Kōura (*Paranephrops planifrons*) populations in the Te Arawa lakes: An ecological assessment using the traditional Māori tau kōura harvesting method and recommendations for sustainable management

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Abstract

Freshwater crayfish are amongst the most influential of biota in many aquatic systems. They have various ecological functions, acting as shredders, detritivores and predators which in turn influence other macroinvertebrate fauna. Furthermore, freshwater crayfish are increasingly used as indicator species because of the important role they play in aquatic ecosystems and their iconic and heritage values. Kōura or freshwater crayfish (*Paranephrops planifrons* White) are endemic to New Zealand where they are an important component of freshwater ecosystems and a source of food for freshwater fish and humans. This study was undertaken to gain a better understanding of kōura populations in the Te Arawa lakes by quantifying relative kōura abundance and distribution and assessing the effects of environmental factors on kōura populations. In addition, basic biological information on sex ratios, breeding and moulting was collected as a basis for setting regulations and management policies for the sustainable management of kōura in the Te Arawa lakes.

Historically, kōura were an important food for the indigenous Māori people, particularly in the central North Island (CNI) lakes where large numbers were harvested for consumption and trading. Today, kōura are considered a 'taonga' species and support important customary fisheries in some CNI lakes (Rotomā, Rotoiti, Tarawera, and Taupō) where large populations of kōura still exist. Nevertheless, there is considerable anecdotal evidence of declines in populations of kōura in the Te Arawa lakes district since European settlement. A number of environmental factors have been implicated in this decline, including introductions of exotic fish and plant species as well as reduced concentrations of dissolved oxygen in the bottom waters of lakes due to eutrophication.

Although the ecology of stream-dwelling *P. planifrons* is well studied in New Zealand, there is limited published biological information on kōura in lakes. The lack of quantitative information on kōura abundance and ecology makes it difficult for iwi (Māori tribes) and government agencies to manage lake dwelling kōura populations. Until recently the main reason for the lack of quantitative information on lake kōura was the absence of suitable representative sampling methods. In a preliminary study of kōura sampling methods in the Te Arawa lakes, it was found that conventional sampling methods, baited traps, SCUBA and underwater video camera surveys had a number of disadvantages. Trapping was found to be highly biased towards large individuals and complicated by reductions in bait quality with time and changes in natural food abundance. SCUBA and underwater video camera surveys are also biased towards large individuals and are strongly dependent on underwater visibility. Given the disadvantages of these conventional kōura assessment methods, a traditional Māori harvesting method, the tau kōura, was adapted for the monitoring of lake kōura populations. The tau kōura captured large numbers and a wide size range (6 – 50 mm Orbit Carapace Length, OCL) of kōura in both shallow (5 m mean depth) and moderately deep water (10 – 17 m depth) in Ōkere Arm and Te Ākau, Lake Rotoiti, respectively. This method also distinguished differences in size structure and biomass between sites and provided information on sex ratios, egg-bearing and moulting. The development of the tau kōura thus enabled research and monitoring of lake kōura populations that may have not previously been representatively sampled and have generally been little studied in New Zealand despite their ecological and cultural significance.

The tau kōura was used to examine population dynamics of kōura, along a eutrophication gradient in seven Te Arawa lakes, in April, July and November 2009. Mean catch per unit effort (CPUE) and depth distribution of kōura were influenced by the combined effects of lake bed sediments, lake morphology, and hypolimnetic conditions related to trophic state. Although limited by the number of lakes that I was able to characterise, my data indicates that lake bed substrate (median sediment particle size) had a stronger influence on population characteristics than the level of enrichment/primary production as indexed by chlorophyll *a* (Chl-*a*). Nevertheless, the negative correlations between kōura abundance, with sediment carbon to nitrogen ratio (C/N), and the positive correlation between abundance and Chl-*a*, suggest that lake productivity does influence kōura. This component of the study indicates that eutrophication has reduced available kōura habitat in the Te Arawa lakes, particularly those that are sheltered, steep-sided and have fine lake bed sediments (with the Rotomahana mud tephra being particularly important). Lake bed substrate composition represented by sediment particle size is therefore a key factor to consider when selecting tau kōura sites for research, monitoring, restoration and harvesting, and when estimating kōura stocks in lakes. I concluded that measures to improve

water quality in the Te Arawa lakes should benefit kōura populations by increasing the amount of oxygenated habitat available in the summer and autumn.

Kōura support important customary fisheries for iwi in some Te Arawa lakes, particularly Rotoiti, Rotomā and Tarawera. However, until recently, there was limited published biological information to provide a basis for fisheries regulations. This knowledge gap has resulted in the adoption of conservative fisheries regulations and management policies by the fishery managers, the Te Arawa Lakes Trust (TALT) and Ministry of Primary Industries (MPI). A further objective of the research was therefore to examine the biological traits of lake kōura and to consider implications of these traits on the current fishing regulations and sustainable management of kōura populations in the Te Arawa lakes.

From a review of past literature and the research findings from this study, it can be concluded that kōura populations in the Te Arawa lakes are currently not over-exploited due mostly to a low number participating in harvesting (almost exclusively Te Arawa) and because commercial harvesting is prohibited. However, the TALT wishes to encourage the revitalisation of traditional fishing practices (e.g., tau kōura) while adhering to the principles of kaitiakitanga – the sustainable protection of resources. The establishment of sustainable management policies and regulations adheres to the principles of kaitiakitanga.

A number of management changes arising from the information collected in this study are suggested to protect and enhance the kōura fishery in the future. These are (1) set a slot limit with minimum size limit of 28 mm OCL and a maximum size limit of 39 mm OCL, (2) prohibit the taking of egg-bearing females, (3) limit deep-water harvest methods to the use of the tau kōura, and (4) implementing a tau kōura harvest season beginning on 1 December and ending on 31 March. These measures will protect breeding females if they are captured and the closed season will allow the majority of females to breed and release their young prior to fishing activity. Improving water quality (and thus increasing available kōura habitat) and preventing the introduction of predatory fish species such as eels (*Anguilla spp.*), catfish (*Ameiurus nebulosus*), and perch (*Perca fluviatilis*), that are efficient predators of kōura, are of the utmost importance in ensuring the sustainability of kōura populations in the Te Arawa lakes.

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Preface

The main body of this thesis is made up of three research chapters presented as individual papers, which have been published in peer-reviewed publications. For this reason, there is some repetition and slight differences in style among chapters. Lake water quality data was provided by the Bay of Plenty Regional Council. All other content in this thesis, unless a citation is given, is based on my own ideas and work. This work was undertaken while under the supervision of Prof. David Hamilton (University of Waikato) and Dr. John Quinn (National Institute of Water and Atmospheric Research).

Co-authors of the papers listed below contributed data and/or helped with study planning and manuscript revisions.

Chapter 2 has been published as "Use of a traditional Māori harvesting method, the tau kōura, for monitoring kōura (freshwater crayfish, *Paranephrops planifrons*) in Lake Rotoiti, North Island, New Zealand" in the New Zealand Journal of Marine and Freshwater Research 2009, Vol. 43, pp. 713-722. Authors: I. A. Kusabs and J. M. Quinn. The chapter contained in this thesis differs from the version published as it includes some minor updates and photos that depict the tau kōura method.

Chapter 3 has been published online as "Effects of benthic substrate, nutrient enrichment and predatory fish on freshwater crayfish (kōura, *Paranephrops planifrons*) population characteristics in seven Te Arawa (Rotorua) lakes, North Island, New Zealand" in Marine and Freshwater Research. Authors: I. A. Kusabs, J. M. Quinn and D. P. Hamilton.

Chapter 4 has been published online as "Sustainable management of freshwater crayfish (kōura, *Paranephrops planifrons*) in Te Arawa (Rotorua) lakes, North Island, New Zealand" in Fisheries Research. Authors: I. A. Kusabs, D. P. Hamilton, B. J. Hicks and J. M. Quinn.

Chapter 1

General introduction

1.1 Kōura in New Zealand

Freshwater crayfish are crustaceans that are widespread and occur on all continents except Antarctica, either as native species or following anthropogenic translocation. They belong to the decapod infra-order Astacidea. The currently known 644 species of crayfish are classified into two major groups that are geographically and morphologically distinct: the Astacoidea (families Astacidae and Cambaridae) and the Parastacoidea (single family Parastacidae) (Crandall and Buhay 2008). New Zealand has two species of freshwater crayfish commonly known as kōura. Their distributions are quite separate, with one found in the North Island and the West Coast of the South Island (*Paranephrops planifrons*), and the other in the east and south of the South Island (*P. zealandicus*). The species present in the Te Arawa lakes is *P. planifrons* (Fig. 1.1). Both species are endemic to New Zealand where they are an important component of freshwater ecosystems and a source of food for fish and humans. Where crayfish are abundant they are amongst the most influential of biota in many aquatic systems and have various ecological functions, acting as a predator, detritivore and as a shredder, which in turn affects other macroinvertebrate fauna (Parkyn, *et al.* 1997; Parkyn, *et al.* 2001). The social and economic significance of crayfish has long been recognised in several regions around the world, including the southern United States, Australia, Europe and China. Moreover, crayfish increasingly feature as indicator species because of their role in aquatic ecosystems and their iconic and cultural values (Reynolds and Souty-Grosset 2012).

Kōura support limited recreational fisheries throughout the country (McDowall 2011). In the Central North Island (CNI), kōura (*P. planifrons*) are considered a ‘taonga’ species and support important customary fisheries in lakes Okataina, Rotoiti, Rotomā, Tarawera and Taupō where abundant populations exist (Kusabs and Quinn 2009).

Prior to European settlement, kōura were an important food for the Te Arawa and Ngāti Tūwharetoa people in the Te Arawa and Taupō lakes (Mair 1918; Hiroa 1921; Best 1929). However, there is considerable anecdotal evidence of declines in populations of kōura since the early 1900s (Hiroa 1921; McDowall 2011). A number of environmental factors have been implicated in this decline, including introductions of exotic fish (McDowall 1987; Barnes and Hicks 2003) and plants (Rowe 2004), as well as reduced concentrations of dissolved oxygen in the bottom waters of lakes owing to the effects of eutrophication (Kusabs, *et al.* 2015).

The ecology of stream-dwelling kōura is well studied in New Zealand (Hopkins 1967a; Hopkins 1967b; Hopkins 1970; Hicks and McCaughan 1997; Rabeni, *et al.* 1997; Parkyn, *et al.* 2001; Parkyn and Collier 2002; Parkyn, *et al.* 2002; Parkyn and Collier 2004; Parkyn, *et al.* 2009) but relatively little is known about kōura populations in New Zealand lakes. The lack of quantitative information on kōura abundance and ecology makes it difficult for government and iwi agencies to manage kōura populations in lakes. Until recently one of the main reasons for the lack of quantitative information on lake kōura was the absence of suitable representative sampling methods. However, the development of the tau kōura, a traditional Māori method for harvesting kōura, has enabled a resurgence of research and monitoring on lake kōura populations that have been little studied in New Zealand (Kusabs and Quinn 2009).

1.2 Kōura ecology

The only substantial research undertaken on lake kōura to date is that by Devcich (1979). His work focussed on Lake Rotoiti (North Island, New Zealand) and provides considerable insight into characteristics of the breeding population and aspects of growth of *P. planifrons*.

Breeding was considered to be continuous in Lake Rotoiti, with February to March being the least likely time to find females with eggs (Devcich 1979). Information from this lake suggested that a main pulse of breeding occurs in late autumn and eggs are carried over winter, while a second breeding season may occur in spring/summer (October to January) when females carry eggs (Devcich 1979). *P. planifrons* is thought to mature in 18 months to 2 years in streams (Jones 1981a;

Parkyn 2000), depending on temperature, and Devcich (1979) postulated that *P. planifrons* matured in their third year in Lake Rotoiti. Age at maturity was considered to depend on growth rate. Once kōura are beyond approximately 21 mm OCL, the smallest egg-bearing female found by Devcich (1979), they are likely to be able to reproduce. The only published study of kōura fecundity in New Zealand was carried out on small (17 to 30 mm OCL) lotic kōura from the Mangatarere River, Wairarapa District, where a linear relationship was found between kōura length and fecundity (Hopkins 1967a).

Estimating age and growth of freshwater crayfish in the wild is difficult for two reasons: (1) the loss of marks after moulting and (2) continuous breeding in much of the North Island, making it difficult to distinguish between age groups. Nevertheless a number of workers have estimated kōura ages in New Zealand. The largest kōura commonly found in stream populations of *P. planifrons* (about 35 mm OCL) are believed to be between 4 and 5 years old (Parkyn, *et al.* 2002), whereas the largest in lake populations (37 – 44 mm OCL) may be between 11 and 16 years old (Devcich 1979). Kōura populations are thought to grow larger in lakes because they have a more continuous growing season, where water temperatures generally exceed 10 ^{o}C (Parkyn and Collier 2002). To be able to grow, kōura, like all other arthropods, must moult their exoskeleton. The calcium content of water is very important both for adequate growth and survival, as kōura are particularly susceptible to cannibalism and predation whilst the exoskeleton is soft. Adequate calcium in the surrounding habitat leads to more rapid hardening of the exoskeleton.

Kōura prefer shade, and in land based aquaculture facilities, death from stress and cannibalism increase when kōura are subject to clear water and bright sunlight (Jones 1981a). Kōura in lakes are strongly influenced by light levels. Devcich (1979) reported that *P. planifrons* in Lake Rotoiti assembled into high-density bands that migrate up and down the lake diurnally with changes in light levels. Most kōura retreat to the darker depths during the day and some burrow into mud or find other cover items.

Although kōura eat a variety of foods (as omnivores) in natural populations it has been found that animal protein contributes most to growth, and that aquatic snails, chironomids and mayflies are the most important food sources (Parkyn, *et al.* 2001). Juvenile kōura probably require more protein than adults to sustain their high rate of growth. Kōura in lakes are thought to concentrate their feeding in the littoral zone where food is most abundant (both animal and detrital) and have probably evolved their diel movement to darker depths during the day and attraction to dark shelters in a response to shag predation. The food sources of kōura in lakes is not well understood although Devcich (1979) found that the energy content of kōura stomachs in Lake Rotoiti was not statistically different across depths of 1, 10, 20, 30 and 50 m (averages ranged from 3759 – 4286 cal g^{-1} dry weight). However, the calorific value of sediments was only high in the littoral zone (i.e., >3400 cal g^{-1} dry weight at less than 6 m) and declined to less than 800 cal g^{-1} dry weight at the other depths (Devcich 1979).

1.2.1 Physico-chemical factors influencing abundance and distribution

The major factors affecting kōura abundance and distribution in the Te Arawa lakes are lake bed substrates, dissolved oxygen (DO) levels in the bottom waters, temperature and calcium availability. In addition, as an important food species for humans, accumulation of naturally occurring contaminants, such as mercury and arsenic, is an additional consideration.

1.2.1.1 Substrate

Studies of crayfish in temperate overseas lakes have generally identified cobble-sized substrate as the most important variable relating to crayfish abundance (Capelli and Magnuson 1983; Kirjavainen and Westman 1999; Smily and Dibble 2000; Hein, *et al.* 2006). The importance of cobbles to crayfish in lakes has been attributed to shelter potential for predator avoidance (Stein 1977) and also preventing cannibalism of egg-bearing females and of individuals undergoing moult (Stein 1977; Capelli and Magnuson 1983; Kershner and Lodge 1995; Nystrőm, *et al.* 2006). Because of their small size and softer exoskeleton, juvenile crayfish is the life stage most vulnerable to predatory fish, but as crayfish grow they are less likely to be consumed by these gape size-limited predators (Stein and Magnuson 1976; Didonato and Lodge 1993).

Kōura generally prefer coarse rather than fine sediment. Devcich (1979) reported very low numbers of kōura (<0.01 m^{-2}) on soft muddy sediments deeper than 23 m in Lake Rotoiti, North Island. Similarly, in the Waikato River hydro lakes, kōura were commonly associated with well-consolidated substrata, such as, rock crevices, boulders and submerged trees, but were rarely found on muddy sediments (Coffey 1995). Kirjavainen and Westman (1999) reported that *Pacifastacus leniusculus* were strongly associated with steeply sloping lake beds suitable for burrowing, or rich in shelters such as rocks and submerged trees, but avoided flat, soft bottoms. In addition, Kershner and Lodge (1995) reported low densities of *Orconectes rusticus* on soft lake bed substrates in some Northern Wisconsin lakes and attributed this to impediment of crayfish movement on fine sediments. The ability of crayfish to withstand increases in concentrations of suspended solids is poorly understood (Westman 1985). The low numbers of kōura on fine, muddy sediments could be due to greater energy and respiration requirements to maintain activity and to prevent them sinking into the substrate (Westman 1985). Devcich (1979) observed kōura imprints in soft sediments below 23 m depth in Lake Rotoiti. He hypothesised that because kōura sank into the mud, greater oxygen demand would have been created in order to maintain activity and that since movements were accompanied by sediment clouds, the gill filaments might become partially clogged, which could restrict respiratory exchange. Usio and Townsend (2000) reported a negative association between *P. zealandicus* and suspended solids in a stream in Otago, South Island.

In New Zealand streams, a numbers of correlative studies have shown that *P. planifrons* were associated with undercut banks, leaf litter, tree roots and wood, and that cover was the controlling factor for daytime presence of crayfish, more important than either substrate or hydraulic variables (Jowett, *et al.* 2008; Parkyn, *et al.* 2009). However, in a study of *P. zealandicus* in an Otago Stream, adults were positively associated with sand and young of the year (YOY) with cobble substrates, while both life stages were positively correlated with wood cover (Usio and Townsend 2000). Adult *P. zealandicus* were also associated with deep pools and leaf litter, suggesting that their association with sand could be related to substrate conditions found in pool habitats.

1.2.1.2 Eutrophication

Overseas studies have shown that crayfish generally have high abundances, growth rates and fecundity in productive lakes (Abrahamsson and Goldman 1970; Jones and Momot 1981; France 1985). This has been attributed to the increasing trophic status of the lake causing an increase in the primary consumer density resulting in higher prey availability for crayfish (Nystrőm, *et al.* 2006; Stenroth, *et al.* 2008). These workers also found a positive correlation between shelter availability and crayfish abundance, irrespective of lake trophic status or predatory fish density (Nystrőm, *et al.* 2006). Hypoxia, temporary or permanent, is often a consequence of eutrophication and organic enrichment (Parr and Mason 2004). Devcich (1979) found strong correlations between kōura presence and DO concentrations in Lake Rotoiti, with an appreciable decline in abundance when DO fell below 5 mg L^{-1}, with crayfish absent when DO levels were below 1.2 mg L^{-1}. This is consistent with other crayfish species which avoid levels below 5 mg L^{-1} (Westman 1985) and are adversely affected at DO levels near 1 – 2 mg L^{-1} (Hobbs and Hall 1974). In the laboratory, studies have shown that *P. planifrons* is tolerant of low oxygen levels with a DO LC_{50} of 0.77 mg L^{-1} (duration 48 hours at 17 ^{o}C) (Landman, *et al.* 2005). The absence of kōura in highly eutrophic Lake Ōkaro (Parkyn, *et al.* 2011) could be attributable to hypolimnetic deoxygenation (>ca. 5 m depth), however multiple stressors associated with the eutrophication process may have also contributed to their decline. Parkyn, *et al.* (2011) suggested that reduced available habitat, due to summer anoxia, seasonal over-turn causing elevated ammoniacal-N concentrations and release of hydrogen sulphide and ingestion of toxic cyanobacteria may all have contributed to the disappearance of kōura from Lake Ōkaro.

1.2.1.3 Calcium

Calcium (Ca) is an essential element for most biota and crayfish exoskeletons contain relatively large amounts (Cairns and Yan 2009; Edwards, *et al.* 2009). Low levels of Ca may limit crayfish survival and production (Capelli and Magnuson 1983). Low Ca environments could make crayfish more vulnerable to predation, cannibalism or competition and impact their growth, survival and reproductive success (Stein 1977; France 1987; Keller, *et al.* 2001; Rukke 2002; Hammond, *et al.* 2006; Cairns and Yan 2009). However, in comparison to the great majority of

Astacoidea (a family of northern hemisphere crayfish), *P. planifrons* is physiologically tolerant to acidic conditions in their surrounding environment, possibly a pre-adaption to the more dilute ionic conditions, particularly of calcium and bicarbonates, in New Zealand waters (Ball 1987; Close and Davies-Colley 1990). However, Hammond, *et al.* (2006) found that survival of cultured *P. zealandicus* increased with higher Ca concentrations and this is thought to be in part due to a lower incidence of moulting related deaths and decreased risk from predation. A calcium concentration value of 20 – 30 mg L^{-1} Ca in water is thought to be ideal for maintaining kōura growth and survivability in aquaculture situations. However, *P. zealandicus*, like *P. planifrons*, also appears to survive in low Ca environments, as it has been recorded in streams where Ca is <3 mg L^{-1} (Hollows 1998).

1.2.1.4 Water temperature

Water temperature is a major factor affecting freshwater crayfish, dictating body temperature and influencing metabolic activity, food intake and growth (Verhoef and Austin 1999). Growth rates typically increase with increasing water temperatures until the optimum is reached, and then decline with further temperature increases (Ponce-Palafox, *et al.* 1997; Jobling 2003). *P. planifrons* is tolerant of high temperatures with mean critical temperature maxima of 31.9 ^{o}C when acclimatised to 20 ^{o}C and 28.8 ^{o}C when acclimatised to 12 ^{o}C (Simons 1984). Jones (1981) reported that kōura grew to 20 mm OCL after 12 – 18 months in unheated aquaria (10 – 21 °C), but this was increased to 35 mm OCL in 18 months in the heated aquaria (18 – 21 °C).

Warmer water temperatures can decrease the survival of juveniles but improve their growth rates, leading to enhanced fecundity and competitive ability (Mundahl and Benton 1990). This is consistent with the findings of Parkyn, *et al.* (2002) who reported that kōura had higher growth rates and, consequently, a shorter life cycle in warmer streams, fed from pastoral land, than in cooler, native forest streams. Excessively high water temperatures have been reported to adversely affect *P. zealandicus* populations (Whitmore, *et al.* 2000). In New Zealand, *P. zealandicus* have high survivability (>80%) rates below 16 °C but temperatures above this correlate with lower rates of survivability (Hammond, *et al.* 2006). In comparison, *P. planifrons* is tolerant of high temperatures with mean critical temperature maxima of

31.9 ^{o}C when kōura acclimatised to 20 ^{o}C, and 28.8 ^{o}C when acclimatised to 12 ^{o}C (Simons 1984).

Water temperatures above 8 – 10 ^{o}C are required for moulting by many cold-water crayfish species (Lodge and Hill 1994). This is consistent with studies in the south-east of the South Island, where *P. zealandicus* does not moult from May to October due to low water temperatures (Jones 1981; Whitmore and Huryn 1999). Furthermore, studies have shown that *P. zealandicus* is less active in winter months, and spends much of this period in shelter and may remain completely inactive for several days at a temperature of 5 °C (Quilter and Williams 1977; Whitmore and Huryn 1999). Whitmore and Huryn (1999) proposed that the low density estimates for *P. zealandicus* recorded during winter were due to inactivity and increased cryptic behaviour during this period.

1.2.1.5 Predation

For freshwater crayfish the most important predators, with respect to effects on abundance, behaviour and growth, are predatory fish (Westman 1985). The high natural abundance of kōura in the Te Arawa lakes may be due to the absence or low numbers of predatory fish species that appear to be more able to exert top-down control on kōura populations. Eels (*Anguilla dieffenbachii, A. australis*) and catfish (*Ameiurus nebulosus*) may be far more effective predators of kōura than trout, but catfish are not present in the Te Arawa lakes and eels are found in very low numbers (Martin, *et al.* 2007). Stomach content analysis of brown bullhead catfish in Lake Taupō showed that catfish commonly consume kōura (Barnes and Hicks 2003) and kōura were the second most frequent prey item of shortfin eels in the Waikato region (Hicks 1997).

The resilience of kōura to trout predation is supported by dietary studies of rainbow trout (*Oncorhynchus mykiss*) in central North Island lakes which have found common smelt (*Retropinna retropinna*) to be their dominant prey item, with predation on other species, such as kōura and common bullies (*Gobiomorphus cotidianus*), being relatively low (Rowe 1984; Cryer 1991; Blair *et al.* 2012). In Lake Rotomā, less than 10% of 2+ year old trout (310 – 470 mm) fed on kōura, but this increased to over 20% for 3+ year old (470 – 570 mm) rainbow trout (Rowe 1984). In Lake Rotoiti, only rainbow trout >400 mm were found to have consumed kōura, which comprised only a minor component of their diet (6.3% of diet by weight) (Blair, *et al.* 2012). Similarly, only medium and large sized rainbow trout (>350 mm) consumed kōura in a study of 749 trout stomachs in Lake Taupō and these had a low proportion (0.5%) of kōura in their stomachs (Cryer 1991). Moreover, Cryer (1991) found that brown trout in Lake Taupō had negligible kōura in their diet compared with rainbow trout, although this may have been due to low sample sizes. In the Te Arawa lakes, brown trout are only found in Lake Rotorua (including the Ōkere Arm) and in small numbers in Lake Rotoiti.

In the South Island, research has focussed more on brown trout (*Salmo trutta*) predation on kōura in rivers and streams. Olsson, *et al.* (2006) reported the presence of brown trout was the main factor affecting the abundance of *P. planifrons* in streams supporting brown trout. Whitmore, *et al.* (2000) and Usio and Townsend (2000) also found a negative effect of brown trout on stream populations of *P. zealandicus*. Shave, *et al.* (1994) found *P. zealandicus* could detect eels more easily than brown trout and hence were better able to avoid predation from eels (with which they have co-evolved) compared with exotic trout.

1.2.1.6 Macrophytes

The interaction between kōura and macrophyte beds is poorly understood. Macrophyte beds are a significant and rapidly evolving part of the Te Arawa lake ecology and may act as a barrier to migration and a refuge against predators. In addition they alter sediment characteristics and potentially affect food availability. All of these characteristics are dependent on the type and extent of macrophytes. Lake Steinsfjorden (southeast Norway) is the only well studied case of an exotic macrophyte invasion on a native crayfish population, *Astacus astacus* (Skurdal and Qvenild 1989; Skurdal, *et al.* 2002). Canadian pondweed *Elodea canadensis* was for the first time observed in the lake in 1977. Over the following years, the plant established dense cover over large parts of the shallow areas, excluding the crayfish from these areas and causing a sudden drop in population size. Direct observation by test fishing and diving confirmed the virtual absence of crayfish within the *Elodea* stands. Dense stands may directly interfere with the movement of adult crayfish. Also strong fluctuations in DO and pH were recorded within the stands, likely acting as a stress factor for crayfish. Thus, while crayfish are able to feed on *Elodea*, they are unable to control the rapid growth of this invader over large areas, resulting in the herbivore being excluded by its potential resource (Skurdal and Qvenild 1989; Skurdal, *et al.* 2002).

Figure 1.1: A large (43 mm OCL) male kōura (*Paranephrops planifrons*) collected from Lake Rotoiti, March 2015.

1.3 Te Arawa lakes

The Te Arawa lakes are situated on the central volcanic plateau in the Bay of Plenty region of New Zealand's North Island (Figure 1.2). The lakes were formed up to 230,000 years before present from a series of volcanic eruptions that characterise the Taupō Volcanic Zone of the central North Island (Lowe and Green 1987; Esler 2010). These volcanic eruptions were not only responsible for the formation of the lakes but also had a major influence on the surrounding topography including the lake bed sediments. The most recent eruption event that of Mount Tarawera in 1886, had a major effect on the surrounding landscape, showering basalt scoria and "Rotomahana Mud" across a large area of the Bay of Plenty (Pullar and Birrell 1973).

Eight lakes were selected for this study; Ōkaro, Rotorua, Rotoiti, Ōkāreka, Rotoehu, Rotokakahi, Rotomā and Tarawera (Figure 1.2), to provide a range of different lacustrine environments within a discrete geographical area. In addition, the Ōkere Arm a lake outlet site where water from lakes Rotorua and Rotoiti flows towards the Kaituna River was also included (Table 1.1). The lakes varied widely in trophic status (oligotrophic to hypertrophic), size (32 – 8,079 ha) and morphology (mean depth 8 – 50 m) (Table 1.1). The lakes are generally monomictic, except for Rotoehu and Rotorua, while the Ōkere Arm outlet site is generally well mixed (Table 1.1). The proportion of catchment in agriculture in the eight study lakes ranged from 21.1% (Lake Tarawera) to 95.7% (Lake Ōkaro) (Table 1.1).

The lakes are highly valued by the Te Arawa iwi who are the legal owners of the lake beds[1]. The iconic lakes are also valued for their natural beauty and for recreational activities such as trout fishing, which attract tourists to the region (Abell, *et al.* 2011). Water quality in several of the lakes has declined over the last 30 – 50 years owing to excess nutrient inputs associated with development in the lakes' catchments (Hamilton 2003). The main sources of nutrients are farming activities, soil erosion, septic tanks and community sewerage schemes (PCE 2006), although natural geological sources of phosphorus are also significant in some catchments (Hoare 1978). Treated sewage was historically discharged into Lake Rotorua (Burns, *et al.* 1997); however, this direct discharge ceased in 1991 following construction of the Rotorua City sewage treatment system. Since then, further works have been undertaken, or are currently underway, to improve sewage treatment and reduce reliance on septic tanks to minimise nutrient loads from these sources. By contrast, nutrient loads (particularly nitrogen) from farmland have increased in several catchments in response to an increased intensity of agricultural production (Rutherford 2003).

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[1] [1] http://www.legislation.govt.nz/act/public/2006/0043/latest/DLM381398.html

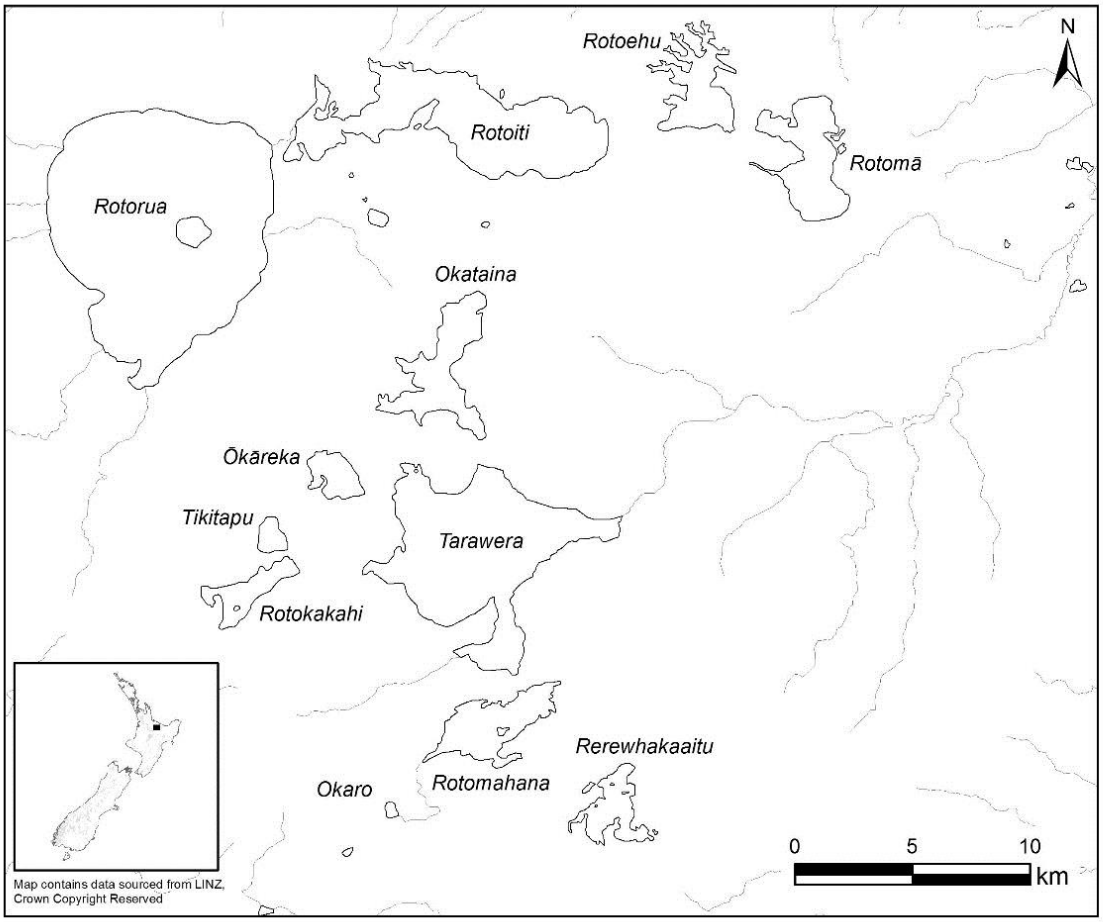


Figure 1.2: Te Arawa lakes in the Bay of Plenty region, North Island, New Zealand.

