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**Quantifying relationships between kōura
(*Paranephrops planifrons*) abundance and micro-habitat features
in Waikato hill-country streams.**

A thesis
submitted in partial fulfilment
of the requirements for the degree
of
Master of Environmental Science
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by
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Abstract

Kōura (*Paranephrops planifrons*) is considered a taonga species by Māori and was once an abundant traditional fishery harvested throughout New Zealand. Kōura populations are under pressure in Waikato hill-country streams due to a range of factors including habitat loss and water quality degradation. Now that stakeholders have been engaging in collaborative decision-making and practices to restore/enhance biodiversity and ecosystem health within the Waikato catchment, there is opportunity to implement measures specifically targeted at kōura. Information on kōura habitat requirements to assist with the development of habitat enhancement work is therefore timely.

This research comprised two discrete studies which, in combination, provide important insights into daytime habitat use by kōura in Waikato hill-country streams. The first study was a field survey that examined in-stream habitat characteristics affecting kōura density and size, with a focus on juveniles ≤ 8 mm orbital carapace length (OCL), across a range of scales ranging from habitat patches to streams with contrasting catchment and riparian vegetation treatments – pasture, early or late riparian planting, and native forest. Micro-habitat variables related to kōura density included water depth and velocity, substrate size, and the area of bank undercuts and organic cover types, with root mat area significantly and positively related to juvenile densities across all scales. Although there was no significant effect of treatment type, there were strong associations between kōura and ponga logs, root systems, and coarse particulate organic matter (CPOM) across scales within and between streams.

The second study was a habitat manipulation experiment conducted to investigate whether kōura abundances, in particular juveniles, could be enhanced by additions of organic habitat consisting of 0.5 m² coconut fibre matting to simulate ponga (*Cyathea dealbata*) root systems that occur on the stream bank, and 1 m² ponga frond bundles to simulate the natural habitat structures formed in native forested areas. These two artificial habitats were compared with natural in-stream cobble habitats. Kōura and toi toi (*Gobiomorphus* spp.), both showed a preference for ponga frond habitats which were predicted to provide submerged habitat for more than 200 days. Although the coconut fibre matting was predicted to outlast ponga

frond bundles by up to 107 days, it was more susceptible to sedimentation and did not provide adequate habitat for kōura due to its dense structure.

This study highlighted the influence of riparian treatments, hydrological processes, and inorganic and organic habitats on kōura populations. Information from this study can provide restoration managers with guidance on how to enhance in-stream and stream edge habitat suitability for kōura and can be used with existing mātauranga Māori, and western and community science, to determine suitable vegetation for riparian planting, assess what factors and drivers contribute to in-stream habitat availability and sustainability, and identify important habitat features that relate to kōura when conducting habitat restoration.

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“Whakarongo ki ngā kupu o ngā Tipuna,
kākahutia i runga i a koe,
mau e hoatu ki te ao...”

*“Learn the wisdom of your Ancestors,
apply it to yourself,
and pass it on...”*

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Te Atiawa Rangatira

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Chapter 1

General Introduction

1.1 Introduction

The two described species of freshwater crayfish, *Paranephrops planifrons* and *P. zealandicus*, are endemic to New Zealand. *Paranephrops planifrons* or northern kōura is exclusively found in the North Island and north-western South Island, and *P. zealandicus* or southern kōura, along the eastern side of the South Island and Stewart Island (Hopkins, 1970; Usio & Townsend, 2000; Parkyn *et al.*, 2002). The division of the two *Paranephrops* species distribution is roughly associated with the mountainous backbone of the South Island's Southern Alps and Kaikōura Mountains (McDowall, 2005). Māori and common names for *Paranephrops* include kōura, kēwai, kēkēwai, wai-kōura, kōura wai-māori, yabbies, and crawlies. In this thesis, I use the term kōura when referring to *P. planifrons*, the focal species in my study, or when making general statements about *Paranephrops* spp.

1.2 Kōura as cultural keystone/taonga species

Worldwide, freshwater crayfish have been used as a food source by many cultures (Crandall & Buhay, 2007). In New Zealand, kōura have long been a staple diet for not only Māori (Best, 1929) but also for many of the early settlers who prized their sweet tasting tail flesh (McDowall, 1995a). Prior to European arrival, Māori traditionally relocated freshwater species, including kōura, throughout the North Island (Hiroa, 1921; Best, 1929), especially where food sources had been eradicated by volcanism (McDowall, 2005). Māori actively managed kōura populations by way of rāhui (fishery closures), ownership rights and releases into waterways to boost numbers, and used traditional aquaculture techniques to harvest lake kōura sustainably (e.g., the tau kōura method (Kusabs, 2015)). Today, tau kōura is not only used for gathering kai but also for monitoring kōura to assess population abundance and structure, for example in Lake Rotoiti, North Island (Kusabs & Quinn, 2009).

The gathering of kōura by Māori as a traditional practice is part of mātauranga Māori, described in the modern era as “Māori knowledge”. However, mātauranga Māori is more complex than just “knowledge” as it weaves in values and attitudes of Māori culture and is indistinguishably linked to Māori identity (Mead, 2012). Traditional ecological knowledge (TEK) and mōhiotanga (understanding) are part of mātauranga Māori that has foundational relationships between everything seen and unseen, humans and more than humans, and the natural and spiritual world, beliefs that shape te ao Māori (the Māori world and its views) and Māori practices (Clapcott *et al.*, 2018).

Historically, Māori also gathered a variety of environmental information for uses in mahinga kai and continue to use these practices into the modern era. This accumulated mātauranga Māori not only gave Māori connection with the whenua (land) and everything in it, but also encouraged the evolution of their identity (Panelli & Tipa, 2007). Additionally, streams and other freshwater environments provided a range of ecosystem services that align with te ao Māori view of cultural health, including drinkable and swimmable water, places of reflection and spiritual connectivity (Quinn & Cooper, 1997), flora and fauna observational areas, and mahinga kai sites.

Noble *et al.* (2016) categorised kōura as a cultural keystone species (CKS) belonging to the cultural identity of Māori. Māori perceive themselves as kaitiaki of their surrounding environment which they so heavily depend upon, including freshwater systems and the species within them. Traditionally, tangata whenua (people of the land) share a spiritual and deep cultural connection with kōura as they were not only valued as a significant food source, but also used in trade and bartering (Hiroa, 1921; Noble *et al.*, 2016).

1.3 Ecological role and biology of kōura

Biodiversity/food-web role

Crayfish act as ecosystem engineers (Jones *et al.*, 1994) benefiting ecosystem function and nutrient transfer within freshwater systems (Whitledge & Rabeni, 1997) and can be considered a keystone species (Creed, 1994). Kōura directly and

indirectly influence aquatic food webs across several trophic levels by consuming algae, macrophytes, macroinvertebrates and fish (Whitmore, 1997). In deep water habitats, crayfish are known to exclude filamentous algae, promote development of epilithic diatoms and grazing invertebrates (Creed, 1994), and modify benthic invertebrate community structure by predation (Momot, 1995). Crayfish can reduce levels of fine sediment through bioturbation (Whitmore, 1997), improve microbial diversity (Parkyn *et al.*, 1997), and increase processing rates of organic matter utilised by stream invertebrates (Collier *et al.*, 1997). Indeed, in some streams crayfish can process as much coarse particulate organic matter (CPOM) as all other freshwater invertebrate shredders combined (Rabeni *et al.*, 1995; Whitledge & Rabeni, 1997). Although kōura are omnivorous, feeding on small invertebrates, detritus and plants (Chapman *et al.*, 2011), studies have shown that juvenile kōura are more likely to be carnivorous feeders while larger kōura start to consume more plant material (Collier *et al.*, 1997). Hollows *et al.* (2002) and Parkyn *et al.* (2001) confirmed that larger crayfish tended to move to more plant-based diet after reaching a certain size, although a study of kōura stable isotopes by Hicks (1997) observed enrichment of $\delta^{13}\text{C}$ in kōura from native streams, suggesting their main source of nutrition was invertebrates.

Biology and habitat

A study by Parkyn *et al.* (2002) in a western Waikato-hill country catchment found female kōura carry their eggs through winter after mating in autumn (March-June). The females can produce 20 to 30 eggs at 17 mm carapace length, and up to 150 eggs at 30 mm carapace length (Hopkins, 1967a). Juveniles hatch onto the female where they remain for up to 2 weeks, and then become free-living once they reach around 3 mm orbital carapace length (OCL; the length of the carapace from the back of the orbital socket to the mid-dorsal posterior border of the carapace) (Hopkins, 1967b; Jones, 1981b; Parkyn *et al.*, 2002). In pastoral streams juvenile kōura became free-living up to 2 months earlier (September-December) than in native streams (December-March) due to c. 4-6 °C water temperature differences between habitats, and during that period have the added benefit of increased growth time (Parkyn *et al.*, 2002).

Growth rates are highly dependent on water temperatures and seasonality. If juvenile kōura became free-living in spring and early summer, under the right

conditions they could reach sexual maturity by the following autumn in pastoral streams. Under these conditions, young of the year kōura (YOY, based on size reached over one year) grew to between 7 to 22 mm OCL in pastoral streams and 5 to 10 mm OCL in native forest streams (Parkyn *et al.*, 2002). Hopkins' (1967b) study of a pastoral stream, 150 m above sea level at the foothills of the Tararua mountain range in the Wairarapa, revealed the mean size of *P. planifrons* at 11.4-11.8 mm carapace length after one year, similar to Waikato streams draining native forest (Parkyn *et al.*, 2002). Jowett *et al.* (2008) classified kōura into two size groups, “young of the year” at c. 3-8 mm OCL and larger kōura (> 8 mm OCL) after size-frequency analysis for use in generalised additive models (GAMs) to evaluate species-environment relationships within native or close-to-native forested streams. However, based on the findings of Hopkins (1967a) and Parkyn *et al.* (2002) it seems likely this larger size class also included YOY kōura. Crayfish size relative to age is difficult to determine and should be treated with caution as growth rates can also depend on genetic differences (Jones, 1981b). As well as being influenced by temperature and genotype, crayfish growth can be density-dependent with the densest populations exhibiting the slowest growth (Hopkins, 1967b).

Paranephrops planifrons have been reported to reached sexual maturity in: (i) 18 months to 2 years in aquaria studies (Jones, 1981a); (ii) after 1 year in pastoral streams and 2 years in native streams at c. 20 mm OCL (17-24 mm OCL (Parkyn *et al.*, 2002)), and (iii) up to 3 years in lakes (Devcich, 1979), in contrast to the southern *P. zealandicus* which can take up to 6-7 years to reach maturity (Devcich, 1979; Usio & Townsend, 2000). Parkyn *et al.* (2002) recorded maximum ages of kōura in pastoral streams of 3-4 years at c. 35 mm OCL, compared to 4-5 years in native streams for kōura of the same size. In North Island lakes *P. planifrons* grew much larger at c. 50 mm OCL after 9-10 years old (Devcich, 1979). *Paranephrops zealandicus* growth rates halt over winter (Whitmore & Huryn, 1999) and the species grows much larger than *P. planifrons*, with the largest recorded specimens estimated to be 85 mm carapace length (> c. 25 years old).

Kōura densities are known to be greater in native forest streams compared to pastoral streams due to the greater longevity of kōura in native forest streams, higher recruitment of juvenile kōura over the warmer summer months, and/or high mortality in pastoral streams over winter (Parkyn *et al.*, 2002). Kōura favour a

variety of habitats that include, leaf litter, woody debris (Parkyn *et al.*, 2009), tree roots (Parkyn & Collier, 2004), undercut banks (Grace, 1959; Hicks, 2003) and the interstitial spaces between substrates ranging in size from small gravels to large cobbles (Usio & Townsend, 2000; Jowett *et al.*, 2008). Kōura are also well known to inhabit holes in streams and river banks (Grace, 1959). Daytime cover habitat provides important protection from predation, and also provides food sources and shade. Crayfish are known to exhibit cannibalistic tendencies and stress fatalities when exposed to too much sunlight and clear water (Jones, 1981b; Olsson & Nyström, 2009). Larger crayfish have been associated with deeper pools and smaller crayfish with shallower waters (Englund & Krupa, 2000; Usio & Townsend, 2000), suggesting a shift in habitat use as they grow. However, studies of kōura show all sizes use both fine and large substrate types (Usio & Townsend, 2000; Jowett *et al.*, 2008; Parkyn *et al.*, 2009) suggesting there may be other causalities associated with kōura habitat preference that are unknown.

