta^{15}\text{N}$		$\delta^{13}\text{C}$		<i>n</i> samples from Te Weta Bay
	Mean	SD	Mean	SD	
Bullies	7.96	1.45	-18.71	1.07	5
Catfish	8.41	0.90	-14.38	1.84	122
Goldfish	7.74	1.02	-14.14	1.02	8
Kōura	8.26	0.63	-17.75	1.89	6

Table 4-10. Probabilistic niche (95%) overlap (the probability of species B overlapping with species A) between bullies, catfish, goldfish and kōura, showing 2.5 and 97.5% quantile probabilities.

Species A	Quantile probability	Species B			
		Bullies	Catfish	Goldfish	Kōura
Bullies	2.5%	-	2	1	23
	97.5%	-	38	40	94
Catfish	2.5%	6	-	45	30
	97.5%	60	-	95	90
Goldfish	2.5%	2	66	-	25
	97.5%	95	100	-	100
Kōura	2.5%	24	12	8	-
	97.5%	90	79	74	-

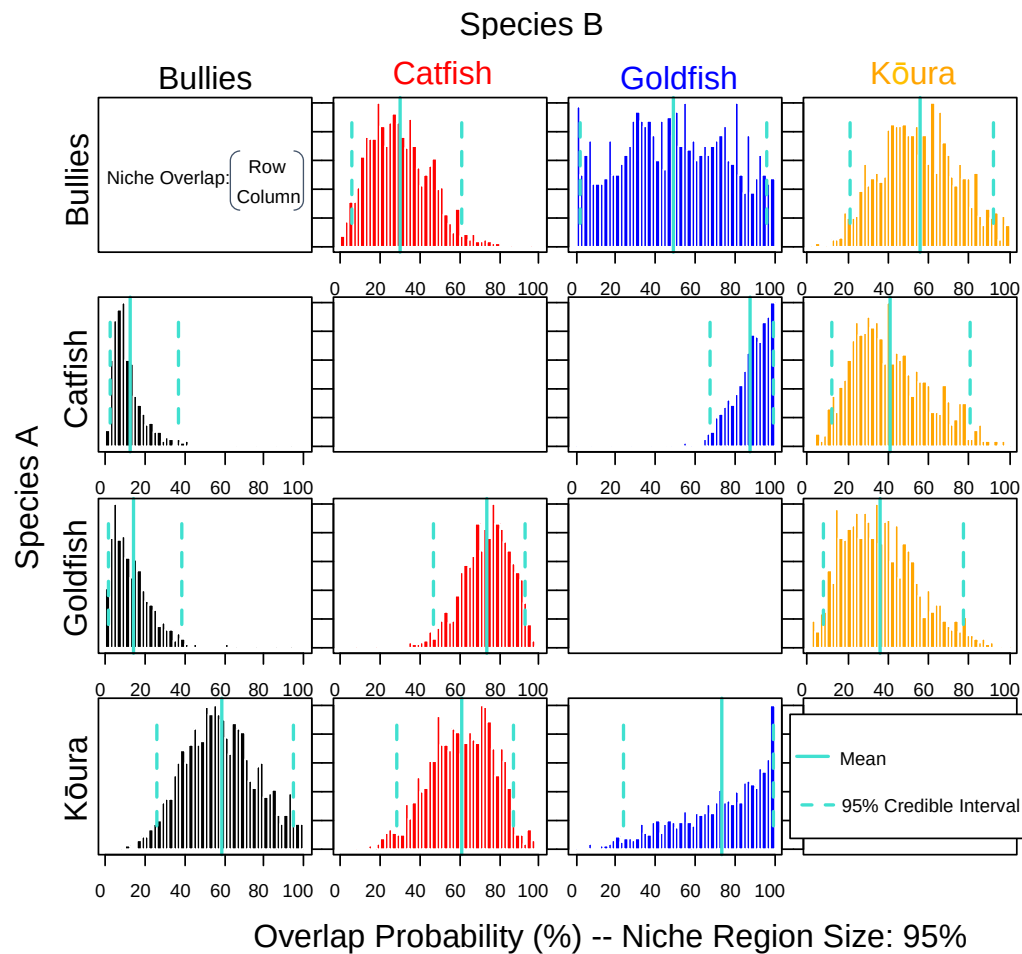


Figure 4-7. Probabilistic niche overlap (probability of species B overlapping with species A) showing 95% niche regions for bullies, catfish, goldfish and kōura. Means and 95% confidence intervals are displayed in green.

4.5.5 Gape-length relationship for fresh and frozen catfish

4.5.5.1 Gape size and length regressions for all fish

Data from fresh and frozen catfish were combined to obtain linear regressions of gape height (mm) vs fork length (mm), gape width (mm) vs fork length (mm), and gape height (mm) vs gape width (mm) (Figure 4-8). All of the regressions were significant (ANOVA $P < 0.001$) and yielded high adjusted r^2 values (> 0.9), indicating strong relationships between the variables. The summary statistics and regression equations can be found in Table 4-11.

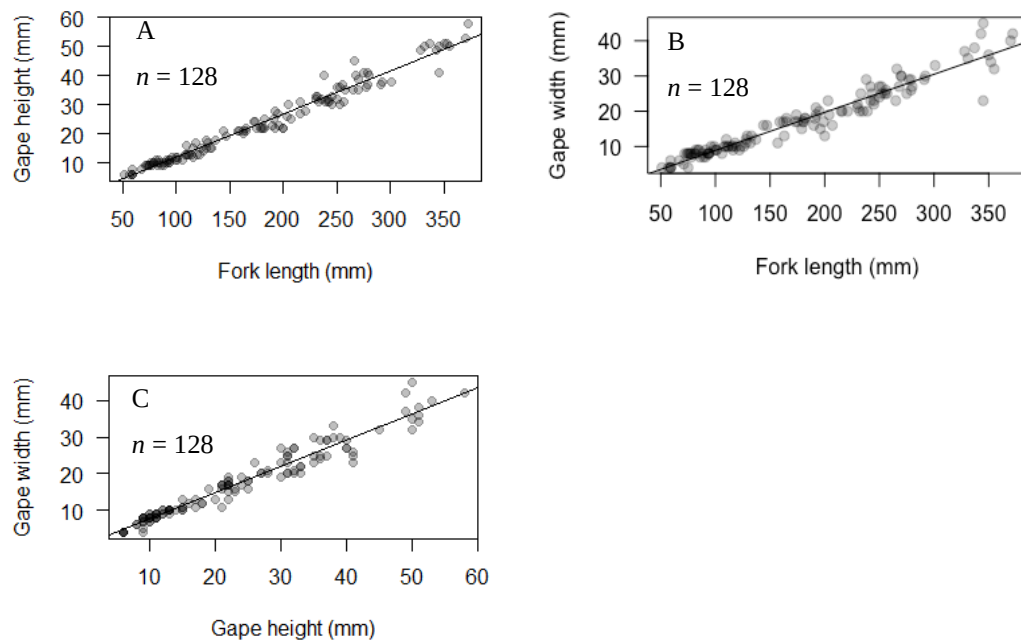


Figure 4-8. Relationships for catfish gape height (A) and gape width (B) against fork length; and the relationship between catfish gape width and gape height (C).