Table 1.1: General catchment and lake characteristics for the eight Te Arawa study lakes and the Ōkere Arm (Lake Rotoiti), North Island, New Zealand. Mixing regime, mean depth, maximum depth, lake area (Scholes 2009). Secchi depth values are means of monthly measurements, 2002 – 2009, except Ōkere Arm where secchi depth are means from September 2008 – September 2009 (Scholes 2009; Scholes 2010). Percentage of catchment in agriculture for all lakes (Bruesewitz, *et al*. 2011) except Rotokakahi (Butterworth 2008). The Ōkere Arm was defined as the area from the control gates upstream to the Ohau channel diversion wall.

Lake	Lake type	Mixing regime	Mean depth (m)	Max depth (m)	Lake area (ha)	Secchi depth (m)	Catchment agriculture (%)
Ōkāreka	Mesotrophic	Monomictic	20	33.5	324	7.7	55.8
Ōkaro	Supertrophic	Monomictic	12.5	18	32	2.4	95.7
Ōkere Arm	Eutrophic	Polymictic	5	8	57	1.6	N/A
Rotoehu	Eutrophic	Polymictic	8	13.5	810	2.9	39.9
Rotoiti	Eutrophic	Monomictic	31.5	124	3,460	4.4	23.9
Rotokakahi	Mesotrophic	Monomictic	17.5	32	452	3.7	26.3
Rotomā	Oligotrophic	Monomictic	36.9	83	1,104	12.8	22.8
Rotorua	Eutrophic	Polymictic	11	45	8,079	2.4	51.8
Tarawera	Oligotrophic	Monomictic	50	87.5	4,165	8.7	21.1

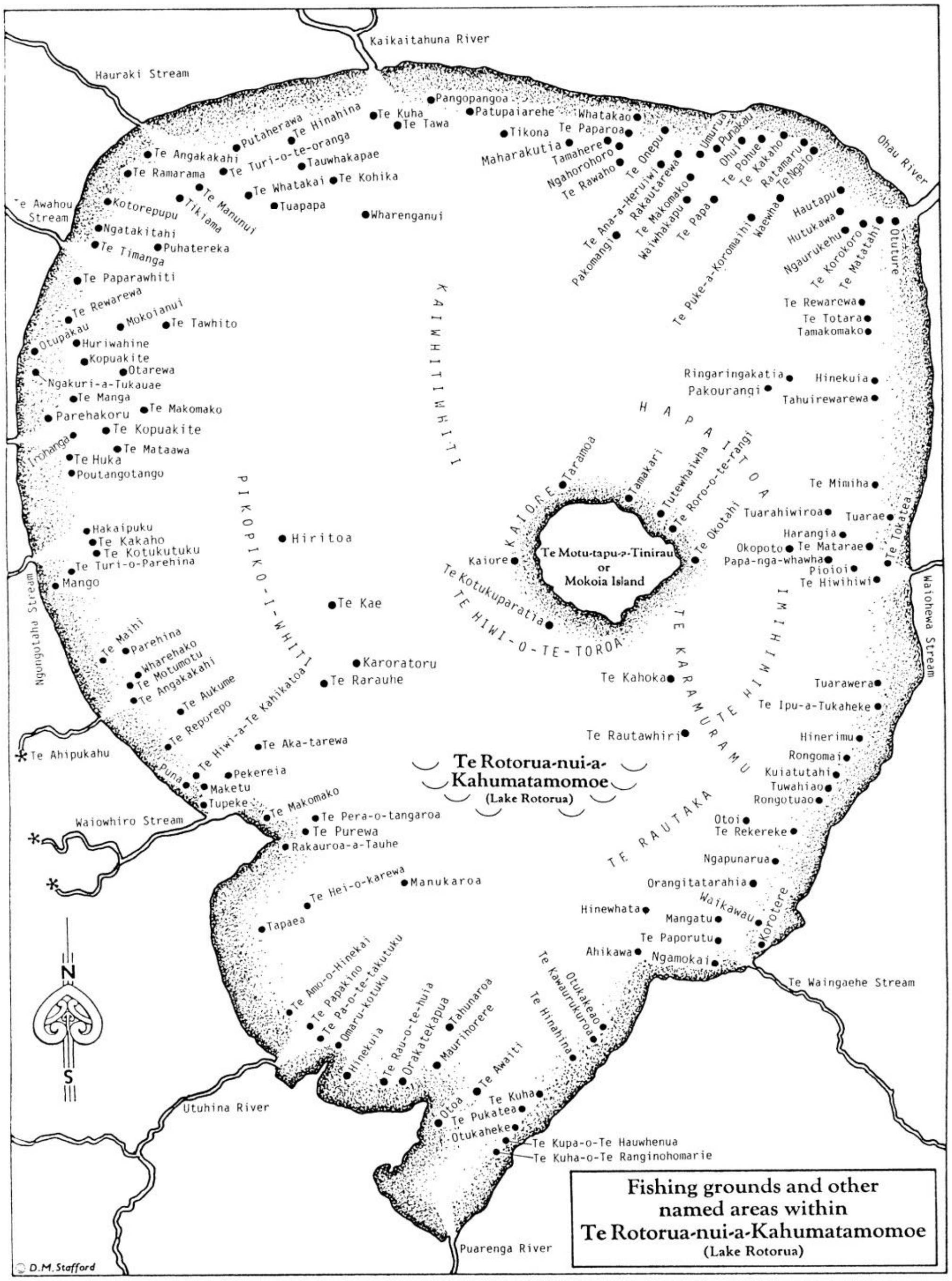
1.3.1 Fisheries - Historical

The Te Arawa canoe arrived in New Zealand around 1350 AD (Stafford 2002). *When Ihenga discovered Lake Rotoiti, he had his dog to thank. While hunting kiwi in the area, his dog, called Potakatawhiti, pursued a kiwi into the lake and in the process of catching it in its mouth, also ingested a large quantity of 'inanga'. When the dog returned to Ihenga, its fur was still wet, indicating that a body of water, perhaps a lake, was nearby. The dog then vomited the 'inanga' onto the ground, which made the party decide to seek out the lake. In this way, they came to the lake and could see for themselves the shoals of 'inanga' leaping in the water. They made a net of fern and when they caught enough they lit a fire, cooked and ate the fish, but kept several baskets to take back to Maketu* (Stafford 2002).

The main fisheries species harvested by Māori in the Te Arawa lakes in pre-European times included the juvenile and adult stages of the kōaro (*Galaxias brevipinnis*), termed 'inanga' and 'kōkopu' respectively (Stafford 1986). Adult common bully or 'toitoi' (common bully) were also caught. Eels, or 'tuna' (*Anguilla spp.*), were not present naturally in these lakes, apart from small numbers in the Lake Tarawera catchment, but elvers were probably stocked from time to time into other lakes, resulting in the occasional capture of one or two eels (Stafford 1986). Invertebrates such as kōura, and the kākahi (freshwater mussel, *Echyridella menziesii*) were also valuable food sources for Te Arawa iwi.

Kōura fisheries were present in most of the Te Arawa lakes; however, the populations in lakes Rotorua, Rotoiti and Tarawera were the most prized (Mair 1918). Kōura were not only a staple food item but were a delicacy that was used for bartering with Māori from outlying districts (Hiroa 1921). The kōura fishery was actively managed by a combination of rāhui (fishery closures) and ownership rights as well as occasional releases into waterways to boost populations. Tau kōura was the favourite traditional fishing method for harvesting lake kōura and was used by Te Arawa in the Rotorua area (Hiroa 1921) and Ngāti Tūwharetoa in the Taupō area (Grace 2002).

Kākahi were collected from all the lakes but were most plentiful and easily harvested in the shallower lakes such as Rotorua and Rotoehu (Hiroa 1921). Kākahi were a readily available source of protein with the advantage of being able to be kept alive for long periods of time if kept moist (Habib 2001). The Māori fisheries for ‘inanga’, kākahi, ‘kōkopu’, kōura and toitoi were widespread in many of the Te Arawa lakes up to the mid-1890s, and fishing grounds for these species were clearly delineated and managed (e.g., in Lake Rotorua, Fig. 1.3) (Hiroa 1921; Mair 1923; Stafford 1994; Stafford 1996).



Fishing grounds and other named areas within Te Rotorua-nui-a-Kahumatamomoe (Lake Rotorua)

This map has been compiled from an examination of several hand prepared originals, each of which purported to provide the same information. Each, in fact, varied somewhat in respect to certain locations, spelling and even in the number of actual sites. There will therefore be variations between this and others held in the community.

Map No. 40

Figure 1.3: Traditional fishing grounds in Lake Rotorua (from Stafford 1994).

Figure 1.4: Whakaweku being transported by waka to be set on a tau kōura in the Ōkere Arm around 1900 (from Stafford 1996).

Later introductions of fish by European settlers, especially rainbow trout, brown trout, goldfish or morihana (*Carassius auratus*) and common smelt, had a large and mainly detrimental impact on the Māori fisheries in the Te Arawa lakes (McDowall 1987). Trout quickly replaced 'kōkopu' as the largest fish present, and as a result of their heavy predation on 'inanga', the fisheries for both 'inanga' and 'kōkopu' soon collapsed (Burstall 1980; Stafford 1986). Although trout became very abundant, to the point where netting was required to reduce the trout population (Hobbs 1948), Māori access to this new fishery was limited and restricted by regulations governing the licensing of anglers and the control of poaching (Stafford 1986). Morihana proved to be a popular fish for eating, but were only abundant and large enough to be worth catching around the warm, geothermally influenced areas, and in summer, in some shallow bays e.g., Okawa Bay, Lake Rotoiti (Pers. comm. W. Newton, Ngāti Pikiao kaumatua) of the lakes. The Māori fishery for the much smaller toitoi was abandoned when the 'inanga' and 'kōkopu' fisheries collapsed, even though toitoi remained abundant in the lakes and have since increased in some (Rowe

1999). In the 1930s, smelt became abundant in all the lakes as a result of stocking to increase the food supply for trout. These smelt provided a localised fishery in the Ohau Channel and in Lake Rotoiti, but this did not replace the 'inanga' fisheries in the lakes.

1.3.2 Fisheries – Present day

The Te Arawa lakes contain a similar fish fauna, composed mainly of rainbow trout, common smelt and common bullies. Rainbow trout support popular recreational fisheries in the lakes, while brown trout are common in Lake Rotorua and its tributaries and present in low numbers in Lake Rotoiti. Today, as the native fish stocks in the Te Arawa lakes, and the rights to manage them, come under closer scrutiny, Te Arawa are renewing interest in their customary fisheries looking at ways of restoring and managing them (Te Arawa Lakes Settlement Act 2006[2]) (Figs. 1.5 and 1.6). This is particularly so for kōura, kākahi, kōaro, common smelt and tuna.

Figure 1.5: Processing kōura on the banks of the Ōkere Arm with Ngāti Pikiao kaitiaki, February 2007.

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[2] http://www.legislation.govt.nz/act/public/2006/0043/latest/DLM381398.html
Accessed 11 May 2015.

Figure 1.6: Te Arawa kaumatua Willie Emery and his mokopuna Trevor Huriwai with a catch of kōura from Lake Rotoiti (20 May 2007).

1.3.3 Preliminary techniques for sampling lake kōura

Obtaining accurate estimates of freshwater crayfish populations in streams and particularly lakes is notoriously difficult and highly dependent on sampling method and habitat (France, *et al.* 1991; Lamontagne and Rasmussen 1993; Rabeni, *et al.* 1997; DiStefano, *et al.* 2003; Dorn, *et al.* 2005). Substrate (i.e. benthic habitat type) is known to structure freshwater crayfish populations and affects, for example, density, growth rates, length-frequency distribution, predation and recruitment success (France, *et al.* 1991). Inter and intra lake comparisons of growth dynamics should therefore be made from freshwater crayfish collected from similar substrates (France, *et al.* 1991). In this study, in order to make between-lake comparisons, tau kōura were deployed in similar depths on mud and sand sediments; the dominant substrate type present in the study lakes. The Te Arawa lakes are of volcanic origin with lake bed and littoral sediments composed mainly of mud, silt and sand, and with smaller areas of cobble substrates. In contrast, most correlative studies of crayfish in temperate overseas lakes have been carried out in lakes of glacial origin, where a high proportion of littoral (and to a lesser extent lake bed) sediments are composed of sand-gravel and cobble-pebble sized substrates (Stein 1977; Capelli and Magnuson 1983; Kershner and Lodge 1995; Nystrőm, *et al*. 2006).

1.3.3.1 Traps

Traps are the most commonly used technique for capturing crayfish in deep-waters. Although traps might serve a capture fishery well, they do not provide good population information (Reynolds and Souty-Grosset 2012). Dorn, *et al*. (2005) assessed the sampling efficiency of baited minnow traps against that of a throw-trap across an experimental density gradient of crayfish (*Procambarus fallax*). The throw-trap catch estimates correlated well with crayfish density and size distribution, whereas minnow traps caught fewer crayfish as density increased and caught mostly larger males (Dorn, *et al*. 2005). The size selectivity and seasonal variations in trapping are well documented and the prevalence of large crayfish (especially large males) in traps has been reported in New Zealand (Devcich 1979) and elsewhere (Capelli and Magnuson 1983; Dorn, *et al.* 2005). Population parameters, such as sex ratios, age and maturity status, may be different in traps than the general population. Female crayfish are generally less active than males, resulting in unequal sex ratios, and some researchers have recommended monitoring only male numbers to estimate population sizes (for example, Nowicki, *et al.* 2008).

Trap surveys can be biased by a number of other factors. Trap mesh size and funnel dimensions both select for crayfish size. Bait type may provide different levels of attraction, and may even repel if stale (Reynolds and Souty-Grosset 2012). Lake catches of many crayfish species are highest if there is a full moon and clear skies (Reynolds and Mathews, 1993). Crayfish are most active and ‘trappable’ in the warmer months, after their moult period (Reynolds and Souty-Grosset 2012). Initial trials in lakes Rotoiti and Taupō showed that the tau kōura method did not have these sampling biases (Table 1.2). The tau kōura is a ‘habitat’ trap with no mesh size or funnel, it is not baited, and it is an ‘integrator’ sampling method that is not dependent on overnight weather, water or lunar conditions. In contrast, traps are ‘spot’ samplers, with catches highest if set overnight and lifted the following morning. Therefore, trapping techniques should be standardised as much as possible. In order to compare crayfish catches between lakes, traps should be set and retrieved (ideally before dawn) under similar sampling conditions. In this study, I monitored kōura populations in seven lakes. To maintain consistency amongst lakes, all whakaweku were deployed and retrieved within a week of each other. To deploy and retrieve 20 baited traps in the seven study lakes over the same sampling period would otherwise have been extremely demanding. An advantage of the tau kōura is that when it is set, it is simply redeployed until the next sampling event or if the whakaweku deteriorate (usually 1 to 2 years) replaced and redeployed. However, baited traps are extremely useful when results (e.g., presence/absence) are required promptly as they do not require the colonisation time (4 – 6 weeks) necessary for a tau kōura.

I compared some key parameters from this study with those recorded by Devcich (1979) who used traps to monitor kōura in Lake Rotoiti from 1975 to 1976 (Table 1.2). The tau kōura had a higher mean CPUE (27 kōura whakaweku^{-1}), captured all size classes of kōura (7 – 51 mm OCL) and had an overall ratio of females to males of about 1:1 (Table 1.2). In comparison, traps had a lower mean CPUE (9 kōura baited trap^{-1}), and were size (minimum OCL 20 mm) and sex selective, with a male to female ratio of 2.8 to 1 (Table 1.2).

Table 1.2: Comparison between the tau kōura (this study) and baited traps (Devcich 1979) in Lake Rotoiti.

Parameter	Traps	Tau kōura
Baited	Yes	No
Mean CPUE	9 kōura baited trap^{-1}	27 kōura whakaweku^{-1}
Size (OCL) range	20 – 48 mm	7 – 51 mm
Sex ratio	2.77:1 (Scuba 1.3:1)	1:1
Optimum saturation time	< 24 hours	> 1 month
Study lakes	1 (1 site x 1 line of 20 traps)	7 (2 sites lake^{-1} x 10 whakaweku)
Monitoring frequency	Monthly for 1 year	3 surveys for 1 year

A potential problem with large, heavy traps is that they may sink into the soft, lake-bed sediments (blocking the trap entrances) particularly in those lakes with a high proportion of Rotomahana mud. Low abundance of lake kōura on fine silt sediments compared with coarser sediments is consistent with my underwater (SCUBA) observations and studies in New Zealand (Devcich 1979) and elsewhere (Kershner and Lodge 1995; Kirjavainen and Westman 1999).

1.3.3.2 Area-based (underwater) surveys

Area-based (underwater) surveys (e.g., quadrats, belt-transects, timed counts, throw traps) are generally considered to generate the most reliable estimates of freshwater crayfish abundance (Davies 1989; France, *et al.* 1991; Olsen, *et al.* 1991; Lamontagne and Rasmussen 1993; Dorn, *et al.* 2005). However, underwater sampling is expensive, time consuming and not practical (or safe) in some of the turbid Te Arawa lakes, especially those where the bed substrates are composed of Rotomahana mud. For example, Devcich (1979) reported that lateral visibility was 0 – 1 m at a depth of 30 m in Lake Rotoiti and movements of divers often disturbed bottom sediments for up to 45 minutes, markedly reducing visibility.

1.3.3.3 Mātauranga

Crayfish monitoring methods are largely derived from traditional capture methods (Reynolds and Souty-Grosset 2012) and the tau kōura is no exception. The tau kōura was the preferred method of harvesting large quantities of kōura in the Te Arawa and Taupō lakes by pre-European Māori. The tau kōura was the culmination of over 500 years of mātauranga (knowledge) and rangahau (research) which proved that it was superior to other methods such as baited traps (called pouraka; similar to minnow traps), hinaki (fyke nets), dredge nets (pae pae) and hand nets (rama kōura). Two tau kōura consisting of 10 whakaweku were deployed in each lake, and in order to make between-lake comparisons, tau kōura were deployed on mud and sand sediments – the predominant substrates in the study lakes. SCUBA observations did show that kōura were most abundant on coarse bed substrates (cobbles, sand) and closely associated with underwater structures such as reefs and submerged logs, however, these habitat types comprise a relatively small proportion of the Te Arawa lake beds. SCUBA diving observations along the tau kōura confirmed our tau kōura catch results in those lakes with good water clarity, i.e. low kōura abundance in Ōkāreka and Tarawera and high kōura abundance in Rotoiti and Rotomā.

I used information on the variability of kōura caught in a trial of 12 whakaweku on a tau kōura set in Lake Rotoiti in March 2006 (Kusabs unpublished data) to determine the number of samples needed to be able to detect differences between means of more than 40%. Using a power and sample size calculator (accessed from http://www.statisticalsolutions.net/pss) on Rotoiti data (mean 39 kōura whakaweku^{-1} and variance of 242 amongst 12 whakaweku) gives a sample size of eight for detecting differences in means of 40% or more in a two-sided test. A sample size of 20 whakaweku, using the same Rotoiti data, gave a power of 0.92 to detect a 30% change in the mean. However, for logistical convenience I deployed the 20 whakaweku on two tau kōura in each lake. This was the only practical means of comparing kōura populations in the seven study lakes (Chapter 3).

In addition, freshwater crayfish often have a variable distribution along a depth gradient (Lamontagne and Rasmussen 1993) and/or exhibit seasonal vertical migration regulated by abiotic parameters like temperature (Skurdal, *et al*. 1988) and dissolved oxygen (DO) concentration (Devcich 1979). Therefore, a tau kōura comprised of 10 whakaweku enabled kōura to be sampled across a range of depths. Moreover, 20 whakaweku fit comfortably into a boat of length 5 – 6 m; any more than this can result in the whakaweku being crushed, which may affect their efficacy.

The Te Arawa lakes are very popular recreational destinations for a range of activities, such as trout fishing, boating and contact recreation. For example, trout fishing is extremely popular, with an estimated 162,500 ± 6,900 angler days in the 2007/2008 angling season (Unwin 2009), with most lakes open to year-round angling. Given the popularity of the lakes for recreational and commercial activities, site and method selection is critical to avoid interference. For example, Hiroa (1921) reported that commercial launches were responsible for the removal of many of the tumu (posts) that tau kōura were attached to in Lake Rotorua in the early 1900s. Tau kōura (and traps) can ‘snag’ angling tackle and this can result in anglers lifting the tau kōura to retrieve their lures (Author’s personal observations).

In lakes, baited traps (like whakaweku on a tau kōura) are usually set 3 – 5 m apart in strings of 10 – 50, and later retrieved from the shore or by boat (Reynolds and Souty-Grosset 2012). Devcich (1979) used 20 baited traps attached to a submerged rope to monitor kōura in in Lake Rotoiti. Traps are usually set in strings for ease of setting and retrieval and to reduce the risk of accidental or deliberate disturbance. An advantage of the tau kōura is that the whakaweku are cheap to construct (compared to the cost of traps) and the tāuhu or bottom rope is difficult to detect – especially when algae-covered. Despite being submerged and camouflaged, tau kōura are still vulnerable to interference, especially in clear lakes, and over the past 10 years I have experienced removal or damage of tau kōura in lakes Taupō, Rotomā and Tarawera. Individual traps or whakaweku attached to floats would be even more conspicuous and liable to interference.

1.4 Objectives

The objectives of this study were to (1) develop an effective method for monitoring lake dwelling kōura to address the lack of suitable representative sampling methods and provide a necessary first step to address the paucity of quantitative information on lake kōura, (2) determine the relative abundance and distribution of kōura in seven Te Arawa lakes which had a gradient of nutrient enrichment from low (oligotrophic) to very high (hypertrophic) and the effects of environmental variables related to bed characteristics, lake morphology, and water column chemistry and biota, and (3) obtain biological information to underpin fishing regulations and measures for the sustainable management of kōura populations in the Te Arawa lakes.

1.5 Thesis overview

This thesis comprises three research chapters (Chapters 2 – 4) that have been separately published in peer-reviewed journals. The first chapter gives a general introduction to the topics presented in the thesis and indicates how each chapter contributes to the overall study objectives. The final chapter gives conclusions and recommendations, suggests areas for further research and includes a conceptual linkage diagram that depicts factors influencing the distribution and abundance of kōura in the Te Arawa lakes.

In Chapter 2 the efficacy of the tau kōura method for sampling lake kōura populations is assessed. This study was a necessary first step for assessing population dynamics of kōura in the study lakes (Objective 1 and 2).

In Chapter 3 kōura populations were quantified along a eutrophication gradient in seven Te Arawa lakes to determine the factors influencing abundance, biomass and size (Objectives 2 and 3). This involved an analysis of various environmental parameters and trout abundance.

In Chapter 4 seven biological traits of Te Arawa kōura were investigated (size, population structure, sex ratio, moulting, egg-bearing, fecundity and size at onset of breeding). These traits underpin four key fishing regulations for Te Arawa kōura: the minimum legal length (MLL), closed fishing season, harvesting method restrictions and protection of egg-bearing females.

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Chapter 2

The use of a traditional Māori harvesting method, the tau kōura, for monitoring kōura (freshwater crayfish, *Paranephrops planifrons*) in Lake Rotoiti, North Island, New Zealand[3]

2.1 Abstract

Sampling of kōura (freshwater crayfish *Paranephrops planifrons*) to assess population abundance and structure in lakes is often difficult or impractical because of the absence of representative methods. The tau kōura is a traditional Māori method used to catch kōura in central North Island lakes by placing whakaweku (bundles of bracken fern *Pteridium esculentum*) on the lake bed that kōura then colonise. It has advantages as a monitoring tool over conventional methods, such as baited traps and dive surveys, as it samples all kōura size classes, can be used in turbid waters and at a wide range of depths, and does not require expensive equipment or specialised expertise (e.g., SCUBA). I demonstrate its use to monitor kōura populations in Lake Rotoiti (mean depth 32 m), North Island, New Zealand. Application of the method allowed differences in population size structure to be distinguished between a shallow and a moderate depth site within Lake Rotoiti and to discern seasonal breeding patterns.

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2.2 Introduction

Large populations of kōura (freshwater crayfish, *Paranephrops planifrons*) have been reported in several central North Island lakes in New Zealand, e.g., Rotoiti, Rotomā, Okataina, Tarawera, and Taupō (Devcich 1979). Kōura are an important traditional food source for Māori (Hiroa 1921). Furthermore, Māori throughout New Zealand are reasserting the principle of kaitiakitanga – the sustainable protection of resources (Tipa and Teirney 2006). Kaitiakitanga ensures conservation, protection and maintenance of resources through responsible actions, behaviour, conduct, and practices. Therefore it is important for iwi (Māori tribe) and hapū (Māori sub tribe) organisations to be active participants in the resource consent monitoring process, i.e., kaitiakitanga, in which Māori monitor their own mahinga kai (traditional food resources and places where they are gathered) as part of active participation in the sustainable management of lake ecosystems.

There is considerable anecdotal evidence of declines in lake populations of kōura since European settlement (Hiroa 1921). A number of environmental factors may be responsible for this decline, including introductions of exotic fish which prey upon kōura (McDowall 1987; Barnes and Hicks 2003), exotic plant species which likely hinder movement and accumulate large amounts of fine organic detritus (Author's personal observations), as well as reduced concentrations of dissolved oxygen in the bottom waters of lakes owing to eutrophication (Vincent, *et al.* 1984; Hamilton, *et al.* 2005). Although these changes have been documented individually, their collective influence may have had a considerable impact on kōura populations.

The ecology of stream dwelling kōura is relatively well studied in New Zealand (Hopkins 1966; Hopkins 1967a; Hopkins 1967b; Hicks and McCaughan 1997; Rabeni, *et al.* 1997; Parkyn, *et al.* 2001; Parkyn and Collier 2002; Parkyn, *et al.* 2002) but little is known about kōura populations in New Zealand lakes. The only detailed study of lake dwelling kōura was carried out by Devcich (1979), who focused on the ecology of kōura in Lake Rotoiti (North Island). The lack of quantitative information on kōura abundance and ecology makes it difficult for iwi and government agencies to manage kōura populations in lakes. The main reason for the lack of quantitative information on lake kōura is the absence of suitable methods to representatively sample populations; hence the need for a more appropriate sampling method. In this paper I describe an adaptation of a traditional kōura harvesting method for use as a monitoring tool by researchers and community groups, and demonstrate its application for assessing kōura population size and structure in Lake Rotoiti.

2.2.1 Background to the traditional tau kōura fishing method

Tau kōura was the predominant traditional fishing method for harvesting kōura used by the Te Arawa (a confederation of iwi and hapū based in the Rotorua district) and Ngāti Tūwharetoa iwi in the Rotorua (Hiroa 1921; Stafford 1994; Stafford 1996) and Taupō lakes (Fletcher 1919), respectively. This method involved the placement of bracken fern (*Pteridium esculentum*) bundles (known as whakaweku) on the lake bed for kōura to take refuge in. To harvest the kōura, the whakaweku were lifted onto a net of woven flax or kōrapa, which prevented the kōura from escaping as they were lifted out of the water and into a canoe. A traditional tau kōura (Fig. 2.1a), comprised a surface line (tāuhu) attached at one end to a surface-reaching pole (tumu) and a float (pōito) at the other end, held in place by an anchor (punga). From the tāuhu, drop lines (pekapeka) extended to the lake bottom to which whakaweku were attached. A tāuhu held the pekapeka together over distances of up to 180 m along the water surface and was pulled taut by an anchor or punga (Mair 1918). Traditionally, tāuhu comprised roots from a climbing plant (e.g., rata, *Metrosideros florida*). Whakaweku were set at intervals of approximately 10 m and were renewed approximately every three years or upon becoming ineffectual owing to decay.

The favoured materials for the tumu or posts were rewarewa (*Knightia excelsa*) and ponga fern (*Cyathea dealbata*) trunks. These had a dual purpose; they were an attachment point for the tau but also a mark of ownership and helped to delineate the boundaries of the various hapū and whānau (extended family groups) (Hiroa 1921). Another variation of the tau kōura was a submerged tau. It was set without tumu or floats, and the tāuhu or long line was allowed to sink to the lake bottom (Hiroa 1921). Submerged tau kōura were less obvious than "surface" tau and were used to avoid korara (kōura thieves) from finding and emptying the tau kōura.

2.2.2 Modern use of tau kōura

Until recently, the tau kōura method was used by relatively few whanau in the Te Arawa rohe (tribal district). Most of these whanau are affiliated to Ngāti Pikiao (a Te Arawa iwi), with fishing carried out in only two lakes, Rotoiti and Rotomā. These practitioners apply the same concepts as the "submerged" tau, but make use of modern materials. The traditional whakaweku are attached by synthetic ropes to a tāuhu of copper wire or synthetic rope which is attached to the shore, typically on a jetty piling, tree or large boulder, and anchored at the lake end by a heavy weight (e.g., a car tyre filled with concrete) (Fig. 2.1b) (Kusabs, *et al.* 2005a). The korapa (or catch net) is made of shade cloth or plastic mesh with an aluminium or steel frame (Kusabs, *et al.* 2005a).

In a preliminary study of kōura sampling methods in the Rotorua lakes, it was found that conventional sampling methods, baited traps, SCUBA and underwater video camera had a number of disadvantages (Kusabs, *et al.* 2005b). Trapping was found to be highly biased towards large individuals and complicated by bait quality influences in relation to time and the abundance of natural food (Devcich 1979). SCUBA and underwater video camera surveys are also biased towards large individuals and are greatly dependent on underwater visibility (Devcich 1979; (Author's personal observation).

Given the disadvantages of these conventional kōura assessment methods, I hypothesised that the traditional Māori method, the tau kōura, would provide a better monitoring method that would provide information on population size structure, catch per unit effort (CPUE), sex ratios, and egg-bearing, and be suitable for use by fisheries managers and researchers as well as by iwi and community groups.

To test whether the tau kōura was able to be used to distinguish key population attributes I compared kōura population structure at a shallow lake outlet (Ōkere) and a moderately deep site (Te Ākau) within Lake Rotoiti (Fig. 2.2). It was hypothesised that the tau set in the deeper waters would capture larger kōura. Moreover, juvenile kōura are released by females in the littoral zone (such as the Ōkere Arm), where there is more food and warmer temperatures (Devcich 1979), therefore it was expected that this tau would capture more juvenile kōura than that at Te Ākau.