1.4 Key threats and stressors

A range of anthropogenic stressors potentially affect kōura, including land use activities, pollution, climate change and pest species (Ataria *et al.*, 2018). Land uses such as agriculture and forestry have changed stream characteristics (Quinn & Cooper, 1997), for example by increased sedimentation, nutrient concentrations, temperature, periphyton biomass and changes in physical habitat and flow, all of which have cascading effects on stream biota (Blaschke *et al.*, 1992; Quinn *et al.*, 1997; Harding *et al.*, 1999; Collier *et al.*, 2000). From hereon I focus on agricultural land use as a key stressor for kōura given its widespread impacts across New Zealand and ongoing intensification. Stream temperature increases due to deforestation are known to be the primary determinant of crayfish growth, and numerous studies have positively associated pastoral streams with higher crayfish growth rates (Jones, 1981b; Musgrove & Geddes, 1995; Whitmore, 1997; Usio & Townsend, 2000; Parkyn *et al.*, 2002). Conversion to agricultural land has led to the fragmentation of forested areas, affecting hydrological and biological factors (Smale *et al.*, 2005) that are negatively associated with kōura distribution (Jansma, 1995), as well as affecting growth rates, predation losses, non-predatory mortality,

habitat loss and stability, water quality, breeding success and food availability (Jones, 1981b; Hicks & McCaughan, 1997; Parkyn *et al.*, 2002).

Retirement and planting of riparian zones in pastoral catchments can help mitigate agricultural impacts on streams by enhancing stream habitat structure, moderating water temperature and light levels, modifying energy inputs, stabilising banks and influencing in-stream processes (Ormerod *et al.*, 1993). In particular, riparian buffers can reduce nutrient, pathogen and sediment loss by increasing infiltration and trapping contaminants carried in overland flow (Aarons & Gourley, 2013). Roots from native riparian trees improve stability of banks so they can withstand intense hydrological conditions (Abernethy & Rutherford, 2000). Riparian vegetation provides crayfish with shelter and shade from undercut banks, tree roots and in-stream debris (Parkyn & Collier, 2004; Brusconi *et al.*, 2008), allochthonous plant detritus inputs provide as a food source (Momot, 1984; Usio & Townsend, 2000), and large woody material changes stream physical characteristics producing habitat such as pools, as well as providing shelter (Jowett *et al.*, 2008).

1.5 Method for sampling kōura

A variety of sampling methods around the world are targeted at the behaviour and the environment of specific species of crayfish, with each methods having its own bias (Parkyn, 2015). For example, baited traps usually tend to be biased towards larger males (Olsen *et al.*, 1991; Price & Welch, 2009; Parkyn, 2015), and seine netting and quadrat sampling are restricted to habitats without obstruction (Olsen *et al.*, 1991). Electrofishing, hand collection and visual observations are reliant on good water visibility (Roell & Orth, 1992), and site selection can be limited to wadeable streams that are shallow, slow-flowing and lack habitat complexity. Electrofishing is known to be less effective in streams with very deep pools and complex habitat structures (Alonso, 2001).

Rabeni *et al.* (1997) compared different kōura sampling techniques and also identified a variety of biases for each technique. Methods tested included hand-netting at night using a three-pass approach, direct observation coinciding with the first pass only of hand-netting, ten quadrat samples during the day to obtain direct

estimates of abundance in the substrate, and electrofishing with three people using methods similar to those outlined by Joy *et al.* (2013). The study site used in Rabeni *et al.* (1997), a Waikato native forest stream, was electro-fished twice on one occasion and five times on another to evaluate precision of the depletion method.

The direct observation method severely underestimated abundances and was not recommended. Hand-netting depletion gave tight confidence intervals for population estimates but greatly underestimated abundance, and this method favoured large kōura capture. As such, it was recommended for abundance estimates only in conjunction with another sampling method. Quadrat sampling captured more kōura < 5 mm OCL than any other method, suggesting it can be used to sample juvenile kōura in appropriate habitats. However, quadrat sampling was not recommended for sampling throughout an entire reach due to the high percentage capture of small kōura (Rabeni *et al.*, 1997). Nevertheless, quadrat sampling can be an effective tool when estimating crayfish densities within micro-habitats (DiStefano *et al.*, 2003). Rabeni *et al.* (1997) concluded that the electrofishing method was the most accurate method used, providing 2-4 times greater abundance estimates than hand-netting.

A traditional Māori harvesting method, the tau-kōura, uses submerged bracken fern bundles for kōura to colonise, and a kōrapa (traditional capture net) to stop them escaping when harvested. The method was used in North Island lakes and streams as a form of representative sampling (Kusabs & Quinn, 2009; Kusabs *et al.*, 2018). Tau-kōura was shown to be an effective sampling tool as it favours a range of kōura sizes and both sexes. Tau-kōura can be used for monitoring catch per unit effort (CPUE) over time and has significant advantages over bait traps and dive surveys in deeper water (Parkyn, 2015). However, the tau-kōura is not a quantitative method and cannot target specific micro-habitats within streams where juvenile kōura might reside during the daytime. Overall, there is little evidence from this and other studies (Rabeni *et al.*, 1997; Jowett *et al.*, 2008; Parkyn, 2015) to support a single satisfactory method for quantifying kōura abundance across all freshwater environments, particularly for collecting small kōura.

1.6 Kōura in Waikato streams

Cultural significance

The western hill-country areas of Waikato, where this study was carried out, are of great cultural and spiritual significance to the many iwi or indigenous tribal groups who have ancestral claim to the land. Local iwi groups call themselves kaitiaki (custodians and guardians) of the land and waterways, and can recall mātauranga Māori pertaining to the area that encapsulates and expresses cultural identity. Oral stories for the region include Māui and Kupe, the great ancestors of both human and divine origins and attributes (Greensill & Ellison, 2004). Stories differ dependent on the sub-tribal group, however, the creationist stories of Mt Karioi and Mt Pirongia in western Waikato are represented by specific gender roles and their relationships show the connection and significance of these landmarks to local Māori.

The first voyagers from the Tainui waka, Hoturoa, Rakatāura and their descendants, were some of the early humans to explore the Waikato region. Kahupeka, a descendant of Rakatāura, named a predominant maunga (mountain) in the western Waikato, Pirongia o Kahu (Mt Pirongia) (Jones & Biggs, 1995). Throughout their early explorations Māori distributed mauri kohatu or talismanic stone emblems along the Hakarimata Ranges and Mt Pirongia to ensure forest bird fertility for food sources (Philips, 1989), and built altars for prayer at a variety of locations including Mt Karioi and Mt Pirongia (Jones & Biggs, 1995). These mountain ranges were a large food source for early Māori, and were celebrated as successful bird-snaring and bird-spearing grounds (Philips, 1995). From these early beginnings, traditional management of resources developed over time formed sustainable practices inclusive of mana whakahaere. Mana whakahaere refers to the authority of local iwi that has been established over many generations (Waikato-Tainui, 2013), and encompasses the custodial role of mana whenua (people of the land) to ensure the mauri or life force throughout the region is balanced. Māori believe that mauri is part of all living things, and that through environmental protection and sustainability the mauri of the people will be sustained. Therefore, Māori believe that the state of the environment and the taonga residing within are intrinsically linked to the welfare of te ao Māori.

Prior to raupatu (a term used to describe the confiscation of more than 1.2 million acres of land in 1865), the fertile lands and waterways of the Waikato rohe (region) was renowned for the abundance of natural resources. The rivers, lakes and wetlands were plentiful with kōura, tuna (eel), inanga (whitebait) and kāeo/kākahi (freshwater mussels) (Waikato-Tainui, 2018). Today, Waikato-Tainui (the ancestral people of Waikato) are concerned over the disappearance of their taonga species, the quality of waterways, intensive farming practices affecting the environment and poor management of resources, leading to the degradation of the cultural, social, environmental, spiritual and economic wellbeing of the Waikato whenua and its people (Waikato-Tainui, 2018).

Waikato region land changes

At the time of European arrival, substantial areas of the Waikato region were already modified, with approximately 54% of the total land area in primary indigenous forest, 41% in fire-induced scrub, shrubland and secondary forest, with the remaining 5% as wetlands (Leathwick *et al.*, 1995). Primary forests were still the predominant vegetation, covering two-thirds of hill-country land. Since European settlement, indigenous vegetation has reduced to 25% throughout the Waikato region (Leathwick *et al.*, 1995), and 82% of remnant indigenous forest and regenerating scrub now exists as patches < 25 ha (Denyer, 2000). On average, an estimated 71 ha of indigenous forest and shrubland continue to be lost per year throughout the region (1996-2012, New Zealand Land Cover Database v. 4.1). These remnant vegetation areas are under constant pressures from domestic livestock, introduced feral pests and elevated nutrient inputs (Dodd & Power, 2007) which has led to diminished vascular plant diversity and natural regeneration inhibition (Smale *et al.*, 2005).

Intensive farming and vegetation management within hill-country areas in the North Island has contributed to the ongoing degradation of biophysical resources (Blaschke *et al.*, 1992). When compared to native forests, Waikato hill-country pastoral streams have reduced shade, narrower channels, reduced wood volume and coarse particulate organic matter (CPOM) inputs, higher water temperatures, increased nutrient loads and dissolved organic carbon (DOC) concentrations, reduced clarity, increased algal abundance, and fewer sensitive invertebrate species (Quinn *et al.*, 1997; Quinn & Stroud, 2002; Quinn *et al.*, 2009). Increased streambed

sedimentation is also a major stressor, and high sediment yields are a major issue in the North Island, generally due to forest clearance and livestock grazing, combined with high rainfall rates, highly erodible lithologies and steep headwater areas (Hicks *et al.*, 1996).

Riparian vegetation restoration is promoted widely throughout the Waikato region to mitigate land use impacts on streams. The Waikato Regional Council (W.R.C.) works with iwi, farmers and community groups to aid in riparian management implementation (W.R.C., 2019). Co-management arrangements and joint management agreements between central government, W.R.C., and local iwi have contributed to the ongoing management of waterways throughout the Waikato rohe, including the restoration of riparian margins. The various iwi, hapū and marae in the Waikato rohe have produced their own management plans, each outlining riparian management actions specific to their area. In addition, community groups taking on local environmental issues can get a range of support from organisations and sponsors to implement riparian management, including from farming representatives such as Dairy NZ, Fonterra and Federated Farmers.

1.7 Objectives and outline of thesis

This thesis builds on previous work conducted on kōura in western Waikato streams by investigating interactions between in-stream habitat factors influenced by riparian vegetation and kōura populations. I was particularly interested in in-stream habitat associations of small kōura which are often not targeted in sampling with the result that their habitat use is poorly known.

The overall aim of this thesis was to identify and quantify in-stream habitat factors associated with kōura in Waikato hill-country streams, in particular juvenile kōura (defined as ≤ 8 mm OCL), by examining streams with varying riparian land uses to provide a range of expected in-stream habitat conditions. This research is intended to provide evidence-based information for iwi and community groups who would like to know more about restoring stream habitat to enhance kōura populations.

Within this aim I had two specific objectives:

- 1) to determine relationships between kōura abundance and size, and in-stream hydraulic, substrate and habitat cover variables at the micro- (band), meso- (sub-reach) and macro- (reach) habitat scales. These relationships encompassed four differing riparian vegetation treatments: pastoral, early riparian, late riparian and native forest;
- 2) to determine whether two constructed habitat types (ponga frond bundles and coconut fibre bundles to mimic CPOM accumulations and root wads, respectively) could enhance kōura abundances compared to natural cobbles in a pastoral stream. Relationships with toi toi (common and Crans bully, *Gobiomorphus* spp.), a species known to be associated with kōura habitat, were also investigated.

This thesis comprises four chapters, with the two main research chapters (Chapter 2 & 3) written in the form of scientific manuscripts for submission to scientific journals, and therefore there is some repetition between these chapters. Following the present chapter, Chapter 2 presents a survey investigating kōura relationships with habitat measured at different scales within 12 Waikato hill-country streams. Chapter 3 presents an experimental study, comparing two artificial habitat types with in-stream cobble habitat in relation to kōura and toi toi abundance and size. Finally, Chapter 4 presents a synthesis of the two preceding chapters by providing an overall discussion summarising the main findings from Chapters 2 & 3, with recommendations to aid in kōura restoration.

Chapter 2

Associations between kōura and in-stream habitat in Waikato hill-country streams

2.1 Introduction

Kōura can be found in multiple contrasting environments throughout New Zealand, from streams in native forested or pastoral farmland, high-country and lowland areas, large lakes to small ponds and in many freshwater wetlands, all with a variety of different habitats. Relationships between crayfish species and habitat have been well documented (Westman, 1985; Englund & Krupa, 2000; Usio & Townsend, 2000; Whitmore *et al.*, 2000; Parkyn *et al.*, 2002; Parkyn & Collier, 2004; Jowett *et al.*, 2008; Parkyn *et al.*, 2009; Reynolds *et al.*, 2013), yet these relationships are not fully understood due to the physical and hydrological complexity within stream environments, and difficulties in sampling kōura populations effectively. Studies throughout New Zealand show contrasting results when associating habitat type with *Paranephrops* spp. abundance (Usio & Townsend, 2000; Jowett *et al.*, 2008; Parkyn *et al.*, 2009), highlighting the variability of kōura habitat requirements.