Table 4-11. Summary statistics for linear regressions ($Y = a + bX$) for catfish gape height (X) vs fork length (Y), gape width (X) vs fork length (Y) and gape width (X) vs gape height (Y).

Relationship	Intercept (a)	Slope (b)	P value	Adjusted R ²	Degrees of freedom	n
Gape height vs fork length	-3.086	0.149	<0.001	0.971	126	128
Gape width vs fork length	-1.911	0.108	<0.001	0.934	126	128
Gape width vs gape height	0.439	0.718	<0.001	0.948	126	128

4.5.5.2 Comparison of gape height and length regressions for fresh and frozen catfish

The slopes of regression lines for gape height vs fork length for fresh and frozen catfish were the same (ANCOVA P 0.550 for the interaction between fork length and gape height; Figure 4-9; Table 4-12). However, there was a significant difference between the intercepts for the regressions for fresh and frozen catfish gape height and length (ANCOVA P 0.022), meaning that the gape heights (mm) of fresh and frozen catfish would need to be obtained from fork length (mm) using separate equations. The separate regression equations and summary statistics for

gape height (mm) vs fork length for fresh and frozen catfish are given in Table 4-13.

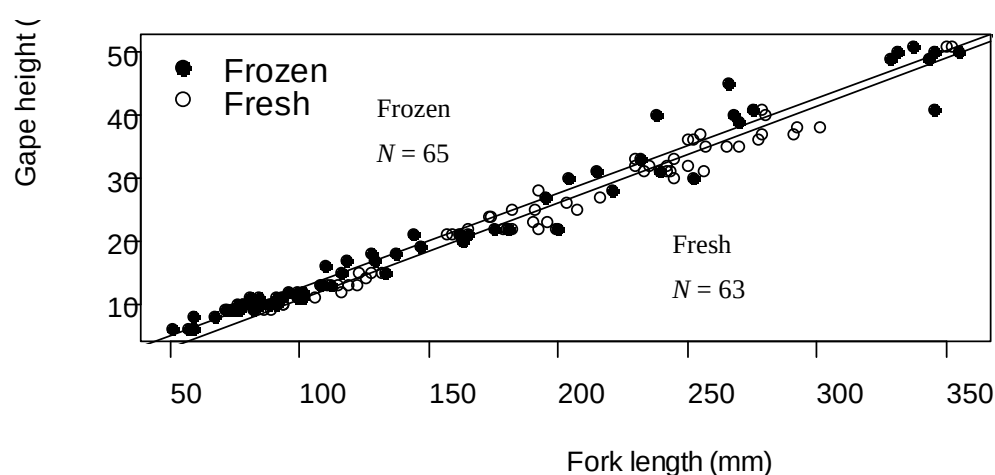


Figure 4-9. Relationships of gape height (Y) against fork length (X) for fresh and frozen catfish.

Table 4-12. ANCOVA test for equality of regression slopes for gape height (Y) against fork length (X) and condition (fresh or frozen).

Coefficients	Estimate	Standard error	t-value	P value
Fork length (mm)	0.154	0.004	43.003	<0.001
Condition	2.167	0.933	2.322	0.022
Fork length (mm):Condition	-0.003	0.005	-0.599	0.550

Table 4-13. Summary statistics and regression equations ($Y = a + bX$) for fresh and frozen catfish gape height (mm) (Y) vs fork length (mm) (X).

Catfish condition	Intercept (a)	Slope (b)	P value	Adjusted R ²	Degrees of freedom
Fresh	-4.762	0.154	<0.001	0.974	61
Frozen	-2.595	0.151	<0.001	0.972	63

4.6 Discussion

The main objective of this study was to understand the threat that catfish pose to kōura and native fish species in Lake Rotoiti. This was investigated by dissecting catfish and kōura stomachs caught from Lake Rotoiti between 2016 and 2018. Additionally, catfish's potential food items were collected from six sites in the lake for stable isotope analysis, to determine (i) what catfish are eating, (ii) the contribution of kōura to catfish diet, and (iii) to determine dietary overlap between both species. The secondary objective was to create a gape-length relationship for catfish, so mouth size can be related back to feeding habits.

4.6.1 Catfish stomach contents analysis

Flexibility in diet is an important adaptation of foraging fishes, allowing colonisation of environments where food availability is inconsistent (Dill 1983). In Lake Rotoiti, catfish diets were diverse comprising a total of 29 different items, with few prey items making up the majority of catfish diet. Chironomid larvae were the most abundant item in catfish diets, being the first or second most commonly consumed food item in catfish guts across all size classes. The high occurrence of chironomid larvae in catfish diet is consistent with other studies (Wise 1990; Kane 1995; Declerck et al. 2002; Collier et al. 2018), where chironomid larvae are the most commonly consumed food item regardless of catfish size (Patchell 1977; Keast 1985a; Declerck et al. 2002). In this study, chironomid larvae made up a greater proportion of small catfish diet than that of medium and large catfish. The importance of chironomids to small catfish diet has been noted in New Zealand and overseas (Barnes 1996; Declerck et al. 2002).

Detritus was common in catfish guts across all size classes, but contributed little volumetrically to catfish diet except for in large catfish. Studies have found detritus to be a frequent item in catfish guts (Patchell 1977; Wise 1990; Kane 1995). Patchell (1977) found that catfish from the Waikato region consumed large amounts of aquatic macrophytes and detritus, making up a large proportion of their gut contents. Similarly, detritus was the second most abundant food item in catfish guts in Hamilton Lake, after chironomid larvae (Kane 1995). Studies have found the consumption of detritus by catfish could be unintentional being consumed when picking out invertebrates and other food items from macrophytes and bottom

substrates (Patchell 1977; Collier et al. 2018). Large catfish probably contain more detritus because of their larger gape that would reduce prey item selectivity (Patchell 1977).

Fish (mainly common bullies), although not consumed by as many catfish (a combined 64% of catfish stomachs), made up a large proportion of catfish diet, particularly that of medium catfish. The high consumption of bullies is unsurprising given their high numbers in the lake (chapter 3). In shallow Waikato lakes, common bullies were found to be important items in large catfish diet (Collier et al. 2018); and fish were the third most abundant item in catfish guts in Hamilton Lake (Kane 1995).