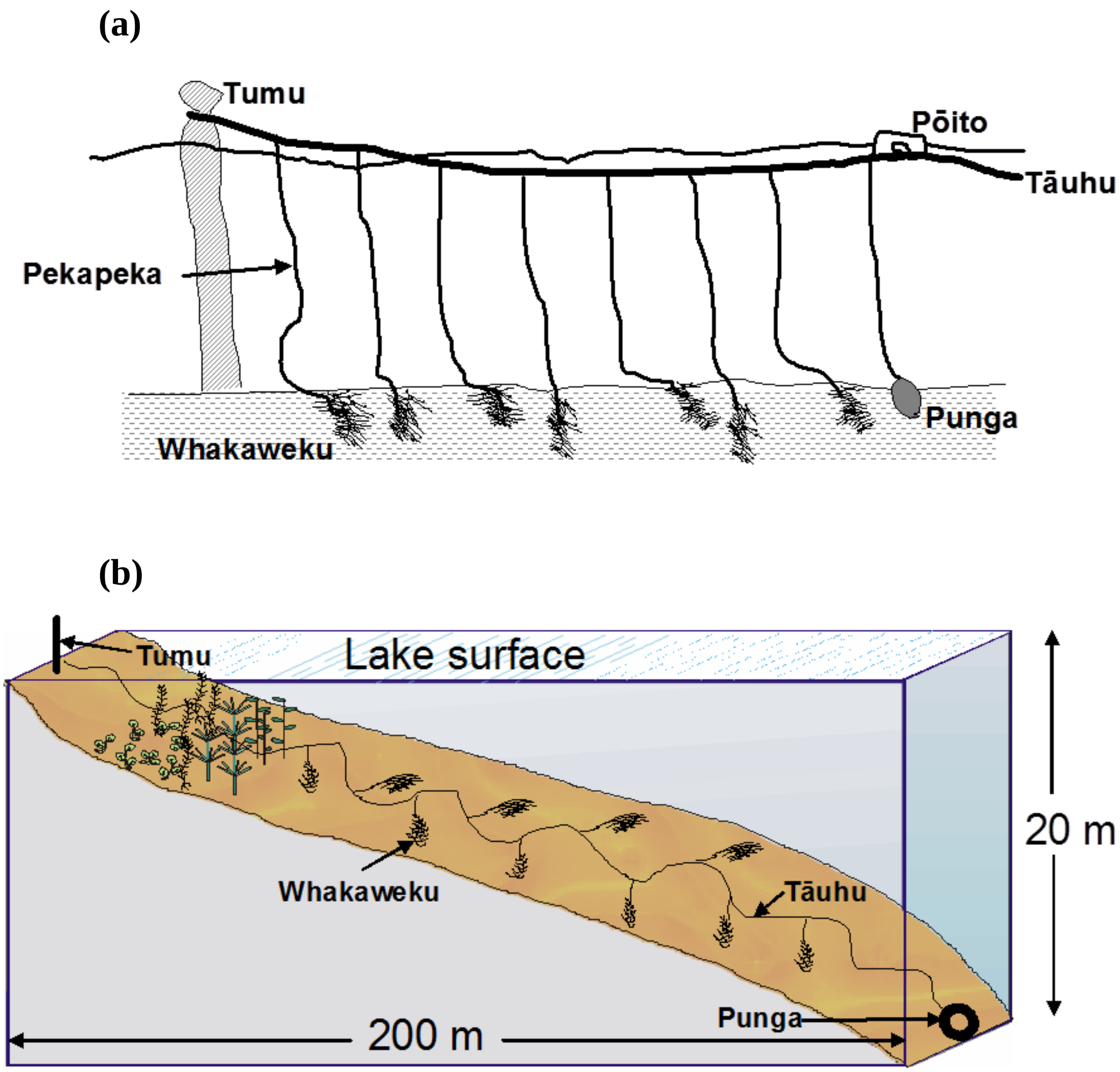

Figure 2.1: Diagrams of (a) the tau kōura, a traditional Māori method for harvesting kōura after Hiroa (1921). Pekapeka (drop line), punga (anchor), pōito (float), tāuhu (surface line), tumu (post) whakaweku (fern bundles); (b) Schematic diagram of the modern day tau kōura. The depth and length of tau are indicative and can be varied depending on lake bathymetry.

2.3 Materials and methods

2.3.1 Study site

Lake Rotoiti, North Island, New Zealand, is a deep (126 m maximum depth, average depth 32 m), moderately large (33.9 km^2), eutrophic lake which lies at 278 m above sea level on the central volcanic plateau (Gibbs 1992) and is known to have large populations of kōura (Devcich 1979). The lake is monomictic, stratifying for around nine months of the year starting in spring and mixing in late autumn. The main inflow (approximately 80%) to the lake is the Ohau Channel which flows out of Lake Rotorua (average discharge of 16 $m^3 s^{-1}$) and into the western basin of Lake Rotoiti (Gibbs 1992). Water leaves Lake Rotoiti by a single outflow, the Kaituna River (Fig. 2.2); the Lake Rotoiti catchment contributes 5 $m^3 s^{-1}$ or about 20% of the total lake discharge to the Kaituna River (Gibbs 1992). Water quality sampling at the Lake Rotoiti outlet at fortnightly or monthly intervals between 1985 and 2003 showed temperature averaged 15.3 (SD = 4.1) °C, dissolved reactive phosphorus 7 (5) mg m^{-3}, total phosphorus 27 (15) mg m^{-3}, ammonium N 15 (15) mg m^{-3}, nitrate + nitrite N 31 (36) mg m^{-3}, and total nitrogen 332(106) mg m^{-3} (Environment Bay of Plenty unpublished data for site BOP110026).

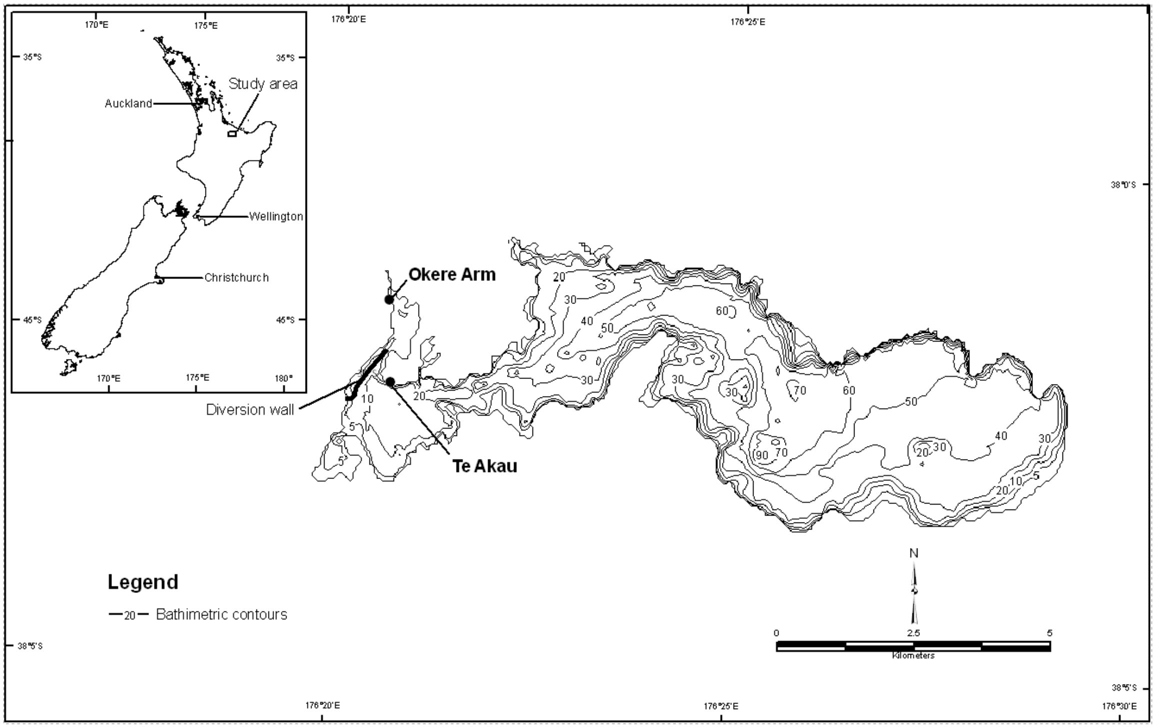

Figure 2.2: Lake Rotoiti, New Zealand, showing the location of the tau kōura sampling sites at Ōkere Arm and Te Ākau.

There are three native fish species in Lake Rotoiti, koaro (*Galaxias brevipinnis*), common bully (*Gobiomorphus cotidianus*), and common smelt (*Retropinna retropinna*). Brown (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) were introduced into the Lake Rotoiti catchment in 1888 and 1898, respectively (Burstall 1980). The invasion of exotic macrophyte species has resulted in marked changes to the submerged vegetation in Lake Rotoiti with the replacement of native species by dense, mono-specific macrophyte beds (Coffey and Clayton 1988). *Elodea canadensis* was first to invade the lake, followed by *Lagarosiphon major* in the 1950s, and *Ceratophyllum demersum* in the 1970s, which is now the dominant tall growing species in Lake Rotoiti (Coffey and Clayton 1988).

2.3.2 Tau kōura construction and use

Tau kōura were set at two locations in Lake Rotoiti: Ōkere Arm (E2803800 N6348162) and Te Ākau, off Te Ākau Peninsula (E2803747 N6346463) (Fig. 2.2). Each tau kōura comprised a 200 m length of 10 mm diameter polyester rope (the tāuhu), with one end attached to the shoreline (the base of a tree), and the other tied to a weighted concrete tyre. Ten whakaweku (bracken fern bundles) each with c. 10 bracken fronds per whakaweku were attached to each tāuhu. The fern fronds were bound together using 300 mm lengths of industrial strength plastic cable ties (Fig. 2.3) and attached to the tāuhu using hay baling twine (approximately 2.5 m long) at approximately 3 m intervals (Fig. 2.1b).

The study was conducted from November 2005 to September 2007. A tau was set in the Ōkere Arm in an area relatively free of large aquatic macrophytes and where water depth varied from approximately 3 to 7 m. A second tau was set in Te Ākau at water depths ranging from 7 to 17 m, i.e., outside of the depth range of the tall growing submerged aquatic macrophyte beds. The tau kōura were left for one month and then subsequently sampled every three months. Owing to decomposition, whakaweku were replaced on 15 March 2006, 3 January 2007 and 31 May 2007.

2.3.3 Kōura collection and measurement

Harvesting was achieved by lifting the shore end of the tau kōura and successively raising each whakaweku while moving along the tāuhu in a boat. A korapa was placed beneath the whakaweku before it was lifted out of the water and shaken to dislodge all kōura from the fern into the korapa, before being returned to the water (Fig. 2.4). All kōura were placed into labelled (2 litre) plastic containers covered by lids to keep kōura shaded and reduce stress before data collection. The analysis consisted of counting all captured kōura and visually estimating biovolume (litres of kōura per whakaweku). In addition, total wet weight of the catch from each tau kōura (i.e., all 10 whakaweku) was measured using a Salter spring balance accurate to 10 g. Subsamples of the population, typically involving measuring all kōura captured on whakaweku 3, 5 and 7, or at least 100 individuals, were assessed for sex, reproductive state (presence of eggs or young), and shell softness (soft or hard).

Figure 2.3: Constructing a whakaweku (fern bundle) for catching kōura in lakes: (a) collecting bracken fern, (b) binding 10 bracken fern fronds together using cable ties, and (c) a finished whakaweku ready for deployment.

Orbit carapace length (OCL) of each kōura in the subsamples was measured using vernier callipers accurate to the nearest 0.5 mm. After processing, all kōura were returned to the water in close proximity to the tau. CPUE was defined as the number of kōura per whakaweku. The minimum breeding size for kōura was determined from observations of the smallest size at which females were bearing eggs or young. Harvestable size was defined as >30 mm OCL based on recommendations by Te Arawa kaumatua (W. Emery pers. comm.).

2.3.4 Data analysis

Two way ANOVAs, with post-hoc Scheffe test multiple comparisons, were used to compare the two sites and three sampling months for kōura CPUE and for analysing differences in size between the sites, sampling months and site versus sampling month combinations. All data were log 10 transformed before ANOVA to approximate the normal distribution.

Figure 2.4: Retrieving the tau kōura: (a) placing a korapa (net) beneath the whakaweku before lifting out of the water, (b) shaking kōura to dislodge them out of the whakaweku into the korapa, before the whakaweku is returned to the water, and (c) close up of a kōura in a whakaweku. Photos a) and b) by S. Parkyn.

2.4 Results

A total of 4204 kōura were captured in the Ōkere Arm tau kōura in the eight surveys from 8 December 2005 to 13 August 2007; 2345 kōura were captured at Te Ākau in four surveys between 14 February 2007 and 10 September 2007 (Table 2.1). The highest catch of kōura (n = 972) at Ōkere Arm was recorded in September 2006, but the greatest biovolume of 17.4 litres was recorded in February 2007 (Table 2.1). In comparison, the highest catch of kōura (n = 967) at Te Ākau was recorded in February 2007 whereas the largest weight (13.8 kg) and biovolume (44 litres) were recorded in May 2007 (Table 2.1).

Kōura at Te Ākau were on average 47% larger (mean OCL, $F_{1413,1} = 681$, $p < 0.0001$ for ANOVA of three months of data when both sites were sampled), and yield (weight of catch) was greater than at Ōkere Arm (Table 2.1). The length frequency distributions of kōura captured from Ōkere Arm and Te Ākau in February 2007 (Fig. 2.5) show the differences between the populations at these two sites.

The percentage of females in subsamples from Ōkere Arm and Te Ākau ranged from 43.8% to 55.4% and 41.3% to 52.8%, respectively (Table 2.2). Females with eggs or young were present at Ōkere Arm in June 2006, September 2006 and August 2007 and at Te Ākau in May, August and September 2007 (Table 2.2). However, no females with eggs or young were sampled in February at Ōkere Arm (2006 or 2007) or at Te Ākau (2007). The proportion of "breeding size" females (the minimum breeding size in this study as determined by females bearing eggs or young was 23 mm OCL) was highest at Te Ākau in September 2007 (55.6%) but also comprised a high proportion in May and August (Table 2.2). The proportion of kōura with soft shells was lowest in February at both sites (0.8 and 0.7%) and was greatest in June 2006 (14.8%) at Ōkere Arm and May 2007 at Te Ākau (6.2%) (Table 2.2).

The mean CPUE at Ōkere Arm ranged from 25.5 to 97.2 kōura per whakaweku, whereas the mean CPUE at Te Ākau ranged from 26.7 to 96.7 kōura per whakaweku (Fig. 2.6). There were no obvious trends in mean CPUE over the two year sampling period at Ōkere Arm, whereas there appeared to be a steady decline in the numbers of kōura caught at Te Ākau over the four sampling periods (Fig. 2.6). There was no significant difference in CPUE between the Ōkere Arm and Te Ākau site for the three sampling months, February, May and August 2007 ($F_{54,1} = 2.6$, $p >$

0.05) when data were available for both sites. However, there were significant differences between sampling months ($F_{54, 2} = 6.6$, $p < 0.01$), with CPUE in February greater than May and August (Scheffe $p < 0.03$), and sites * sampling months ($F_{54, 2} = 7.3$, $p < 0.01$), notably with higher CPUE at Te Ākau in May 2007 (Scheffe, $p < 0.004$), but no significant differences in February or August 2007 (Scheffe, $p > 0.05$).

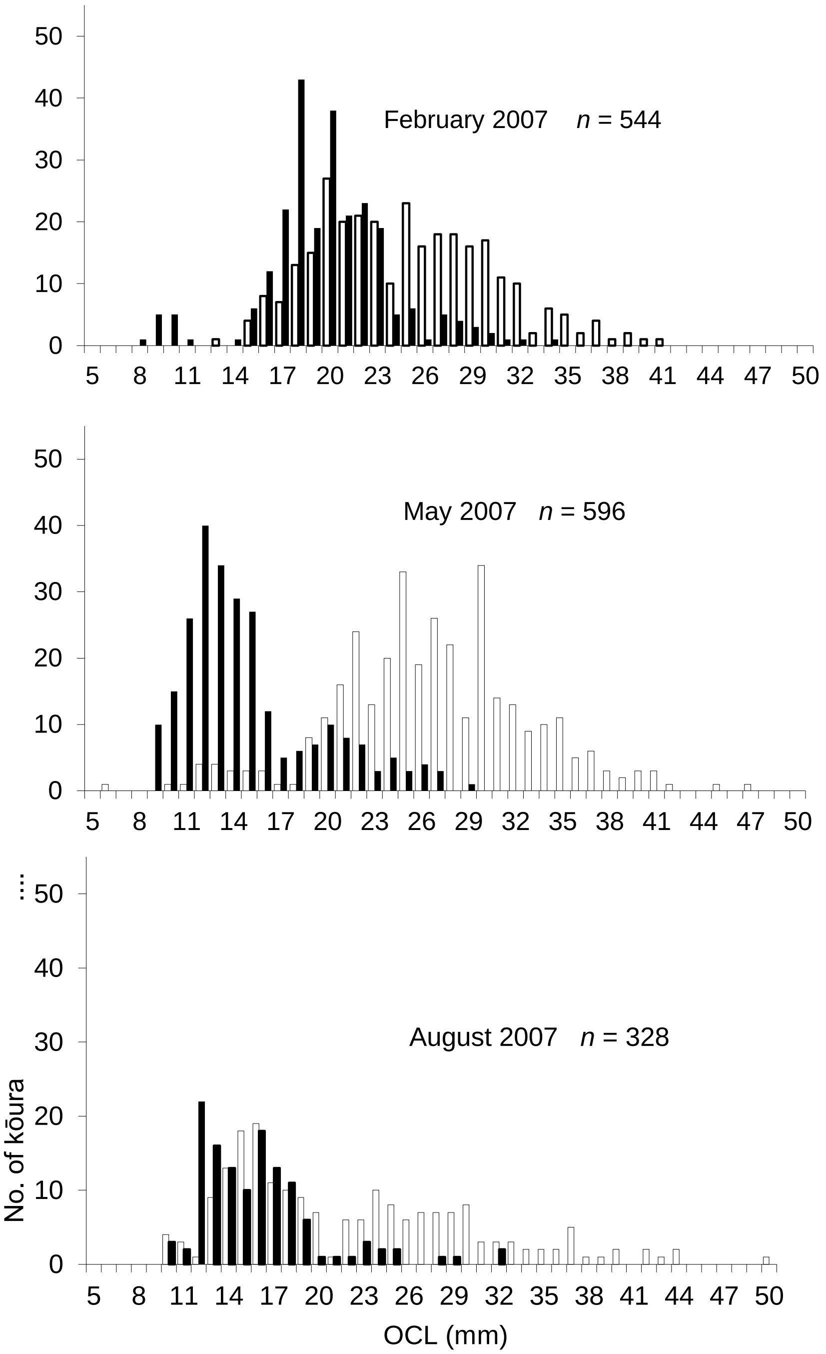

Figure 2.5: Orbit carapace length (OCL) frequency distributions of kōura captured from tau kōura set at Te Ākau Point (clear bars) and Ōkere Arm (shaded bars), Lake Rotoiti, New Zealand, February, May and August 2007.

Table 2.1: Number, biovolume (l) and wet weight of catch (kg) and mean (mm ± SD) and range (mm) orbit carapace length (OCL) of kōura captured in tau kōura (*n* = 10 whakaweku) set in Ōkere Arm between 8 December 2005 and 13 August 2007, and at Te Ākau (Lake Rotoiti, New Zealand) between 14 February 2007 and 10 September 2007. ND = no data collected.

	Number of kōura		Biovolume (l)		Weight of catch (kg)		Mean OCL (mm ±SD)		OCL range (mm)	
Sampling date	Ōkere	Te Ākau	Ōkere	Te Ākau	Ōkere	Te Ākau	Ōkere	Te Ākau	Ōkere	Te Ākau
8 December 2005	803	ND	14.9	ND	ND	ND	20.5 (5.9)	ND	12 – 40	ND
23 February 2006	286	ND	5.7	ND	ND	ND	21.6 (4.6)	ND	9 – 36	ND
8 June 2006	288	ND	7.9	ND	ND	ND	19.2 (6.4)	ND	9 – 44	ND
12 September 2006	972	ND	12.3	ND	ND	ND	15.0 (3.5)	ND	9 – 29	ND
13 December 2006	256	ND	9.7	ND	1	ND	17.0 (4.0)	ND	11 – 31	ND
14 February 2007	742	967	17.4	38.5	6.6	12.8	19.8 (4.1)	24.9 (5.5)	8 – 34	13-41
9 May 2007	255	712	2.7	44	1.8	13.8	14.8 (4.3)	26.8 (6.2)	9 – 29	6-47
13 August 2007	602	399	6.6	16	2	4.7	15.8 (4.1)	22.2 (8.2)	10 – 32	10-50
10 September 2007	ND	267	ND	12.7	ND	4.6	ND	22.1 (7.3)	ND	10-38

Table 2.2: Percentage of breeding size females with eggs or young (defined as >23 mm orbit carapace length OCL) and percentage of kōura with soft shells, in subsamples taken from tau kōura set in the Ōkere Arm, 8 December 2005 to 13 August 2007 and at Te Ākau (TA) (Lake Rotoiti, New Zealand), 14 February 2007 to 10 September 2007. *n* = actual number of females with eggs or young, ND = no data collected.

Sampling date	No. of kōura sexed		% of females in sample		% of breeding size females with eggs (*n*)		% of kōura with soft shells	
	Ōkere	Te Ākau	Ōkere	Te Ākau	Ōkere	Te Ākau	Ōkere	Te Ākau
8 December 2005	74	ND	44.6	ND	0 (0)	ND	ND	ND
23 February 2006	139	ND	54.7	ND	0 (0)	ND	ND	ND
8 June 2006	121	ND	50.4	ND	33.0 (7)	ND	14.8	ND
12 September 2006	322	ND	43.8	ND	50.0 (8)	ND	7.8	ND
13 December 2006	256	ND	54.7	ND	0 (0)	ND	3.5	ND
14 February 2007	233	299	55.4	52.8	0 (0)	0	0.8	0.7
9 May 2007	240	341	51.6	45.7	0 (0)	36.8 (45)	1.6	6.2
13 August 2007	123	200	50.4	44	100.0 (2)	54.3 (19)	2.3	3.5
10 September 2007	ND	75	ND	41.3	ND	55.6 (5)	ND	1.3

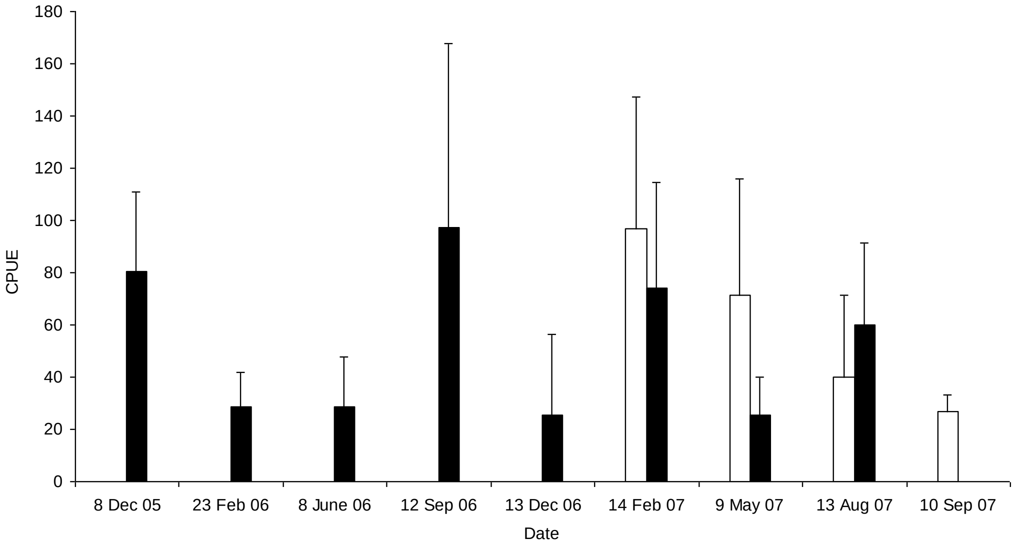

Figure 2.6: Mean catch per unit effort (CPUE + SD; *n* = 10, mean number of kōura captured per whakaweku), of kōura captured in the Ōkere Arm (closed bars) and Te Ākau (open bars) tau kōura, Lake Rotoiti, for all sampling occasions, December 2005 to September 2007.

2.5 Discussion

The tau kōura captured large numbers (mean CPUE from 25.5 to 96.7 per whakaweku) and a wide size range (6 to 50 mm OCL) of kōura in both shallow (<7 m depth) and moderately deep water (7 – 17 m depth) in Lake Rotoiti. This method also distinguished differences in size structure and biovolume yield between sites and provided information on sex ratios, egg-bearing, and moulting.

2.5.1 The tau kōura as a method

The use of any trapping tool makes assumptions that the CPUE is indicative of population density and that the catch composition (sex ratios, egg-bearing females, size distribution, and moulting kōura) is representative of the population (Rabeni, *et al.* 1997). Given the limits of alternative census methods (trapping devices, diving and underwater video surveys) it is difficult to verify that population information from the tau kōura method is representative. One of the main advantages of the tau kōura method over conventional trapping and dive surveys was that it captured large numbers of small kōura (OCL 6 – 18 mm), thus enabling information to be gathered on recruitment and juvenile abundance. In comparison, the smallest kōura captured by Devcich (1979) using conventional baited crayfish traps in Lake Rotoiti was 18 mm OCL. Moreover, small kōura (<18 mm OCL) are almost impossible to observe when SCUBA diving or using underwater video camera at locations such as the Ōkere Arm site where underwater visibility was often poor owing to algae blooms and suspended sediment (Author's personal observations). Tau kōura were colonised by male and female crayfish of all size classes and I contend that it provides more representative data on population structure than alternative methods.

A main limitation of the tau kōura method is that it cannot be effectively deployed in high-growing aquatic macrophyte beds, or areas of large boulder or large wood substrate, because the whakaweku become entangled and difficult to retrieve (Author's personal observations). However, dense aquatic macrophyte beds are also a common problem with conventional baited traps and SCUBA/underwater video camera surveys (Kusabs, *et al.* 2005b). In addition, whakaweku continually decay and must be replaced on a regular basis. In this study in eutrophic Lake Rotoiti whakaweku were replaced on a six monthly basis, however, in a preliminary study in oligotrophic Lake Tarawera, whakaweku lasted for up to two years (Author's personal observations). This difference in bracken fern decay rate is attributable to the higher nutrient concentrations in Lake Rotoiti (e.g., three fold higher total phosphorus concentration, Environment Bay of Plenty unpublished data), which are known to increase leaf litter decay rates in fresh waters (Robinson and Gessner 2000; Royer and Minshall 2001; Gulis and Suberkropp 2003). The development of long lasting artificial whakaweku would overcome this problem, but would increase the cost of tau materials and may not meet approval by traditional practitioners.

2.5.2 Kōura size in Lake Rotoiti

As hypothesised, kōura were significantly larger at Te Ākau (moderate depth) than at Ōkere (shallow depth), where the size range was similar to that of stream populations (Parkyn, *et al.* 2002). The greater proportion of juveniles at Ōkere Arm was consistent with the findings of Devcich (1979), that juvenile kōura are released by females into the productive littoral zone in Lake Rotoiti where there is more food and warmer temperatures, whereas adult kōura assemble into high-density bands above the 30 m depth contour during the day. This aggregation of kōura is a response to light levels and, during periods of stratification (i.e., spring to autumn), to deoxygenation of the hypolimnion (Devcich 1979). The declining water quality in Lake Rotoiti in recent years (Hamilton, *et al.* 2005) may have resulted in an exacerbation of this "habitat squeeze" (i.e., hypolimnetic deoxygenation forcing all kōura to move into the oxygenated epilimnetic waters, resulting in effective loss of habitat area).

2.5.3 Breeding

Breeding appeared to be continuous in Lake Rotoiti, although the least likely time to find females with eggs was in February. Parkyn, *et al.* (2002) found that kōura carried eggs in winter and juveniles were released between September and December in pasture streams and between December and March in cooler, native forest, streams. Hopkins (1967a) found that incubation of eggs and juveniles in the Mangatarere River in the Wairarapa district (North Island) takes place between April and December. In the South Island, Whitmore and Huryn (1999) found that another species of freshwater crayfish, *P. zealandicus*, bred in December and January, with eggs hatching the following December and juveniles released by April. The percentage of "breeding" size females with eggs in the current study was highest in September and August at Te Ākau and Ōkere Arm, respectively. This information is particularly valuable to iwi and hapū as it can be used to set sustainable fishing regulations, for example, kōura harvesting may be restricted from May to September when female kōura are more likely to be bearing eggs or young. Overall, females with eggs comprised a markedly higher proportion of the catch in the Te Ākau tau than in the Ōkere Arm, reflecting the markedly greater number of breeding sized kōura than at Ōkere Arm. It is probable that the shallow waters of the Ōkere Arm provide relatively little habitat compared with the deeper waters of Te Ākau where large numbers of breeding sized kōura are known to assemble into high density bands during the day (Devcich 1979).

2.5.4 Future use of the tau kōura

The tau kōura method is particularly suited for use by iwi (who have exclusive rights to harvest kōura in the Rotorua and Taupō lakes), as it is inexpensive and does not require specialist expertise and safety requirements associated with SCUBA. It is hoped that the tau kōura method will assist iwi to develop the information base on kōura populations needed for sustainable management of kōura populations in their lakes. Tau deployment designs will vary with study objectives and lake characteristics such as the depth at which the thermocline develops and the oxygen levels in the hypolimnion. However, as a practical approach for general assessing of lake kōura population abundance, size structure, sex ratio, and time of egg-bearing, I recommend deploying the tau line from the lake edge to 200 m from the edge or 30 m depth (whichever is reached first) with at least 10 whakaweku (bracken fern bundles) at equally spaced intervals along the tau and sampling at monthly to quarterly intervals. Details on duration of deployment before sampling are still being developed, but I recommend allowing at least one month for colonisation after deployment before the first sampling. A single tau, deployed as described above, should be adequate to monitor long term (decadal) trends in kōura populations in a lake. Consideration should be given to deploying multiple tau kōura to include significant variations in lake bathymetry that are likely to influence kōura populations. Furthermore, for between lake comparisons that focus on water quality influences, I recommend deploying tau kōura in areas of similar lake bathymetry and lake bed substrate in all lakes.

2.5.5 Conclusions

I contend that the tau kōura is a suitable tool for monitoring kōura by fisheries managers, researchers, iwi and community groups, as it is inexpensive, captures kōura of all sizes, can be used in a range of habitat types and depths, and appears to have fewer biases than the more conventional kōura/crayfish capture methods, such as baited traps. The tau kōura method is the principal monitoring method used in this thesis and its use has enabled me to evaluate the effects of nutrient enrichment, benthic substrates and trout abundance on kōura population dynamics (Chapter 3) and to determine sustainable fishing regulations and management policies for kōura in the Te Arawa lakes (Chapter 4). Furthermore, the development of this method has recently led to a resurgence of research and monitoring on lake kōura populations that have been neglected in New Zealand despite the ecological and cultural significance of kōura.

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Chapter 3

Effects of benthic substrate, nutrient enrichment and predatory fish on freshwater crayfish (kōura, *Paranephrops planifrons*) population characteristics in seven Te Arawa (Rotorua) lakes, North Island, New Zealand[4]

3.1 Abstract

Populations of kōura, or freshwater crayfish (*Paranephrops planifrons*), were quantified along a eutrophication gradient in seven Te Arawa lakes using the tau kōura, a traditional Māori harvesting method, in April, July and November 2009. Six of the seven lakes contained kōura. No kōura were captured in hypertrophic Lake Ōkaro. Kōura catches were highly variable and mean catch per unit effort (CPUE) varied from 1.5 to 99.3 kōura per whakaweku (fern bundle) in the six lakes with kōura present. The highest abundance of kōura was recorded in eutrophic Lake Rotorua and the highest biomass in oligotrophic Lake Rotomā. Kōura orbit carapace length (OCL) ranged from 6 to 52 mm, with the largest kōura recorded in lakes Rotoiti and Rotomā. My results suggest that benthic substrate is more important in determining kōura population abundance than nutrient enrichment (using chlorophyll-*a* as a proxy) or predatory fish (rainbow trout abundance). Nevertheless, lake trophic status in conjunction with lake morphology appeared to indirectly affect kōura distribution in the sheltered, steep-sided lakes, through hypolimnetic deoxygenation.

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3.2 Introduction

3.2.1 Issue

Freshwater crayfish (*Paranephrops planifrons*) are endemic to New Zealand where they are known locally by the Māori name kōura. Where they occur they are an important component of freshwater ecosystems and a source of food for freshwater fish (Hicks 1997) and humans (Kusabs and Quinn 2009). Freshwater crayfish are considered a keystone species in freshwater ecosystems (Momot 1995; Nystrőm, *et al.* 2006), have various ecological functions, acting as shredders, detritivores and predators which in turn influence other macroinvertebrate fauna (Parkyn, *et al.* 1997; Parkyn, *et al.* 2001). Furthermore, crayfish increasingly feature as indicator species because of their important role in aquatic ecosystem food webs and their iconic and heritage values (Reynolds and Souty-Grosset 2012; Kuklina *et al.* 2013).

Although the ecology of stream-dwelling *P. planifrons* is well studied in New Zealand (Hopkins 1970; Hicks and McCaughan 1997; Rabeni, *et al.* 1997; Parkyn, *et al.* 2001; Parkyn and Collier 2002; Parkyn, *et al.* 2002; Parkyn and Collier 2004; Parkyn, *et al.* 2009), only two detailed assessments have been carried out on populations of kōura in lakes (Devcich 1979; Kusabs and Quinn 2009), both in Lake Rotoiti, North Island, New Zealand. Despite their ecological and cultural significance, this lack of quantitative information makes it difficult for iwi (Māori tribes) and government agencies to manage kōura populations in lakes. Until recently the main reason for the lack of information on lake dwelling kōura was the absence of suitable representative sampling methods. However, the development of the tau kōura (Fig. 3.1), a traditional Māori method for harvesting kōura, has enabled a resurgence of research and monitoring on lake kōura populations (Kusabs and Quinn 2009).