Habitat can vary across a range of different scales, from micro-habitat providing localised cover that includes different-sized inorganic substrate types, undercut banks, vascular plant root systems, and woody debris where smaller organic matter accumulates (Parkyn & Collier, 2004; Jowett *et al.*, 2008; Parkyn *et al.*, 2009), through to macro-scale factors that differ between streams, such as riparian land cover. Habitat is heavily relied upon during the day as a food source and cover from predation or high flow events, but the scale(s) over which different habitat features influence kōura are not well known, particularly for juvenile kōura.

Juvenile kōura ≤ 8 mm orbital carapace length (OCL) have been reported to be associated with fine substrate and edge habitat in shallow, slow flowing areas (Jowett *et al.*, 2008; Parkyn *et al.*, 2009), and they may also favour dense root systems for protection (Parkyn & Collier, 2004). In contrast, Usio and Townsend (2000) associated juvenile *P. zealandicus* with coarse substrates, leaf litter and

wood, while adult *P. zealandicus* showed positive associations with sand but not coarse substrates. Larger crayfish also tend to be associated with deeper pools (Englund & Krupa, 2000; Usio & Townsend, 2000), and with gravels and cobbles. However, they are not as abundant around boulders, possibly due to interstitial spaces being too large and increasing susceptibility to predation or other broad-scale factors associated with boulder-dominated streams (Jowett *et al.*, 2008).

A study by Parkyn *et al.* (2002) concerning growth of kōura in pastoral streams indicated kōura grow to between 7 – 22 mm OCL in the first year (YOY) when entering the population as free-living juveniles between the warmer September to December months. Very little is known about the habitat use by recently-released free-living kōura (c. 3 – 4 mm OCL) due to difficulties around detection and sampling. For the purpose of this study, a size threshold of ≤ 8 mm OCL was used to describe juvenile kōura. This value was chosen as it was the median for YOY kōura (5-10 mm OCL) found in native streams (Parkyn *et al.*, 2002) and was used by Jowett *et al.* (2008) for generalised additive models to evaluate species-environment relationships.

This study was conducted in western Waikato hill-country streams that were in different stages of riparian fencing and planting (i.e., land treatments) — either none (pastoral), or early- or late-stage planting with fencing, or native forest. Agricultural practices in the Waikato hill-country have changed stream edges and altered hydraulic and physicochemical parameters in these streams that were once surrounded by native vegetation (Collier *et al.*, 2000; Quinn & Stroud, 2002; Hughes & Quinn, 2014). These changes have affected macroinvertebrate and fish communities by altering community structure including species habitat diversity (Quinn & Cooper, 1997; Quinn *et al.*, 1997; Hicks, 2003; Quinn *et al.*, 2009). This study looked at habitat inter-relationships and differences within streams, between streams and between land treatment types to identify land use effects on habitat availability for kōura.

2.1.1 Study aim and objectives

The major aim of this study was to determine relationships between kōura abundance and multiple in-stream habitats measured at different spatial scales, with a focus on micro-habitat and juvenile kōura. The different types of vegetation alongside streams were expected to influence particular aspects of habitat, thereby providing a gradient of habitat complexity from pasture to native sites. In particular, the study aimed to identify where juvenile kōura reside during the daytime compared to kōura generally, and determine the influences of different hydraulic, substrate and habitat cover variables that occurred within and between streams.

This aim was achieved through the following objectives: (i) to quantify habitat characteristics and variability along multiple 2-m (band) and 10-m (sub-reach) sections of channel at sites differing in riparian characteristics; (ii) to measure kōura abundance and size using proven and modified sampling techniques at the same scales; and (iii) to explore inter-relationships between kōura population parameters, including juvenile densities, and corresponding habitat variables measured at the same scale. The null hypothesis was that, within streams, between streams and across treatment types there would be no relationships between hydraulic, substrate and cover variables and kōura density or size.

2.2 Study area

This study was conducted in the north-western Waikato region which is bordered by dissected hills and ranges formed mainly on Mesozoic basement rocks with a thin cover of tertiary sedimentary rocks (Edbrooke, 2005). A total of twelve study sites were selected on nine streams with headwaters originating from three predominantly high-country areas, Mt. Karioi, Mt. Pirongia and the Hakarimata Range (Figure 2-1). The volcanic cones of Mt Karioi (756 m a.s.l.) and Mt Pirongia (959 m a.s.l.) dominate the landscape in this area and are located within the Pirongia Forest Park conservation area. The Hakarimata Ranges are located to the north, with the highest point being Mt Kokako (365 m a.s.l.) within the Kakariki Scenic Reserve. Headwaters within these areas are administered by the Department of Conservation, with pastoral farming downstream.

Mount Karioi and Mt Pirongia are part of the Alexandra Volcanic group comprised of basalt, basaltic andesite and andesite lava, tuff and tuff breccia with lahar deposits and andesite dikes (Edbrooke, 2005). The eastern base of Mt Pirongia is surrounded by alluvial and colluvial gravel, sand and mud (Edbrooke *et al.*, 2014). The Mt Kokako forest area, at the southernmost end of the Hakerimata Ranges, was formed from Late Triassic sedimentary rocks consisting of sandstones, siltstones and greywacke, known as the Newcastle Group part of the Murihiku Supergroup (Edbrooke *et al.*, 2014). The three maunga (mountains) are dominated by indigenous podocarp-broadleaved forests, tea-tree and tree ferns, surrounded with mixed indigenous scrub, grassland and improved pasture (2012 Biodiversity Vegetation (BIOVEG) data sourced from Waikato Regional Council).

The northern Waikato climate is humid and temperate (Hughes & Quinn, 2019), with a mean annual temperature of 13.9 °C and a mean annual rainfall of 1616 mm (1981-2010, Hamilton AWS station data (NIWA, 2019)). Mean annual rainfall can vary markedly between Mt Karioi (1357 mm; 1981-2010, Raglan, Karioi meteorological station data), Mt Pirongia (2318 mm; 1981-2010, Mt Pirongia, Makeokeo station data) and Mt Kokako Forest Range (1616.2 mm; 1981-2010, Whatawhata 2 EWS station data (NIWA, 2019)).

2.3 Methods

2.3.1 Site selection and description

Study sites were selected to represent a likely range of different levels of in-stream habitat complexity based on surrounding land use: pastoral (no riparian management), early riparian (planting age 1-5 years), late riparian (planting age 6-15 years), and native forest (conservation or reserve land) (Table 2-1; n = 3 per type). Riparian planting age information and likelihood of kōura presence was sourced from Kelly (2019). Kōura presence was based on: (i) Waikato Regional Council electrofishing records; (ii) direct assessment for kōura presence by walking a 10-m reach and inspecting 2-5 kicknet samples (following Stark *et al.* (2001)); or (iii) speaking with landowners. Streams that had no kōura or low kōura abundance were avoided as the intention was to associate kōura density with habitat availability.

Two study streams, the Whakakai and the Kiripaki, were located in proximity to the Mt Kokako forest ranges. The Whakakai study site was located within the Kakariki Scenic Reserve and the Kiripaki study site bordered the reserve. Two study streams, the Ahiawa and Wainui, were located on the north-eastern side of Mt Karioi with a third stream, the Toreparu, on the eastern side (one study site each). The Wainui study site was located in the Pirongia Conservation Area with the Ahiawa and Toreparu study sites on private land. The remaining four streams, the Te Pahu (three study sites), Rangitukia (two study sites), Mangakara and Mangamauku (one study site each), were all concentrated toward the north-eastern side of Mt Pirongia (Figure 2-1). One of the Rangitukia study sites was in the Pirongia Conservation Area, whereas the remainder were on private land (Table 2-1). For study sites on the same stream network, different tributaries > 300 m from stream confluence were chosen or sites were > 1 km apart to avoid direct upstream influence. All sites were on either first or second order streams.

The three study sites within pastoral areas (K3, T1 and MK1; Table 2-1, Figure 2-1) were representative of hill-country streams, unfenced from stock with predominantly grassy banks. The six study sites with early or late riparian planting (R1, TP6, TP5, TP1, MM1, AA1; Table 2-1, Figure 2-1) were surrounded by pasture but had fencing and riparian vegetation that included a mix of shrubs and small trees of different sizes, including tree ferns (*Cyathea* and *Dicksonia* spp.), harakeke (*Phormium tenax*), *Coprosma* spp., *Pittosporum* spp., mānuka and kānuka (*Leptospermum* & *Kunzea* spp.), parataniwha (*Elatostema rugosum*), koromiko (*Hebe* spp.), tī kōuka (*Cordyline australis*) and māhoe (*Melicytus ramiflorus*), as well as dominant forest canopy trees (e.g., rimu (*Dacrydium cupressinum*), rewarewa (*Knightia excelsa*), tōtara (*Podocarpus totara*) and kauri (*Agathis australis*)). Early riparian plantings also had a mixture of pastoral grasses and exotic plant species. Details of riparian zone vegetation composition are given in Kelly (2019).

The remaining three sampling sites (R2, W2 and WK1; Table 2-1, Figure 2-1) all had native forest regrowth or original indigenous forest surrounding them and the upstream catchments enclosed by fencing, and were sampled to provide reference sites unimpacted by land use development. R2 and W2 were situated on Mt Pirongia and Mt Karioi, respectively, within the Pirongia Forest Park. Both sample sites were

surrounded by indigenous podocarp-broadleaved vegetation characteristic of the remaining native forest remnants throughout the Waikato (Clayton-Greene & Wilson, 1985). WK1 was situated within the Kakariki Scenic Reserve and was vegetated in regenerating podocarp-broadleaf forest, having been retired in the early 20th century and undisturbed by human activities for the past 85 years (Hughes et al., 2012).

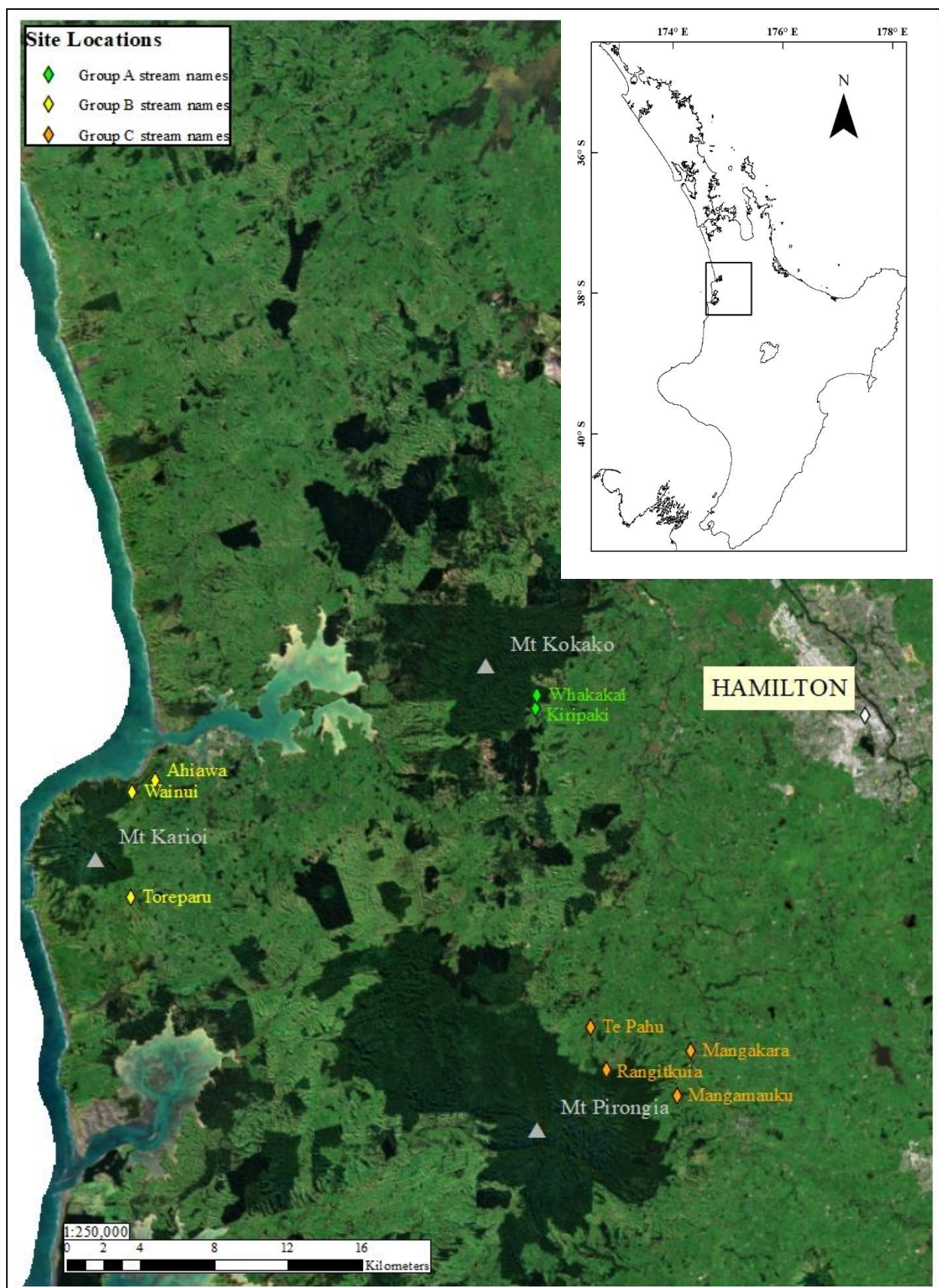


Figure 2-1 Map of study site locations in north-western Waikato. Streams are grouped by geographical location near dominant high-country mountains. Mt Kokako (green) = Group A, Mt Karioi (yellow) = Group B, Mt Pirongia (orange) = Group C (see Table 2-1).