Kōura were infrequent items in catfish stomachs and were only found in large catfish (>240 mm FL) that had been caught in Te Weta Bay. Of the full large catfish stomachs analysed ($n = 73$), 9 contained kōura (12% of large catfish stomachs), which made up 5% of large catfish diet. Sizes of intact kōura found in catfish stomachs ranged from approximately 10 to 35 mm OCL. Barnes and Hicks (2003) found that 64% of large catfish stomachs (>250 mm FL) taken from rocky sites in Lake Taupo contained kōura, that suggests that the kōura consumption rates by catfish in Lake Rotoiti should be higher due to the abundance of the resource. However, in a different site in Lake Taupo which was weedy, only 15% of large catfish stomachs contained kōura, indicating that habitat may play an important role in kōura consumption (Barnes 1996). The higher consumption of kōura in rocky sites is likely because both catfish and kōura aggregate around rocky substrates for shelter (Johnsen and Taugbøl 2008), likely making kōura the most abundant food source. Rocky substrates are uncommon in the littoral zones of Lake Rotoiti, and are situated more around the entrances of bays, including Te Weta Bay (G. Ewert, BOPRC, pers. comm.).

Invertebrates, including Odonata, unidentified insects and snails were infrequent items in catfish stomachs, occurring more in medium and large catfish stomachs than in small catfish. Volumetrically, invertebrates made up similar proportions of small and medium catfish diet, making up a larger proportion of large catfish diet. Barnes (1996) also found that Odonata consumption increased with increasing

catfish size, and snails were consumed in relatively equal proportions by all size classes.

Zooplankton occurred in 7% of small catfish stomachs, 3% in medium and 1% in large catfish stomachs. Other studies have found cladocerans (zooplankton) to be important items in catfish diet, particularly that of small catfish (Keast 1985a; Barnes 1996). In this study, zooplankton were largely removed when the samples were sieved, meaning that its contribution to catfish diet could not be examined using stomach contents.

4.6.2 Kōura stomach contents analysis

Detritus, plants, and small invertebrates are key items in kōura diet (Devcich 1974; Nyström et al. 1996; Whitmore et al. 2000). In this study, kōura stomachs contained between 1 and 6 food subgroups (e.g., fish, invertebrates, terrestrial matter), with an average 4.4 food groups out of a possible 10. Animal material was the most abundant food group in kōura stomachs occurring in all 28 kōura analysed, and was mostly fish (mostly common bullies). There is a possibility that the importance of fish has been overestimated, because some fish parts (e.g., vertebrae and otoliths) persist in the gut long after muscle, skin, and fins have been digested (Momot 1995). Kōura and bullies could come in to contact when bullies move inshore at night to feed in the littoral zone (Forsyth and James 1988), or during summer and spring when bullies lay their eggs in nets in shallow waters (<5 m; Rowe 2002). Kōura could also scavenge on dead fish remains.

Invertebrates were found in the majority of kōura guts, but only contributed to 11% of their diet. Invertebrate remains included chironomid larvae and pupae, kōura exoskeleton, oligochaetes, dipteran larvae, purse caddis larvae, cladocerans, and fragments of wings and mouth parts of unidentified insects. Other studies have also found that similar quantities of invertebrates in kōura stomachs, with invertebrates representing ~10% of kōura diet in Lake Rotoiti in 1974 and in Powder Stream in Otago (Devcich 1974; Whitmore et al. 2000).

Detritus was the second most important food group in kōura guts, contributing a third to kōura diet. Detritus largely composed of terrestrial vascular plant material

and aquatic macrophytes, with small quantities of filamentous algae. Other studies have also noted the importance of vascular plant detritus to crayfish diet. Whitmore et al. (2000) found that the majority of kōura stomachs analysed from a forested stream in Otago contained vascular plant detritus. Similarly, a previous study in Lake Rotoiti found that detritus (80%) and vascular plant material (10%) made up a large proportion of kōura diet (Devcich 1974). The consumption of detritus is thought to increase with crayfish size beyond 30 mm OCL (Gutiérrez-Yurrita et al. 1998; Whitmore et al. 2000), which may explain why plant detritus consumption was low in this study, as the kōura analysed were all under 32 mm OCL.

4.6.3 Stable isotopes

4.6.3.1 Complete food web

Most aquatic macrophytes and terrestrial plant species in Lake Rotoiti, with the exception of egeria, coarse particulate organic matter (CPOM), hornwort, and charophytes were either very depleted or enriched in $\delta^{13}\text{C}$ relative to other taxa. This suggests that they are not important foods to the higher trophic levels given their distance from consumers. Further evidence to support this claim came from the large spread ($>20\text{‰}$) in $\delta^{13}\text{C}$ values, indicating that aquatic macrophyte contribution to the food web is low (Hecky and Hesslein 1995). $\delta^{15}\text{N}$ macrophyte values are also further than the 2.3‰ expected increase away from consumers (McCutchan et al 2003).

Aquatic macrophytes are not always important to lake food webs in temperate climates (Hecky and Hesslein 1995; James et al. 2000; McBride 2005). Animals in lakes could instead be supported by attached algae or phytoplanktonic carbon (Hecky and Hesslein 1995; James et al. 2000; Vadeboncoeur and Power 2017). In this study, periphyton scraped from a rock was highly enriched in $\delta^{13}\text{C}$ relative to invertebrates, implying that the periphyton sample was unrepresentative of the true value, or that the invertebrates did not consume periphyton. Algal communities have variable $\delta^{13}\text{C}$ values, which is reflected by the broad range of invertebrate $\delta^{13}\text{C}$ values (Hecky and Hesslein 1995). This suggests that more samples should be taken in order to obtain better estimates of the true value. Another alternative is to use the signature of aquatic snails, as they are effective long-term integrators of the resource (Post 2002).

Several aquatic insect species including dragonfly larvae, oligochaetes, snails, water boatmen, chironomid larvae, and damselflies shared a similar positioning in the food web, and had $\delta^{13}\text{C}$ values closer to that of the pelagic food web. The majority of these invertebrates likely consume the same algal resource either directly or indirectly by consuming invertebrates as suggested, based on their proximity to grazing snails (Post 2002).

Isotopic values of zooplankton, phytoplankton, and seston were variable with the season. Winter zooplankton and phytoplankton samples were enriched in $\delta^{15}\text{N}$ relative to spring seston, with $\delta^{13}\text{C}$ being similar among the three samples. The lower $\delta^{15}\text{N}$ values for spring seston suggests that it was missing zooplankton, which was confirmed under the microscope with the sample consisting of *Dolichospermum* (30%) and diatoms (70%). Winter zooplankton samples were void of large bodied zooplankton (I. Duggan, University of Waikato, pers. comm.), but contained smaller bodied zooplankton species. The variability in isotopic values is unsurprising given seston composition changes dependent on where and when and how you sample (Zohary et al. 1994). Mesh size used can also affect species composition of the sample (McBride 2005). Mussels are efficient consumers of seston, and could be used as isotopic indicators in the same way that snails have been used as indicators of periphyton isotopes (Post 2002); if this is the case, seston samples were indeed depleted in $\delta^{15}\text{N}$ relative to mussel flesh.