Historically, kōura were an important food for the indigenous Māori people, particularly in the central North Island lakes where large numbers were harvested for consumption and for trading (Hiroa 1921). Today, kōura are considered a ‘taonga’ or heritage species and support important customary fisheries in some North Island lakes (Rotomā, Rotoiti, Tarawera, and Taupō) where large populations are still present (Kusabs and Quinn 2009). Nevertheless, there is considerable anecdotal evidence of declines in populations of kōura in the Te Arawa lakes district since European settlement (Hiroa 1921; Kusabs and Quinn 2009). Several environmental factors have been implicated in this decline, including introductions of exotic fish (McDowall 1987; Barnes and Hicks 2003) and plant (Rowe 2004) species as well as reduced concentrations of dissolved oxygen in the bottom waters of lakes owing to eutrophication (Vincent, *et al.* 1984; Rowe 2004; Brookes and Hamilton 2009).

The effects of nutrient enrichment on water quality (Vincent, *et al.* 1984; Gibbs 1992; Hamilton 2003; Burger, *et al.* 2007), fish (Fish 1968; Burnet and Wallace 1973; Rowe 1984; Rowe and Chisnall 1995; Rowe 1999; Rowe and Schallenberg 2004; Rowe and Taumoepeau 2004) and the growth of aquatic macrophytes and algae (Schallenberg 2004) in New Zealand lakes are well documented but there is little information on the effects on kōura. The Te Arawa lakes have undergone eutrophication at varying rates over the past 30 – 50 years, mostly owing to excess nutrient inputs associated with development in the lakes' catchments (Abell, *et al.* 2011). The main sources of nutrients are farming activities, soil erosion, septic tanks, and community sewerage schemes (PCE 2006). Treated sewage was also discharged into the largest lake, Lake Rotorua, until 1991 and is currently irrigated to production forests within the lake catchment, after tertiary treatment (Burns, *et al.* 1997).

Freshwater crayfish in productive lakes generally have high abundances, growth rates, and fecundity (Abrahamsson and Goldman 1970; Jones and Momot 1981; France 1985). This has been attributed to increasing trophic status causing an increase in the primary consumer density, i.e., higher prey availability for crayfish in eutrophic lakes (Stenroth, *et al.* 2008). Although, the increased productivity of nutrient enriched systems can potentially increase freshwater crayfish production (Nystrőm, *et al.* 2006), several abiotic and biotic changes occur simultaneously, which could have negative effects on crayfish populations (Nystrőm 2002). Hypoxia, temporary or permanent in deeper waters, is often a consequence of eutrophication and organic enrichment (Wetzel 1983; Parr and Mason 2004). These interacting effects necessitate a correlative approach to examine how kōura are affected by nutrient enrichment using a number of lakes where kōura abundance is variable.

In this study, the tau kōura method (Kusabs and Quinn 2009) was used to collect kōura (Fig. 3.1) in seven Te Arawa lakes which had a gradient of nutrient enrichment from low (oligotrophic) to very high (hypertrophic). I hypothesised that kōura would show a subsidy-stress response (sensu Odum *et al*. 1979) to increasing nutrient enrichment, with increasing nutrient levels initially promoting greater kōura abundance through increased food supply, but higher nutrient levels leading to hypolimnetic deoxygenation that would reduce kōura abundance by restricting the available habitat.

Studies outside of New Zealand (Nystrőm, *et al.* 2006) suggest that, if physico-chemical parameters are suitable (e.g., calcium concentration, oxygen levels, and temperature), then the most important factors influencing the abundance and size distribution of crayfish are food supply, predatory fish, and benthic substrates. The aim of this study was therefore to improve the basis for sustainable management of kōura in Te Arawa lakes by characterising population abundance, biomass and size distribution and evaluating the influences of primary production, predatory fish and substrates. I also sought to investigate potentially confounding effects whereby eutrophication could reduce available habitat (e.g., by deoxygenation of bottom waters) whilst there were concurrent increases in food supply.

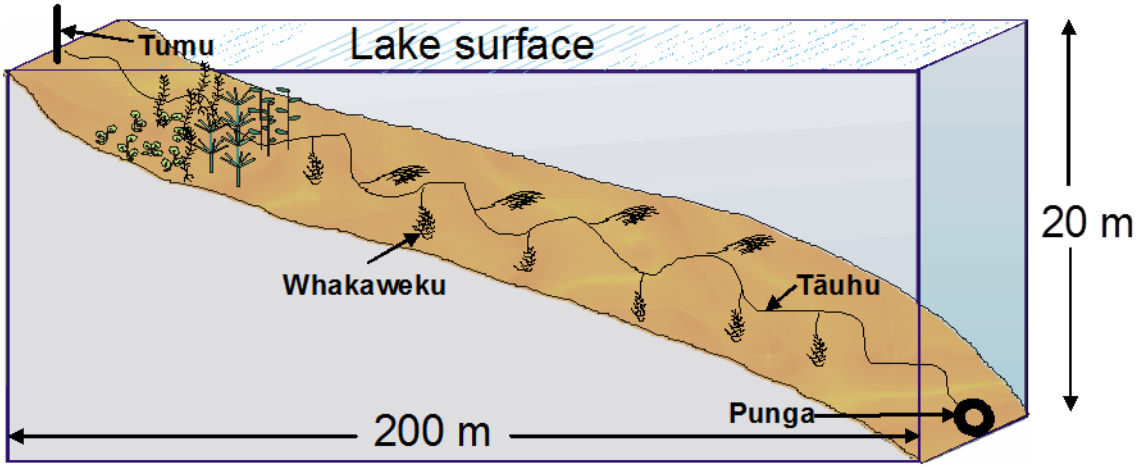

Figure 3.1: Schematic diagram of a tau kōura. The depth and length of tau are indicative and can be varied depending on lake morphology.

3.3 Materials and methods

3.3.1 Study sites

The Te Arawa lakes are situated on the central volcanic plateau in the Bay of Plenty region of New Zealand's North Island (Fig. 3.2). The lakes were formed between *c*. 230 000 years ago (Lake Rotorua) and 700 years ago (Lake Ōkaro) from a series of volcanic eruptions that characterise the Taupō Volcanic Zone (Lowe and Green 1987; Esler 2010). Seven lakes were selected for this study; Ōkaro, Rotorua, Rotoiti, Ōkāreka, Rotokakahi, Tarawera and Rotomā, to provide a range of different lacustrine environments within a discrete geographical area (Fig. 3.2). These lakes vary in trophic status (oligotrophic to hypertrophic), size (32 – 8,079 ha) and morphology (mean depth 11 – 50 m) (Table 3.1). All lakes are monomictic except for Lake Rotorua, which is polymictic (Table 3.1).

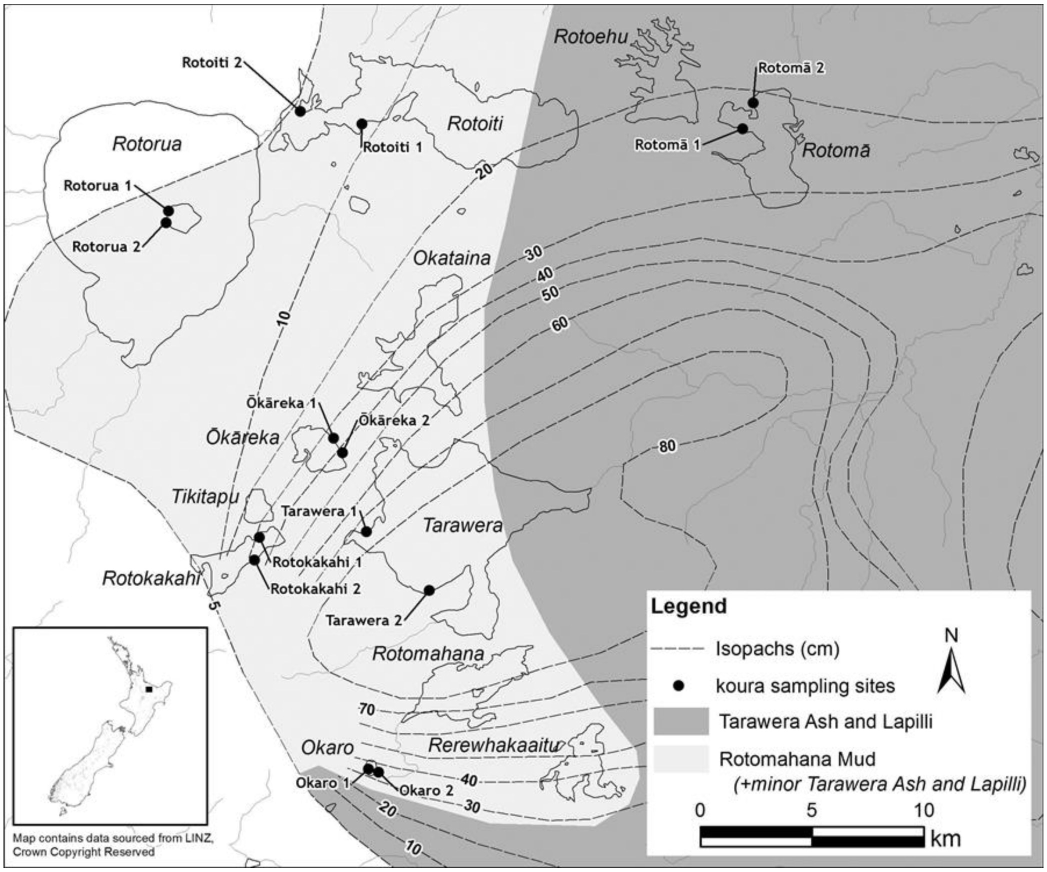

Figure 3.2: Te Arawa lakes in the Bay of Plenty region of New Zealand, showing location of tau kōura sampling sites and distribution of Rotomahana Ash.

Table 3.1: Morphometry and limnological characteristics of the seven study lakes, Te Arawa Lakes District, North Island, New Zealand. Mixing regime (M, monomictic; P, polymictic), mean depth, maximum depth, lake area, catchment area, Osgood Index (Scholes 2009), percentage of catchment in agriculture for all lakes (Bruesewitz *et al.* 2011), pH and calcium concentration (Ca) from BOPRC (sampled 13 August 2012 – 15 August 2012), weed (macrophyte) depth from NIWA. Trophic Level index (TLI) average from 2002 – 2009 (TLI units), Secchi depth, total nitrogen (TN), total phosphorus (TP) and chlorophyll-*a* (Chl-*a*) values are means of monthly measurements, 2002 – 2009 (Scholes 2009, 2010). The temperature range is the mean of the annual temperature minima–mean of the annual temperature maxima 2002 – 2009 (Scholes 2009, 2010).

Lake	Trophic state	Mixing regime	Mean depth (m)	Max depth (m)	Lake area (ha)	Catch-area (ha)	Osgood Index	Agri-culture (%)	Weed depth (m)	TLI	TP (mg m^{-3})	TN (mg m^{-3})	Chl-*a* (mg m^{-3})	Ca (mg m^{-3})	Secchi depth (m)	Mean temp (°C)	Annual temp range (°C)	pH
Ōkaro	Hypertrophic	M	12.5	18	32	407	22.82	95.7	4.6	5.3	77.4	958.1	28.3	5.2	2.4	12.3	8.6 – 21.8	7.6
Rotorua	Eutrophic	P	11	45	8,079	52,346	1.23	51.8	7	4.8	37.9	458.4	21.3	3.5	2.4	15	9.3 – 21.7	6.7
Rotoiti	Eutrophic	M	31.5	124	3,460	12,462	5.43	23.9	8	4.1	40.4	356.6	12.2	3.6	4.4	12.8	10.8 – 22.1	7.2
Ōkāreka	Mesotrophic	M	20	33.5	342	1,958	10.94	55.8	8.1	3.2	8.4	212.6	4.1	3.5	7.7	12.4	9.3 – 22.2	7.7
Rotokakahi	Mesotrophic	M	17.5	32	452	1,872	8.41	23.9	9.5	4.1	18	249	6.3	2.9	3.7	12.9	9.4 – 21.2	8
Tarawera	Oligotrophic	M	50	87.5	4,165	14,494	7.79	21.1	14	2.8	13.9	114	1.5	9.7	8.7	12.5	10.9 – 21.4	7.8
Rotomā	Oligotrophic	M	36.9	83	1,104	2,914	11.07	22.8	16	2.5	4.6	141.2	1.3	2.1	12.8	12.5	10.6 – 21.3	7.4

3.3.2 Kōura, fish and cormorant species

P. planifrons is the only freshwater crayfish species present in the Te Arawa lakes. The lakes contain a similar fish fauna, comprised mostly of rainbow trout (*Oncorhynchus mykiss*), common smelt (*Retropinna retropinna*) and common bullies (*Gobiomorphus cotidianus).* Rainbow trout are present in all seven study lakes, whereas brown trout (*Salmo trutta*) are common in Lake Rotorua and present in low numbers in Lake Rotoiti.

I obtained an approximate estimate of relative trout abundance by incorporating the following in my analyses, *(i)* the number of rainbow trout released from the Eastern Fish & Game Council (EFGC) hatchery per year in each lake, (*ii*) the number of trout released per year per hectare of lake surface area, and (*iii*) the mean ratio of stocked to wild trout in angler catches, using records gained from EFGC creel surveys from 2002 to 2009. Trout are not stocked into Lake Rotokakahi therefore relative trout abundance was estimated by comparing opening day angling records (Author's unpublished data) with those from Lake Tarawera.

Cormorants are well known predators of freshwater crayfish and three species are commonly found in the Te Arawa lakes district; *Phalacrocorax carbo*, *P. melanoleucos*, and *P. sulcirostris* (Potts 1977). However, the predatory impact on kōura was not considered in this study as they feed mainly in waters less than 3 m (Heather and Robertson 2005) deep (whakaweku were set >4 m depth) and because they are wide ranging, roving amongst the closely situated lakes (Authors' personal observation).

3.3.3 Physico-chemical information

Total phosphorus (TP), total nitrogen (TN), and chlorophyll-*a*, were obtained from Scholes (2009) (Table 3.1). The Trophic Level Index (TLI) is an indicator of lake trophic status in New Zealand lakes and is derived from concentrations of Chl-*a*, Secchi depth (SD), TP and TN (Burns, *et al.* 1997). Values of TLI for 2002 to 2009 were obtained from Scholes (2009, 2010) who used the annual average value of the four key variables to derive the TLI. Dissolved calcium (Ca) and pH were obtained from water samples collected by the Bay of Plenty Regional Council (BOPRC) and analysed by Hills Laboratories, Hamilton. Water samples were taken when the lakes were mixed (winter 2012; 13 – 15 August) with a depth integrated sample from surface to a set depth specific to each lake (pers. comm. P. Scholes, BOPRC).

Osgood Index (Osgood 1988) was calculated using the formula mean depth (m) divided by the square root of the surface area (km^2) (Table 3.1). Water temperature and dissolved oxygen (DO) were measured monthly at a mid-lake station in each of the lakes at 1 or 2 m intervals throughout the water column with a conductivity-temperature-depth (CTD) profiler (SBE 19 plus, Seabird Electronics) with CTD-mounted DO sensors (Seabird Electronics). The volume of water in each lake with concentrations of DO <5 mg L^{-1} was then established from these monthly DO profiles (Scholes 2010) and hypsographic tables. I chose this concentration threshold because kōura begin to exhibit symptoms of respiratory stress below 5 mg DO L^{-1} in lakes (Devcich 1979) and this value would equate to the worst case scenario (i.e. least volume) for kōura habitat availability.

3.3.4 Sampling methods

Two tau kōura were set in each lake with each tau and comprised of a 200 – 250 m length of 10 mm diameter polyester rope (the tāuhu), with one end attached to the shoreline, and the other tied to a concrete filled tyre (Fig. 3.1). Ten whakaweku (bracken ferns, *Pteridium esculentum*, bundles) each with c. 10 bracken fronds per whakaweku were attached to each tāuhu. The fern fronds were bound together using 300 mm lengths of industrial strength plastic cable ties and attached to the tāuhu using twine (~5 mm in diameter and 2.5 m in length) at approximately 3 m intervals. In order to make between-lake comparisons, tau kōura were deployed in depths ranging from 6 – 34 m on the dominant substrate type present in each of the seven study lakes. Typically, the lake bed sediments in the Te Arawa lakes are comprised mainly of mud, silt and sand. Tau kōura were set at two locations in each lake (Fig. 3.2). Depths were determined using an electronic depth finder (Furuno LCD sounder LS 6000, Furuno Electric Co. Ltd. Nishinomiya, Japan). Tau kōura were set in each lake in areas that were free of large, invasive macrophyte beds, underwater obstructions such as reefs or boulders. The tau kōura were set in March 2009 and collected, checked and redeployed in April, July and November 2009.

3.3.5 Kōura measurements

Orbit carapace length (OCL, mm) of each kōura was measured using vernier callipers (± 0.5 mm) and the sex of kōura (OCL >11 mm; the sex of kōura less than tis size could not be determined in the field) assessed. A power regression equation previously determined (Hicks and Riordan unpublished data) was used to estimate kōura wet weight (g) from OCL (mm):

$$\text{Wet weight} = 0.000648\ \text{OCL}^{3.0743} \qquad \text{(Eqn 3.1)}$$

After processing, all kōura were returned to the water in close proximity to the tau kōura. Catch per unit effort (CPUE) was defined as the number of kōura per whakaweku and biomass per unit effort (BPUE) as estimated wet weight (g) of kōura per whakaweku.

3.3.6 Sediment characteristics

An Ekman grab sampler was used to collect sediment samples (area 0.04 m^2) from three sites alongside each tau line (shallow, mid depth and deep) from 13 to 15 April 2010. Each of the three samples was subsampled for chemical and particle size analyses. Particle sizes were dried to a constant weight at 60 ^{o}C in a Contherm oven. The fraction >250 µm was weighed while the fractions <250 µm was determined with an EyeTech model CIS-100 stream-scanning laser particle sizer (Ankersmid, Amsterdam). Substrate types were classified according to the Wentworth Scale: clay (1 – 3.9 µm), very fine silt (3.9 – 7.8 µm), fine silt (7.8 – 15 µm), medium silt (15.6 – 31 µm), silt (31 – 62.5 µm), very fine sand (62.5 – 125 µm), fine sand (125 – 250 µm), medium sand (0.25 – 0.5 mm), coarse sand (0.5 – 1 mm), very coarse sand (1 – 2 mm), granule (2 – 4 mm) and pebble (>4 mm). The fraction <250 µm was analysed for particulate nitrogen (PN) and carbon (PC) by the NIWA Chemistry Laboratory, Hamilton.

3.3.7 Data analysis

Multi-level analysis of variance with Fisher's protected least significant difference multiple comparison tests were used to document variability in CPUE, BPUE and mean OCL related to between lake, between site and between month effects. The CPUE and BPUE results were log transformed to better satisfy model assumptions. Restricted Maximum Likelihood (REML) was used to check that the split-plot model was adequate for the between month repeated measures. Using correlation analyses I also investigated how productivity (Chl-*a*), sediment carbon to nitrogen (C/N), benthic substrate size (median sediment size), Ca concentration and relative trout abundance were related to the abundance, biomass and size of kōura. The median sediment size, relative trout abundance and Ca concentration were transformed (inverse square root) to correct skewed distributions in the data.

3.4 Results

3.4.1 Lake water quality

Water chemistry data indicated that the survey lakes formed a trophic gradient with respect to surface water TP (range 4.6 – 77.4 mg m^{-3}), TN (range 114 – 958.1 mg m^{-3}), and phytoplankton Chl-*a* concentration (range 1.3 – 28.3 mg m^{-3}) (Table 3.1). All seven study lakes provided suitable physico-chemical conditions for kōura. Dissolved Ca concentrations ranged from 2.1 to 9.7 mg m^{-3} and mean pH ranged from 6.7 to 8.0 in the lakes (Table 3.1). Lake Rotorua had a mean temperature of 15 ^{o}C whereas the other six lakes showed a lower mean temperature, in the range of 12.4 to 12.9 ^{o}C (Scholes 2009; Scholes 2010).

Minimum and mean oxic volumes ranged from 9.3 to 98% and from 73.2 to 100%, respectively (Table 3.2). Lakes Ōkaro had the lowest volume and Lake Tarawera had highest (Table 3.2). In Lake Tarawera there was always >5 mg L^{-1} dissolved oxygen in surface and bottom waters, even in summer when the lake was thermally stratified. However, deoxygenation became progressively more pronounced and of longer duration in order of lakes Rotomā, Rotorua, Ōkāreka, Rotokakahi, Rotoiti, Ōkaro (Table 3.2).

3.4.2 Sediments

Analysis of sediment composition showed that sediments from Lake Rotorua, Rotoiti (Site 1), and Rotomā had high proportions of coarse (>250 µm) material and that Lake Rotorua had the highest proportion of pebble sized material (Table 3.2, Fig. 3.3). The other lakes were dominated by fine sediments <250 µm (Table 3.2, Fig. 3.3). Sediments generally became finer with increasing water depth within individual lakes (Author's unpublished data). The two sites in Lake Rotoiti were not combined because these were the only within-lake sites where median sediment sized was markedly different (Table 3.2, Fig. 3.3).

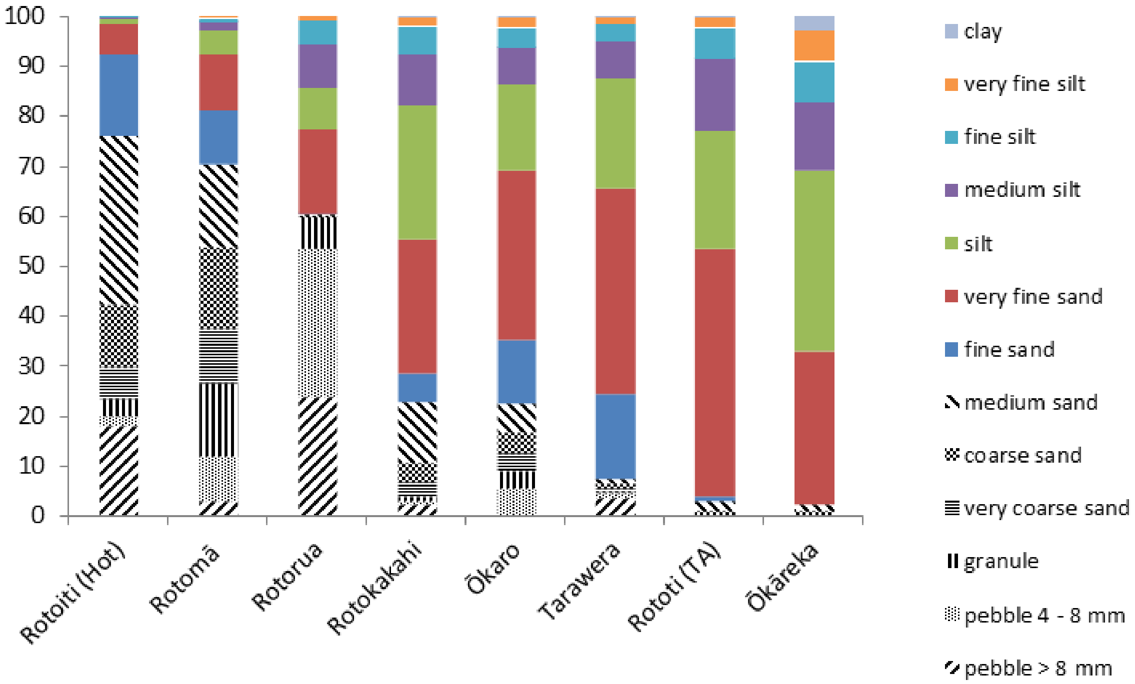

Figure 3.3: Mean percentage particle size composition of the sediments sampled in the seven lakes. Lakes are ordered by mean particle size from left to right. Substrate types were classified according to the Wentworth Scale (see Methods). Patterned lines >250 µm, solid fill coloured <250 µm. Rotoiti (Hot) = site 1, Rotoiti (TA) = site 2.

Table 3.2: Mean and median sediment sizes, % organic matter, carbon to nitrogen (C/N) ratio of sediment samples collected from tau kōura lines, % mean and % minimum oxic volumes calculated for Lakes Ōkaro, Rotorua, Rotoiti (2 sites), Ōkāreka, Rotokakahi, Tarawera, and Rotomā. Note: the sites in Lake Rotoiti were separated because of markedly different lake bed substrates.

Lake	Mean sediment size (mm)	Median sediment size (mm)	% Organic matter	C/N ratio	% Mean oxic	% Minimum oxic
Ōkāreka	0.062	0.035	7.6	12.2	90.6	59.6
Ōkaro	0.588	0.07	15.3	10.8	73.2	9.3
Rotoiti (Hot)	2.703	0.375	5.5	8.1	82.3	41.8
Rotoiti (TA)	0.077	0.047	9.8	9.2	82.3	41.8
Rotokakahi	0.466	0.047	6.3	9.5	85.9	54.7
Rotomā	1.669	0.375	6.5	9.4	99	85
Rotorua	4.812	3	8	7.5	99	69.3
Tarawera	0.568	0.07	5.1	8.9	100	98

3.4.3 Trout

Estimates of rainbow trout abundance in the lakes ranged from 3 fish ha^{-1} in Lake Rotokakahi to 466 fish ha^{-1} in Lake Rotorua (Table 3.3). These estimates are approximate only, particularly those for lakes Rotorua and Rotokakahi, where the proportion of hatchery trout stocking is very low or non-existent (Table 3.3).

Table 3.3: Stocking rates, percentage of wild origin trout in recreational catch and relative trout abundance (wild + hatchery) in seven Te Arawa lakes, North Island, New Zealand (means 2000–2009 ± SD).

Lake	Surface area (ha)	Stocking rate (fish year^{-1})	Stocking rate (fish ha^{-1} year^{-1})	Percentage of wild trout caught	Relative trout abundance (fish ha^{-1})
Ōkāreka	342	6000 ± 2160	18.2 ± 6.5	15.0 ± 7.21	21
Ōkaro	32	735± 515	22.3 ± 15.6	0	22
Rotoiti	3460	24250 ± 3522	7.0 ± 1.0	38 ± 5.4	11
Rotokakahi	452	0	0	100	3
Rotomā	1104	4925 ± 1166	4.4 ± 1.0	40.6 ± 18.7	7
Rotorua	8079	1000 ± 0	0.12 ± 0.0	97.9 ± 2.0	466
Tarawera	4165	18250 ± 1799	4.4 ± 0.4	24.1 ± 5.0	6

3.4.4 Kōura population characteristics

Six of the seven lakes contained kōura. No kōura were captured in Lake Ōkaro. A total of 8,403 kōura were captured in the six lakes in the study. The highest catch of kōura was recorded in Lake Rotorua (site 1) in November 2009 (mean CPUE = 99.3) but the highest biomass was recorded in Lake Rotomā (site 2) in November 2009 (mean BPUE = 1067.6 g) (Table 3.4). Kōura OCL ranged from 6 – 52 mm (Table 3.5).

For CPUE and BPUE the between lake effects (CPUE $F_{6,35} = 1.08$, $p < 0.001$) (BPUE $F_{6,\ 35} = 17.05$, $p < 0.005$) were significant and accounted for more than 75% of the variability with the remainder being almost entirely due to between month random effects, with between site variation being non-significant after accounting for between month effects. For mean OCL the between lake effect (OCL $F_{6,\ 35} = 6.49$, $p < 0.05$) was again significant accounting for 60% of the variation, with the between month accounting for 35%.

3.4.5 Kōura abundance and biomass

Kōura catches were highly variable and mean CPUE varied from 1.5 to 99.3 kōura per whakaweku in the six lakes with kōura present (Table 3.4). There was no obvious trend in mean CPUE over the study, with CPUE highest in Tarawera, Rotokakahi, and Rotoiti in July, Rotorua in November and Ōkāreka and Rotomā in April (Fig. 3.4a). In general, BPUE was consistently high in Rotorua, Rotomā, and Rotoiti and low in Ōkāreka, Tarawera and Rotokakahi (Fig. 3.4b). Although kōura were significantly more abundant in Rotorua (Table 3.4), their smaller mean size resulted in BPUE values similar to Rotoiti and Rotomā (Fig. 3.4b). There was no obvious trend in mean BPUE over the study, with BPUE highest in Tarawera, Rotokakahi and Rotoiti in July, Rotorua in November and Ōkāreka and Rotomā in April (Table 3.4).

3.4.6 Depth distribution of kōura

The depth distribution of kōura in the six study lakes, where they were present, varied both seasonally and among the lakes (Table 3.4). Kōura were captured from depths of 6.2 to 34 m (Table 3.4). I typically observed the lowest CPUE in the deep whakaweku locations (Author's unpublished data) where DO concentrations measured near or below 5.0 mg L^{-1}. In April, when lakes Ōkāreka, Rotokakahi and Rotoiti were stratified, kōura were not found below the base of the surface mixed layer depths of 15 m, 14 m and 25 m, respectively (Table 3.4). Depth distribution of kōura was not affected by DO in the six lakes in July when the lakes were mixed and November when levels of DO were still >5 mg L^{-1} (Table 3.4). The absence of kōura in highly eutrophic Lake Ōkaro could be attributable to rapid and prolonged hypolimnetic deoxygenation (>ca. 5 m depth).

Table 3.4: Depth range (m) of fern bundles, maximum kōura depth (m), mean catch per unit effort (mean CPUE ± SD) and calculated mean biomass per unit effort (mean BPUE (g) ± SD) of kōura captured in two tau kōura (comprising 10 whakaweku; fern bundles) set in seven Te Arawa lakes on 3 to 6 March 2009 and retrieved on 14 – 17 April 2009, 9 – 14 July 2009 and 5 – 9 November 2009. Maximum kōura depth numbers represent the number of fern bundles in oxygenated (DO > 5.0 mg L^{-1}) locations.