Table 2-1 Stream names with site codes and locations of all twelve sample sites grouped by riparian treatment with age of riparian planting where relevant, surrounding land ownership, geographical locational group (see Figure 2-1), and River Environment Classification (REC) data on catchment area, elevation and channel slope

Stream name	Site code	GPS top of reach (easting, northing)		Locational group	Treatment	Age of riparian planting	Landowner type	Catchment area (m ²)	Top reach elevation (m a.s.l.)	Slope of reach (°)
Kiripaka	K3	1782307	5816301	A	Pastoral	0	Private	420424	64.39	0.33
Toreparu	T1	1760345	5805687	B	Pastoral	0	Private	1797450	405.1	5.16
Mangakara	MK1	1790711	5797113	C	Pastoral	0	Private	3203466	375.6	3.82
Rangitukea	R1	1787065	5798650	C	Early Rip	1-5 years	Private	1100215	156.53	2.31
Te Pahu trib	TP6	1785303	5798430	C	Early Rip	1-5 years	Private	156656	118.19	3.32
Te Pahu trib	TP5	1785597	5798443	C	Early Rip	1-5 years	Private	326818	129.24	5.07
Mangamauku	MM1	1789958	5794580	C	Late Rip	6-15 years	Private	1863738	538.2	7.23
Te Pahu trib	TP1	1784693	5796957	C	Late Rip	6-15 years	Private	367329	408.12	8.28
Ahiawa	AA1	1761662	5812249	B	Late Rip	6-15 years	Private	365431	79.33	2.34
Rangitukea	R2	1786101	5796053	C	Native	n/a	Conservation	612226	476.27	9.13
Wainui	W2	1760400	5811589	B	Native	n/a	Scenic Reserve	3129518	358.5	3.59
Whakakai	WK1	1782354	5817042	A	Native	n/a	Conservation	232269	79.06	2.15

2.3.2 Reach measurements

Samples were collected over representative 50-m reaches for each of the 12 sites. GPS coordinates (Garmin 64s, NZTM2000) were recorded (see Table 2-1) and photographs were taken at the top and bottom of the 50 m reach (see Appendix 2.1). Water temperature (°C), conductivity ($\mu\text{S}/\text{cm}$ at 25 °C) and dissolved oxygen (mg/L and %) were recorded using YSI ProDSS™ or YSI Pro2030™ multiparameter meters at the bottom of each sample site prior to sampling (Table 2-2).

2.3.3 In-stream habitat measurements

Each 50-m reach was divided into 5 x 10-m sub-reaches, and the first, third and fifth sub-reaches were sampled (i.e., there was a gap of 10 m between sub-reaches). Each sub-reach was then sub-divided further into 5 x 2 m bands for a total of 15 bands per reach. Sub-reaches were visually inspected for accumulations of submerged coarse particulate organic matter (CPOM; > 1 cm in size) which were quantified before electrofishing and disturbance within the stream commenced. CPOM was grouped into four categories: ponga log (PL), ponga/nikau fronds (combined as native fronds, NF), other large wood (W), and other smaller organic matter (OM; predominantly leaves). CPOM accumulations within each band were measured for length and width using a 1 m ruler to the nearest 0.05 m to calculate submerged horizontal planar area (m^2).

Following electrofishing (see below), assessments of other in-stream habitat variables within each band were conducted. Available submerged root habitat was measured along the planar area (length x width) grouped into willow roots (WR), grass roots (GR), fern roots (FR), and “other” root mats (RM). Undercut habitat was also measured in each band by inserting a 1 m ruler horizontally to the back of the undercut to measure undercut depth to the nearest 0.05 m, which was then multiplied by undercut length to determine undercut area. Stream wetted width and channel width were measured across the mid-point of each band, and at three points across each band transect (25%, 50% and 75% of wetted width). Water depth (using a metric wading rod to 0.01 m) and velocity (using a Marsh-McBirney™ Flo-Mate 2000 and Hach™ FH950 Velocity Flow Meter at 40% depth to 0.01 m/s accuracy) were also measured at these locations.

Within each band, substrate size composition was measured using a Wolman square sampler with Wentworth size scales (Wolman, 1954) based on particle size across the b-axis dimension which was then classified into size groupings. Ten particles were sampled at uniformly-spaced intervals along each band transect line across the wetted width. An inorganic substrate size index was then calculated based on sums of the weighted substrate percentages (Jowett *et al.*, 1991). The weighting values were slightly modified from the original substrate codes (Bovee, 1982) to allow for two cobble categories, large and small: Substrate size index = $0.08 \times \text{bedrock\%} + 0.07 \times \text{boulder\%} + 0.06 \times \text{large cobble\%} + 0.05 \times \text{small cobble\%} + 0.04 \times \text{gravel\%} + 0.03 \times \text{sand/silt\%} + 0.02 \times \text{clay\%}$.

Additionally, substrate compactness, embeddedness and algal cover were estimated within each band. Substrate compactness was determined by disturbing the streambed by foot to indicate the degree of stability of the substrate (Harding *et al.*, 2009). Compactness was assessed on a 1-4 scale (1 = loose, easily moved substrate; 2 = mostly loose, little compaction; 3 = moderately packed; 4 = tightly packed). Substrate embeddedness was measured by visual assessment of the amount of fine sediment surrounding the dominant substrate. Embeddedness was also assessed on a 1-4 scale (1 = not embedded, the substrate on top of the bed; 2 = slightly embedded, < 25% of the particle buried or attached to the surrounding substrate; 3 = firmly embedded, approximately 50% of the substrate embedded or attached to the surrounding substrate; 4 = heavily embedded, > 66% of the substrate buried). Algal cover was estimated by touching the substrate and visually assessing presence on a 1-5 scale (1 = none, 0% cover; 2 = slippery, 1-25%; 3 = thin algal mat/short filamentous, 26-50%; 4 = medium algal mat/filamentous, 51-75%; 5 = thick algal mat/long filamentous, > 75% (Wooster *et al.*, 2012)).

2.3.4 Kōura sampling

A fixed stop net with 5-mm mesh was secured perpendicular to the stream at the downstream end of each 10-m sub-reach to capture any kōura missed during electric fishing. Each 2-m band within a sub-reach was fished with a Kainga back-pack electric fishing machine (EFM300; NIWA Instrument Systems) using soft bristled brooms in place of scoop nets to sweep kōura into a hand-held stop net. This

spatially-focussed approach (at the 2-m scale) was intended to relate data on kōura abundance, size and sex with in-stream habitat characteristics within each band. Two consecutive electric fishing passes were completed for each band. At sites MK1, TP1, AA1, R2, W2 and WK1, first and second pass kōura numbers were compared and showed that 72% of the 245 kōura from two passes over the six sites were caught in the first pass.

Captured kōura from each band were retained in separate buckets on the stream edge until the entire sub-reach had been fished. Vernier callipers were then used to measure kōura orbital carapace length (OCL) from the back of the eye socket to the mid-dorsal posterior border of the carapace (Hopkins, 1967b) to the nearest 0.5 mm. Sex for larger kōura (typically > 11 mm OCL) was identified by observing the male genital openings on the bases of the last pair of walking legs, compared to the females genital openings on the 2nd pair of walking legs (Chapman *et al.*, 2011).

2.3.5 Targeted sampling of organic habitats

For a comparative study between habitat types and kōura abundance, organic habitats were sampled for kōura along a 400 m stretch at an independent location directly upstream from the manipulation study site in Chapter 3 (see Section 3.2 for detailed site description). Sampling took place at two locations on 26 November 2018 and one location on 12 March 2019. Habitats identified to sample were the macrophytes *Nitella* and watercress (*Nasturtium officinale*), various submerged root systems (referred to collectively as root mats), and coarse particulate organic matter made up of leaves, branches and other organic debris accumulations. Kōura in these habitats were sampled by placing a rectangular net (0.5 m x 0.4 m open face by 0.6 m long net, 0.5 mm mesh) below each habitat and then disturbing it with a broom and creating current to push kōura into the net. Kōura caught using this approach were counted, measured for orbital carapace length (OCL) to the nearest 0.5 mm using Vernier callipers and sexed if > 11 mm OCL. Due to the number of unidentifiable small kōura, sex determination did not provide relevant data.

2.3.6 Statistical analysis

All statistical tests were performed in Statistica 64™ (v. 13, TIBCO Software Inc. 2017).

Relationships between variables

Correlations amongst habitat variables, and between the kōura and habitat variables were analysed using non-parametric Spearman rank test to explore whether these factors could be influencing one another. $P < 0.01$ was used as a conservative threshold for determining statistical significance to reduce the possibility of making Type I errors due to the high numbers of multiple comparisons. Since statistical significance is dependent on degrees of freedom which is related to sample size, the threshold for significance varied across the three scales tested. Thus, when interpreting strength of the absolute r_s values to compare across scales the following guide (Statstutor, 2019) was used:

- $\pm .00-.19$ “very weak”
- $\pm .20-.39$ “weak”
- $\pm .40-.59$ “moderate”
- $\pm .60-.79$ “strong”
- $\pm .80-1.0$ “very strong”

Habitat variables tested were grouped into hydraulic, substrate and cover variables. Habitat inter-correlations were determined at the band-scale, while habitat-kōura correlations were performed across three scale ranges of band, sub-reach and reach to explore whether relationships varied with scale. The kōura variables tested were total kōura and juvenile abundances within each sampling unit (band, sub-reach) and per unit of wetted streambed area (m^2). Juvenile kōura were defined as those with $OCLE \leq 8$ mm. This analysis tested the null hypothesis that there was no significant correlation between kōura densities or size, stream characteristics, habitat types and stream edge treatments either within or between sites.

Comparisons between sites and treatments

Kruskal Wallis non-parametric analysis based on ranked data was used to compare kōura variables across sites and treatments at the band, sub-reach and site (treatments only) scales. If significant values were identified at $p < 0.05$, post-hoc pairwise comparisons were performed using Z-tests. This analysis tested the null hypothesis that total kōura and juvenile abundances, and mean sizes were not affected by site or treatment differences.

2.4 Results

2.4.1 Physicochemical and habitat characteristics

Spot water temperatures measured before 10:00 h were $< 15.4^{\circ}\text{C}$ at all sites, with the highest temperature at a native forest site in early January (all other sites were measured in November or December) (Table 2-2). Conductivity ranged from $53.5\ \mu\text{S}/\text{cm}$ (at 25°C) to $130.1\ \mu\text{S}/\text{cm}$, with lowest and highest values at native forest sites. Measured dissolved oxygen levels covered a narrow range ($10.0\text{--}11.1\ \text{mg}/\text{L}$) and were close to saturation ($> 96\%$).

Table 2-2 Physicochemical data, with date and time sampled, for each site. Sites are grouped by pastoral, early riparian, late riparian, and native treatments (light to dark green shades, respectively).

Site code	Date sampled	Time sampled	Water temp. ($^{\circ}\text{C}$)	Conductivity ($\mu\text{S}/\text{cm}@25^{\circ}\text{C}$)	Dissolved oxygen (mg/L)	(%)
K3	7/11/2018	09:30:00	12.4	112.8	10.9	102.1
T1	12/11/2018	09:17:00	13.9	79.8	10.5	101.4
MK1	29/11/2018	08:38:00	14.3	69.8	10.7	105.0
R1	13/11/2018	08:24:00	12.9	71.8	11.1	110.0
TP6	14/11/2018	09:30:00	14.3	72.1	10.6	103.9
TP5	16/11/2018	08:49:00	13.7	68.6	10.2	97.9
MM1	15/11/2018	08:43:00	14.5	57.5	10.6	103.7
TP1	19/11/2018	09:30:00	12.1	68.7	10.6	98.1
AA1	27/11/2018	09:03:00	15.1	106.8	10.0	99.4
R2	22/11/2018	08:28:00	10.0	53.2	11.0	96.2
W2	7/12/2018	08:31:00	11.7	113.8	11.1	103.3
WK1	7/01/2019	09:31:00	15.4	130.1	10.9	108.2

The average stream wetted and channel widths across all sample sites ranged from 0.8 m to 4.36 m, and 1.14 m to 4.97 m, respectively, with the lowest and highest wetted width values recorded at early riparian treatment sample sites (Table 2.3). Average depth was similar across all sites (0.12-0.21 m) except for the native site R2 where it averaged 0.06 m. Average velocity ranged from 0.06 m/s to 0.29 m/s with no patterns evident in relation to treatment (Table 2.3). In terms of hydraulic habitat variability, coefficients of variation (cv) within sites (SD/mean) were < 0.38 for width, while depth and velocity were much more variable (0.37-0.90 and 0.66-1.11, respectively), but there were no consistent patterns related to treatment.