Close positioning of bullies, gambusia, smelt, kōura, catfish and goldfish in the food web suggests they could have similar diets, which likely consists of benthic invertebrates such as chironomid larvae, Odonata and snails. This is consistent with the literature, with small invertebrates, particularly chironomid larvae and other insects (e.g., snails, Odonata, snails, amphipods) being important dietary items of all species (Boubee and Ward 1997; Mansfield and McArdle 1998; Morgan and Beatty 2007; Wilhelm et al. 2007). Zooplankton (copepods and daphnids) was also of importance to the fish and crustacean species examined, either as juveniles or throughout their lives.

Large trout (>400 mm FL) were the most enriched in $\delta^{15}\text{N}$ compared to other taxa, which is likely due to the consumption of common smelt (McBride 2005; Blair et al. 2012), crayfish (Blair et al. 2012), and other fish species such as bullies (Rowe

1984) and kōaro (Blair et al. 2012). Unfortunately we were unable to obtain kōaro for SIA, but they are a food source for trout (Rowe 2002) and potentially catfish. Small trout (<100 mm FL) possessed different diets to large trout, and were less enriched in $\delta^{15}\text{N}$. Blair et al. (2012) found juvenile rainbow trout (<200 mm FL) in Lake Rotoiti consumed amphipods, oligochaetes, smelt, shrimps and terrestrial and aquatic invertebrates.

4.6.3.2 Catfish and kōura diet

Catfish

Dual isotope plots of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ corrected for catfish indicated that catfish had diverse diets consisting of fish and invertebrates. The high number of potential food items in the food web was unsurprising given catfish's diverse and opportunistic diet (Barnes and Hicks 2003). Diet also appeared to change little among catfish size classes, getting slightly more enriched in $\delta^{15}\text{N}$ with increasing catfish size, likely to the increased consumption of fish and kōura with size (Scott and Crossman 1973; Barnes 1996; Declerck et al. 2002).

Positioning of damselflies in the food web suggested that they were the main source of catfish nutrition from the sites examined. This was unexpected given few catfish stomachs contained damselflies (Odonata consisted mainly of dragonfly larvae) and the damselfly numbers were low during whakaweku sampling (chapter 3). This is similar to what Collier et al. (2018) found where Odonata or other predatory invertebrates with similar signatures, were important for catfish nutrition based on core niche ellipses, even though they were infrequent items in catfish guts. Collier et al. (2018) hypothesised that catfish were consuming large numbers of invertebrates when their abundances are high (i.e., insect emergence) and retain the assimilated carbon signature and trophic positioning, even with their varied diets. Carbon and nitrogen muscle tissue turnover rates of fish can also be slow. For example, when common carp (*Cyprinus carpio*) were switched to a plant-based diet it took 44 days for $\delta^{13}\text{C}$ in muscle flesh to reach 50% equilibration (t_{50}) and 190 days to reach equilibrium (t_{95}); for $\delta^{15}\text{N}$ it took 102 days in muscle flesh to reach 50% equilibration (t_{50}) and 441 days to reach equilibrium (t_{95} ; Winter et al. 2019).

Dragonfly larvae and chironomids appeared to be of similar importance to catfish diet. Based on stomach contents, it was hypothesised that chironomid larvae would be positioned closest to catfish in the isotope plots, but this was not the case. This suggested that although commonly consumed (Patchell 1977; Keast 1985b; Kline and Wood 1996; Declerck et al. 2002; Collier et al. 2018), chironomids are not as important to catfish nutrition.

Egeria and hornwort were inside the polygon, suggesting they are a potential carbon source of catfish. However, both plant species had lower $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values than catfish, even allowing for the assumed trophic shift between a consumer and its food (-0.4‰ for $\delta^{13}\text{C}$ and 2.3‰ for $\delta^{15}\text{N}$; McCutchan et al. 2003). Catfish were on average between 3.48‰ more enriched in $\delta^{13}\text{C}$ than egeria, and 4.8‰ more enriched in $\delta^{13}\text{C}$ than hornwort. Furthermore, $\delta^{15}\text{N}$ values of egeria and hornwort were on average -3.99‰ and -4.42‰ more depleted than catfish. This suggests macrophytes are unimportant to catfish nutrition, even though they occurred in many guts. Nutrition and energy from plant matter could instead be gained through the consumption of invertebrates and other animals (Collier et al. 2018).

Bullies and kōura were too isotopically similar to be distinguished, so the contribution of both species to catfish diet could not be examined. Gut content analysis revealed that catfish consumed kōura and bullies, but ate considerably more bullies.

Kōura

A food web corrected for kōura identified invertebrates (i.e., dragonfly larvae, oligochaetes, and chironomids), bullies, periphyton and aquatic macrophytes (i.e., hornwort and egeria) as items of moderate to little importance to kōura nutrition, suggesting that kōura gain most of their nutrition from elsewhere. Kōura could be obtaining most of their nutrition from other invertebrate species not collected for SIA, as chironomid larvae were the only invertebrates positively identified in kōura guts obtained for SIA.

4.6.3.3 Dietary overlap

Diets of catfish and kōura overlapped, with kōura's niche space overlapping more with catfish's than vice versa, likely due to catfish's broad diet (Stewart et al. 2017). Dietary items both species had in common in gut contents and stable isotope food webs were chironomid larvae, Odonata larvae and common bullies; implying that dietary overlap would be highest when invertebrates are most abundant (e.g., emergence during warmer periods; Collier et al. 2018). This is because both species utilize invertebrates when available (Whitmore et al. 2000; Collier et al. 2018). Invertebrates are particularly important for kōura, as they require animal protein for growth (Momot 1995) and are an essential component of their diets (Devcich 1974; Nyström et al. 1996; Whitmore et al. 2000). This suggests that catfish have the potential to affect kōura indirectly through competition, as well as directly through consumption in Lake Rotoiti. Catfish diet overlapped the most with goldfish of the species investigated, which is unsurprising as both species occupy the same habitats and eat the same things (i.e., plant material, detritus, small insects and crustacea; Collier and Grainger 2015).