		Tau depth range	Maximum kōura	Mean CPUE (± SD)			Mean BPUE (g, ± SD)		
Lake	Site	(m)	depth April (m)	April	July	Nov	April	July	Nov
Ōkāreka	1	7.5 – 22	15 (*n* = 8)	6.6 (9.6)	5.0 (3.4)	2.2 (1.5)	115.3 (149.0)	130.7 (94.2)	91.5 (84.8)
	2	8 – 18.5	15 (*n* = 7)	7.5 (6.5)	2.2 (2.0)	1.5 (1.3)	135.6 (151.0)	38.8 (55.2)	35.4 (23.6)
Rotoiti (Hot)	1	10 – 25	24 (*n* = 8)	12.5 (11.9)	44.9 (23.1)	35.5 (12.2)	230.4 (227.8)	932.3 (494.7)	723.6 (337.4)
(TA)	2	11 – 16		32.4 (15.6)	21.9 (14.2)	10.9 (4.3)	760.7 (350.6)	615.1 (412.4)	306.1 (141.8)
Rotokakahi	1	9 – 23	14 (*n* = 2)	2.3 (5.1)	8.7 (7.0)	8.2 (9.0)	34.3 (82.5)	97.0 (96.6)	93.2 (99.7)
	2	9 – 21	15 (*n* = 5)	4.7 (7.2)	16.8 (10.8)	8.8 (3.9)	52.7 (78.3)	144.3 (88.9)	78.0 (47.1)
Rotomā	1	10 – 34		38.1 (26.7)	36.3 (29.7)	18.2 (12.5)	777.8 (559.8)	940.5 (844.2)	536.5 (367.1)
	2	11 – 29		45.5 (24.6)	23.6 (14.1)	34.1 (21.0)	822.2 (484.8)	350.9 (228.7)	1067.6 (814.2)
Rotorua	1	5 – 17		34.5 (13.2)	61.3 (45.0)	99.3 (46.1)	490.4 (288.3)	571.7 (683.7)	967.7 (570.1)
	2	6 – 17		41.2 (12.7)	51.6 (19.6)	90.0 (23.4)	841.0 (405.3)	432.8 (262.7)	796 (255.5)
Tarawera	1	8 – 26		3.9 (3.0)	4.4 (4.5)	2.6 (3.3)	63.5 (59.8)	93.7 (92.6)	33.3 (51.9)
	2	12.9 – 25		2.9 (3.1)	14.4 (10.5)	5.8 (4.4)	57.8 (70.4)	381.4 (293.2)	116.7 (81.0)

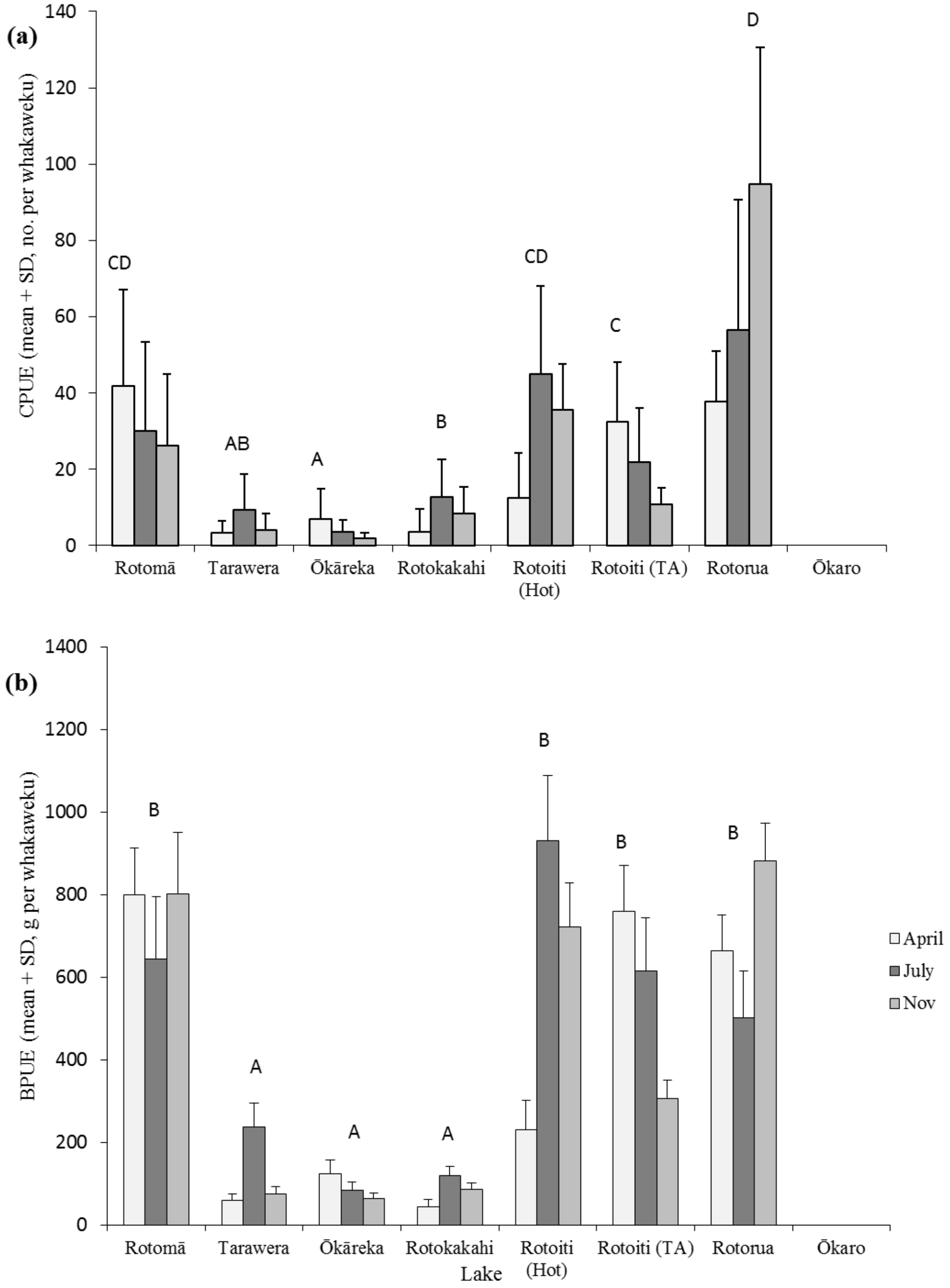

Figure 3.4: (a) Catch per unit effort (mean + SD) and (b) biomass per unit effort (mean (g) + SD) (*n* = 10 x two sites) of kōura captured in seven Te Arawa lakes (two sites in Lake Rotoiti) in April, July and November 2009. Lakes ordered in terms of increasing Chl-*a* concentration. Rotoiti (Hot) = site 1, Rotoiti (TA) = site 2. Lakes with the same letters did not differ significantly.

3.4.7 Size

In terms of size, the lakes ranked from highest to lowest, were Rotoiti, Rotomā, Tarawera, Ōkāreka, Rotokakahi and Rotorua (Fig. 3.5). The highest mean OCL (34.3 mm) was recorded in Ōkāreka and the lowest mean OCL (19.1 mm) was recorded in Rotorua (Table 3.5). Mean kōura OCLs were highest in Ōkāreka, Rotoiti and Rotomā in November, Rotokakahi and Rotorua in April, and Tarawera in July (Table 3.5).

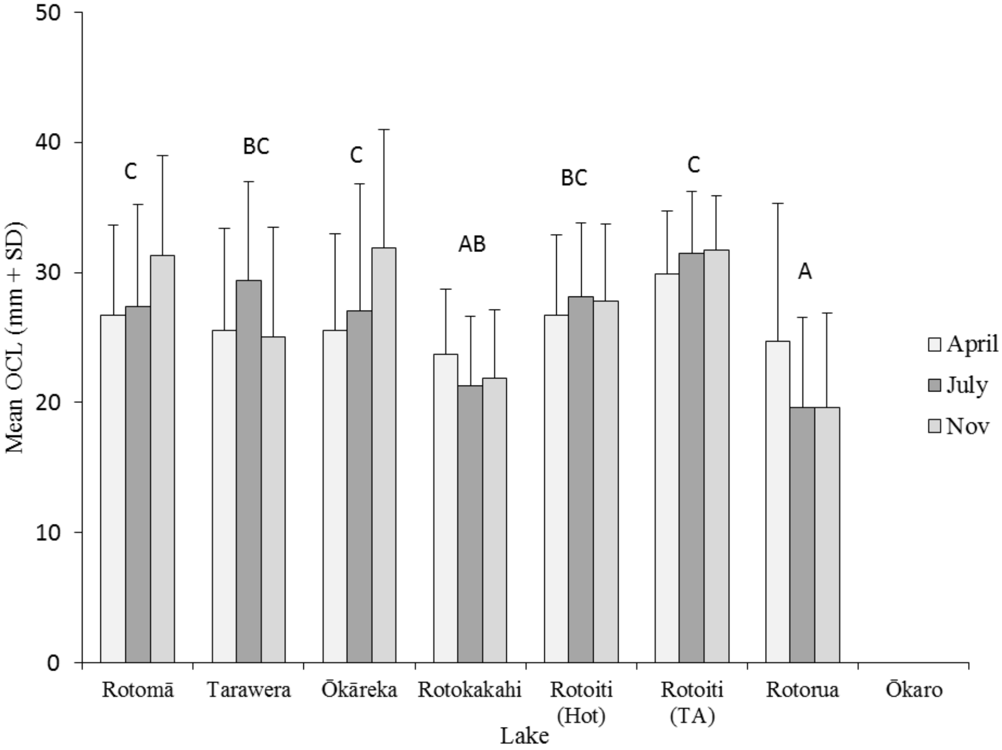

Figure 3.5: Mean orbit carapace length (mm + SD; n = 10 x two sites) of kōura captured in seven Te Arawa lakes (two sites in Lake Rotoiti) in April, July and November 2009. Lakes with the same letters did not differ significantly. Rotoiti (Hot) = site 1, Rotoiti (TA) = site 2.

Table 3.5: Orbit Carapace Length (mm, ± SD) mean and range of kōura collected from two tau kōura (comprising 10 fern bundles) set in seven Te Arawa lakes on 3 to 6 March 2009 and retrieved on 14 – 17 April 2009, 9 – 14 July 2009 and 5 – 9 November 2009.

		Mean OCL (mm, ± SD)			OCL range (mm)		
Lake	Site	April	July	Nov	April	July	Nov
Ōkāreka	1	26.1 (6.2)	28.5 (9.4)	34.3 (9.2)	18 – 45	11 – 50	19 – 52
	2	25.1 (8.5)	23.8 (9.9)	28.5 (7.9)	14 – 43	11 – 45	14 – 38
Rotoiti (Hot)	1	26.7 (6.2)	28.1 (5.7)	27.8 (5.9)	8 – 38	12 – 44	11 – 43
(TA)	2	29.9 (4.8)	31.5 (4.7)	31.7 (4.2)	16 – 45	21 – 50	21 – 43
Rotokakahi	1	25.0 (5.8)	22.2 (6.1)	22.4 (6.1)	15 – 38	11 – 39	11 – 40
	2	23.1 (4.5)	20.9 (4.8)	21.4 (4.1)	12 – 31	10 – 38	12 – 30
Rotomā	1	28.4 (6.2)	29.8 (6.9)	31.2(6.9)	14 – 51	11 – 49	17 – 50
	2	26.1 (7)	23.7 (7.6)	31.4 (8.1)	9 – 49	6 – 48	9 – 48
Rotorua	1	24.4 (10)	20.1 (6.9)	20.1 (7.3)	7 – 47	9 – 45	10 – 47
	2	24.8 (10.7)	19.1 (6.9)	19.1 (7.4)	9 – 51	9 – 46	11 – 47
Tarawera	1	24.3 (8.3)	27.3 (8.1)	23.7 (5.8)	11 – 43	8 – 41	13 – 34
	2	27.0 (7.2)	30.0 (7.4)	25.6 (9.4)	12 – 42	12 – 42	13 – 48

3.4.8 Kōura relationships with environmental and trout variables

The relationships between population characteristics and key environmental variables in six of the study lakes were investigated using correlation analysis. Lake Ōkaro was excluded because the absence of kōura in this lake is most likely due to episodic whole lake deoxygenation and high ammonia concentrations at turnover which are not captured in the long-term environmental monitoring dataset.

Relative abundance ($\log_{10}$ (mean CPUE)) was used as the response variable in the correlation analyses because there was a strong relationship between CPUE and BPUE of kōura ($r = 0.931$, $p < 0.005$). Neither CPUE ($r = -0.167$, $p = 0.72$) nor BPUE ($r = 0.192$, $p = 0.679$) were correlated with mean kōura size.

The abundance of kōura was strongly correlated with benthic substrate (measured as median particle size) (Table 3.6; Fig. 3.6) and weakly correlated (significant at $p < 0.10$) with trophic status of the lakes measured as Chl-*a* and C/N ratio (Table 3.6; Fig. 3.6). However, there was a strong correlation between CPUE and Chl-*a* when Lake Rotomā was removed ($r = 0.931$, $p < 0.005$). Transformed sediment size was not significantly correlated with Chl-*a* ($r = -0.488$, $p = 0.267$). However, Rotorua had the highest Chl-*a* and highest median sediment size (Tables 3.1 and 3.2). There was no correlation between kōura abundance and relative trout abundance or Ca concentration (Table 3.6). Kōura size was not correlated with any of the key predictor variables (Table 3.6).

Table 3.6: Correlations between mean kōura abundance ($\log_{10}$ (mean CPUE)) and size (OCL) with key environmental variables and relative trout abundance in six Te Arawa lakes.

Variable	Origin of dataset	$\log_{10}$ Mean CPUE	Mean OCL (mm)
$1/\sqrt{}$ sediment median size (μm)	This study	$r = -0.857$, $p = 0.014$	$r = -0.318$, $p = 0.488$
Carbon to nitrogen (C/N) ratio	This study	$r = -0.752$, $p = 0.051$	$r = -0.302$, $p = 0.510$
$1/\sqrt{}$ relative trout abundance (ha^{-1})	This study	$r = -0.474$, $p = 0.282$	$r = -0.120$, $p = 0.799$
Mean annual average Chl-*a* ($mg\ m^{-3}$) July 2002– Nov 2009	Scholes 2009 & 2010	$r = 0.688$, $p = 0.087$	$r = -0.422$, $p = 0.346$
$1/\sqrt{}$ Ca ($mg\ m^{-3}$)	Scholes 2009 & 2010	$r = -0.429$, $p = 0.337$	$r = -0.091$, $p = 0.846$

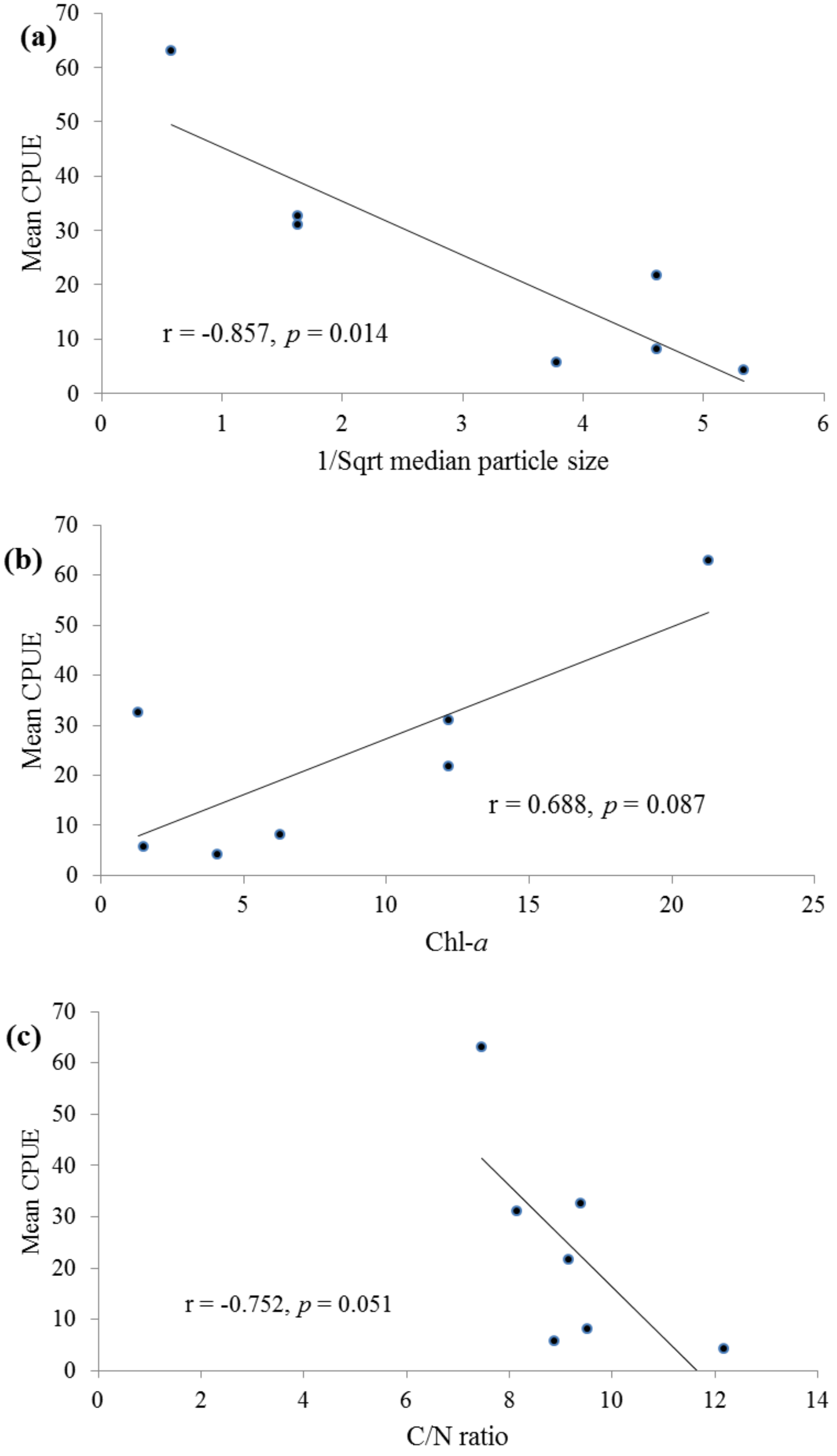

Figure 3.6: Correlation plots for Te Arawa lakes (*n* = 6) showing the association between relative kōura abundance (mean CPUE) and, (a) 1/Sqrt median particle size; (b) Chl-*a*; (c) C/N mass ratio.

3.5 Discussion

Kōura population characteristics varied across the lakes indicating that kōura management strategies need to account for variations between lakes as discussed further in Chapter 4. Although limited by the number of lakes I was able to characterise, my data indicate that lake bed substrate (median sediment particle size) had a stronger influence on population characteristics than the level of enrichment/primary production as indexed by Chl-*a*. Nevertheless, the negative correlations of kōura abundance with sediment C/N ratio, and the positive correlation between abundance and Chl-*a* (when Lake Ōkaro was excluded) suggest that productivity does influence kōura populations. In this context, the absence of kōura from hypertrophic Lake Ōkaro, where kōura were present historically (Gee 1960) and currently occur in the tributary stream (Author's personal observation) provides some support for a subsidy–stress response (sensu Odum *et al.* 1979) to increasing nutrient enrichment.

3.5.1 Sediments and lake morphology

Sediment particle size was identified as the strongest driver of kōura abundance in the study lakes. The Te Arawa lakes are of volcanic origin with lake bed and littoral sediments comprised mainly of mud, silt, and sand, and with smaller areas of cobble-size substrates. For example, the eruption of Mount Tarawera in 1886 deposited Rotomahana 'mud' (fine, silty ash) to the lakes south-west of Mt. Tarawera (i.e. lakes Ōkāreka, Ōkaro, Okataina, Rotokakahi, Tarawera, Tikitapu, Rerewhakaaitu) (Fig. 3.1) (Pullar and Birrell 1973). In contrast, most correlative studies of crayfish in temperate overseas lakes have been carried out in lakes of glacial origin, where a high proportion of littoral (and to a lesser extent lake bed) sediments are comprised of sand-gravel and cobble-pebble sized substrates (Stein 1977; Capelli and Magnuson 1983; Kershner and Lodge 1995; Nystrőm*, et al.* 2006). Moreover, these studies have generally identified cobble-sized substrate as the most important variable related to crayfish abundance (Capelli and Magnuson 1983; Kirjavainen and Westman 1999; Smily and Dibble 2000; Hein*, et al.* 2006).

Nystrőm, *et al.* (2006) found a positive correlation between shelter availability and crayfish abundance, irrespective of lake trophic status or even predatory fish density. The importance of cobbles to crayfish in lakes has been attributed to shelter potential for predator avoidance (Stein 1977) and also to prevention of cannibalism of females with eggs and of individuals moulting (Stein 1977; Capelli and Magnuson 1983; Kershner and Lodge 1995; Nystrőm, *et al.* 2006).

Low abundance of lake kōura on fine, silt sediments compared to coarser sediments is consistent with my underwater (SCUBA) observations and from studies in New Zealand (Devcich 1979) and elsewhere (Kershner and Lodge 1995; Kirjavainen and Westman 1999). Further, differences in the composition of lake bed sediments could explain the higher abundance of kōura in Lake Rotomā than in similarly oligotrophic Lake Tarawera. Previous tau kōura surveys in Lake Tarawera on underwater reefs and sand substrates found six fold higher kōura CPUE (Authors' unpublished data) than in this study where tau were set on fine, silt substrates, providing further within-lake evidence for the importance of substrate size in controlling kōura abundance. Lake morphology and wind exposure were also found to effect lake bed sediments in Lake Rotorua where mixed sand-gravel substrates occurred to depths of 12 – 13 m due to wind-induced wave action and water currents across the large (area 80.8 km^2), exposed area in this lake.

3.5.2 Eutrophication and hypolimnetic deoxygenation

Lake productivity, indexed as Chl-*a* and decreasing sediment C/N, was positively correlated, with kōura abundance, but not size. This is consistent with several other correlative studies that have shown that crayfish in productive lakes generally have high abundances, growth rates and fecundity (Abrahamsson and Goldman 1970; Jones and Momot 1981; France 1985). In contrast, a study by Nystrőm, *et al.* (2006) in ten Swedish lakes found that Chl-*a* was positively correlated with size of the crayfish *Pacifastacus leniusculus* but not with abundance or biomass. Instead, abundance of crayfish seemed to be related to the substratum particularly the availability of cobbles in the littoral zone.

In this study, lake trophic status in conjunction with lake morphology appeared to indirectly affect kōura distribution in the sheltered, steep-sided lakes, through hypolimnetic deoxygenation.

Kōura were excluded from the deoxygenated hypolimnion of lakes Ōkāreka, Rotokakahi, and Rotoiti in April when the lakes were stratified and concentrations of DO <5 mg L^{-1}. Periodic stratification events also cause intermittent hypolimnetic deoxygenation in Lake Rotorua (Burger, *et al.* 2008; Trolle, *et al.* 2011) which leads to the movement of kōura into shallower water (Kusabs and Butterworth 2011). Moreover, the absence of kōura in highly eutrophic Lake Ōkaro could be attributable to rapid and prolonged hypolimnetic deoxygenation (>ca. 5 m depth), however a range of other stressors associated with eutrophication may have also contributed to their decline. Parkyn, *et al.* (2011) suggested that reduced available habitat, due to summer anoxia, seasonal over turn causing elevated ammoniacal-N concentrations and release of hydrogen sulphide may all have contributed to kōura extirpation in Lake Ōkaro, i.e., multiple stressors. Lake morphology affected the location of tau kōura sampling sites, particularly in Lake Rotorua where the only lake beds with sufficient slope for deployment were situated off Mokoia Island (Fig. 3.1). Tau kōura location may therefore have resulted in an overestimate of kōura abundance in this lake.

3.5.3 Predation

For freshwater crayfish the most important predators, with respect to effects on abundance, behaviour and growth, are fish (Nystrőm 2002). In this study, the highest CPUE of kōura was recorded in Lake Rotorua, which has the highest abundance of rainbow trout of the seven study lakes. In contrast, only low numbers of kōura were captured in lakes Tarawera and Rotokakahi which have low densities of trout. Kōura resilience to trout predation is supported by dietary studies of rainbow trout in central North Island lakes which have found common smelt to be the dominant prey item for rainbow trout, with predation on other species, such as kōura and common bullies, being relatively low (Rowe 1984; Blair, *et al.* 2012). However, the introduction of predaceous fish, other than trout, such as eels (*Anguilla spp.*), catfish (*Ameiurus nebulosus*), and perch (*Perca fluviatilis*), that are efficient predators of kōura, could adversely affect kōura populations in the Te Arawa lakes. Catfish and perch are not yet present in the Te Arawa lakes and eels are found in extremely low numbers. Kōura were the second most frequent prey items of shortfin eels in forested streams in the Waikato (Hicks 1997). Catfish have been reported to commonly consume kōura in Lake Taupō (Barnes and Hicks 2003) and the introduction of perch to Lake Ototoa (Auckland region) reduced the abundance of kōura by over 90% (Rowe 2014).

3.5.4 Other factors influencing kōura populations

Dissolved Ca is a vital functional component of crustacean physiology (Edwards, *et al.* 2013) and low concentrations have found to be a major determinant of crayfish abundance and distribution in Northern Hemisphere lakes (Capelli and Magnuson 1983). However, compared to the great majority of Astacoidea, *P. planifrons* are physiologically tolerant to acidic conditions in their surrounding environment (Olsson, *et al.* 2006). This is supported by the results of this study where there was no correlation between Ca concentrations and kōura population characteristics. The presence of kōura in Lake Tikitapu (Fig. 3.1) where Ca concentrations are as low as 0.7 mg L^{-1} (Forsyth 1978), provides further evidence that Ca concentrations are not a limiting factor for kōura populations in the Te Arawa lakes.

Water temperature has a major influence on freshwater crayfish, dictating body temperature and influencing metabolic activity, food intake and growth (Verhoef and Austin 1999). Growth rates typically increase with increasing water temperature until the optimum is reached, and then decline with further temperature increases (Ponce-Palafox, *et al.* 1997; Jobling 2003). However, in this study water temperatures were well within the environmental tolerances of *P. planifrons* and therefore it is unlikely that temperature is a limiting factor. Nevertheless, high mean water temperatures in conjunction with elevated nutrients may be a factor in the high abundance, and smaller mean size of kōura in Lake Rotorua. Warmer water temperatures can decrease the survival of juveniles but improve their growth rates, leading to enhanced fecundity and competitive ability (Mundahl and Benton 1990).

3.6 Conclusion

Benthic substrates appear to be more important in determining kōura population abundance in the Te Arawa lakes than nutrient enrichment or rainbow trout abundance. However, lake trophic status in conjunction with lake morphology, appeared to affect kōura distribution indirectly in the sheltered, steep-sided lakes, through hypolimnetic deoxygenation. Measures to improve water quality in some Te Arawa lakes should benefit kōura populations by reducing hypolimnetic deoxygenation, thereby increasing the amount of available habitat in the summer and autumn. Furthermore, the quantitative information collected in this study should assist iwi and government agencies to more effectively manage the culturally and ecologically important kōura populations in the Te Arawa lakes.

3.7 References

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Chapter 4

Sustainable management of freshwater crayfish (kōura, *Paranephrops planifrons*) in Te Arawa (Rotorua) lakes, North Island, New Zealand[5]

4.1 Abstract

Freshwater crayfish or kōura (*Paranephrops planifrons* White, 1842) support important customary fisheries for Te Arawa iwi (tribal members) in the Te Arawa lakes, North Island, New Zealand. Until recently, however, there was limited published information on which to base fisheries regulations. I sampled over 9000 kōura in eight lakes using a traditional Māori harvesting method known as the tau kōura, which comprised bundles of bracken fern fronds (*Pteridium esculentum*) laid on the lake bed. I examined the catch rates and biological traits of kōura in the Te Arawa lakes and the implications for the current fishing regulations and kōura management. Kōura were present in all of the study lakes except Ōkaro, but harvestable quantities were only found in Rotorua, Rotomā and Rotoiti. The overall ratio of females to males was about 1:1. Egg-bearing kōura were found throughout the year, but only occasionally during the summer months. Kōura fecundity increased as a power function of orbit-carapace length (OCL). Size at onset of breeding for 50% of females, in lakes where kōura were present, ranged from 22.1 mm OCL to 27.5 mm OCL. In addition to existing regulations, the following management measures are recommended: (1) implementing a slot limit with a minimum size of 28 mm and a maximum size of 39 mm OCL, (2) banning the taking of egg-bearing kōura, (3) limiting deep-water harvest methods to the use of the tau

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kōura, and (4) implementing a tau kōura harvest season beginning on 1 December and ending on 31 March.

4.2 Introduction

4.2.1 Issue

New Zealand has two species of freshwater crayfish that are collectively known by the indigenous Māori word ‘kōura’. The northern kōura, *Paranephrops planifrons* (White, 1842) occurs in the North Island and the West Coast of the South Island, and the southern kōura, *P. zealandicus* (White 1847) occurs in the east and south of the South Island (McDowall 2011). Kōura were once an important food for Māori throughout New Zealand, particularly in areas of the Te Arawa and Taupō lakes, where large numbers of kōura were harvested (Hiroa 1921; Best 1929). Anecdotal evidence suggests that kōura populations have declined markedly since European settlement (Hiroa 1921; McDowall 2011). Environmental factors implicated in this decline include, introductions of exotic fish (McDowall 1987; Barnes and Hicks 2003) and plants (Rowe 2004), as well as eutrophication, which has reduced concentrations of dissolved oxygen in the hypolimnion of lakes owing to eutrophication (refer Chapter 3; Kusabs and Quinn 2009; Kusabs, *et al*. 2015). Kōura are considered a ‘keystone’ species in many New Zealand waterways and have various ecological functions, which in turn influence other macroinvertebrate fauna (Parkyn *et al*., 1997, 2001). Kōura support limited recreational fisheries throughout New Zealand (McDowall 2011) and important customary fisheries in the Te Arawa lakes and Lake Taupō, which collectively comprise the Central North Island lakes, where northern kōura are abundant (Kusabs and Quinn 2009; Kusabs, *et al*. 2015). Throughout the rest of this chapter kōura is used to refer to northern kōura unless otherwise indicated.

Determining regulations to sustain a fishery is often complex, particularly when little biological information is available. To achieve a sustainable fishery, regulations should be based on specific biological information, supported by fishers’ knowledge, implemented by expert management, and updated as new information becomes available (Winstanley 1992). Information on fecundity and the size at onset of breeding (SOB) or sexual maturity (SOM) are key biological traits needed to assess egg production and recruitment and to set size limits (Hobday and Ryan 1997). However, no fecundity or SOB estimates have been published for kōura in New Zealand lakes. Knowledge of reproduction and recruitment timing is vital to enable the protection of species, to justify closed seasons and to establish reserves or areas closed to fishing.

In New Zealand, there are two fishing regulations pertaining to kōura; a recreational daily bag limit of 50 per person and a ban on the sale of kōura for commercial purposes (Fisheries (Amateur Regulations) 2013)[6]. However, the historical importance of kōura to Māori in the Central North Island lakes is recognised in legislation with harvesting in the Te Arawa and Taupō lakes managed by, and restricted to, local iwi (Māori tribes). In the Te Arawa Lakes, the Te Arawa Lakes Trust (TALT) is empowered to manage the customary and recreational food gathering of kōura and other indigenous fisheries species (Te Arawa Lakes Settlement Act 2006[7]). In Lake Taupō, however, only members of the Ngāti Tūwharetoa tribe may take kōura for their own use (Māori Land Amendment and Māori Land Claims Adjustment Act 1926[8]). Until recently, there was a lack of quantitative information on kōura abundance and ecology that made it difficult for iwi and government agencies to manage kōura populations in the Te Arawa and Taupō lakes. However, development and use of the tau kōura, a traditional Māori harvesting method, for monitoring (Kusabs and Quinn 2009; Kusabs, *et al*. 2012, Kusabs and Butterworth 2013;) and research purposes (Clearwater, *et al*. 2012; Wood, *et al*. 2012; Kusabs, *et al*. 2015) has greatly increased understanding of kōura populations in Te Arawa lakes. For instance, kōura abundance and distribution in seven Te Arawa lakes is influenced by the combined effects of lake-bed sediments, lake morphology and composition of water in the hypolimnion that is related to trophic state (Kusabs, *et al*. 2015). Sediment particle size was identified as the strongest driver of kōura abundance and biomass, with kōura populations increasing with sediment particle size.

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[6] http://www.legislation.govt.nz/regulation/public/2013/0482/latest/DLM3629901.html?src=qs
[7] http://www.legislation.govt.nz/act/public/2006/0043/latest/DLM381398.html
[8] http://www.legislation.govt.nz/act/public/1926/0064/latest/DLM5389702.html
All accessed 11 May 2015.

The objectives of this study were to examine biological traits of kōura in the Te Arawa lakes and to discuss the implications of these data in relation to fisheries management and regulations for Te Arawa kōura harvest. Seven biological traits were investigated (population structure, sex ratio, individual size, moulting, egg-bearing, fecundity and SOB). These traits underpin four key fishing regulations for Te Arawa kōura: the minimum legal length (MLL), closed fishing season, harvesting method restrictions and protection of egg-bearing females.

4.3 Methods

4.3.1 Study sites

The Te Arawa lakes are situated on the central volcanic plateau in the Bay of Plenty region of New Zealand's North Island (Fig. 4.1). They are highly valued by the indigenous Te Arawa people who have a cultural relationship with the lakes and are the legal owners of the lake beds (Te Arawa Lakes Settlement Act 2006). Te Arawa lakes were formed about 230,000 years ago (Lake Rotorua) and 700 years ago (Lake Ōkaro) from a series of volcanic eruptions that characterise the Taupō Volcanic Zone of central North Island (Lowe and Green 1987; Esler 2010). They comprise 12 major lakes: Ōkāreka, Ōkaro, Okataina, Rerewhakaaitu, Rotokakahi, Rotoehu, Rotomā, Rotomahana, Rotoiti, Rotorua, Tarawera and Tikitapu (Fig. 4.1) in the Okataina Volcanic Complex (Nairn 1992; Klemetti, *et al*. 2011). This study included two sites in each of eight of these lakes as well as a lake outlet site in the Ōkere Arm, where water from lakes Rotorua and Rotoiti flows towards the Kaituna River (Table 4.1, Fig. 4.1). This study included two sites in each of eight of these lakes as well as a lake outlet site in the Ōkere Arm, where water from lakes Rotorua and Rotoiti flows towards the Kaituna River (Table 4.1). The Ōkere Arm was treated as a separate habitat because it is shallow (<8 m deep) and is a lake outlet, a habitat that is distinct from the much deeper Lake Rotoiti, of which it is a part. The lakes vary widely in size (32 – 8,079 ha), trophic status (from oligotrophic to highly eutrophic) and in morphology (mean depth 5 – 50 m) (Table 4.1). The lakes are generally monomictic, except for lakes Rotoehu and Rotorua, while the Ōkere Arm outlet site is generally well mixed (Table 4.1).