Root mats made up 27% of the substrate at TP1 and were also recorded on the substrate at sample sites K3 (2%) and R2 (5%) (Figure 2-2). Both the pastoral sample site K3 and native site WK1 had predominately gravel substrates (49% and 55% respectively) with the highest bedrock percentage (23%) recorded at WK1 in the absence of boulders at this site (Figure 2-2). Dominant substrate types across all other sites ranged from gravels (2-60 mm) to boulders (> 250 mm). The averages for the weighted inorganic substrate size index (i.e., root mats were excluded from calculations) per reach from the total band scores (n = 180 bands) ranged from 3.32 to 5.88 (Table 2-3). Coefficients of variations in substrate scores was low between pastoral treatments (< 0.12) with the lowest variation at site MK1 (0.05; Table 2-3). Variation in substrate size composition was high (0.48) at TP1 (4.27), and there was notable variation (0.30) at site TP5 (3.32) which was dominated by a sand/silt (75% < 2 mm) and clay (9%) bottom (Figure 2-2).

The average compactness of the substrate ranged from 2 (mostly loose) to 4 (tightly packed) across all sample reaches. Pastoral sites averaged either mostly packed or tightly packed and across all late riparian sites the average compactness score was 3 (mostly packed) (Table 2.3). Four sites, MK1, R1, MM1, W2 had no surficial fine sediment (embeddedness = 1); each site was from a different treatment i.e. pastoral, early riparian, late riparian and native, respectively. No sample site recorded an average score of 4 (heavily embedded, > 66% of the substrate buried) (Table 2.3). On average, algae were not visible in sample reaches at 7 sites, K3, T1, TP5, MM1, TP1, R2, and WK1. At sites MK1 and W2, algal cover averaged a score of 3 (thin algal mat/short filamentous, 26-50%). Remaining sites had filamentous algal cover less than this.

Table 2-3 Hydraulic and substrate values for each reach. Values are means of 15 bands per reach (n = 180 bands) with SD (standard deviation) and CV (coefficient of variation) where appropriate, grouped by pastoral, early riparian, late riparian, and native treatments (light to dark green shades, respectively).

Site code	Hydraulic variables												Substrate variables					
	Wetted width (m)			Channel width (m)			Depth (m)			Velocity (m/s)			Substrate size index			Compact-ness (1-4)	Embedded-ness (1-4)	Algal cover (1-5)
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV			
K3	2.09	0.25	0.12	2.28	0.33	0.14	0.17	0.13	0.74	0.12	0.10	0.83	4.28	0.45	0.11	3	2	1
T1	1.66	0.39	0.23	1.83	0.67	0.36	0.17	0.08	0.45	0.24	0.18	0.76	5.75	0.64	0.11	4	2	1
MK1	3.91	1.14	0.29	4.97	0.96	0.19	0.19	0.10	0.52	0.25	0.16	0.66	5.46	0.26	0.05	3	1	3
R1	4.36	0.58	0.13	4.85	0.51	0.10	0.16	0.07	0.42	0.27	0.22	0.79	5.61	0.44	0.08	3	1	2
TP6	3.74	0.89	0.24	3.77	0.89	0.24	0.18	0.06	0.35	0.29	0.23	0.78	5.77	0.52	0.09	4	2	2
TP5	0.80	0.29	0.37	1.14	0.34	0.30	0.12	0.06	0.54	0.06	0.06	0.99	3.32	1.01	0.30	2	3	1
MM1	3.25	0.91	0.28	3.84	0.79	0.21	0.15	0.09	0.63	0.23	0.18	0.81	5.88	0.44	0.08	3	1	1
TP1	1.85	0.57	0.31	2.14	0.63	0.29	0.14	0.12	0.90	0.25	0.27	1.08	4.27	2.05	0.48	3	2	1
AA1	2.15	0.66	0.31	2.49	0.51	0.20	0.21	0.08	0.40	0.12	0.13	1.11	5.32	0.87	0.16	3	3	2
R2	1.56	0.59	0.38	2.01	0.58	0.29	0.06	0.02	0.37	0.08	0.08	0.99	5.03	0.94	0.19	3	2	1
W2	3.11	0.64	0.20	3.75	0.44	0.12	0.15	0.06	0.39	0.26	0.18	0.69	5.59	0.56	0.10	3	1	3
WK1	3.69	0.66	0.18	4.24	0.53	0.12	0.21	0.12	0.58	0.09	0.10	1.11	4.95	1.23	0.25	2	2	1

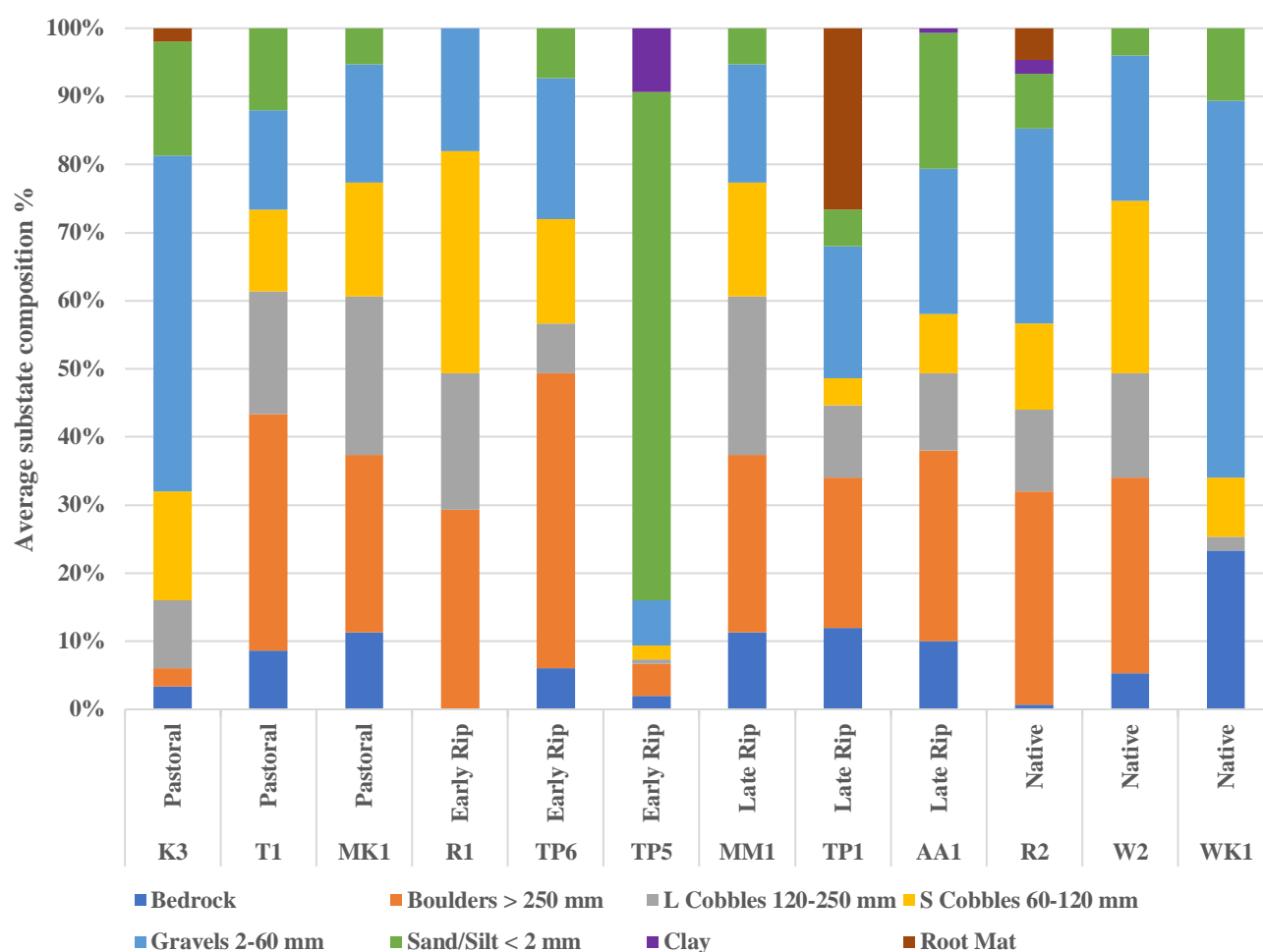


Figure 2-2 Substrate composition at the twelve sites (n = 15 bands per site) grouped by treatment. For cobbles, L = large; S = small.

Habitat cover by roots, bank undercuts and CPOM across the twelve sample reaches is shown as the percent of areal streambed cover in Table 2-4. Willow roots were recorded at one pastoral site (K3) while grass roots were most common at pastoral (average for 3 sites = 2.5% of total reach area) and early riparian (1.8% on average) sites, although there was considerable variation between sites. Only one pastoral treatment (MK1) accumulated small stick and leafy debris (1.4%) with no CPOM recorded at remaining pastoral sites. Fern roots (average for 3 sites = 0.7%), ponga logs (average for 3 sites = 0.1%), “other” organic matter (average for 3 sites = 1.1%) and “other” tree root systems (average for 3 sites = 0.5%) started to increase at the early riparian sites, however, these sites had no large woody material which appeared only in late riparian and native sites. Across the late riparian sites, combined fern roots and “other” tree root systems (average 4.9% of total stream area for 3 sites) became dominant over grass roots (average for 3 sites = 2%).

The average of total CPOM cover was highest within native forest (3.8%) when compared across all treatments, and bank habitat area was predominantly tree and fern roots with an absence of grass roots. Average percentage of potential habitat area that was undercut across three sites grouped by treatment was highest overall at pastoral (3.7%) and early riparian (3.1%) sites compared to late riparian (2.5%) and native (1.3%) sites. Variability among sites appeared high in pastoral streams, with T1 and MK1 recording highest (8.5%) and lowest (0.3%) percentage of undercut habitat.

Table 2-4 Percentage of wetted stream area covered by submerged root habitats, bank undercuts and CPOM for each sample reach (sum of 15 bands per reach), grouped by pastoral, early riparian, late riparian and native treatments (light to dark green shades, respectively).

Bank habitat (%)							CPOM (%)				
Site code	Willow root	Grass root	Fern root	Root mat	Total root	Total undercut	Large wood	Ponga log	Native Fronds	Organic matter	Total CPOM
K3	1.98	0.91	0.00	0.00	2.90	2.44	0.00	0.00	0.00	0.00	0.00
T1	0.00	6.52	0.06	0.08	6.66	8.45	0.00	0.00	0.00	0.00	0.00
MK1	0.00	0.19	0.00	0.00	0.19	0.29	0.00	0.00	0.00	1.44	1.44
R1	0.00	0.47	0.02	0.15	0.64	1.64	0.00	0.00	0.00	0.28	0.28
TP6	0.00	3.60	0.11	0.28	3.98	2.51	0.00	0.11	0.00	0.50	0.61
TP5	0.00	1.42	1.84	1.00	4.27	5.19	0.00	0.08	0.00	2.38	2.47
MM1	0.00	1.44	0.36	1.27	3.07	2.99	0.12	0.00	0.00	0.70	0.82
TP1	0.00	3.14	0.34	10.29	13.77	2.00	0.00	1.87	0.00	0.83	2.70
AA1	0.00	1.54	1.37	0.92	3.82	2.41	0.28	0.00	0.00	1.97	2.25
R2	0.00	0.00	0.30	2.76	3.06	0.86	0.26	0.45	0.00	5.38	6.08
W2	0.00	0.00	0.04	1.48	1.51	1.79	0.30	0.43	0.16	0.76	1.65
WK1	0.00	0.00	1.09	1.26	2.35	1.17	1.65	0.74	1.22	0.00	3.61

2.4.2 Intercorrelations among hydraulic, substrate and cover variables

Unsurprisingly, there was a strong correlation between wetted width and channel width, which was also correlated inversely with surficial fine sediment cover (embeddedness) and positively with algal cover, such that wider streams had lower embeddedness and more algal cover. Statistically significant ($p < 0.01$) positive correlations were also found between width and mean water depth, and velocity and substrate size index, indicating that wider streams tended to be deeper, faster flowing and have coarser substrates. Mean velocity also showed a significant positive correlation with the substrate size index, compactness and algal cover, but was negatively correlated with embeddedness (Table 2-5). Indeed, substrate size index, compactness, embeddedness and algal cover were all intercorrelated.