4.6.4 Gape-length relationship in catfish

Mouth size of fishes is considered the most important factor influencing the size and type of prey items consumed, whereby the larger the predator, the larger the size of prey that can be consumed (Wilson 1975; Boubée and Ward 1997). Brown bullhead catfish are opportunistic feeders with broad mouths (Keast 1985a) that consume prey types of varying sizes (Barnes and Hicks 2003). As catfish grow in size they become increasingly piscivorous and include kōura in their diets as their gape size and food availability allows (Barnes and Hicks 2003). The ability of large catfish to utilize these larger resources gives them a competitive advantage over their smaller counterparts (Wilson 1975), and helps the fish to achieve their increasing energy demands (Galis et al. 1994). Currently, no gape size-length relationship for brown bullhead catfish exists. Therefore, the present aim is to create a relationship between gape characteristics and fork length so in the future, mouth area can be tested against feeding habitats.

In order to be able to determine the size of prey that catfish can consume, gape-length relationships were established for gape height vs fork length, gape width vs

fork length, and gape height vs gape width. All of the relationships were significant (ANOVA $P < 0.001$) and had high adjusted R^2 values (> 0.9). However, catfish are often frozen prior to analysis for preservation, so we further aimed to determine if fresh and frozen gape-length relationships were the same.

When comparing the relationships for fresh and frozen catfish, the slopes were the same (ANCOVA $P = 0.550$) but the intercepts were not (ANCOVA $P = 0.022$). This meant that fresh and frozen catfish had different gape height-length relationships of $Y = -4.762 + 0.154x$ and $Y = -2.595 + 0.151x$ (where x is fork length) for fresh and frozen catfish respectively. Differences in the intercepts of fresh and frozen catfish are thought to be due to the shrinkage of catfish when placed in the freezer. Catfish fork length was reduced by ~ 10 mm, with shrinkage decreasing with increasing fish size. Although catfish fork length was reduced when frozen, gape size of the catfish remained the same, giving rise to the two equations. A reduction in size when frozen is not uncommon. Buchheister and Wilson (2005) found that freezing of juvenile walleye pollock, capelin and eulachon significantly reduced fish mass and length. Lengths of the juvenile fish (< 2 years old) reduced in length between 1.8 and 4.2 mm dependant on species. However, once frozen, the fish do not continue to shrink over periods of 1.5 to 27 months, suggesting the equation does not need to be corrected for time spent frozen.

4.7 Conclusion

Catfish diet was highly diverse and included food items of plant and animal origin. Chironomid larvae were the first or second most commonly consumed item by catfish size classes, followed by detritus and fish (largely common bullies). Detritus was the most commonly found item in large catfish guts and contributed little to catfish nutrition. Kōura and other invertebrates were less common in catfish guts, with kōura only occurring in 12% of large catfish (> 200 mm FL) stomachs. Stable isotope plots corrected for catfish suggested that catfish diet did not change much with size and that damselflies, although not common in catfish guts, contributed the most to catfish's nutrition. This was thought to reflect seasonal availability of invertebrates and slow $\delta^{13}\text{C}$ muscle tissue turnover rates.

Kōura diet comprised largely of animal remains and detritus. Common bully remains were found in all kōura stomachs analysed, but were unimportant to kōura nutrition, likely reflecting the longevity of hard fish remains in kōura stomachs. Invertebrates were also found in the majority of kōura guts. Diets of kōura and catfish overlapped, with kōura's niche area overlapping more with catfish's than vice versa, likely reflecting the broader diet of catfish. Based on stomach contents and SIA, chironomid larvae, Odonata and common bullies are shared resources of catfish and kōura, suggesting that dietary overlap would be highest when invertebrates are most abundant.

Gape-length equations for fresh and frozen catfish were different, which was due to catfish's length shrinking when placed in the freezer, but its gape size staying the same. In future, these equations can be used to estimate catfish gape size, which can be related to the size and number of prey items consumed to make inferences about catfish's feeding habits.

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5 Chapter 5

General discussion

The overarching aim of this study was to attempt to quantify the effects of brown bullhead catfish (*Ameiurus nebulosus*) on kōura (*Paranephrops planifrons*) in Lake Rotoiti (a lake recently invaded by catfish). Long-term monitoring suggests that kōura populations are in decline in Lake Rotoiti and catfish are a potential culprit (Kusabs 2016). However, only one study has tried to quantify the effects of catfish on kōura in Lake Taupo by doing an inter-lake comparison using tau kōura, and the method used likely under sampled areas where catfish and kōura are most likely to interact (depths <10 m; Kusabs and Taiaroa 2015). Several studies have indicated that catfish could be having an impact on kōura populations in the Waikato region. Large numbers of kōura were observed in catfish stomachs from Lake Taupo (Barnes and Hicks 2003), and when populations of catfish were high in the Waikato River, kōura numbers were generally lower (Clearwater et al. 2014). There is also an absence of overseas literature on the effects of *A. nebulosus* on crayfish species. The lack of understanding around the impacts that catfish can have on kōura, a taonga (treasured) and ecologically significant species is concerning, given the rapid population growth and expansion of catfish in the Bay of Plenty region. It is also highly likely that catfish will spread to previously uninhabited waterbodies in the Bay of Plenty and Waikato regions (Leathwick et al. 2016). Therefore, it is imperative that the effects of catfish on kōura are better studied to inform future catchment management decisions.

To address the knowledge gap on catfish and native species interactions, long-term Bay of Plenty Regional Council (BOPRC) routine monitoring fyke netting data collected between 2016 to 2018 was used in combination with data collected from a short-term habitat survey. Routine fyke netting data was used to explore the relationship between kōura and native fish abundance and catfish densities, as well as observing the expansion of catfish in the lake. The short-term habitat study used fine-meshed fyke nets and whakaweku (bracken fern bundles) to examine kōura habitat preferences, and kōura numbers, sexes, and sizes. In addition to fishing, catfish and kōura stomachs were examined to determine diet; and samples of fish, invertebrates, terrestrial plants, aquatic macrophytes, and seston, were also

collected for stable isotope analysis, to make inferences about trophic structure, dietary overlap, and carbon and nitrogen flows through food webs.

5.1 Catfish spread and effects

Catfish have spread throughout the western end of Lake Rotoiti since March 2016, and their abundance is rapidly increasing in the lake due to the successful recruitment of juveniles. The number of known sites where catfish are present in Lake Rotoiti has also increased from six sites in 2016 to 11 sites in 2018. The rapid expansion of catfish in the lake is thought to be in-part due to the availability of suitable catfish habitat (i.e., sheltered bays with exotic macrophytes) and warmer temperatures aiding catfish spawning (Hicks and Allan 2018). This suggests that habitat availability is not restricting catfish expansion in Lake Rotoiti, unlike in Lake Taupo where catfish's preferred habitat is minimal (Barnes and Hicks 2003).