4.3.2 Kōura and fish species

Northern kōura is the only crayfish species present in the Te Arawa lakes. The lakes contain a similar fish fauna, comprised mainly of rainbow trout (*Oncorhynchus mykiss* Richardson, 1836), common smelt (*Retropinna retropinna* Richardson, 1848) and common bullies (*Gobiomorphus cotidianus* McDowall, 1975*)*. Rainbow trout were introduced into the Te Arawa lakes in the late 1800s (Burstall 1980) and support popular recreational fisheries in the eight study lakes, while brown trout (*Salmo trutta* Linnaeus, 1758) are common in Lake Rotorua and present in low numbers in Lake Rotoiti and the Ōkere Arm.

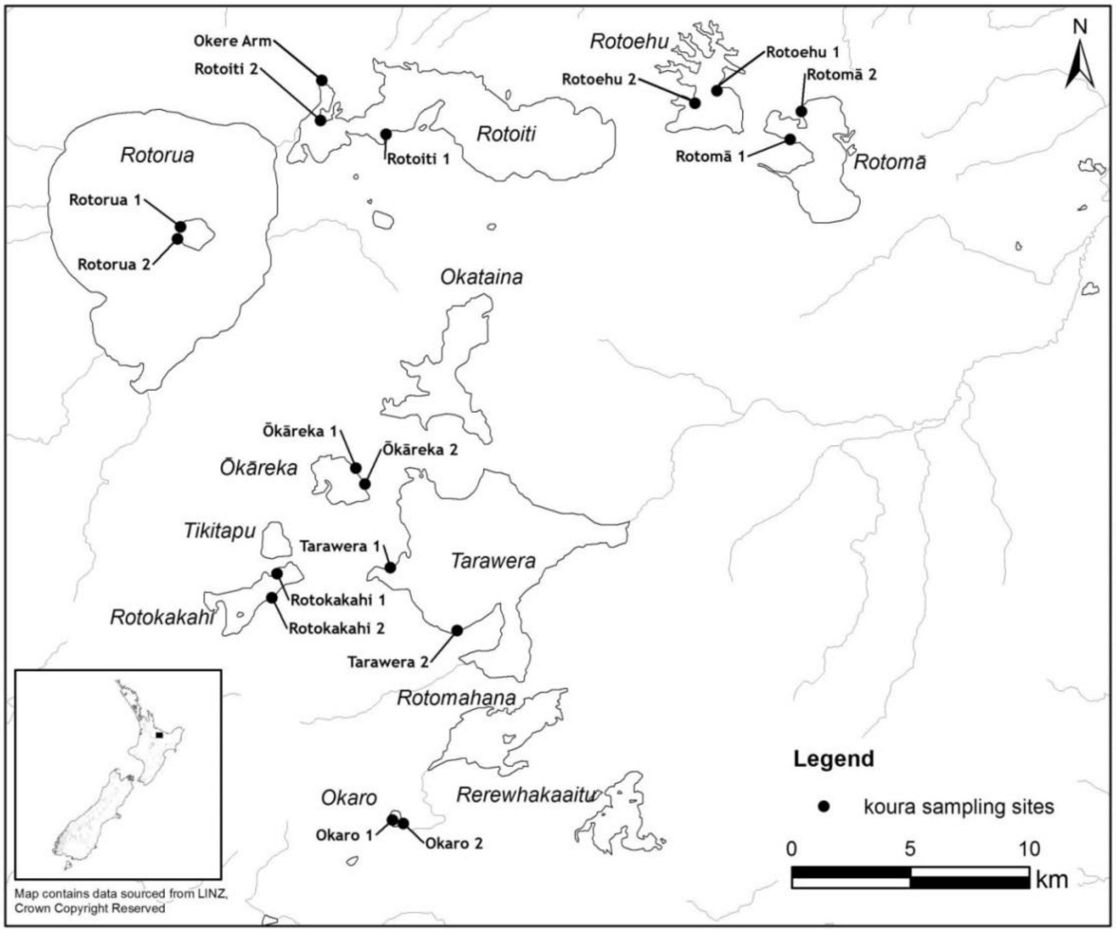

Figure 4.1: Te Arawa lakes in the Bay of Plenty region of New Zealand, showing the locations of sampling sites for kōura (*Paranephrops planifrons*).

Table 4.1: Morphometry and limnological characteristics of the eight study lakes and the Ōkere Arm, Te Arawa lakes district, North Island, New Zealand. M = monomictic, P = polymictic, Chl-*a* = chlorophyll *a*, TP = total phosphorus, TN = total nitrogen. Mixing regime, mean depth, maximum depth, lake area, (Scholes 2009), TN, TP, Chl-*a*, and Secchi depth values are means of monthly measurements, 2002–2009, except Ōkere Arm where Secchi depth and Chl-*a* values are means from September 2008 – September 2009 (Scholes 2009; 2010). The Ōkere Arm was defined as the area from the control gates upstream to the Ohau Channel diversion wall.

Lake	Lake type	Mixing regime	Mean depth (m)	Maximum depth (m)	Lake area (ha)	Secchi depth (m)	Chl-*a* (mg m^{-3})	TP (mg m^{-3})	TN (mg m^{-3})
Ōkāreka	Mesotrophic	M	20	34	324	7.7	4.1	8.4	212.6
Ōkaro	Supertrophic	M	13	18	32	2.4	28.3	77.4	958.1
Ōkere Arm	Eutrophic	P	5	8	57	1.6	13.7	29.2	373.4
Rotoehu	Eutrophic	P	8	14	810	2.9	10.1	32.6	382.8
Rotoiti	Eutrophic	M	32	124	3,460	4.4	12.2	40.4	356.6
Rotokakahi	Mesotrophic	M	18	32	452	3.7	6.3	18.0	249.0
Rotomā	Oligotrophic	M	37	83	1,104	12.8	1.3	4.6	141.2
Rotorua	Eutrophic	P	11	45	8,079	2.4	21.3	37.9	458.4
Tarawera	Oligotrophic	M	50	88	4,165	8.7	1.5	13.9	114.0

4.3.3 Sampling methods

Kōura were sampled using the tau kōura, a traditional method used by Te Arawa and Ngāti Tūwharetoa (Māori tribes) to catch kōura in the Central North Island lakes, New Zealand (Kusabs and Quinn 2009). This method involves placing whakaweku (bundles of bracken fern, *Pteridium esculentum*) on the lakebed that kōura colonize, the whakaweku are then retrieved into a boat and kōura harvested. Each tau kōura comprised a 200 – 250 m length of 10-mm diameter polyester rope (the tāuhu), with one end attached to the shoreline, and the other tied to a concrete-filled tyre. Ten whakaweku each with ca. 10 fronds per whakaweku, were attached to each tāuhu. The fern fronds were bound together using 300-mm lengths of heavy duty plastic cable ties and attached to the tāuhu using synthetic lashing (approximately 5 mm in diameter and 2.5 m in length) at approximately 3 m intervals. In order to make between-lake comparisons, tau kōura were deployed in depths ranging from 4 to 34 m on the dominant substrate type present in each of the lakes. Typically, mud, silt, and sand comprise the lake bed sediments in the Te Arawa lakes. Tau kōura were set at two locations in each lake and at one location in Ōkere Arm (Fig. 1). Depths were measured using an electronic fish finder (Furuno LCD sounder LS6000, Furuno Electric Co. Ltd. Nishinomiya, Japan). All kōura (>11 mm OCL) were assessed for sex, reproductive state (presence of eggs or hatchlings) and shell softness (soft or hard). Orbit carapace length (OCL) of each kōura was measured using vernier callipers (± 0.5 mm). A power regression equation previously developed for this species (Hicks and Riordan unpublished data; Riordan 2000), was used to estimate kōura wet weight (g) from OCL (mm):

$$\text{Wet weight} = 0.000648\ \text{OCL}^{3.0743} \qquad \text{(Eqn 4.1)}$$

After processing, all kōura were returned to the water in close proximity to the tau kōura. Catch per unit effort (CPUE) was defined as the number of kōura per whakaweku and biomass per unit effort (BPUE) as estimated wet weight (g) of kōura per whakaweku. Egg-bearing female kōura were collected from lakes Rotomā on 5 November 2013 (*n* = 26), Rotoiti on 12 November 2013 (*n* = 15), 30 January 2014

($n = 3$), 27 May 2014 ($n = 26$), and Rotoehu on 22 May 2014 ($n = 7$). To ensure minimal egg loss, egg-bearing kōura in the early to mid-stage of development were selected for fecundity analysis.

The relative abundance and biomass of kōura in seven Te Arawa lakes has previously been determined in Chapter 3. However, for the purposes of this study, data from Lake Rotoehu and the Ōkere Arm were also included, increasing the number of lakes to eight and one lake outlet (Ōkere Arm). Tau kōura were sampled on 14 – 17 April 2009, 9 – 14 July 2009 and 5 – 9 November 2009, except in Lake Rotoehu which was sampled on 22 November 2011, 21 May 2013 and 31 July 2013.

4.3.4 Data analysis

Estimates of SOB refer to the size class in which 50% of females are mature, determined by the presence of eggs, hatchlings or spermatophoric mass. Data from sexually mature females were collated and divided into 5 mm OCL size classes (e.g., the 20 mm OCL class contained kōura between 17.5 and 22.4 mm OCL) using size-structure analysis (length frequency histogram). Following the methods proposed by Hobday and Ryan (1997), the percentage of mature females in each size class (OCL) was determined and then the Linear and Nonlinear Mixed Effects Models package in R 3.0.2 was used to fit the logistic model:

$$M = 1[(1 + \exp(-S \text{ x } (L - L_{50}))] \qquad \text{(Eqn 4.2)}$$

where M is the percentage of mature females in a size class, S is the parameter defined by the slope of the curve at the inflection point, L is the OCL in mm, and L_{50} is the length at which 50% of females are mature (defined as the SOB).

Multi-level analysis of variance with Fisher's protected least significant difference multiple comparison tests were used to document variability in CPUE, BPUE and mean OCL related to between lake, between site and between month effects. The CPUE and BPUE results were log transformed to better satisfy model assumptions. Restricted Maximum Likelihood (REML) was used to check that the split-plot model was adequate for the between month repeated measures. ANCOVA was used to compare the egg to OCL size ratio for Te Arawa and Mangaterere Stream kōura.

4.4 Results

4.4.1 Kōura abundance, biomass and size

Seven of the eight lakes and Ōkere Arm contained kōura. No kōura were captured in Lake Ōkaro. For relative kōura abundance (CPUE) the lakes ranked from highest to lowest were Rotorua, Ōkere Arm, Rotomā, Rotoiti, Rotoehu, Rotokakahi, Tarawera, Ōkāreka and Ōkaro (Table 4.2, Fig. 4.2a). The corresponding rank order for biomass was Rotomā, Rotorua, Rotoiti, Ōkere Arm, Tarawera, Rotoehu, Ōkāreka, Rotokakahi, with no catch in Ōkaro (Table 4.2, Fig. 4.2b). The highest mean CPUE and mean BPUE were recorded from Rotorua (CPUE = 63 kōura whakawheku^{-1}) and Rotomā (BPUE = 683 g of kōura whakawheku^{-1}), respectively (Fig. 4.2). Mean CPUE and BPUE differed significantly between the eight lakes where kōura were present (CPUE $F_{7,\ 44} = 37.06$, $p < 0.001$; BPUE $F_{7,\ 44} = 21.09$, $p < 0.001$), but not between months (CPUE $F_{2,\ 44} = 2.32$, $p = 0.117$; BPUE $F_{2,\ 44} = 2.3$, $p = 0.119$).

The smallest kōura were found in Ōkere Arm, Rotorua, Rotoehu, Rotokakahi, and the largest were in lakes Tarawera, Rotomā, Ōkāreka and Rotoiti (Table 4.3, Fig. 4.3). The highest mean OCL (29 mm) and lowest mean OCL (17.5 mm) were recorded in Lake Rotoiti and Ōkere Arm, respectively (Table 4.3). Mean kōura OCL size differed significantly between the eight lakes where kōura were present ($F_{7,\ 44} = 9.97$, $p < 0.004$), but not between months ($F_{2,\ 44} = 1.3$, $p > 0.939$).

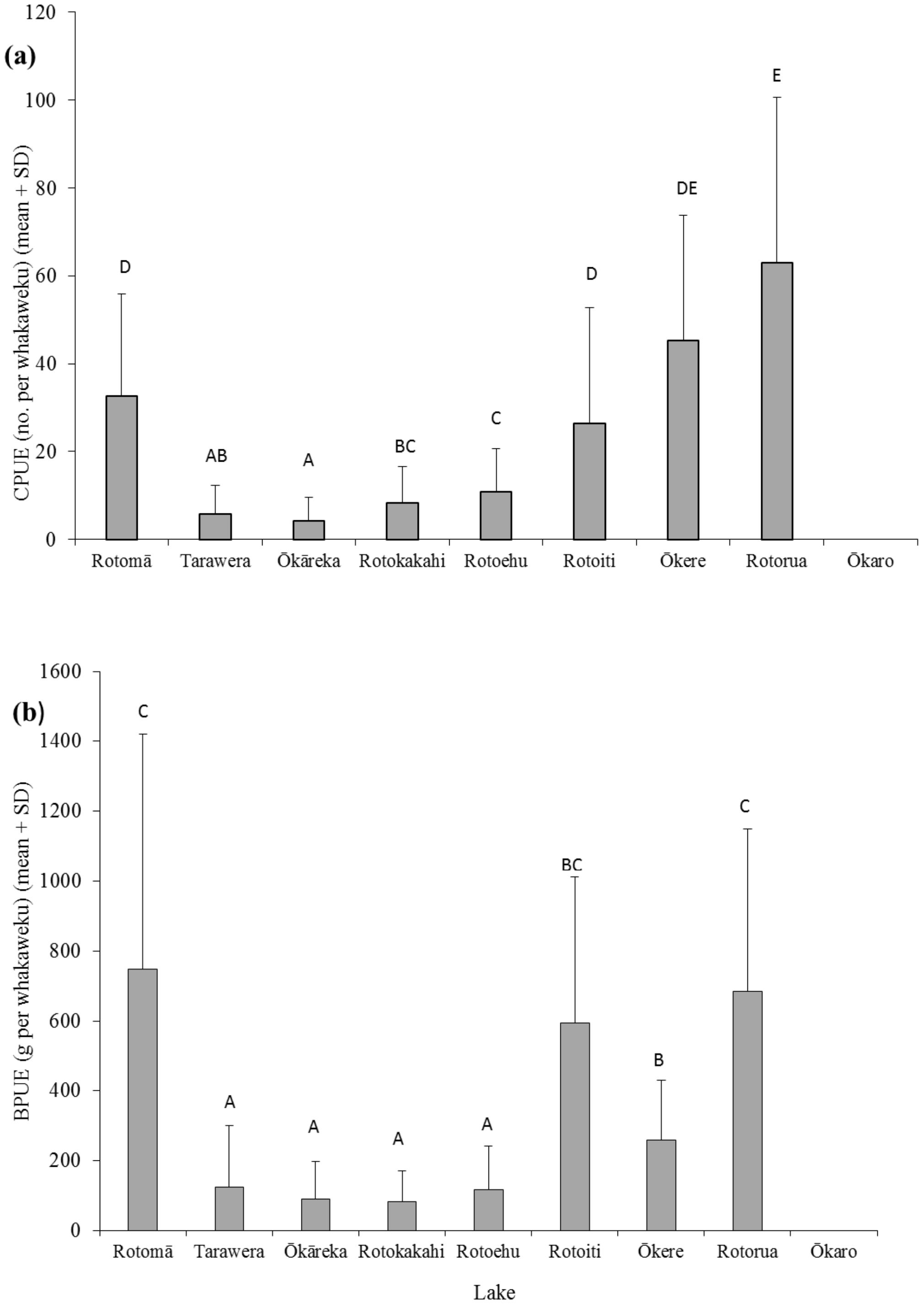

Figure 4.2: (a) Mean catch per unit effort (CPUE + SD) and (b) mean biomass per unit effort (BPUE + SD) of kōura captured in eight Te Arawa lakes and the Ōkere Arm. Tau kōura were retrieved from all lakes in April, July and November 2009, except Lake Rotoehu which was retrieved in November 2011, May 2013 and July 2013.

Table 4.2: Mean catch and biomass per unit effort (CPUE, BPUE) of kōura and combined means (all) in samples of kōura captured in tau kōura (*n* = 10 x two sites) set in eight Te Arawa lakes and the Ōkere Arm (*n* = 10 x one site). Tau kōura sampled on 14 – 17 April 2009, 9 – 14 July 2009 and 5 – 9 November 2009, and Lake Rotoehu on 22 November 2011, 21 May 2013, 31 July 2013. Tau depth (m) = the range of depths at which whakaweku were set. SD in brackets.

		CPUE (*n* whakaweku^{-1})			BPUE (g whakaweku^{-1})		
Site	Tau depth (m)	April	July	Nov	April	July	Nov
Rotorua	5 - 17	37.9 (13.1)	56.5 (34.1)	94.7 (35.9)	665.7 (386.7)	502.2 (509.1)	881.8 (438.9)
Ōkere Arm	4 - 7	62.7 (26.7)	52.7 (26)	20.1 (12.3)	376.7 (163.4)	283.0 (139.8)	118.5 (97.5)
Rotomā	10 - 34	41.8 (25.3)	30.0 (23.6)	26.2 (18.7)	800 (510.2)	645.7(673.7)	802.0 (672.3)
Rotoiti	10 - 25	22.5 (16.9)	33.4 (22.1)	23.2 (15.4)	495.5 (396.0)	773.7 (472.2)	514.8 (330.6)
Rotoehu	4 - 13	17.4 (13.2)	7.4 (3.9)	7.8 (6.5)	228.8 (144.4)	52.6 (35.2)	66.4 (18.3)
Rotokakahi	9 - 23	3.5 (6.2)	12.8 (9.8)	8.5 (6.8)	43.5 (78.9)	120.7 (93.6)	85.6 (76.3)
Tarawera	8 - 26	3.4 (3)	9.4 (9.4)	4.2 (4.1)	60.7 (63.6)	237.6 (258.0)	75.0 (78.9)
Ōkāreka	7 - 22	7.1 (7.9)	3.6 (3.1)	1.9 (1.4)	125.4 (146.4)	84.8 (88.7)	63.4 (67.0)
Ōkaro	7 - 16	0	0	0	0	0	0

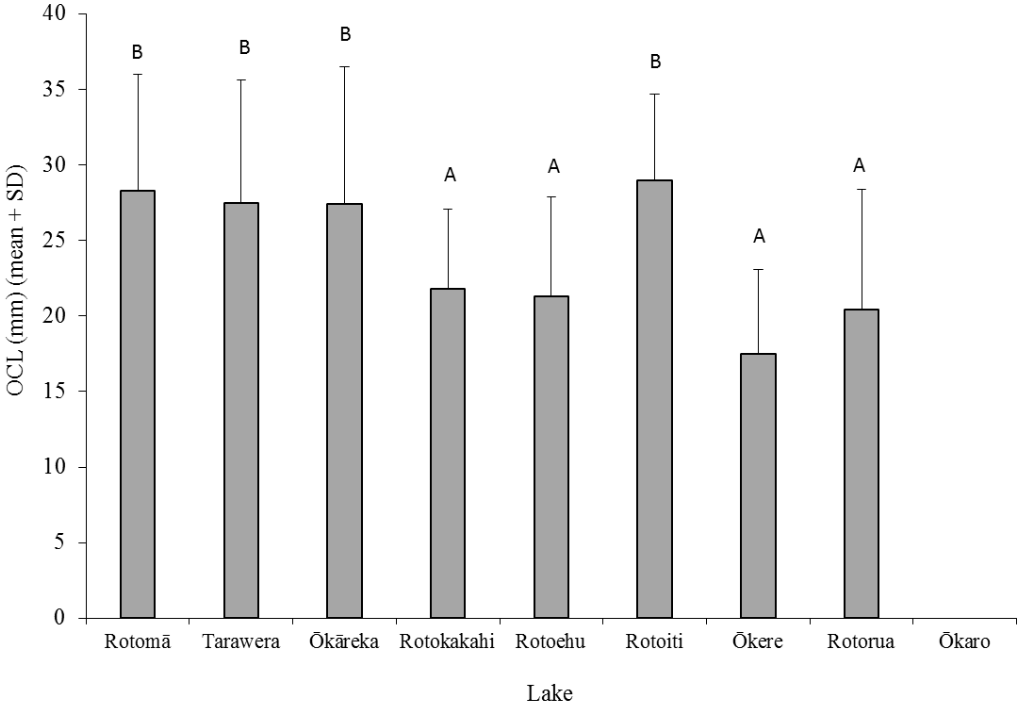

Figure 4.3: Mean orbit carapace length (OCL, mm + SD; n = 10 × two sites) of kōura captured in eight Te Arawa lakes and the Ōkere Arm (n = 10 × one site). Tau kōura were retrieved from all lakes in April, July and November 2009, except Lake Rotoehu which was retrieved in November 2011, May 2013 and July 2013. Lakes are ordered from the highest to the lowest mean CPUE. Lakes with the same letters did not differ significantly.

Table 4.3: Orbit-carapace length (OCL) range and mean (± SD) in samples of kōura captured in two tau kōura (*n* = 10 x two sites) set in eight Te Arawa lakes and one tau kōura (*n* = 10 x one site) set in the Ōkere Arm. Tau kōura sampled on 14 – 17 April 2009, 9 – 14 July 2009 and 5 – 9 November 2009, and Lake Rotoehu on 22 November 2011, 21 May 2013, 31 July 2013. *n* = number of kōura analysed.

		OCL range (mm)			OCL mean ± SD (mm)		
Site	(*n*)	April	July	Nov	April	July	Nov
Rotorua	3555	7 – 51	9 – 46	10 – 47	24.7 (10.6)	19.6 (6.9)	19.6 (7.3)
Ōkere Arm	618	8 – 38	9 – 34	9 – 35	17.6 (6)	16.9 (5.7)	18.0 (5.0)
Rotomā	1749	9 – 51	6 – 49	9 – 50	26.7 (6.9)	27.4 (7.8)	31.3 (7.7)
Rotoiti	1466	8 – 45	12 – 50	11 – 43	28.7 (5.6)	29.2 (5.6)	28.7 (5.8)
Rotoehu	533	7 – 38	8 - 32	10 - 36	23.7 (6.5)	18.7 (6.1)	20.3 (5.8)
Rotokakahi	495	12 – 38	10 – 39	11 – 40	23.7 (5.0)	21.3 (5.3)	21.9 (5.2)
Tarawera	340	11 – 43	8 – 42	13 – 48	25.5 (7.9)	29.4 (7.6)	25.0 (8.5)
Ōkāreka	250	14 – 45	11 – 50	14 – 52	25.5 (7.5)	27.0 (9.8)	31.9 (9.1)

4.4.2 Length frequency analysis

Age of kōura cohorts could not be estimated from length-frequency distributions because shallow habitats, where the majority of smaller sized individuals were found, were under sampled. Of the eight lakes and lake outlet, only Rotorua and Ōkere Arm had a high proportion of small kōura (<15 mm OCL) in the catch; at these sites the absence of extensive macrophyte beds allowed the whakaweku to be set at shallow depths (starting at 4 and 6 m in Ōkere Arm and Rotorua, respectively). In Lake Rotorua, a first-year age class of 9 to 18 mm OCL was identified from the length-frequency graph in July (Fig. 4.4).

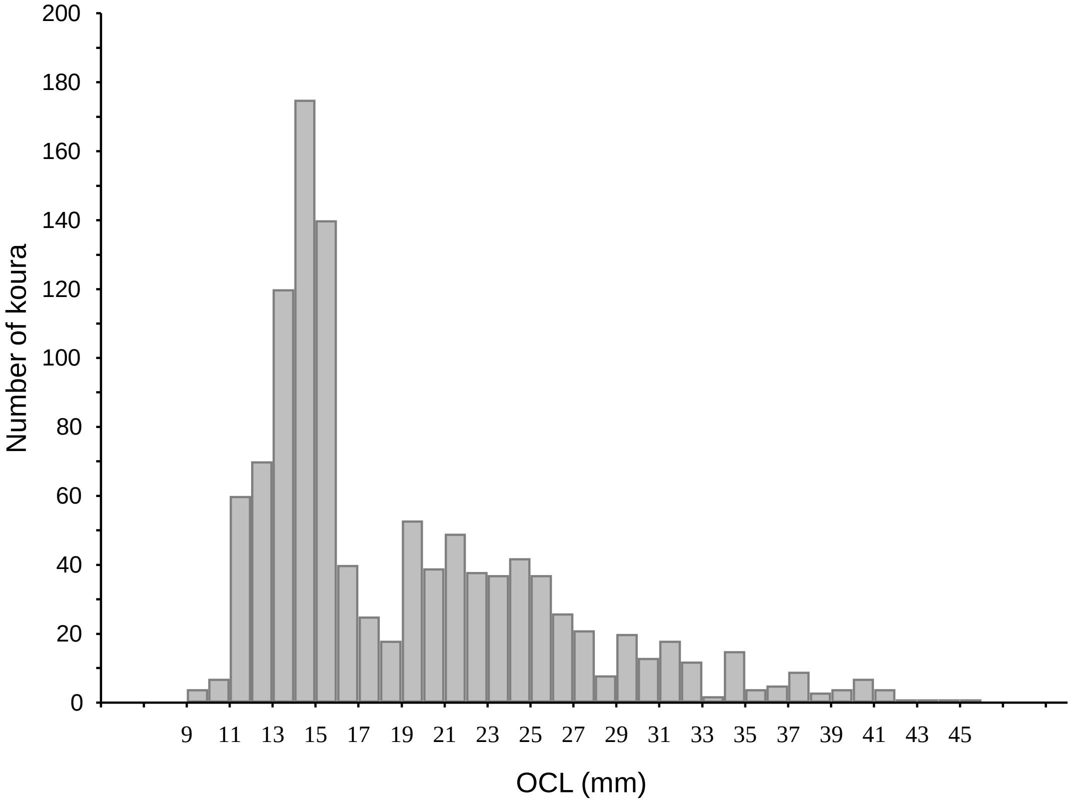

Figure 4.4: Length (OCL) frequency graph for kōura captured from Lake Rotorua on 10 July 2009 (*n* = 1129).

4.4.3 Sex ratios

The overall ratio of female to male kōura was 55% (*n* = 8764). There was no consistent difference between female and male ratios for the nine size classes (Fig. 4.5). The percentage of female kōura caught by the tau kōura method varied amongst the lakes, with Rotomā having the highest percentage of females with 59% and Rotokakahi the lowest 40% (Table 4.4). Female to male ratios were highest in April in lakes, Ōkāreka, Rotoehu, Rotoiti, Rotokakahi, Rotorua and Tarawera, and November in the Ōkere Arm and Rotomā (Table 4.4). The percentage of females ranged from 33% in Rotokakahi (November) to 72% in Rotorua (April) (Table 4.4).

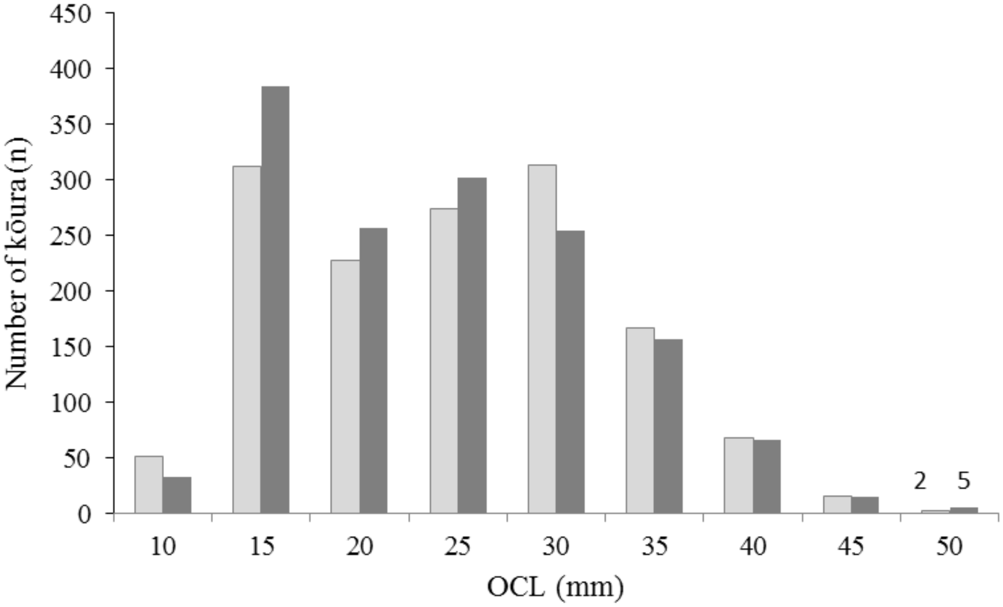

Figure 4.5: Size distribution of female (light grey bars) and male (dark grey bars) kōura (*n* = 3171) captured in seven Te Arawa lakes (Rotorua, Rotomā, Rotoiti, Rotoehu, Rotokakahi, Tarawera, Ōkāreka) and Ōkere Arm. Tau kōura were retrieved from all lakes between 9 – 14 July 2009, except Lake Rotoehu which was retrieved on 31 July 2013.

Table 4.4: Percentage of females and percentage of sample with soft shells, in samples of kōura captured in tau kōura (*n* = 10 x two sites) set in eight Te Arawa lakes and the Ōkere Arm (*n* = 10 x one site). Tau kōura were sampled on 14 – 17 April 2009, 9 – 14 July 2009 and 5 – 9 November 2009 and Lake Rotoehu on 22 November 2011, 21 May 2013, 31 July 2013. *n* = number of kōura analysed. Note: sex was not determined for 242 kōura <11 mm OCL. Number of soft-shelled kōura for each month given in parentheses following the percentage.

	Percentage of females in sample					Percentage of sample with soft shells				
Site	*n*	April	July	Nov	All	*n*	April	July	Nov	All
Rotorua	3413	72.1	49.7	54.8	55.7	3555	2.1 (11)	6.3 (70)	6.3 (120)	5.6
Ōkere Arm	568	53.9	54.3	56.0	54.8	618	6.2 (12)	1.7 (3)	34.8 (70)	13.8
Rotomā	1744	55.9	52.8	71.2	59.4	1749	3.2 (20)	10.6 (63)	1.9 (10)	5.3
Rotoiti	1465	65.2	50.0	57.3	55.8	1466	11.1 (37)	10.6 (63)	15.1 (70)	11.3
Rotoehu	491	58.8	47.2	51.6	53.6	533	10.0 (23)	2.7 (2)	8.4 (13)	7.5
Rotokakahi	494	55.7	39.6	33.1	39.7	495	10.0 (7)	4.3 (11)	12.4 (21)	11.0
Tarawera	339	61.2	50.3	48.8	51.9	340	14.9 (10)	6.4 (12)	3.6 (3)	6.8
Ōkāreka	250	55.3	36.1	35.1	46.8	250	6.4 (9)	8.3 (6)	16.2 (6)	8.4

4.4.4 Moulting

The proportion of kōura with soft shells (mean 7.4%, *n* = 9006) varied among lakes and months (Table 4.4). There was no obvious trend in the proportion of kōura with soft shells in the study lakes over the sampling period, with highest proportions recorded in April in Rotoehu and Tarawera, July in Rotomā and Rotorua and November in Ōkāreka, Ōkere Arm, Rotoiti, Rotokakahi and Rotorua (Table 4.4). The highest and lowest proportions of kōura with soft shells were both found in the Ōkere Arm, ranging from 34.8% in November to 1.7% in July (Table 4.4).