There were several significant correlations among cover variables, particularly the various measures of CPOM, large wood and root mat types (Table 2-5). Notably, where grass roots were more abundant, other root mat systems and CPOM were less common which was observed to be typical of grass-bank dominated streams. Significant positive correlations occurred for undercuts with depth, and for root mats and large wood with depth CV, indicating undercut area was associated with deeper water and that root mats and wood increased depth heterogeneity. An inverse correlation between velocity and total CPOM suggests that water flow can potentially reduce the amount of CPOM maintained in-stream. Total root mat systems, consisting of 42% grass roots and 58% other tree roots, were significantly correlated with embeddedness and inversely with algae. These relationships, along with significant positive correlations between embeddedness and ponga logs, CPOM and total roots, indicates that vascular plant material accumulation is associated with increased surficial sediment cover. Compaction was inversely related to the area occupied by ponga logs suggesting they may influence substrate stability.

Table 2-5 Matrix of Spearman rank correlation coefficients (r_s) for hydraulic, substrate and cover variables (light to dark yellow shades, respectively) measured at each band (n = 180). CV = coefficient of variation. P < 0.01 (**bold**) was used to infer statistical significance to reduce Type 1 error from multiple comparisons. Only variables with at least one correlation with p < 0.01 are shown.

	Wetted width (m)	Channel width (m)	Mean depth (m)	Depth CV	Mean velocity (m/s)	Compactness (1-4)	Embeddedness (1-4)	Algae (1-5)	Ponga/fern root (m ²)	Grass root (m ²)	Other root mat (m ²)	Large wood (m ²)	Ponga log (m ²)	Ponga/nikau fronds (m ²)	Other organic matter (m ²)
Channel width (m)	0.94														
Mean depth (m)	0.27	0.22													
Mean velocity (m/s)	0.32	0.33	-0.30	0.14											
Compactness (1-4)	0.08	0.10	0.05	-0.02	0.48										
Embeddedness (1-4)	-0.45	-0.48	0.05	-0.06	-0.60	-0.52									
Algae (1-5)	0.47	0.52	0.13	-0.01	0.42	0.24	-0.46								
Inorganic substrate index	0.30	0.34	0.14	0.00	0.40	0.59	-0.44	0.40							
Other root mat (m ²)	0.01	-0.03	0.00	0.22	-0.03	-0.07	0.18	-0.03	-0.14	-0.25					
Total root (m ²)	-0.05	-0.13	0.16	0.11	-0.07	0.04	0.26	-0.25	0.23	0.51	0.40				
Total undercut (m ²)	0.04	-0.05	0.32	-0.01	-0.02	0.07	0.02	0.02	-0.01	0.21	-0.05				
Large wood (m ²)	0.09	0.10	0.00	0.25	-0.01	-0.08	0.05	-0.01	0.06	-0.07	0.22				
Ponga log (m ²)	0.09	0.08	0.07	0.00	-0.17	-0.19	0.21	-0.11	0.16	-0.15	0.15	0.21			
Ponga /Nikau fronds (m ²)	0.18	0.14	0.09	0.08	-0.13	-0.19	0.03	-0.07	0.14	-0.10	0.11	0.15	0.31		
Total CPOM (m ²)	0.06	0.05	-0.04	-0.02	-0.21	-0.19	0.20	0.03	0.09	-0.28	0.29	0.32	0.35	0.27	0.81

2.4.3 Kōura population characteristics

Kōura abundance, mean size, number of juveniles (≤ 8 mm OCL; Jowett *et al.* (2008)), and number of females > 11 mm OCL were determined at the band scale and extrapolated out to the sub-reach and reach scales. Ten kōura were found in the stop nets at 6 different sub-reach locations after sampling; these were not included in the band calculations but were included in the sub-reach and reach calculations. A total of 497 kōura were collected over the 12 reaches with 115 kōura too small to be sexed (≤ 11 mm OCL). From the remaining 382 identifiable kōura, 49% were female (sex ratio 1:1), with two in berry. Analysis of female data separately did not reveal any patterns that were not evident by examining total kōura, so sexes were not differentiated in subsequent calculations. Juveniles comprised 22% of kōura collected and the average shock time per m^2 was 16.5 seconds. Because abundance (total number) and density (number per m^2) measures for total kōura and juvenile kōura were highly correlated ($r_s = 0.91$ and 0.99 , respectively), only density and mean size data for total kōura were used in statistical analyses.

2.4.4 Differences within and between sites

Early riparian sites TP6 and TP5 recorded highest (85 kōura) and lowest (11 kōura; Table 2-6) abundances, respectively. After accounting for wetted width and total area fished, total kōura density did not mirror abundances; sites TP1 and R2 recorded the highest densities (> 1 kōura per m^2) and MK1 and W2 the lowest (0.1 - 0.2 per m^2) (Table 2-6). Sites R2 and TP1 also had the highest juvenile abundances (39 juveniles each) and densities (0.84 and 0.70 per m^2 , respectively), whereas no juvenile kōura were collected at sites K3, T1, MK1, TP5 and MM1 (Table 2-6).

Using sub-reaches as replicates, Kruskal-Wallis test indicated significant differences ($p < 0.05$) between sites for total and juvenile kōura density (Table 2-7), but no pairwise comparisons were significant. More detailed comparisons between sites based on band-scale data showed highly significant effects of site ($H = 50.35$, $df = 11$, $n = 180$, $p < 0.001$), and revealed lower total kōura densities at sites T1, MK1 and W2 compared to sites TP6, TP1 and R2 (Figure 2-3A; Appendix 2.2). For juvenile kōura densities at the band scale ($H = 87.52$, $df = 11$, $n = 180$, $p < 0.001$),

pairwise comparisons showed that juvenile kōura densities at site R2 were higher than all sites apart from TP1, AA1 and WK1 (Figure 2-3C).

Table 2-6 Kōura population characteristics for each site showing total numbers across 15 bands (2 m long), and band averages with standard deviations (SD) for each site reach (n = 180 bands; OCL = orbital carapace length). Grouped by pastoral, early riparian, late riparian, and native treatments (light to dark green shades, respectively).

Site code	Kōura number	Kōura per m ²	Mean size ±SD (mm OCL)		Female kōura (%)	Juvenile kōura number	Juvenile kōura per m ²
K3	33	0.53	14.07	±3.57	45	0	0
T1	13	0.26	14.79	±1.85	31	0	0
MK1	15	0.13	18.27	±5.62	53	0	0
R1	47	0.36	13.58	±4.36	45	2	0.02
TP6	81	0.72	13.33	±4.41	36	5	0.04
TP5	11	0.46	14.23	±2.20	73	0	0
MM1	61	0.63	16.08	±3.46	48	0	0
TP1	72	1.30	9.46	±4.53	26	39	0.70
AA1	27	0.42	11.34	±3.67	41	5	0.08
R2	57	1.22	7.80	±3.55	19	39	0.84
W2	17	0.18	11.22	±1.31	59	3	0.03
WK1	53	0.48	9.62	±4.21	30	16	0.14

Average kōura size per band ranged from 4.5 mm to 25 mm OCL, with site MK1 having the largest kōura size on average and site R2 the lowest (Table 2-6). Using sub-reaches as replicates, Kruskal-Wallis test indicated significant differences among sites for mean size (Table 2-7), but no pairwise comparisons were significant. Comparisons among sites based on band-scale data showed highly significant effects of site ($H = 72.97$, $df = 11$, $n = 180$, $p < 0.01$), with significant pairwise differences ($p < 0.05$) in mean kōura size between MK1 and TP1, AA1, R2, W2, and WK1 (Figure 2-3B; Appendix 2.2). For site MM1, which also supported large kōura (mean size 16.08 mm OCL \pm 3.46 SD), similar significant pairwise

differences were also evident for the same five sites. The native forest site R2, which had the lowest mean kōura size, showed significant differences to sites K3, T1, MK1, R1, TP6, and MM1 all of which had mean size > 13 mm OCL and were in either pastoral or early riparian locations.

Table 2-7 Summary of Kruskal-Wallis results comparing kōura densities and mean size across 12 sample sites (n = 3 sub-reaches per site) and four treatments (n = 3 sites per treatment). H = Kruskal-Wallis statistic, df = degrees of freedom, **bold** = probability (p) < 0.05.

Site					
Kōura variables	Median	H	df	N	p value
Kōura per m²	0.37	23.98	11	36	0.01
Mean size (mm OCL)	13.39	27.89	11	36	<0.01
Juvenile kōura per m²	0	26.69	11	36	0.01
Treatment					
Kōura variables	Median	H	df	N	p value
Kōura per m²	0.47	2.54	3	12	0.47
Mean size (mm OCL)	13.45	6.44	3	12	0.09
Juvenile kōura per m²	0.02	6.04	3	12	0.11

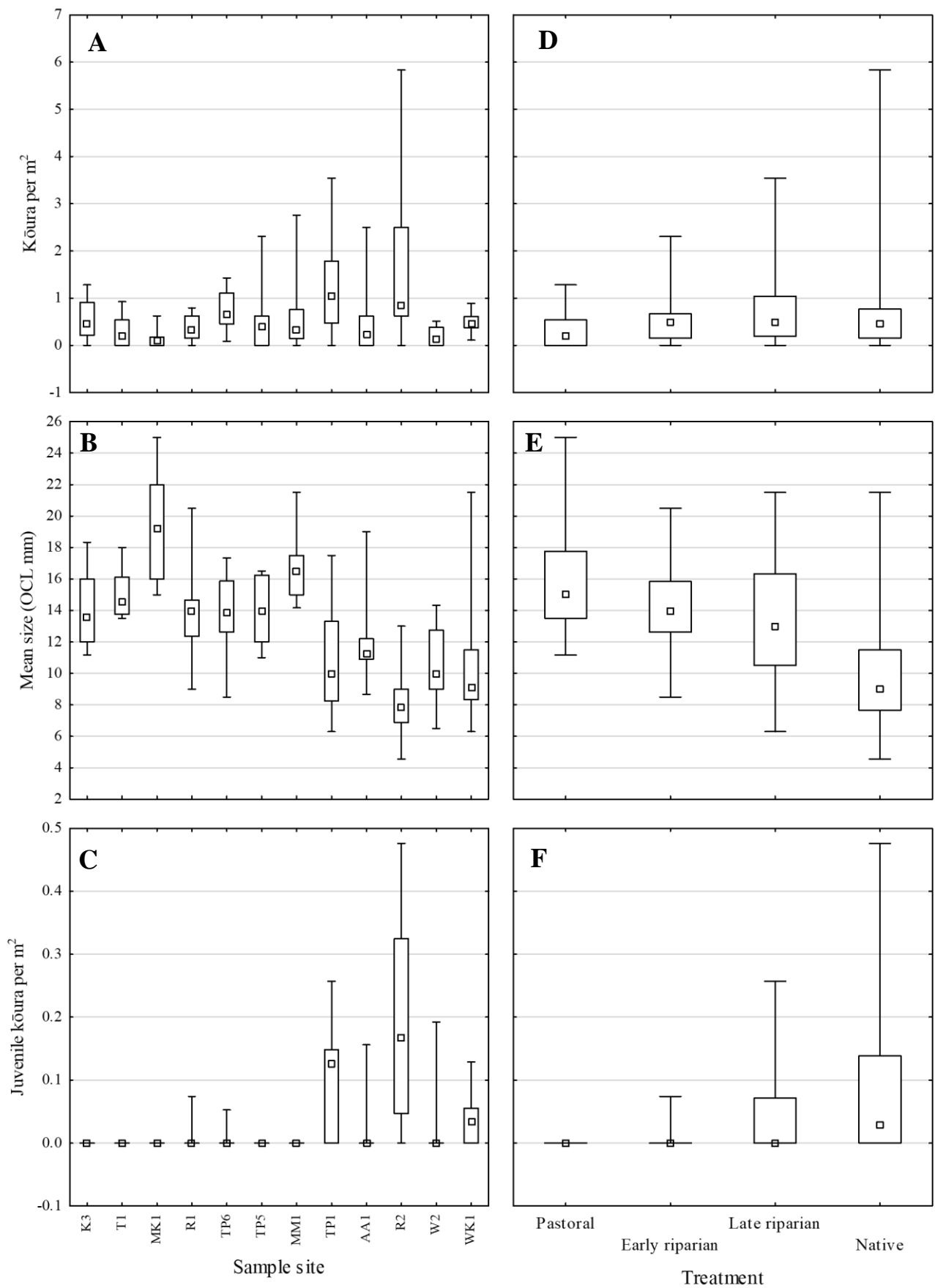


Figure 2-3 Differences of kōura densities and mean sizes between 12 sites ($n = 15$ bands per site; A-C) or between 4 treatments ($n = 3$ sites per treatment; D-F), showing median as the middle square, 25%-75% spread as larger boxes, and min/max values as whiskers.