Long-term fyke net monitoring data indicated that kōura catch rates have declined in Lake Rotoiti since 2016 as catfish have spread, suggesting that catfish are primarily responsible. Kōura catch per unit effort (CPUE) has declined in the lake since the initiation of the fyke netting programme, with mean catch rates dropping from 10.6 kōura net⁻¹ night⁻¹ in 2016 to 4.2 kōura net⁻¹ night⁻¹ in 2018. Over the same period, catfish CPUE has increased, with the highest catch rates in Te Weta Bay, where mean catch rates have increased from 1.1 catfish net⁻¹ night⁻¹ in 2016 to 63.7 catfish net⁻¹ night⁻¹ in 2018. Kusabs (2016) also noted a reduction in kōura numbers in the lake between 2005 and 2016 and identified catfish, expansion of exotic aquatic macrophytes, and changes in physiochemical conditions as potential reasons for their decline. When analysing routine fyke netting data from 2016-18 using a Spearman's rank order correlations, catfish were the only species to be negatively associated with kōura CPUE ($r = -0.180$). The inverse relationship between catfish and kōura could be due to catfish reducing kōura numbers through direct consumption or competitive exclusion from the lake's littoral zones. Catfish also had different habitat preferences to kōura, which could have contributed to the inverse relationship between both species. Catfish CPUE was highest on muddy substrates and at sites that hosted dense stands of exotic macrophytes, whereas kōura were positively associated with broken rock substrates and were negatively associated with muddy substrates. Kōura have also been negatively associated with

aquatic macrophytes through exclusion from the littoral zone (Hessen et al. 2004). Although, our study did not find a significant relationship. Whakaweku were ineffective at catching kōura in the shallow littoral zones of Lake Rotoiti, which was attributed to cool autumn water temperatures, low kōura numbers in the lake littoral zone, and the availability of alternative kōura habitat (e.g., rocks, logs and vegetation).

5.2 Catfish and kōura diet and dietary overlap

The stomachs of 238 catfish were analysed for diet from Lake Rotoiti. Catfish contained 29 different food items in their stomachs, with few items making up the majority of catfish diet. Chironomid larvae, detritus, fish (mostly common bullies), and non-kōura invertebrates (unidentified insects, Odonata, and snails) were key items in catfish diet. Kōura were less common. Large catfish (>200 mm FL) were the only size class to consume kōura, with 12% of large catfish containing kōura (i.e., 9 out of 73 full catfish stomachs contained kōura), which made up 5% of large catfish diet. The consumption of kōura by large catfish provides further evidence to suggest that catfish are responsible for the recent reductions in kōura abundance.

Diet changed little among the catfish size classes, with slightly differing consumption rates for certain food groups (e.g., fish and kōura), shown by the differing $\delta^{15}\text{N}$ values of catfish. Stable isotope plots corrected for catfish in Te Weta Bay suggested that damselflies or a food item with a similar signature were important for catfish nutrition. However, few Odonata were found in catfish guts and consisted largely of dragonfly larvae with few damselflies. This suggested that catfish can integrate long-term signatures of food groups, resulting from a time when the insect was most available (e.g., insect emergence; Collier et al. 2018). Chironomid larvae, detritus, and common bullies, although commonly consumed by catfish, contributed little to assimilated catfish carbon and nitrogen. It is possible that a key food item is missing from the isotope data, or that the assumed trophic enrichment is incorrect (Elsdon et al 2010).

The stomachs of 28 kōura from Lake Rotoiti were also dissected for diet. Kōura stomach contents mostly comprised of common bullies, detritus, and invertebrates. Common bully remains were found in all kōura stomachs analysed. Kōura could be

catching bullies or consuming dead fish remains. Detritus was the second most commonly consumed food group by kōura, which contributed a third volumetrically their diet, and comprised vascular terrestrial organic matter and aquatic macrophytes. Invertebrates were found in the majority of kōura guts analysed, but contributed little to kōura diet volumetrically. Invertebrates found in kōura stomachs included chironomid larvae and pupae, kōura exoskeleton, oligochaetes, dipteran larvae, purse caddis larvae, and cladocerans. Stable isotope corrected for trophic enrichment of kōura revealed that bullies, chironomid larvae, and aquatic macrophytes, were of roughly equal importance to kōura nutrition, as indicated by stomach contents.

Niche regions of catfish and kōura did overlap, with kōura's niche area occupying more of catfish's than the contrary, likely due to the broader diet of catfish. Using 95% probabilistic niche regions, catfish shared between 12-79% of their diets with kōura, and kōura shared between 30-90% of their diets with catfish. Shared dietary items were common bullies, chironomid larvae, and Odonata, suggesting dietary overlap would be higher when invertebrates are most abundant. Invertebrates are important for kōura growth (Parkyn et al. 2001), suggesting catfish can affect kōura indirectly through competition for shared food resources.

5.3 Management implications and future work

This study has furthered our understanding of the threat that catfish pose to kōura. The catfish population in Lake Rotoiti is rapidly expanding and they are spreading where habitat is suitable, including in areas outside of the lake. At present, catfish are being removed by the BOPRC, but the catfish problem is no longer able to be mediated by removal. With time, we can expect the number of large catfish in the lake to increase. This is of particular concern for kōura, as with more large catfish, we predict higher kōura predation rates and competition for shared food resources. This research emphasises the importance of preventing the spread of catfish and other introduced species, which can have devastating and unforeseen consequences on native biota. Education on the spread of introduced species is necessary, and nets and boat trailers should be checked and cleaned if they have been in waters with catfish. An unchecked boat trailer from Lake Taupo is probably how catfish arrived and established in Lake Rotoiti (Bay of Plenty Regional Council 2018a).

In future, it would be worthwhile continuing fyke netting in the lake to monitor fish and kōura catch rates as the catfish population expands. In addition to measuring catfish length during routine fyke netting, it would also be useful to measure kōura size, so the effects of catfish can be further examined. Factors other than catfish may also be contributing to the decline of kōura, and more research is needed to understand the effects of exotic macrophytes and physicochemical changes on kōura distributions and abundances in the lake. Although kōaro catch rates were not negatively associated with catfish in this study, they could be important food items for catfish and we recommend that kōaro are obtained for stable isotope analysis to add to the trophic information. Lastly, we have established a gape-length equation for catfish. It would now be useful to relate prey size in catfish's stomach to gape size to make inferences about the potential feeding habits of catfish.

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Appendices

Appendix 1. Mean catch per unit effort (CPUE) of kōura and fish in choked and unchoked fine-meshed meshed fyke nets, and the number of fine-meshed nets set for 2016-18 years.