4.4.5 Egg-bearing kōura

Egg-bearing females were found on all three sampling occasions in the lakes containing kōura except in Ōkāreka in November (Table 4.5). The OCL of egg-bearing females ranged from 19 to 50 mm (mean 32 mm). Mean size of egg-bearing females was highest in Ōkāreka (35.5 mm OCL) and lowest in Rotokakahi (24.5 mm OCL). For mean size of egg-bearing females, the lakes ranked from highest to lowest were Ōkāreka, Rotomā, Rotorua, Tarawera, Rotoiti, Rotoehu, Ōkere Arm and Rotokakahi (Table 4.5). Minimum breeding size as determined by females bearing eggs or young was 21 mm OCL except in Rotokakahi and Rotomā (20 mm OCL), and Rotoehu (19 mm OCL). The highest proportion of breeding size females with eggs was recorded in July in Ōkāreka, Ōkere Arm, Rotoiti, Rotokakahi and Tarawera, in November in Rotomā and Rotorua, and April in Rotoehu (Table 4.5). Spermatophores were found attached to egg-bearing females in April and July but were not present in November (Table 4.5). The highest proportion of breeding size females with spermatophores was recorded in April in Lake Rotorua (58.6%) and in July in Lake Rotomā (14.5%).

Table 4.5: Range and mean OCL (mm ± SD) of egg-bearing females, percentage of breeding-sized females with eggs, and percentage of breeding-sized females with spermatophores, in samples of kōura captured in tau kōura (*n* = 20 whakaweku) set in eight Te Arawa lakes and the Ōkere Arm (*n* = 10 whakaweku). Tau kōura sampled on 14 – 17 April 2009, 9 – 14 July 2009 and 5 – 9 November 2009, and Lake Rotoehu on 22 November 2011, 21 May 2013, 31 July 2013. (*n*) = number of females bearing eggs or spermatophores. % of breeding-sized females with eggs includes those with eggs and/or hatchlings and spermatophores. % of breeding sized-females with spermatophores (includes females with eggs and/or spermatophores).

	OCL range and mean of egg-bearing females (mm)				Percentage of breeding-sized females with eggs (*n*)			Percentage of breeding-sized females with spermatophores (*n*)		
Site	April	July	Nov	Mean (n)	April	July	Nov	April	July	Nov
Rotorua	26 – 49	21 – 43	22 – 47	33.6 (486)	55.2 (144)	35.5 (89)	67.3 (253)	58.6 (153)	0.4 (1)	–
Ōkere Arm	24 - 27	21 - 27	25 - 29	25.0 (21)	8.0 (4)	36.0 (12)	15.6 (5)	2.0 (1)	–	–
Rotomā	32 – 39	20 – 48	21 – 50	33.7 (439)	1.4 (4)	63.1 (166)	75.4 (269)	0.3 (1)	14.5 (38)	–
Rotoiti	21 – 36	21 – 44	23 – 43	31.2 (434)	16.9 (35)	73.5 (239)	62.7 (160)	12.1 (25)	2.5 (8)	–
Rotoehu	19 – 36	21 – 31	20 – 32	26 (109)	65.5 (79)	52.4 (22)	16.7 (8)	–	–	–
Rotokakahi	21 – 30	20 – 38	26 – 28	24.5 (35)	17.6 (6)	38.0 (27)	5.7 (2)	17.7 (6)	–	–
Tarawera	28 – 35	25 – 40	21 – 36	31.6 (73)	24.1 (7)	67.9 (53)	46.4 (13)	21.0 (6)	1.3 (1)	–
Ōkāreka	21 – 42	21 – 47	–	35.5 (13)	10.7 (6)	35.0 (7)	–	8.9 (5)	10.0 (2)	–

4.4.6 Fecundity

Fecundity estimates from 77 female kōura collected from lakes Rotomā, Rotoiti, and Rotoehu were found to vary with OCL (Fig. 4.6) according to the relationship:

$$F = 0.0204\, L^{2.5261}$$

where F = number of eggs per female and L = OCL in mm. For this equation, $r^2 = 0.886$.

The number of eggs ranged from 26 for a 17.5 mm OCL female from Lake Rotoehu to 315 for a 44.8 mm OCL female from Lake Rotomā. For all lakes, the mean number of eggs was 104 with a mean female kōura size of 29.3 mm OCL.

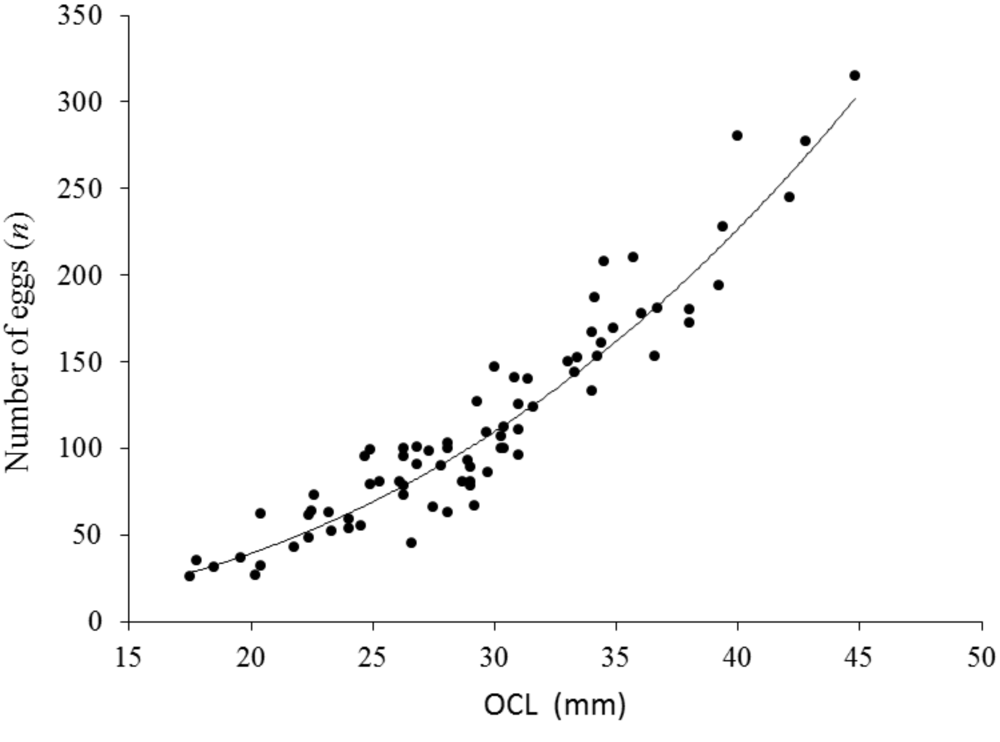

Figure 4.6: Relationship between OCL size (mm) of female kōura and number of eggs (*n* = 77). Egg-bearing kōura were collected from lakes Rotomā on 5 November 2013 (*n* = 27), Rotoiti on 12 November 2013 (*n* = 14), 30 January 2014 (*n* = 3), 27 May 2014 (*n* = 26) and Rotoehu on 22 May 2014 (*n* = 7).

4.4.7 Size at onset of breeding (SOB)

SOB was calculated from equation 4.2. For all the lakes combined (*n* = 3,566), the size class in which 50% of female kōura were sexually mature was 26.3 mm OCL (Table 4.6, Fig. 4.7). The SOB ranged from 26 mm OCL to 27.5 mm OCL for all lakes except Lake Rotoehu where the SOB was 22.1 mm OCL (Table 4.6).

Table 4.6: Size at onset of breeding (SOB defined as L_{50} from equation 2), slope (*S* from equation 4.2), *n* (number of female kōura in sample) and r^2 for female kōura from six Rotorua lakes, 2009 – 2013. Egg-bearing female data obtained from the peak of the egg-bearing seasons for each lake, i.e. lakes Rotoehu (May, July 2013), Rotoiti and Rotomā (July, November 2009) , Rotokakahi and Tarawera (July 2009), Rotorua (April, May, November 2009). The Ōkere Arm and Lake Ōkāreka were not included due to low sample sizes. A non-breeding female kōura >40 mm was removed from the Rotokakahi analysis. SE in brackets.

Lake	SOB (SE) OCL (mm)	Slope (SE)	*n*	r^2
All six lakes	26.3 (0.68)	0.289 (0.05)	3566	0.98
Rotoehu	22.1 (1.62)	0.437 (0.25)	183	0.82
Rotoiti	26.1 (0.48)	0.335 (0.05)	600	0.99
Rotokakahi	26.9 (1.53)	0.214 (0.07)	101	0.93
Rotomā	26.0 (1.03)	0.227 (0.5)	686	0.96
Rotorua	27.5 (0.49)	0.365 (0.06)	1902	0.99
Tarawera	26.1 (1.32)	0.413 (0.2)	94	0.88

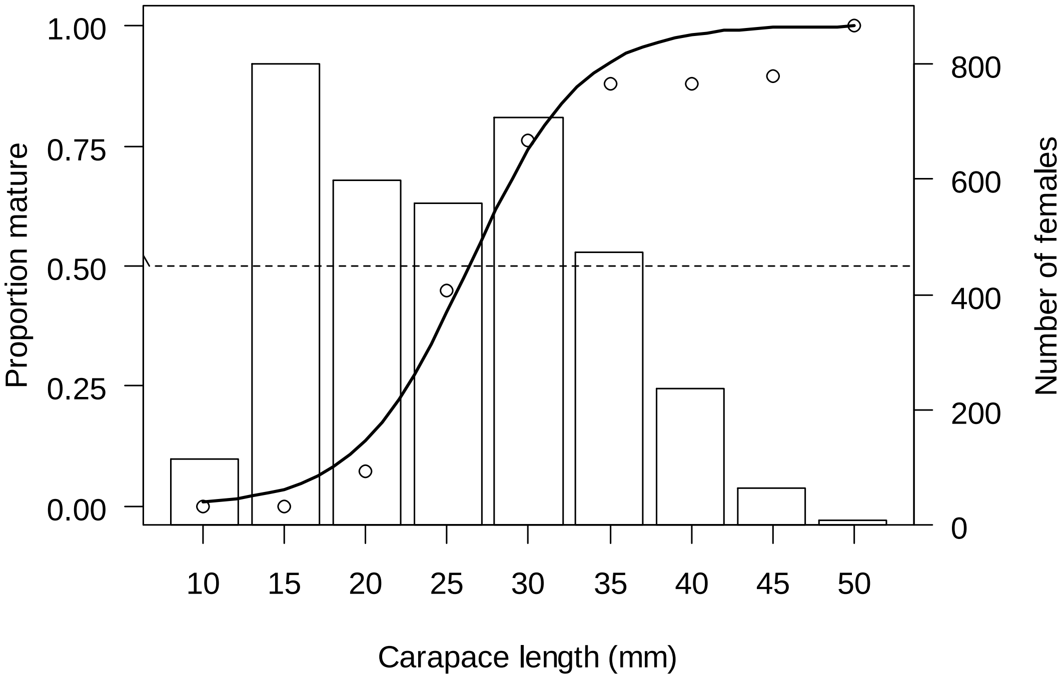

Figure 4.7: Orbit carapace length frequencies (bars, *n* = 3,566), proportion of egg-bearing females (including eggs or spermatophores, *n* = 1,525) per size class (dots), fitted line (black line) and associated L_{50} value (dashed line) for female kōura from six Rotorua lakes, 2009 – 2013. Egg-bearing female data obtained from the peak of the egg-bearing months for each lake, i.e. lakes Rotoehu (May, July 2013), Rotoiti and Rotomā (July, November 2009), Rotokakahi and Tarawera (July 2009), Rotorua (April, May, November 2009). The Ōkere Arm and Lake Ōkāreka and Ōkaro were not included due to low sample sizes while no kōura were captured in Lake Ōkaro.

4.4.8 Harvestable sized kōura

In this study 3,386 harvestable sized kōura were recorded (Fig. 4.8). Harvestable size was defined as >27.5 mm OCL, the SOB for Rotorua (the highest recorded in this study) (Table 4.6). However, 40% (*n* = 1361) of all harvestable sized kōura captured (*n* = 3386) were egg-bearing females (Table 4.7). The percentage of egg-bearing females >27.5 mm was particularly high in Rotoehu in April and July, Rotoiti and Rotomā in July and November, and Rotoiti, Rotomā and Rotorua in April and November, where they comprised >40% of all harvestable sized kōura caught (Fig. 4.8).

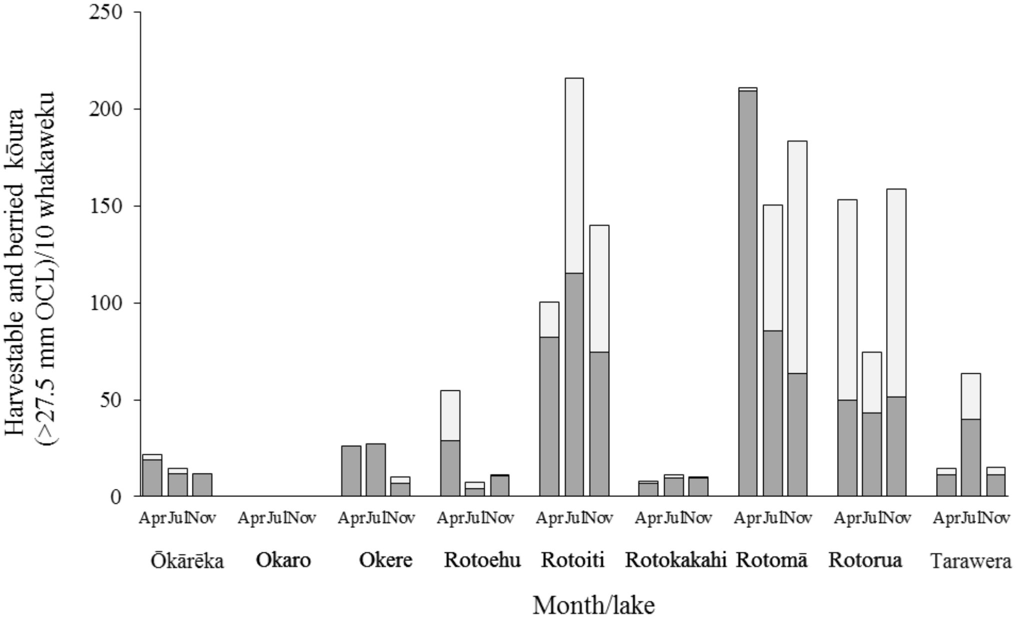

Figure 4.8: Mean catch of harvestable (dark grey bars) and egg-bearing (light bars) kōura >27.5 mm OCL per tau kōura comprised of 10 whakaweku set in eight Te Arawa lakes and the Ōkere Arm and sampled on 14 – 17 April 2009, 9 – 14 July 2009 and 5 – 9 November 2009, and Lake Rotoehu on 22 November 2011, 21 May 2013, 31 July 2013.

I calculated the relative contribution of different sized females to the reproductive output of the lakes. From the number of females with eggs, pooled across the seven lakes, I calculated the proportion of each size class with eggs (P), and from Eq. (3) I calculated E, the number of eggs per female in that class (Appendix 1). This allowed for calculation of the relative reproductive output of different size classes (Fig. 4.9) and estimation of the effect of a slot limit whereby kōura <28 mm OCL and >39 mm OCL would be returned to the water. The reproductive output of kōura at the current size distribution between and including 28–39 mm OCL, represents 69% of the total reproductive output. Kōura <28 mm OCL contribute only 9% to the reproductive output compared to 22% for kōura ≥ 40 mm OCL. Thus the combined effect of a slot limit would be to protect 31% of the reproductive capacity of kōura in the Te Arawa lakes assuming the size distribution does not change with harvest.

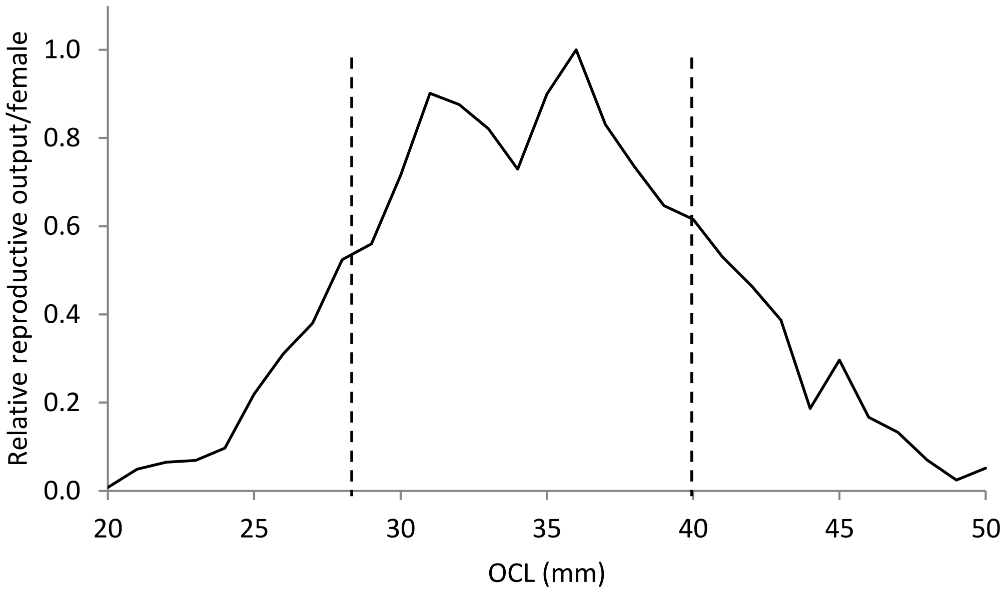

Figure 4.9: Normalised reproduction of female kōura by size class captured in seven Te Arawa lakes (Rotorua, Rotomā, Rotoiti, Rotoehu, Rotokakahi, Tarawera, Ōkāreka) and Ōkere Arm. Dotted lines show suggested lower and upper limits of harvestable size.

Table 4.7: Mean catch per tau kōura (n = 10 whakaweku) of kōura >27.5 mm OCL (N), % egg-bearing kōura >27.5 mm OCL and mean number of harvestable kōura, captured from two tau kōura comprised of 10 whakaweku (n = 20) set in eight Te Arawa lakes and one tau kōura (n = 10) set in the Ōkere Arm. Tau kōura sampled on 14 – 17 April 2009, 9 – 14 July 2009 and 5 – 9 November 2009 and Lake Rotoehu on 22 November 2011, 21 May 2013, 31 July 2013.

Lake	April			July			November		
	n	Proportion of egg-bearing females (%)	Harvestable	n	Proportion of egg-bearing females (%)	Harvestable	n	Proportion of egg-bearing females (%)	Harvestable
Rotorua	153	67.6	49.5	74.5	42.3	43.0	158.5	67.5	51.5
Ōkere Arm	26	0	26.0	27.0	0	27.0	10.0	30.0	7.0
Rotomā	211	0.9	209.0	150.5	43.2	85.5	183.5	65.4	63.5
Rotoiti	101	14.4	86.0	215.5	46.6	115	140.0	46.8	74.5
Rotoehu	54.5	46.8	29.0	7.5	46.7	4.0	11.0	4.5	10.5
Rotokakahi	8	12.5	7.0	11.0	13.6	9.5	10.0	5.0	9.5
Tarawera	14.5	20.7	11.5	63.5	37.0	40.0	15.0	26.7	11.0
Ōkāreka	21.5	11.6	19.0	14.5	17.2	12.0	12.0	0	12.0

4.5 Discussion

4.5.1 Kōura abundance

Kōura were present in all of the study lakes except Ōkaro, but high numbers of harvestable sized kōura were only found in Rotorua, Rotomā and Rotoiti. In lakes Ōkāreka, Ōkaro, Rotoehu, Rotokakahi and Tarawera, kōura abundance was too low for sustainable tau kōura harvesting while in the Ōkere Arm there were too few kōura of harvestable size. Lakes Rotomā and Rotoiti currently support customary tau kōura fisheries, but Rotorua, historically the most productive kōura fishery (Hiroa 1921), is no longer used by customary kōura fishers. This may be due to the decline in water quality (Burger, *et al*. 2007; Abell, *et al*. 2010) and concerns over the safety of kōura for human consumption due to mercury contamination from natural geothermal inputs (Phillips, *et al*. 2014).

4.5.2 Restricted access to the fishery

Commercial sale of kōura is prohibited in the Te Arawa lakes, with customary harvesting carried out mainly by iwi (Te Arawa). This results in a low number of participants and low levels of exploitation; hence there is little need for comprehensive fishery regulation at present. However, the TALT, the fishery manager, wishes to revitalise the traditional kōura fishery while adhering to the principles of kaitiakitanga – the sustainable protection of resources (Tipa and Teirney 2006). The aim of kaitiakitanga is to ensure conservation, protection and maintenance of resources through responsible actions, behaviour, conduct, and practices. Implementing sustainable management policies and regulations is an essential component of kaitiakitanga. The findings of this study suggest that a sustainable increase in the harvest of kōura may be possible in lakes Rotoiti, Rotomā and Rotorua. Freshwater crayfish studies have highlighted the resilience of populations to overexploitation (Morrissy 1978; Momot 1993; Tulonen, *et al*. 2008) with populations adjusting to exploitation by varying the age of female maturity (McGriff 1983; Lawrence, *et al*. 2006). However, caution must be exercised in allowing increased harvesting effort as yield reductions due to increased exploitation and removal of undersized crayfishes has previously been demonstrated for other stocks of freshwater cray-fish (Skurdal, *et al*. 1993; Hein, *et al*. 2006; Sadykova, *et al*. 2011). I therefore recommend maintaining the existing recreational daily bag limit of 50 kōura per person, with allowance for additional customary harvesting as recognised in the Te Arawa Lakes Settlement Act 2006. Under this legislation a permit is issued by the TALT (or representative) which entitles the holder to take kōura (e.g., in excess of the daily recreation bag limit of 50, during the closed season) for customary purposes. The permit holder is then required to report their catch to the TALT within 48 h of harvesting.

4.5.3 Minimum legal length

The minimum legal length (MLL) is one of the most widely used fisheries regulation tools and sets the smallest legal length at which a particular species can be retained if caught (Zukowski, *et al*. 2012).The MLL is generally implemented to protect pre-spawning stock by allowing reproductive opportunities for females before they are recruited into the fishery (Annala, *et al*. 1980). At present there is no MLL for kōura in New Zealand. One way to set the MLL is to use the SOB (Hobday and Ryan 1997). SOB (sexual maturity) in crayfish species can be affected by temporal (Annala *et al*., 1980) and geographical (Hobday and Ryan 1997) influences, as well as other factors such as population density, food availability, growth rate and water temperature (Annala, *et al*. 1980). Kusabs, *et al*. (2015) reported that water temperatures in the Te Arawa lakes were well within the environmental tolerances of *P. planifrons* and therefore it was unlikely that temperature is a limiting factor to kōura growth. Our logistic model showed that the size class at which 50% of female kōura were sexually mature for all the lakes was 26.3 mm. However, geographical variations were present in the study, with SOB ranging from 22.1 mm in Lake Rotoehu to 27.5 mm in Lake Rotorua. If the management goal is to ensure that at least 50% of females reach reproductive age before being legally targeted in the Te Arawa lakes, then the MLL would need to be set to at least 27.5 mm OCL (i.e. the SOB for Lake Rotorua) and I therefore recommend 28 mm OCL be used for the Te Arawa lakes district. An important finding of this study was that kōura fecundity increased as a power function of OCL, with larger female kōura producing far more eggs than smaller ones. The only other published study of *P. planifrons* fecundity in New Zealand was carried out on smaller (17 – 31 mm OCL) kōura from lotic habitats (the Mangaterere River, Wairarapa District), where there appeared to be a linear relationship between kōura length and fecundity (Hopkins 1967), possibly because of the restricted length range. The Mangaterere River kōura had on average 28% more eggs ($p < 0.001$) fora given size than Te Arawa lakes kōura over the 17 – 30mm OCL size range where the two data sets overlapped. However, the Mangaterere River lacked the larger sizes (30 – 45 mm) that had the highest fecundity in Te Arawa lakes. This indicates that caution is needed when applying the fecundity-length relationship for Te Arawa lakes kōura to other locations. Data from a greater range of lake and river kōura populations are needed to evaluate whether the higher size-specific fecundity of Mangaterere River compared to Te Arawa lakes reflects a general pattern for both rivers and lakes. Exploitation of fish populations can induce evolutionary responses in life histories (Kuparinen and Merilä 2007). For example, harvesting the largest individuals in a population may induce selective changes in age-specific maturation, fecundity and longevity, and possibly induce maturity at smaller sizes (Stokes and Law 2000; Reznick and Ghalambor 2005; Allendorf and Hard 2009; Stenseth and Dunlop 2009). Given the low exploitation rate of kōura, it is doubtful that harvest selection is currently occurring in the Te Arawa lakes. Nevertheless, if exploitation rates increase then the release of large-sized female kōura should be considered to protect the most fecund females. Strategies that ensure a proportion of large individuals go unharvested each year are more likely to offer protection to the population than implementing a minimum harvest size (Jones and Coulson 2006; Sadykova, *et al*. 2011). I recommend that a slot limit be implemented, where by it would be legal to harvest kōura between 28 and 39 mm OCL. By protecting the largest individuals (≥39 mm OCL), I would expect to maintain higher recruitment, which can buffer against catch-induced declines, as well as guarding against potential evolutionary changes towards smaller individuals (Conover and Munch 2002; Birkeland and Dayton 2005; Jones and Coulson 2006; Sadykova, *et al*. 2011).

4.5.4 Closed seasons

Closed fishing seasons are implemented to protect fish during the spawning season and enable uninterrupted spawning, limit the magnitude of yearly catch rates and conserve exploited species (Cooke and Cowx 2006; Zukowski, *et al*. 2012). At present there is no closed season for harvesting of kōura in New Zealand. Egg-bearing kōura were found predominantly through winter and only occasionally in the summer months of January to March (Devcich 1979; Kusabs and Quinn 2009). Information from Devcich (1979) from Lake Rotoiti suggests that a main pulse of breeding occurs during late autumn and that eggs are carried over winter (i.e. April – August). Eggs develop into juvenile kōura in approximately 3 weeks while remaining attached to the underside of their mother's abdomen. A second breeding season may occur in spring and summer where females carry eggs from October to December and juvenile kōura are released between September and December. Therefore, the likelihood of finding females with eggs or young throughout much of the year makes it difficult to set a closed season while allowing customary harvesting. Nevertheless, if one of the aims of the restricted season is to allow females to reproduce undisturbed, the open season should not commence until a significant proportion of all females have had an opportunity to mate and come into berry. Implementing an open season from December to March, similar to the traditional tau kōura season in Lake Rotorua (Hiroa 1921), would enable a significant proportion of females to breed undisturbed in the Te Arawa lakes.

4.5.5 Protection of egg-bearing females

Prohibition on taking of egg-bearing female crayfish is a widely used fishing regulation which acts to protect mature females, eggs and hatchlings, limit fishing levels and help ensure population sustainability (Cooke and Cowx 2006). This study and others (Kusabs and Quinn 2009; Kusabs, *et al*. 2012) have shown that egg-bearing kōura are commonly captured using the tau kōura method. Although fishing regulations prevent the taking of adult egg-bearing female crayfish, handling of egg-bearing females can result in damage and a reduced number of eggs and hatchlings reaching juvenile status. Zukowski, *et al*. (2012) showed that even careful handling of egg-bearing Murray crayfish (*Euastacus armatus*) resulted in eggs being dislodged (a mean of 3.9 eggs when the tail was lifted). Furthermore, the long-term effects of handling on egg retention and recruitment success are unknown. Although the rates of egg dislodgement were not specifically investigated in this study, initial observations confirm the findings of Zukowski, *et al*. (2012). The implementation of a closed season from April to November, the peak kōura spawning period, would prevent disturbance to egg-bearing females and reduce the risk of egg dislodgement.

4.5.6 Protection of soft-shelled kōura

Fishers are often required to return crayfish in the soft shell stage to the water. Closed seasons are also used to protect crayfish when they are moulting and have soft exoskeletons making them susceptible to handling pressure (Zukowski, *et al*. 2012). Kōura in the Te Arawa lakes do not have a distinct moulting period, with a relatively small proportion (mean 7.3%) of kōura having soft shells at any one time. Therefore, it is not possible to protect moulting kōura by implementing a closed season while allowing harvesting. A regulation requiring the release of soft-shelled kōura may not be effective given that they only comprise a small proportion of the catch at any one time and their survivability post-handling maybe low. Further studies are required into post-handling survival of kōura, particularly those with soft shells, to ascertain if there is any value in a regulation requiring their release.

4.5.7 Harvesting method restrictions

Restrictive fishing methods are implemented to reduce exploitation of populations and conserve exploited species by influencing the efficiency of fishing, and the size and species of fish caught (Cooke and Cowx 2006). At present, kōura in the Te Arawa lakes are mostly captured using three traditional harvesting methods; tau kōura, rama and ruku kōura. The tau kōura is a deep-water method used to harvest kōura from the lake bed outside the depth range of the tall-growing submerged aquatic macrophyte beds to depths in excess of 35 m, while rama kōura is used to capture kōura at night from the shallow littoral (<2 m depth) zone using a spot-light and a hand-held scoop net. Ruku kōura, or collecting kōura by hand often while free diving, is also used in shallow waters. Rama and ruku kōura are used in some of the Te Arawa lakes, particularly lakes Rotoiti, Ōkāreka, Okataina, Rotomā, and Tarawera where the lake-bed slopes are relatively steep (allowing kōura access to deeper water) and the littoral lake-bed substrates are comprised mainly of sand and cobbles (in contrast to the limnetic zones in Ōkāreka and Tarawera which are comprised mostly of muddy substrates) (Kusabs, *et al*. 2015).

The tau kōura is a harvesting method that also provides cover habitat for kōura (e.g., egg-bearing, moulting, and juvenile kōura), and when used in conjunction with regulations (i.e., size limit and release of egg-bearing females) could enhance the fishery. In addition, the tau kōura is considered a lake structure (Te Arawa Lakes Settlement Act 2006) and requires approval from the lake bed owners. Hence, the number and location of tau kōura can be controlled by the TALT, who can also request that all fisheries catch data be recorded and returned to them, improving management of the kōura fishery. The shallow-water methods, rama and ruku kōura are considered to have a relatively low impact on kōura populations because they are confined to the littoral zone of the lakes where egg-bearing kōura are rare, are mostly carried out in the summer, and are dependent on suitable weather, lunar and lake conditions (I. Kusabs, pers. obs.).

In the Te Arawa lakes, kōura are susceptible to over-harvesting by SCUBA divers because of the generally featureless lake bottoms composed mainly of sand and mud, particularly in the oligotrophic lakes. Harvesting by SCUBA or commercially available traps, unlike the tau kōura, would not require approval from the TALT, which makes it difficult for fisheries managers to determine fishing effort and catch rates. For this reason, I recommend the tau kōura form the basis of future harvesting practice.

4.6 Conclusion and recommendations

Kōura populations in the Te Arawa lakes are currently under-exploited due to the low number of participants, and because commercial harvesting is prohibited. Nevertheless, intended revitalisation of traditional kōura fishing practices will result in the increased exploitation of Te Arawa kōura. Therefore, it is prudent to establish appropriate fisheries regulations to ensure healthy fish stocks for future generations. This study provides biological information to underpin fishing regulations for kōura in the Te Arawa lakes. The following management changes are recommended to protect and enhance the kōura fishery in the future. These are (1) set a slot limit with minimum size limit of 28 mm OCL and a maximum size limit of 39 mm OCL, (2) ban the taking of egg-bearing females, and (3) limit deep-water harvest methods to the use of the tau kōura, and (4) implementing a tau kōura harvest season beginning on 1 December and ending on 31 March. These measures will protect breeding females if they are captured and the closed season will allow the majority of females to breed and release their young prior to fishing activity.

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4.8 Appendices

Appendix 4.8. Reproductive output of kōura captured in seven Te Arawa lakes (Rotorua, Rotomā, Rotoiti, Rotoehu, Rotokakahi, Tarawera, Ōkāreka) and Ōkere Arm.