2.4.5 Differences between treatments

The total number of kōura per band varied across pastoral (0-5), early riparian (0-11), late riparian (0-17), and native (0-9) treatments. Overall, total kōura density tended to increase from pastoral (61 kōura in all bands across three sites) to early riparian (139 kōura) to late riparian (161 kōura) treatments, and then decreased slightly in the native sites (127 kōura). The late riparian treatments twice recorded the highest number of kōura caught in a single band (Figure 2-4) compared to highest densities found in the native treatments (Figure 2-3D). For statistical comparison of treatments (Kruskal-Wallis test), three sub-reaches within sites were combined (i.e., $n = 3$ sites per treatment) and showed no significant differences in total kōura densities between treatments ($p > 0.05$; Table 2-7).

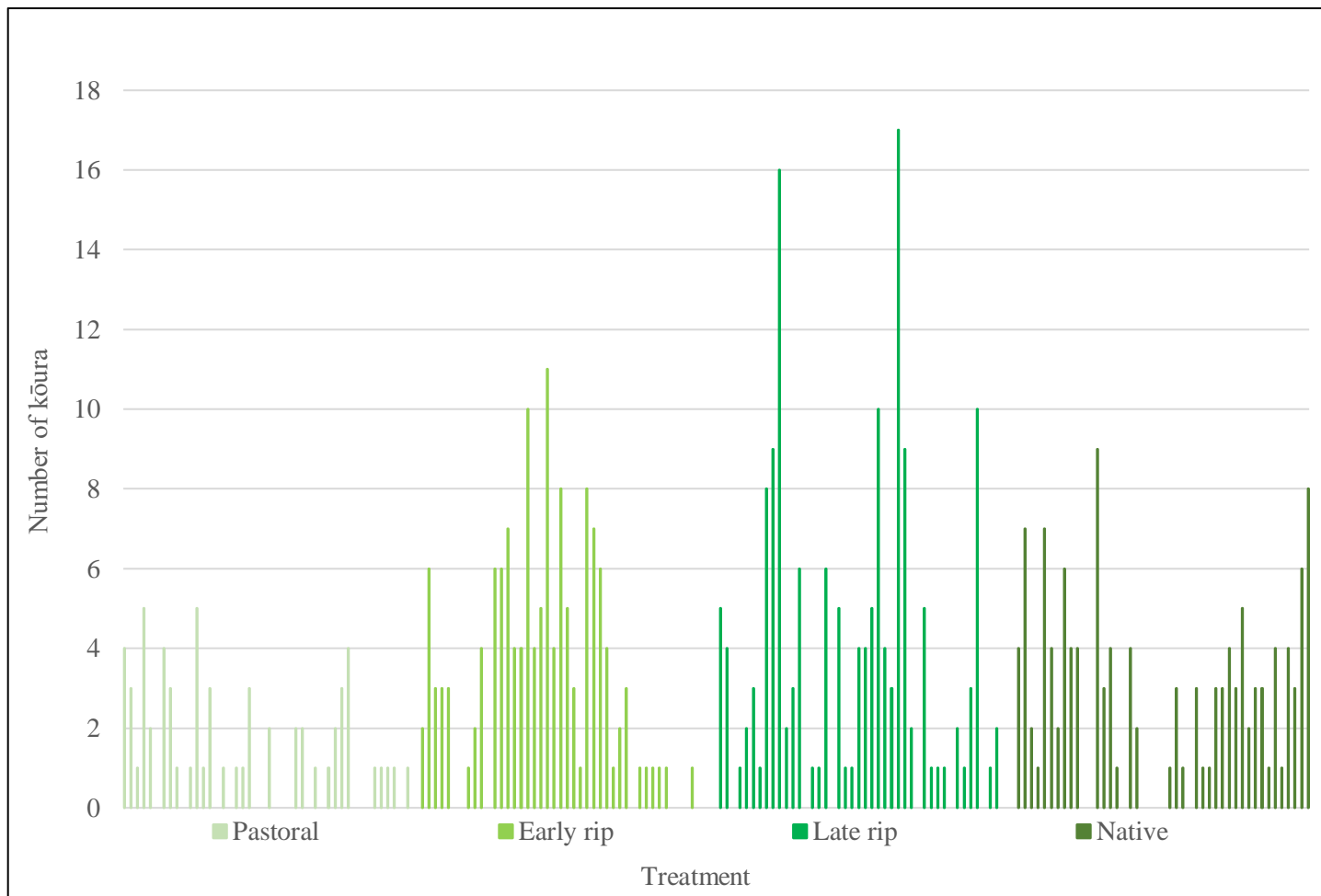


Figure 2-4 Total number of kōura collected per band, ordered by sites shown in Table 2-6 (15 bands per site) and grouped by pastoral, early riparian, late riparian and native treatments (light to dark green, respectively).

Average kōura size decreased as adjacent riparian cover increased (Figure 2-3E) (i.e., pastoral 15.2 mm OCL \pm 4.3 SD; early riparian 13.4 mm OCL \pm 4.3 SD; late riparian 12.3 mm OCL \pm 5.0 SD; native 9.0 mm OCL \pm 4.0 SD). Across treatments there were no kōura \leq 8 mm OCL collected in pastoral sites, compared to 2% of total kōura in early riparian sites, 7% in late riparian sites and 13% in native sites where juvenile kōura densities were highest (Table 2-6; Figure 2-3F). Kruskal-Wallis tests showed no significant differences ($p < 0.05$) in ranked juvenile kōura densities and mean kōura size among treatments, although both juvenile density ($p = 0.11$) and mean size differences ($p = 0.09$) had probabilities close to the statistical significance threshold of $p < 0.05$ (Table 2-7).

2.4.6 Relationships between kōura and habitat variables across scales.

Correlation analysis showed noticeable consistencies in factors associated with kōura size and density across the band, sub-reach and reach scales (Table 2-8). Scatterplots for key variables measured at the band scale where relationships had significant slopes are shown in Figure 2-5; coefficients of determination for all these relationships were low ($R^2 < 0.15$).

Most effect strengths were considered “weak” ($r_s \pm 0.20$ -0.39) at the band scale (Table 2-8). There were significant positive correlations for both total kōura and juvenile densities with “other” root mat cover (i.e., roots excluding those of grass, willow, ponga and fern; Table 2-8). Scatterplots showed relationships with root mats were determined by the larger submerged root mat area within several late riparian treatment bands supporting kōura (Figure 2-5 A&E). Total kōura densities also showed a significant correlation with total root mats, which included grass and willow root, although juvenile densities were inversely related to grass root area due largely to high variability in numbers within native bands where grass roots were absent (Table 2-8; Figure 2-5D). The high number of bands with low kōura densities and low total root area within native treatments in particular, combined with high variability among late riparian bands, seemed to drive the relationship with total root mat cover (Figure 2-5B).

Table 2-8 Spearman rank correlation coefficients (r_s) for relationships between kōura density and mean size with hydraulic, substrate and cover variables measured at the band (n = 180), sub-reach (n = 36), and reach (n = 12) scales. P < 0.01 (**bold**) was used to infer statistical significance to reduce Type 1 error from multiple comparisons. For comparing absolute r_s values across scales: *italic underlined* = correlation values > 0.6 and < -0.6 used to infer “strong” effect size across scales; underlined = correlation values > 0.4-0.59 and < -0.4-0.59 used to infer “moderate” effect size across scales (Statstutor, 2019). Only variables with at least one “moderate” correlation are shown.

	Kōura per m ²	Mean size (mm OCL)	Juvenile kōura per m ²
Band scale			
Velocity (m/s)	-0.19	<u>0.41</u>	-0.22
Embeddedness (1-4)	0.28	-0.32	0.29
Algal cover (1-5)	-0.24	0.05	-0.08
Compactness (1-4)	-0.09	0.26	-0.16
Inorganic substrate size index	-0.15	0.22	-0.12
Grass root (m ²)	0.06	0.17	-0.23
Other root mat (m ²)	0.21	-0.28	0.30
Total root (m ²)	0.33	-0.13	0.07
Ponga log (m ²)	0.08	-0.20	0.22
Other organic matter (m ²)	0.00	-0.10	0.25
Total CPOM (m ²)	0.03	-0.23	0.26
Sub-reach scale			
Velocity CV	0.36	-0.35	<u>0.41</u>
Embeddedness (1-4)	<u>0.43</u>	<u>-0.49</u>	0.38
Other root mat (m ²)	<u>0.44</u>	<u>-0.49</u>	<u>0.50</u>
Total root (m ²)	0.39	<u>-0.40</u>	0.25
Ponga log (m ²)	0.17	<u>-0.51</u>	<u>0.50</u>
Total CPOM (m ²)	0.18	-0.24	<u>0.51</u>
Reach scale			
Depth (m)	<u>-0.41</u>	0.17	-0.05
Velocity CV	<u>0.58</u>	<u>-0.59</u>	<u>0.59</u>
Embeddedness (1-4)	<u>0.53</u>	<u>-0.46</u>	<u>0.41</u>
Algal cover (1-5)	<u>-0.44</u>	-0.06	0.17
Inorganic substrate size index	-0.36	<u>0.53</u>	-0.33
Fern root (m ²)	0.37	-0.40	<u>0.46</u>
Other root mat (m ²)	<u>0.48</u>	<u>-0.76</u>	<u>0.76</u>
Total root (m ²)	<u>0.61</u>	-0.26	0.31
Large wood (m ²)	-0.04	<u>-0.46</u>	<u>0.45</u>
Ponga log (m ²)	<u>0.45</u>	<u>-0.78</u>	<u>0.72</u>
Total CPOM (m ²)	0.09	<u>-0.51</u>	<u>0.62</u>

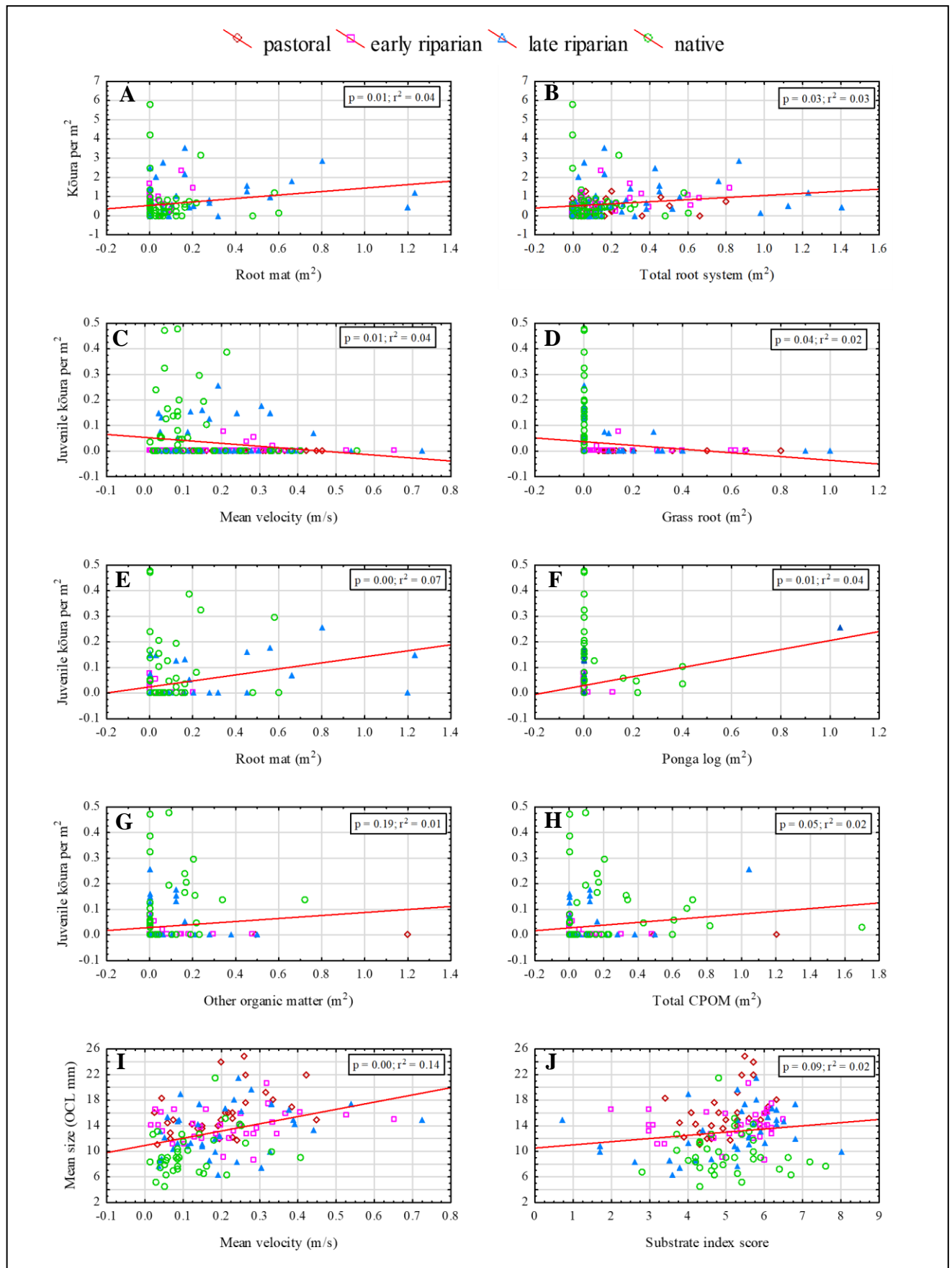


Figure 2-5 Scatterplots of band-scale relationships between kōura density (total and juveniles ≤ 8 mm OCL) and mean size with selected habitat variables grouped by treatment (see legend). Relationships are shown for correlations that were significant in Table 2-8 unless they were based on ordinal scores (e.g., embeddedness, algal cover); for total kōura and mean size only relationships that were not evident for juvenile kōura or were markedly stronger are shown. R^2 = coefficient of determination.