Year	Site	CPUE (number net ⁻¹ night ⁻¹)								n nets
		Catfish	Bullies	Kōura	Kōaro	Goldfish	Longfin eel	Smelt	Trout	
2016	Delta	0	72.7	5.9	0	0.3	0	0	0	7
	Eastern Lake	0	56.7	11.0	0	0.2	0	29.7	0	6
	Mid-lake	0	61.7	32.7	0	0.4	0	27	0	7
	North	0	33.8	23.2	0	13.8	0	6.3	0	10
	Ohau Channel									0
	Okere Inlet	0	159.3	14.9	0	15.6	0.03	17.9	0	30
	Otaramarae	0	98.5	9.6	0	7.6	0.05	5.9	0	21
	Outside Te Weta Bay	0	91.4	10.6	0	16.1	0	5.2	0	14
	South	0	106.0	12.8	0	4.0	0	0	0	5
	Southern Shoreline	0	71.6	11.4	0	5.5	0	4.9	0	21
	Te Arero Bay	0	34.9	13.4	0	2.4	0	0	0	7
	Te Weta Bay	0.94	145.4	4.8	0	6.5	0	1.1	0.01	71
2017	Delta	0	144.3	4.8	0	9.0	0	12.7	0.08	26
	Eastern Lake	0	216.7	15.0	0	2.3	0	30	0	3
	Mid-lake	0	68.3	11.8	0.09	3.1	0.09	12.9	0	23
	North	0.05	57.6	14	0.48	9.7	0	13.4	0.04	82
	Ohau Channel									0
	Okawa Bay	0.05	285	1.8	0.02	18.1	0.02	69.9	0.41	128
	Okere Inlet	0.08	140.3	9.5	0.03	23.8	0.02	21.3	0.05	277
	Otaramarae	0.01	52.1	5.6	1.12	10.1	0	5.8	0	68
	Outside Te Weta Bay	0.05	52.7	7.1	0.74	9.0	0	17.4	0.06	158
	South	0	111.4	9.2	0.58	9.2	0	18.8	0	33
	Southern Shoreline	0.05	89.2	6.8	0.04	14.4	0	58.5	0.01	195
	Te Arero Bay	0	57.2	19.4	4.00	14.8	0	10.8	0	20
	Te Weta Bay	5.08	215.3	2.4	0.03	19.8	0	9.9	0.01	737
2018	Delta	0.67	103.9	3.1	0.04	2.2	0	23.9	0.01	202
	Eastern Lake	0	108.2	4.4	1.37	1.6	0	10.7	0	19
	Mid-lake	0.16	65.5	11.4	0.84	1.5	0.02	10.7	0.08	49
	North	3.37	91.5	8	0.81	5.3	0.01	9.4	0.01	155
	Ohau Channel	1.96	43.9	0.8	0.02	2.3	0.03	51.5	0.02	713
	Okawa Bay	3.05	286.4	1.5	0.43	23.5	0.02	94.6	0.01	145
	Okere Inlet	25.84	193.9	9.3	0.27	22	0.05	75.8	0.02	185
	Otaramarae	0.21	105.6	5.0	2.56	16.3	0.02	6.6	0.02	63
	Outside Te Weta Bay	12.15	51.5	5.6	0.28	12.6	0.04	8.2	0	81
	South	0.18	110.9	6.5	0.18	4.9	0	7.3	0	11
	Southern Shoreline	3.21	162.8	7.4	0.46	13.7	0.01	13.2	0	151
	Te Arero Bay	0	72.3	13.2	0.59	17.4	0.03	9.4	0	32
	Te Weta Bay	65.27	106.6	0.9	0.2	19.9	0	3.6	0.01	407

Appendix 2. Mean $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values and ranges for items collected for stable isotope analysis from A. Okawa Bay, B. Okere Inlet, C. Otaramarae, D. Southern Shoreline, E. Te Arero Bay, and F. Te Weta Bay in Lake Rotoiti.

A. Okawa Bay

	<i>n</i> samples	$\delta^{15}\text{N}$ (‰)			$\delta^{13}\text{C}$ (‰)		
		Mean (SD)	Min.	Max.	Mean (SD)	Min.	Max.
Coarse particulate organic matter	1	2.49			-27.95		
Common bullies	5	8.85 (1.10)	7.52	9.93	-16.19 (0.89)	-17.4	-15.45
Catfish size classes combined	12	9.18 (0.66)	7.58	10.10	-14.98 (1.24)	-16.55	-12.78
Large Catfish	5	9.19 (0.53)	8.79	10.10	-14.76 (1.24)	-16.15	-12.78
Medium Catfish	2	9.30 (0.10)	9.23	9.37	-15.06 (0.96)	-15.74	-14.38
Small Catfish	5	9.12 (0.95)	7.58	9.89	-15.19 (1.53)	-16.55	-12.79
Chironomid larvae	1	4.39			-19.54		
Kōura	2	9.20 (0.34)	8.96	9.44	-19.62 (0.59)	-20.03	-19.20
Oligochaetes	1	5.57			-13.81		
Phytoplankton (winter)	1	4.76			-23.97		
Rainbow trout <100 mm	1	7.92			-20.22		
Smelt	2	10.23 (0.34)	9.99	10.47	-17.63 (0.01)	-17.63	-17.62
Snail: <i>Physa</i>	1	2.70			-11.60		
Zooplankton (winter)	1	5.18			-21.53		

B. Okere Inlet

	<i>n</i> samples	$\delta^{15}\text{N}$ (‰)			$\delta^{13}\text{C}$ (‰)		
		Mean (SD)	Min.	Max.	Mean (SD)	Min.	Max.
Coarse particulate organic matter	1	3.43			-22.05		
Common bullies	5	9.47 (0.93)	8.37	10.41	-16.85 (2.25)	-19.19	-14.13
Catfish size classes combined	16	10.03 (0.73)	8.55	11.14	-17.03 (1.44)	-19.06	-14.40
Large Catfish	6	10.16 (0.95)	8.89	11.14	-16.06 (1.38)	-17.92	-14.40
Medium Catfish	5	10.22 (0.45)	9.54	10.79	-18.06 (1.00)	-19.06	-16.90
Small Catfish	5	9.69 (0.68)	8.55	10.31	-17.17 (1.29)	-18.58	-15.47
Chironomid larvae	1	4.84			-21.05		
Kōura	5	9.34 (0.34)	8.88	9.82	-15.08 (1.17)	-16.51	-13.70
Longfin eel	3	11.62 (0.90)	10.58	12.14	-19.44 (1.87)	-21.31	-17.57
Phytoplankton (winter)	1	5.27			-22.56		
Rainbow trout size classes combined	3	11.80 (2.57)	8.84	13.51	-19.63 (1.13)	-20.65	-18.42
Rainbow trout <100 mm	1	8.84	8.84	8.84	-20.65		
Rainbow trout >400 mm	2	13.28 (0.33)	13.05	13.51	-19.12 (0.99)	-19.82	-18.42
Smelt	5	11.00 (0.43)	10.37	11.58	-19.34 (0.61)	-19.95	-18.34
Snail: <i>Physa</i>	1	6.68			-19.36		
Zooplankton (winter)	1	5.68			-21.06		