OCL (mm)	Number of females with eggs	Proportion of females with eggs, *P*	Number of eggs per female, *E*	Normalised contribution to egg production (*P* x *E*)
20	3	0.0021	39	0.008
21	17	0.0117	45	0.049
22	20	0.0138	50	0.065
23	19	0.0131	56	0.069
24	24	0.0166	63	0.097
25	49	0.0339	69	0.219
26	63	0.0435	77	0.311
27	70	0.0484	84	0.380
28	88	0.0608	92	0.524
29	86	0.0594	101	0.560
30	101	0.0698	110	0.716
31	117	0.0809	119	0.901
32	105	0.0726	129	0.876
33	91	0.0629	140	0.821
34	75	0.0518	151	0.729
35	86	0.0594	162	0.900
36	89	0.0615	174	1.000
37	69	0.0477	187	0.831
38	57	0.0394	200	0.734
39	47	0.0325	213	0.646
40	42	0.0290	227	0.616
41	34	0.0235	242	0.531
42	28	0.0194	257	0.464
43	22	0.0152	273	0.387
44	10	0.0069	289	0.187
45	15	0.0104	306	0.296
46	8	0.0055	324	0.167
47	6	0.0041	342	0.132
48	3	0.0021	360	0.070
49	1	0.0007	380	0.024
50	2	0.0014	399	0.052

Chapter 5

Conclusions

5.1 Research summary

The overall aim of this thesis was to gain a better understanding of the ecology of kōura in the Te Arawa lakes, by quantifying their relative abundance and distribution and assessing the effects of environmental factors on their populations. In addition, information on biological traits was collected as a basis for setting sustainable regulations and management policies. A better understanding of the ecology and biological traits of Te Arawa kōura is important because; they are one of the most influential of biota in many aquatic ecosystems, are considered a taonga species in much of New Zealand, and they support important customary fisheries in the Te Arawa lakes.

The major objectives of this study were achieved by (1) developing an effective method for monitoring lake kōura to address the lack of suitable representative sampling methods and thus providing a necessary first step to address the paucity of quantitative information on lake kōura, (2) determining the relative abundance and distribution of kōura in seven Te Arawa lakes which had a gradient of nutrient enrichment from low (oligotrophic) to very high (hypertrophic) and the effects of environmental variables related to bed characteristics, lake morphology and water column chemistry and biota, and (3) obtaining biological information to underpin fishing regulations and measures for the sustainable management of kōura populations in the Te Arawa lakes.

Lake kōura populations are little studied in New Zealand and overseas lakes because of the absence of suitable sampling methods. Therefore the first objective of this study was to find a method that was simple, repeatable, relatively inexpensive and capable of catching large numbers of kōura, at water depths to 35 m. In a preliminary study of kōura sampling methods in the Rotorua lakes, it was found that conventional sampling methods, such as baited traps, SCUBA, underwater video camera and nighttime spotlighting surveys, had numerous disadvantages (Kusabs, *et* *al.* 2005). All were found to be biased towards large individuals while all except trapping were dependent on weather and/or water clarity. I successfully used the tau kōura at a shallow and moderately deep site in Lake Rotoiti and concluded that it was a suitable tool for monitoring kōura by fisheries managers, researchers, iwi and community groups, as it is inexpensive, captures kōura of all sizes, can be used in a range of habitat types and depths and appears to have fewer biases than the more conventional kōura/crayfish capture methods, such as baited traps.

To achieve the second study objective (determine the factors influencing kōura abundance and distribution), I examined kōura abundance, biomass, size and distribution along a eutrophication gradient in seven Te Arawa lakes. Although limited by the number of lakes I was able to characterise, my data indicates that lake bed substrate (median sediment particle size) had a stronger influence on population characteristics than the level of enrichment/primary production as indexed by chlorophyll *a* (Chl-*a*). Nevertheless, the negative correlations between kōura abundance and biomass, with sediment C/N ratio, and the positive correlation between abundance and Chl-*a* (when Lake Ōkaro was excluded) suggest that productivity does influence kōura abundance. In this context, the absence of kōura from hypertrophic Lake Ōkaro, where kōura were present historically provides some support for a subsidy-stress response to increasing nutrient enrichment. Lake bed substrate composition is therefore a key factor to consider when selecting tau kōura sites for research, monitoring, restoration and harvesting, and when estimating kōura stocks in lakes. Furthermore, my study indicates that progressive eutrophication has reduced available kōura habitat in the Te Arawa lakes, particularly for sheltered, steep-sided habitats which have a high proportion of fine lake bed sediments. I conclude that measures to improve water quality in the Te Arawa lakes should benefit kōura populations by increasing the amount of available habitat, particularly in the summer and autumn when anoxia poses a major constriction on habitat.

To achieve the third study objective (to determine sustainable fisheries regulations and policies), I examined population and biological traits of kōura in eight Te Arawa lakes and the Ōkere Arm. I then discussed the implications of this data in relation to the current fishing regulations and management policies for Te Arawa kōura. I concluded that kōura populations in the Te Arawa lakes are currently under-exploited due to the low number of fisheries participants and because commercial harvesting is prohibited. This study provided biological information to underpin fishing regulations for kōura in the Te Arawa lakes. A number of management changes arising from this information are suggested to protect and enhance the kōura fishery. These are to (1) set a slot limit with minimum size limit of 28 mm OCL and a maximum size limit of 39 mm OCL, (2) prohibit the taking of egg-bearing females, and (3) limit deep-water harvest methods to the use of the tau kōura, and (4) implementing a tau kōura harvest season beginning on 1 December and ending on 31 March. These measures are essentially designed to protect breeding females.

5.1.1 Kōura conceptual models

At the commencement of this study the factors influencing the distribution and abundance of kōura in the Te Arawa lakes were summarised (Parkyn and Kusabs 2007) and depicted in a kōura conceptual model (Fig. 5.1) (Quinn and Parkyn 2008). The model defined three key factors (habitat quality, food supply and predation) which collectively contributed to the quantity of kōura in the lakes. Each of the key factors is described by a range of variables (boxes), while the arrows describe the relationships between the variables.

However, this study has greatly improved understanding of the factors influencing Te Arawa kōura resulting in a number of modifications to the original model (Fig. 5.2). In summary, the new model includes the objectives of the Te Arawa customary fisheries management plan, the proposed kōura harvest regulations, lake management interventions undertaken by the Bay of Plenty Regional Council, land use management, factors affecting food safety (cyanobacteria blooms, heavy metals and pesticides), the effects of lake bed substrates and the influence of macrophytes.

Sediment particle size was identified as the strongest driver of kōura populations in the study lakes with kōura abundance and biomass increasing with particle size. The low abundance of lake kōura on fine, silt sediments compared to coarser sediments is consistent with my underwater (SCUBA) observations and from studies in New Zealand (Devcich 1979) and elsewhere (Kershner and Lodge 1995; Kirjavainen and Westman 1999).

Introduced macrophytes have increased markedly in some of the Te Arawa lakes, e.g., Lake Rotoiti, in recent years as a result of increased water clarity (Kusabs, *et al.* 2013). Hornwort (*Ceratophyllum demersum*) is particularly problematic. It is a brittle, poorly attached plant (anchorage is by buried, modified leaves) and is prone to dislodgement by water currents, wave action and other disturbances. Because it is easily dislodged, hornwort can smother the whakaweku, not only restricting kōura access to the whakaweku but also leading to the rapid decay of the fern itself. Furthermore, weed proliferation and accumulation of decaying organic matter can markedly degrade the habitat quality of the surrounding lake bed (Kusabs, *et al.* 2013).

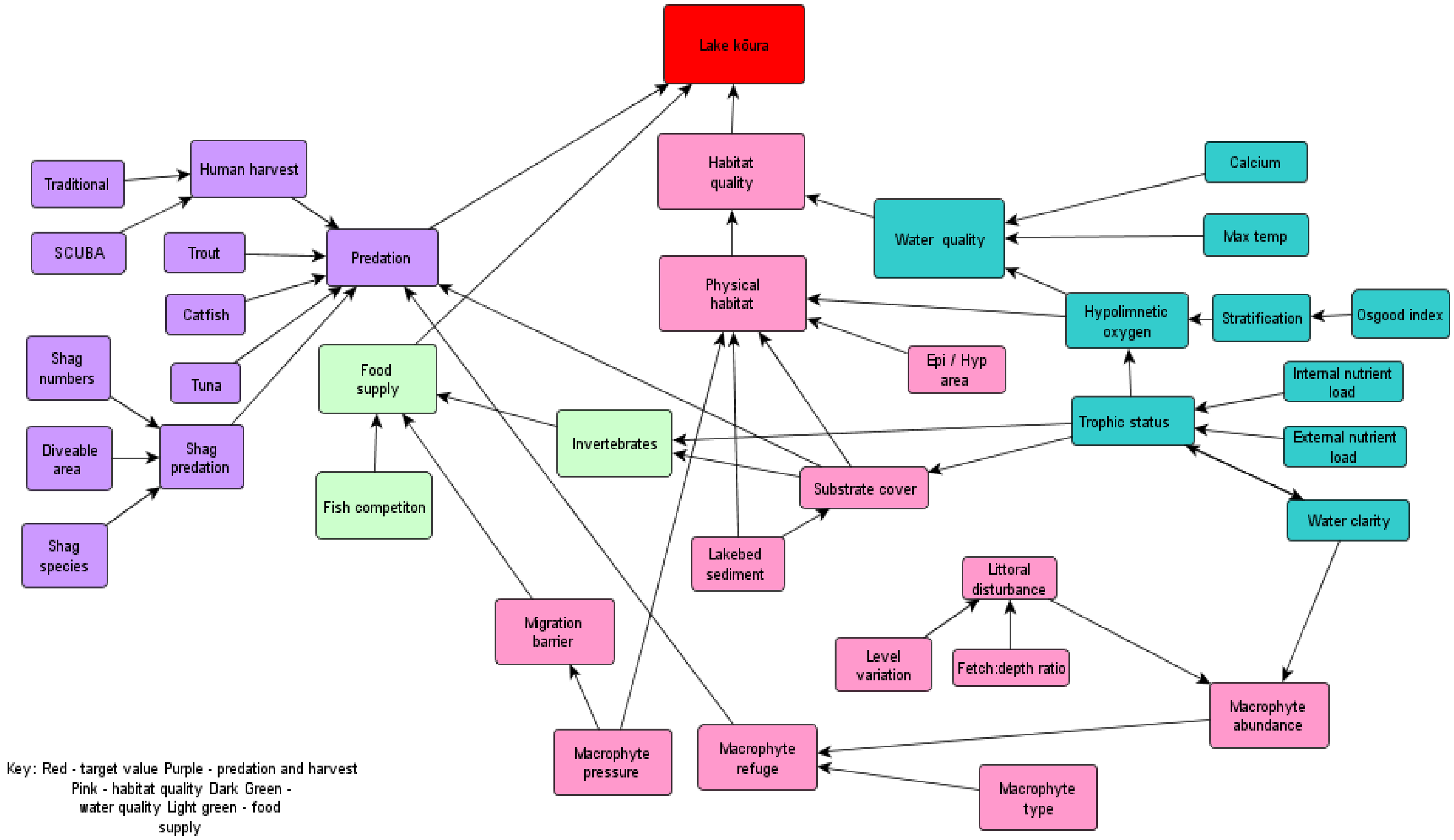

Figure 5.1: Original kōura conceptual model from Quinn and Parkyn (2008).

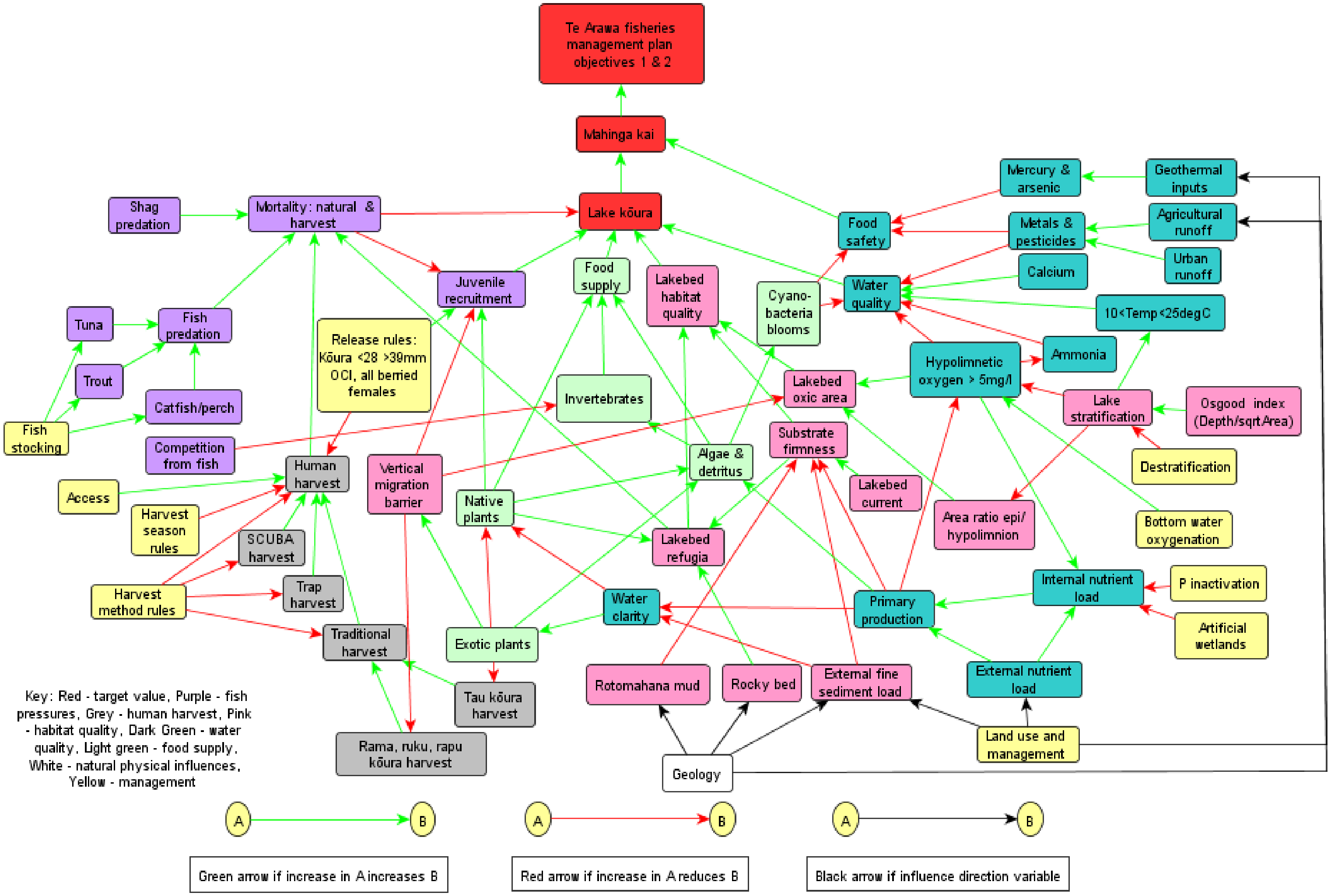

Figure 5.2: Updated kōura conceptual model.

5.1.2 Management implications and recommendations for future work

5.1.2.1 Monitoring of kōura populations

This study showed that the tau kōura is a suitable tool for monitoring the relative abundances of kōura populations in the Te Arawa lakes, however, in order to make between lake comparisons, tau kōura must be deployed at similar depths and lake bed substrates, and set and retrieved around the same time. This may not always be achievable due to logistical reasons, weather conditions or lake morphology. For example, in Lake Rotorua the only areas of lake bed with sufficient slope to site a tau kōura were near Mokoia Island. This limitation may have resulted in an overestimate of lake average kōura abundance.

Kōura were found to be most abundant on coarse lake bed substrates and, based on SCUBA observations, to be closely associated with coarse substrate such as underwater reefs, cobbles and submerged logs. Determining the substrate composition of the lake beds from depths of 10 to 40 m, and sub-sampling the kōura population on the variety of substrates at this depth, would give a better estimate of overall kōura abundance in each lake.

At present little is known of the kōura populations in those Te Arawa lakes that were not included in this study, i.e. Okataina, Rerewhakaaitu, Rotomahana, Tikitapu, Ngapouri and Ngahewa. Kōura surveys are required to obtain baseline information and to determine if the fishing regulations (i.e. minimum legal length and closed season) proposed in this study are also applicable to kōura stocks in these lakes. In addition, monthly sampling of kōura populations in the Te Arawa lakes would help to clarify the differences in breeding times among the various lakes. In this study, peak breeding seasons varied among the study lakes with the highest proportion of egg-bearing female kōura recorded in the Ōkere Arm and lakes Ōkāreka, Rotoiti, Rotokakahi, Rotomā and Tarawera in July, lakes Rotomā and Rotorua in November and Lake Rotoehu in May. It is not known why the highest proportion of egg-bearing female kōura was recorded in November in lakes Rotomā and Rotorua. Further monitoring of the kōura populations in December and January in these lakes is required to determine the extent of the breeding season and the appropriateness of the proposed closed season.

5.1.2.2 Fisheries management

It was found that the study lakes varied in their capacity to support customary tau kōura fisheries. Lakes Rotorua, Rotoiti and Rotomā have high numbers of kōura of harvestable size whereas in lakes Ōkāreka, Ōkaro, Rotoehu, Rotokakahi, Tarawera and the Ōkere Arm, kōura abundance is too low or kōura are too small to make tau kōura harvesting worthwhile. The minimum legal length (MLL) is one of the mostly widely used fisheries regulation tools. Size at onset of sexual maturity (SOM) or size at onset of breeding (SOB), are often used to determine the MLL. The logistic model showed that the size class in which 50% of Te Arawa kōura were sexually mature was at OCL of 26.3 mm. However, geographical variations were present in this study, with SOB ranging from OCL of 22.1 to 27.5 mm in lakes Rotoehu and Rotorua, respectively. If the management goal is to ensure that at least 50% of females reach reproductive age before being legally targeted in the Te Arawa lakes, then the MLL would need to be set to at least 28 mm OCL (i.e. the SOB for Lake Rotorua).

An important finding of this study was that kōura fecundity increases with size, with larger female kōura producing more eggs than smaller ones. Therefore, the release of large-sized female kōura (≥40 mm) should be considered if exploitation rates increase. The continuous breeding season and the differences in peak spawning periods amongst the study lakes make it difficult to set a closed season while allowing customary harvesting. Nevertheless, if one of the aims of the restricted season is to allow females to reproduce largely undisturbed, the open season should not commence until a significant proportion of all females have had an opportunity to mate and come into berry. Implementing a closed season from April to November would enable a significant proportion of females to breed undisturbed without risk of capture in the Te Arawa lakes. This study and others (Kusabs and Quinn 2009; Kusabs, *et al.* 2013) have shown that large numbers of egg-bearing kōura are commonly captured when using the tau kōura method, a prohibition on taking of egg-bearing female kōura should therefore be considered for Te Arawa kōura.

Restricted fishing methods are implemented to limit catch rates and conserve exploited species. In the Te Arawa lakes, kōura are susceptible to over-harvesting by SCUBA divers because of the generally featureless lake bottoms composed mainly of sand and mud, particularly in the oligotrophic lakes. Harvesting by SCUBA or commercially available traps, unlike the tau kōura, would not require approval from the TALT, which makes it difficult for fisheries managers to determine fishing effort and catch rates. For this reason, I recommend the tau kōura form the basis of future deep-water harvesting practice. Kōura in the Te Arawa lakes do not have a definitive moulting period, with a relatively small proportion (mean 7.3%) of kōura having soft shells at any one time. The requirement for a regulation requiring the release of soft-shelled kōura should be carefully considered given that they only comprise a small proportion of the catch and their survivability post-handling may be very low.

5.1.2.3 Effects of lake intervention measures

Kōura were absent from the deoxygenated hypolimnion of lakes Ōkāreka, Rotokakahi and Rotoiti in April when the lakes were stratified, but present in July when the lakes were mixed, and also in November after the lakes had stratified but when there had not been substantial deoxygenation. This indicates that progressive eutrophication has reduced useable kōura habitat most in those lakes that are sheltered, steep-sided and have a high proportion of fine lake bed sediments. Kōura distributions are therefore ‘squeezed’ from above, by light intensity, cormorant predation and biotic barriers created by invasive submerged macrophyte beds, and from below by hypoxia. Therefore, measures to improve water quality in the Te Arawa lakes (e.g., lakes Ōkāreka, Ōkaro, Rotokakahi, Rotorua, Rotoehu) should benefit kōura populations by increasing the amount of available habitat in the summer and autumn. In addition, removal of introduced aquatic macrophyte beds would increase available habitat in the shallow littoral and may be an option where lake water quality improvements are likely to be very slow.

5.1.2.4 Invasive species – predatory fish and non-indigenous crayfish

Preventing the establishment of predatory fish and non-indigenous crayfish in the Te Arawa lakes is a high priority for the Te Arawa Lakes Trust and other environmental agencies. Several studies have revealed that fish predation has an impact on crayfish populations (Reynolds and Souty-Grosset 2012) and the absence of benthic piscine predators is thought to be a key factor in the present and historical abundance of kōura in the Te Arawa lakes. The main predatory fish, rainbow trout, is a mid-water lentic feeder that feeds mainly on common smelt. The introduction of predatory fish, other than trout, such as eels, catfish and perch which are efficient predators of crayfish, could adversely affect kōura populations in the Te Arawa lakes. These fish species are not yet present (catfish and perch), or are found in extremely low numbers (eels), in the Te Arawa lakes. Brown bullhead catfish have been reported to commonly consume kōura in Lake Taupō (Barnes and Hicks 2003) while kōura were the second most frequent prey items of shortfin eels in forested streams in the Waikato (Hicks 1997). In the North Island, perch were illegally introduced to Lake Ototoa (South Kaipara Head) around 2000. Before this, kōura were abundant in this lake. However, between 2003 and 2011 and following the development of a large perch population, kōura abundance in this lake was reduced by over 90% (Rowe 2014). Moreover, Molony, *et al.* (2004) reported that perch in Lake Navarino, South-Western Australia, had a predatory impact on an endemic freshwater crayfish (*Cherax cainii*) almost 60 times greater than the impact imposed by rainbow trout.

The effect of predatory fish on crayfish populations is influenced by several factors including habitat complexity and size of the crayfish. Experimental studies indicate that predatory fish often reduce the abundance of juvenile crayfish, but the availability of cobbles can reduce predation risk by providing refuges for the vulnerable young life stages present (Stein 1977; Capelli and Magnuson 1983; Garvey, *et al.* 1994; Kershner and Lodge 1995; Nystrőm, *et al.* 2006). The Te Arawa lakes are of volcanic origin with lake bed and littoral substrates comprised mainly of mud and sand, with limited cobble refuge areas for juvenile kōura.

Small scale releases of eels into the Te Arawa lakes have been carried out for many years with little effect due to the low numbers released. In recent times, however, there has been some discussion of establishing eel fisheries in some of the lakes. Observations in the upper Waikato River indicate that large populations of eels co-existing with kōura are not compatible. Kōura (and trout) were once plentiful in the upper Waikato River lakes (Coffey 1997). However, a dramatic decline in kōura abundance coincided with the introduction of eels (approximately 2 million elvers per annum). Phillips, *et al.* (2006) captured no kōura in lakes Maraetai and Waipapa in a 2006 survey compared with catches ranging from 3 to 8 kōura per net in 1995 (Boubée, *et al.* 1995). Furthermore, in a recent survey of the upper Waikato, kōura were found to be extremely rare (or absent) in the margins, of the upper river and lakes Ohakuri and Ātiamuri (Author's personal observation). This is supported by studies in Europe where eels introduced into the Rumensee in Switzerland reduced an expanding *Procambarus clarkii* population to less than 10% within three years (Muller and Frutiger 2001). In the Lower Guadalquivir Basin in Spain, before the introduction of *P. clarkii*, eels mostly preyed upon fish species, whereas after crayfish introduction the dominant prey item was *P. clarkii*, occurring in up to 67% of eel stomachs (Montes, *et al.* 1993).

The global expansion of non-indigenous crayfish and the damage caused by them to indigenous species and habitats is a cause for increasing concern (Reynolds and Souty-Grosset 2012). There are numerous examples where introductions of non-native crayfish have resulted in a decline or replacement of native species with aggressive non-native crayfish often out competing native species (Nystrőm 2002). The mechanisms suggested for this include, a higher capacity for population increase, larger individual size (resulting in increased success in aggressive interactions and decreased vulnerability to gape-size limited predators), interspecific mating and interference competition for shelters among juveniles (resulting in increased exposure to predators) (Garvey, *et al.* 1994; Hill and Lodge 1999).

The replacement of native species may be further facilitated by habitat degradation and the presence of predators (Didonato and Lodge 1993). The Australian crayfish or marron (*Cherax tenuimanus*) was introduced to New Zealand for aquaculture purposes in the late 1990s because of its faster growth rate and larger size. However, a review of the global impacts caused by introduced crayfish (Rowe 1992) found that a number of endemic stocks had declined after such invasions because the endemic females prefer to breed with the larger introduced males. As the introduction of the larger marron posed a clear threat to the endemic kōura, the stocks present in New Zealand were eradicated.

As with other invasive species, it is far more cost effective to prevent the introduction of piscine predators and non-indigenous crayfish species than to take reactive measures after their introduction and establishment (Reynolds and Souty-Grosset 2012). As a consequence, it is imperative that education and monitoring programmes are established to minimise the risk of an introduction and that post-introduction mitigation and remediation protocols and processes, such as contingency plans, are always in place. These should enable rapid detection and response in order to minimise and ideally, eliminate the threats by invasive species.

5.1.3 Future research

5.1.3.1 Population estimates using mark-recapture

In order to make between lake comparisons of kōura abundance in this study, tau kōura have been deployed and retrieved within a week and set at similar depths on mud and sand lake bed substrates. This required considerable coordination and was dependent on good weather conditions which may not always be realised. The tau kōura is a relative index of abundance which does not provide information about actual population size. To estimate kōura population size in the Te Arawa lakes a mark-recapture programme may be more appropriate. A number of marking methods have been employed in crayfish research. These include clipping or punching holes in the telson or uropods, branding with a soldering iron, marking with fluorescent pigment and tattooing with ink. All these methods have limitations. However, one of the major problems encountered when tagging arthropods is the loss of marks after moulting. Further, tagging may potentially cause biological damage (side-effects). The PIT (Passive Integrated Transponder) tag system has been used successfully but the cost is high, particularly for tagging large field samples or if natural mortalities are high. Clipping pleura and punching holes in the telson and uropods or marking using visible implant elastomer (V.I.E.) tags (Northwest Marine Technology) are probably the best ways to mark kōura in the Te Arawa lakes. These methods are suitable for field studies on population size, density and dispersal or migration of crayfish. However, care must be taken if the method is applied to estimate growth because there can be significant reductions (~20%) in the moult increment of carapace length after marking treatment (Guan 1997).

In lakes, quantitative area-based estimates of population size are extremely rare (exceptions include sampling with quadrats and SCUBA e.g., Lamontagne and Rasmussen 1993) and enclosure traps (Engdahl, *et al.* 2013). Baited traps are the most commonly used method of crayfish sampling and by their nature they draw crayfish from a wide and unspecified area. Mark recapture methods of population estimates rely on an assumption of equal catchability, and Johnsen and Taugbøl (2008) found clear evidence of sex and size bias in the catches. Numerous other studies have reported that baited trap data is skewed towards large crayfish and males (e.g., Abrahamsson 1966; Dorn, *et al.* 2005; Price and Welch 2009). The tau kōura method does not have these biases (i.e., it has a wide size range and no sex bias) associated with baited traps so may be more useful in mark-recapture studies.

In addition, mark–recapture studies could help to clarify age and growth rates of Te Arawa kōura. In this study, kōura could not be aged from length-frequency distributions. Size frequency analysis is limited to populations with short life spans and discrete periods of recruitment (France, *et al.* 1991). Even if size modes were revealed by this analysis, their significance would be doubtful since the size frequencies are complicated by an extended period of egg hatching from September to May (Devcich 1979), and by those kōura which moult more or less frequently than others in their cohort. In addition, juvenile kōura are generally under-represented in tau kōura catches because the whakaweku are set from below the aquatic macrophyte beds, not in the shallow littoral zones where juvenile kōura are most abundant (Devcich 1979).

Invasive macrophytes are known to establish dense stands that directly interfere with movement of adult crayfish and cover shallow areas of lakes, thereby, excluding crayfish (Hessen, *et al.* 2004). The extensive macrophyte beds present in many of the Te Arawa lakes (Clayton and Edwards 2006) may prevent the movement of kōura from the littoral to pelagic zones resulting in distinct populations in some areas. If this does occur then harvesting of kōura from the littoral zones may require regulations designed to conserve populations and help provide a desirable fishing experience (i.e. sufficient kōura to harvest rather than to protect spawning females). Further research is required to determine the interactions between littoral kōura and those kōura living below the macrophyte beds in the Te Arawa lakes.

5.1.3.2 Fisheries enhancement/commercial exploitation

Freshwater crayfish aquaculture industries exist in the southern United States, Australia, Europe and China and small operations exist in New Zealand with both *P. zealandicus* and *P. planifrons*. Commercial exploitation of wild stocks of kōura in New Zealand is prohibited by the Freshwater Fisheries Regulations 1983, so aquaculture is currently the only option available to produce kōura for sale. Over the years, there have been a number of proposals to release artificially raised kōura to both enhance and arrest the perceived decline in natural populations in the Te Arawa lakes. However, the results of this study show that kōura abundance is heavily influenced by abiotic factors, especially the composition of lake bed sediments; with no evidence to suggest that kōura populations are limited by juvenile recruitment. Evaluating the survival of hatchery-reared juveniles would also be problematic. Increasing useable habitat for kōura by improving lake water quality and removing invasive macrophyte beds, and preventing the establishment of pest fish (and exotic crayfish) populations may be a far better use of resources.

This study and others (Kusabs and Butterworth 2011; Kusabs and Butterworth 2013; Kusabs, *et al.* 2013) have shown that the tau kōura can capture good numbers of harvestable sized kōura (>30 mm OCL) in some Te Arawa lakes, e.g., Rotomā, Rotoiti and Rotorua. It is feasible that kōura populations in these lakes could sustain increased levels of exploitation (including limited commercial harvesting) because fishing pressure is currently low (mainly due to the low number of fishers).

The best management and harvesting strategies of commercial populations of large decapod crustaceans (crabs, lobsters and crayfish) may differ from those of fish for various reasons. In particular, recruitment rates and population growth rates of crustaceans may be lower, which may contribute to vulnerability to over exploitation unless the population is managed by suitable regulation (Sadykova, *et al*. 2011). Some freshwater crayfish studies have highlighted the resilience of populations to over exploitation (Morrissy 1978; Momot 1993; Tulonen, *et al*. 2008) with populations adjusting to exploitation by varying the age of female maturity (McGriff 1983; Lawrence, *et al*. 2006). However, caution must be exercised in allowing increased harvesting effort as yield reductions due to increased exploitation and removal of undersized crayfishes has previously been demonstrated for other stocks of freshwater crayfish (Skurdal, *et al*. 1993; Hein *et al*. 2006; Sadykova, *et al*. 2011).

The protection of the largest individuals may be beneficial for maintaining the most productive population size. The rationale for this is that fecundity increases linearly with crayfish size and also that larger crayfish offer better protection of their pleopod eggs and early juveniles (Sadykova, *et al*. 2011). Devcich (1979) showed that Lake Rotoiti kōura possess some of the characteristics of K-selected species by having low growth rates (reaching maturity at an age of 3 years), low fecundity and direct development (no larval stages). Kōura are also long lived animals with the largest Rotoiti kōura (greater than 40 mm OCL) estimated to be between 11-16 years of age (Devcich 1979).

Nevertheless, there are a number of political, legal and social (equity) issues that would need to be resolved before commercial fishing can be considered seriously. Further studies are also required into the safety of Te Arawa kōura for human consumption (particularly for commercial sale) given their propensity to accumulate heavy metals such as arsenic and mercury, particularly in those lakes with naturally high geothermal inputs, e.g., Rotorua and Rotoiti. Most studies to date have been based on relatively small samples sizes collected from limited sampling localities (Kim and Burggraaf 1999; Phillips, *et al*. 2014).

5.1.3.3 Post handling survival

The proposed fishing regulations requiring the release of undersize, egg-bearing and moulting kōura are based on the assumption that released kōura have a high rate of survival. However, the effects of handling on kōura survival and egg retention and recruitment success in New Zealand are unknown. The capture and release of kōura from depths >30 m are likely to be far more stressful than for those captured from shallow or lotic habitats. Further studies are required into post-handling survival of kōura particularly those with soft shells. Determining post-handling survivability has important management implications; if post-handling survival is low then regulations would need to be adjusted/prioritised accordingly, i.e., duration of the closed season and closed fishing areas.

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