C. Otaramarae

	<i>n</i> samples	$\delta^{15}\text{N}$ (‰)			$\delta^{13}\text{C}$ (‰)		
		Mean (SD)	Min.	Max.	Mean (SD)	Min.	Max.
Coarse particulate organic matter	1	1.74			-28.86		
Common bullies	5	9.04 (1.22)	8.06	10.89	-18.81 (3.02)	-22.58	-15.59
Catfish size classes combined	12	9.63 (0.89)	8.49	11.43	-17.13 (2.43)	-21.97	-13.91
Large Catfish	2	10.09 (1.01)	9.37	10.80	-15.92 (2.25)	-17.51	-14.33
Medium Catfish	5	9.98 (1.04)	8.49	11.43	-18.39 (2.63)	-21.97	-14.82
Small Catfish	5	9.09 (0.47)	8.65	9.81	-16.35 (2.14)	-19.50	-13.91
Damselflies	5	5.47 (0.24)	5.17	5.77	-14.58 (0.62)	-15.56	-13.86
Dragonfly larvae	3	4.03 (0.24)	3.83	4.30	-13.46 (1.98)	-15.31	-11.38
Gambusia	1	8.59			-20.46		
Kōura	5	8.02 (0.50)	7.38	8.59	-18.48 (3.72)	-24.06	-15.79
Mussel	1	6.98			-18.76		
Phytoplankton (winter)	1	4.97			-23.00		
Seston (spring)	1	5.14			-21.61		
Smelt	3	11.90 (0.50)	11.32	12.24	-19.93 (0.82)	-20.83	-19.22
Snail: <i>Physa</i>	1	3.54			-24.46		
Zooplankton (winter)	1	5.54			-23.90		

D. Southern Shoreline

	<i>n</i> samples	$\delta^{15}\text{N}$ (‰)			$\delta^{13}\text{C}$ (‰)		
		Mean (SD)	Min.	Max.	Mean (SD)	Min.	Max.
Coarse particulate organic matter	1	-1.51			-26.43		
Common bullies	5	6.52(1.14)	5.08	7.75	-20.15 (0.95)	-21.41	-19.20
Catfish size classes combined	14	8.11 (0.87)	6.84	10.12	-17.20 (1.36)	-19.38	-14.39
Large Catfish	5	8.06 (0.32)	7.82	8.62	-17.06 (1.48)	-18.96	-15.11
Medium Catfish	4	8.31 (0.95)	7.30	9.48	-18.01 (0.95)	-19.38	-17.20
Small Catfish	5	8.00 (1.28)	6.84	10.12	-16.68 (1.45)	-18.37	-14.39
Chironomid larvae	1	1.10			-22.01		
Dragonfly larvae	5	1.59 (0.39)	1.26	2.23	-22.31 (0.71)	-23.44	-21.46
Gambusia	1	8.63			-20.90		
Kōura	5	5.81 (1.90)	3.85	8.63	-18.38 (2.40)	-20.62	-14.71
Longfin eel	1	11.19			-16.03		
Phytoplankton (winter)	1	3.71			-24.95		
Rainbow trout <100 mm	1	9.86			-21.16		
Smelt	5	10.47 (0.28)	10.16	10.89	-18.79 (1.27)	-20.21	-16.74
Snail: <i>Physa</i>	1	0.66			-22.97		
Water Boatmen	1	3.10			-17.07		
Zooplankton (winter)	1	4.18			-24.02		

E. Te Arero Bay

	<i>n</i> samples	$\delta^{15}\text{N}$ (‰)			$\delta^{13}\text{C}$ (‰)		
		Mean (SD)	Min.	Max.	Mean (SD)	Min.	Max.
Coarse particulate organic matter	1	1.85			-30.10		
Common bullies	5	8.62 (2.24)	5.18	10.88	-18.63 (1.92)	-20.65	-15.69
Kōura	5	8.60 (1.55)	6.01	10.11	-16.75 (2.26)	-20.13	-15.01
Phytoplankton (winter)	1	6.19			-25.92		
Smelt	4	11.41 (0.52)	10.75	11.96	-19.11 (0.38)	-19.36	-18.54
Snail: <i>Physa</i>	1	5.66			-20.61		
Zooplankton (winter)	1	5.81			-26.47		

F. Te Weta Bay

	<i>n</i> samples	$\delta^{15}\text{N}$ (‰)			$\delta^{13}\text{C}$ (‰)		
		Mean (SD)	Min.	Max.	Mean (SD)	Min.	Max.
Coarse particulate organic matter	1	2.29			-29.10		
<i>Egeria densa</i>	1	4.93			-18.37		
Common bullies	5	7.96 (1.45)	5.53	9.39	-18.71 (1.07)	-19.70	-16.92
Catfish size classes combined	122	8.41 (0.90)	6.23	10.45	-14.38 (1.84)	-21.71	-10.30
Large Catfish	54	8.81 (0.81)	7.18	10.37	-14.21 (1.32)	-17.24	-11.73
Medium Catfish	28	8.28 (0.85)	7.21	10.45	-15.35 (1.60)	-18.47	-12.12
Small Catfish	40	7.97 (0.82)	6.23	10.44	-13.93 (2.33)	-21.71	-10.30
Charophytes	1	-0.17			-16.50		
<i>Coprosma</i> spp.	1	0.05			-29.35		
Crack willow	1	2.23			-30.37		
Dragonfly larvae	5	3.51 (0.52)	2.81	4.22	-18.13 (2.86)	-23.20	-16.54
Gambusia	1	7.73			-16.59		
Goldfish	8	7.74 (1.02)	5.90	8.83	-14.14 (2.57)	-18.17	-11.28
Hornwort	1	3.61			-18.80		
Kōura	6	8.26 (0.63)	7.45	9.15	-17.75 (1.89)	-19.60	-15.48
<i>Lagarosiphon major</i>	1	1.76			-7.18		
Mahoe	1	0.80			-30.59		
Oligochaetes	1	1.96			-21.78		
Myriophyllum spp.	1	2.84			-6.48		
Periphyton	1	4.55			-13.26		
Phytoplankton (winter)	1	5.94			-22.22		
Raupo	1	3.01			-29.37		
Seston (spring)	1	2.33			-21.97		
Smelt	5	10.55 (1.00)	9.10	11.50	-17.25 (2.07)	-18.80	-13.79
Snail: <i>Physa</i>	1	2.67			-19.11		
Eleocharis	1	4.57			-28.08		
Zooplankton (winter)	1	6.02			-21.07		