Total kōura density showed a significant inverse relationship with algae and a positive relationship with surficial fine sediment (embeddedness) (Table 2-8). At the band scale juvenile densities also showed a significant positive relationship with embeddedness, and an inverse relationship with velocity such that greater juvenile densities occurred in bands where velocity was slower and fine sediment cover was higher (Table 2-8). Examination of scatterplots (Figure 2-5C) revealed high variability in juvenile kōura numbers among bands with mean velocity < 0.2 m/s. In addition to the relationships with root mat area noted above, positive relationships occurred between juvenile density and various measures of CPOM area (total CPOM, other organic matter, and ponga logs) suggesting that CPOM provided cover for juvenile kōura. However, the relationship with ponga logs appeared to be driven in part by an outlier late riparian site, and the large number of bands with no logs where variability in juvenile densities was high at native sites (Figure 2-5 F-H).

Mean kōura size per band had a “moderate” strength positive relationship with velocity, which along with “weak” negative correlations with embeddedness, “other” root cover and CPOM were all deemed statistically significant (Table 2-8). The scatterplot (Figure 2-5C) showed smaller kōura tended to be associated with slow velocity bands in native treatments, with no juveniles found at velocities above 0.45 m/s. Average kōura size increased as velocity, substrate particle size and compactness increased, while correlations between these habitat variables and total and juvenile kōura densities were absent (Table 2-8; see also Figure 2-5J). The scatterplots for mean size showed clear grouping of treatments, with largest kōura in pastoral bands and smallest kōura in native bands, and greater variability of substrate size within the late riparian treatment sites.

At the sub-reach scale, statistically significant correlations considered “moderately” strong persisted between total kōura densities and surficial fine sediment cover (embeddedness), as well as total kōura and juvenile kōura densities with root mats, and, juvenile densities with ponga log area and CPOM cover (Table 2-8). Juvenile densities and velocity variability showed a “moderate” correlation, such that more variable velocity supported more juvenile kōura. As found at the band scale, mean kōura size was significantly and negatively correlated with embeddedness and “other” root cover. “Moderate” negative relationships also occurred with total root

mat and ponga log area, suggesting lower mean size in sub-reaches where fine sediment and these organic matter cover variables were higher (Table 2-8).

Reach-scale analysis showed no statistically significant ($p < 0.01$) correlations between total kōura densities and any habitat variable, although there were positive “moderate-strong” associations for total root cover, followed by velocity variability, embeddedness and cover by root mats and ponga logs compared to negative “moderate” relationships for reach algal cover and depth, which showed no relationships at smaller scales (Table 2-8). The variability of velocity and embeddedness at the reach scale also showed a positive “moderate” effect for juvenile densities as did fern root and large wood cover. However, juvenile kōura densities were again significantly and positively correlated with root mat and ponga log area, exhibiting “strong” relationships at the reach-scale (Table 2-8). These two relationships were reflected in negative correlations with average kōura size (Table 2-8). Relationships with juvenile kōura density were often reflected by corresponding significant relationships with mean size at all scales, although as expected these relationships were in the opposite direction, as can be seen in Figures 2-5 C&I.

As the analysis was extrapolated across increasing scales, the number of statistically significant relationships at $p < 0.01$ decreased while the number of “moderate-strong” effect strengths increased, with only reach-scale relationships exhibiting “strong” r_s values (Table 2-8). When comparing “moderate-strong” correlations ($r_s > 0.4$ and < -0.4) across scales (Table 2-8), a consistent pattern of correlation relationships occurred with root mat cover and ponga logs (Table 2-8). For CPOM and root mat relationships, juvenile kōura density correlations were much stronger at all scales than total kōura densities (Table 2-8), although positive relationships occurred between total kōura densities and other root mat types (excluding willow root and grass root) and total root systems (including willow root and grass root) at the band and/or sub-reach scales (Table 2-8; see also Figure 2-5 A-B). Direct relationships between velocity, mean size and juvenile kōura densities were only found at the band scale, however, as scale increased velocity variability became significant and this was most evident for the sub-reach scale where it showed “moderate” effect strengths for total and juvenile densities and mean size (Table 2-8).

2.4.7 Organic habitat sampling comparisons

The largest areas of organic habitats sampled at the independent site were watercress and root mats (both > 2 m²) (Table 2-9). Watercress yielded the lowest number of kōura (4) and no juveniles, while root mats had the highest total (92) and juvenile (79) numbers. The largest kōura on average were found in watercress, while other habitat had similar-sized kōura on average. Densities of both total and juvenile kōura were highest by far in root mats, followed by *Nitella* sp. and CPOM which had similar juvenile densities to each other. Percentage of the kōura caught comprising juveniles was $\geq 70\%$ across all samples apart from watercress.

Table 2-9 Organic habitats sampled over two time periods (26 November 2018 and 12 March 2019) showing mean size, abundance and density for total and juvenile (≤ 8 mm OCL) kōura caught. CPOM = coarse particulate organic matter.

	Area (m ²)	Number of kōura	Mean size (mm) ± SD	Number of juvenile kōura	Kōura per m ²	Juvenile kōura per m ²	% of juvenile kōura
<i>Nitella</i> sp.	0.89	10	6.95 ± 5.29	7	11.24	7.87	70%
Watercress	2.01	4	18.25 ± 5.01	0	1.99	0	0%
Root mats	2.26	92	7.32 ± 3.94	79	40.80	35.03	86%
CPOM	1.22	10	8.52 ± 5.46	8	8.20	6.56	80%

2.5 Discussion

This chapter investigated kōura-habitat associations at different scales in streams with different types of riparian vegetation cover, ranging from unfenced riparian grasses, to different growth stages of riparian planting (early, late) through to unmodified native forest. The aim was to determine relationships between kōura abundance and multiple measures of in-stream habitat, some of which would be influenced by riparian vegetation, to inform future management targeting kōura. In particular, I wanted to identify where juvenile kōura resided during the daytime compared to larger kōura. Specific objectives were to:

- (i) characterise in-stream habitat variables along multiple 2-m (band), 10-m (sub-reach) and 50-m (reach) sections of channel at multiple sites;
- (ii) explore inter-relationships between kōura abundance and size, including juvenile densities, and corresponding hydraulic, substrate and cover habitat variables at different scales.

2.5.1 The role of physicochemical and hydraulic variables

There were no apparent patterns in physicochemical characteristics between treatments, as might be expected from one-off spot samples taken in the morning. More intensive studies have shown that streams where riparian shading is absent or minimal usually exhibit warmer daily mean and peak stream temperatures (Quinn *et al.*, 2000; Quinn *et al.*, 2009). Warmer temperatures associated with small pastoral streams are known to contribute toward faster kōura growth (Jones, 1981b; Parkyn *et al.*, 2002). In the present study, the largest kōura were caught in pastoral treatments, and size averages decreased as riparian planting (and presumably shading) increased, supporting suggestions that water temperature plays a key role in determining kōura size.

Other studies have also shown that dissolved oxygen can be a key physicochemical variable affecting freshwater crayfish. In lake habitats, significant correlations have been detected between kōura presence and dissolved oxygen, with declines in kōura abundance recorded below 5 mg/L and absence below 1.2 mg/L (Kusabs, 2015). Laboratory experiments found kōura (*P. planifrons*) to show high tolerances to low oxygen levels with a 48 hour LC₅₀ of 0.77 mg/L at 17 °C (Landman *et al.*, 2005). However, avoidance likely occurs at higher concentrations, as stated by Westman (1985) who reported on aquaria studies involving *Austropotamobius pallipes*, *Orconectes virilis* and *Orconectes rusticus* in their intermoult period, showing that below dissolved oxygen levels of 5 mg/L they experienced acute hypoxia demonstrated by increased gill ventilation and heart rate. Stream dissolved oxygen levels are likely to be lowest in the early morning due to overnight respiration, so the spot measurements of > 10 mg/L at all sampling sites indicates that it was unlikely to affect kōura abundances in the present study.

The hydraulic variables investigated in this study were stream width, and water depth and velocity, as well as the variation in depth and velocity at different scales. Habitat in wider sections of stream tended to be deeper and faster than in narrow sections, presumably reflecting the greater discharge in streams with larger catchment areas. Studies within a Waikato hill-country area have shown that native forest streams are wider than pastoral streams by up to 60% (Quinn *et al.*, 1997), suggesting a reduction of bed habitat available to kōura from native to pastoral treatments. Hicks (2003) found that kōura abundance decreased longitudinally

down a North Island river system due to the increasing channel width and the known association of kōura with stream edge and not total streambed area. Stream size may also affect organic matter retention, as shown by Jowett *et al.* (2008) who described smaller streams as more likely to retain CPOM and woody debris than larger streams, although there was no significant association of stream width (channel or wetted) and the area of organic habitat across the narrow range of stream sizes sampled in the present study.

The finding that velocity and depth were highly variable within band to reach scales is unsurprising given that spatial variation of velocity and depth are key drivers of habitat heterogeneity (Rosenfeld *et al.*, 2011). A negative relationship between the average velocity and average depth was found across all bands, illustrating how deeper pools correspond with slow flows (Rosenfeld *et al.*, 2011). Velocity is usually associated with the amount of habitat cover available, and the organic habitat preferred by kōura (such as logs and CPOM) is typically more abundant in slow-flowing streams (Jowett *et al.*, 2008). In support of this, the present study showed that faster-flowing habitats had a significant but “weak” inverse correlation with CPOM area, but not with other cover habitats quantified.

Both total kōura densities and juvenile kōura densities exhibited negative correlations with velocity, consistent with results from Usio and Townsend (2000) involving *P. zealandicus* in Otago forested streams. However, unlike Usio and Townsend (2000), no significant correlations were found between total kōura density or juvenile density and depth. Although this contradicts other studies that have reported that crayfish inhabit deep pools (Englund, 1999; Englund & Krupa, 2000; Usio & Townsend, 2000; Parkyn *et al.*, 2009), my findings may partly reflect the lack of deep pools available in these small hill-country streams. Smaller kōura are known to prefer shallower water (Jowett *et al.*, 2008), and overseas a shift in distribution by small (25-35 mm body length) *Cambarus bartonii* and *Orconectes putnami* species to shallow waters appears to be driven by both terrestrial and aquatic predation (Englund & Krupa, 2000).

My study did not measure the effect of velocity on individual kōura directly but did associate kōura abundances with areas of varying velocity. I found a negative association of smaller kōura with higher water velocities at the band scale, with

high juvenile densities found over a range of reach-scale velocities. For example, native sites R2 and WK1 had average site velocities < 0.09 m/s and higher juvenile densities than most other sites, as did TP1 which had amongst the highest densities of both total kōura and juvenile kōura coinciding with a mean velocity of 0.25 m/s, less than the > 0.3 -0.4 m/s where most crayfish species lose their footing (Maude & Williams, 1983; Nakata *et al.*, 2003). Jowett *et al.* (2008) reported kōura used low velocity refugia amongst large cover at velocities up to 1.6 m/s, indicating they are able to persist in more extreme flows where shelter is available. Variance in velocity appeared to be most influential at the reach scale, as also found for certain fish species (Rosenfeld *et al.*, 2011), and may reflect the availability of flow refugia. In the present study faster-flowing streams tended to have larger overall substrate size which was more compact with low surficial fine sediment. The interstitial habitat associated with the low embeddedness at these sites may have provided refugia for larger kōura.

2.5.2 Kōura relationships with benthic inorganic substrates

Kōura size was weakly positively correlated with substrate size at the band and reach scales, such that larger kōura (> 8 mm OCL) tended to be associated with larger substrate types, and smaller kōura with smaller substrates, even though there was no statistically significant correlation between the substrate size index and juvenile kōura densities. Kōura ≤ 8 mm are known to associate with fine substrate while larger kōura use interstitial spaces formed by gravels and cobbles, but not so much by boulders due to interstitial spaces being large enough to increase susceptibility to predation ((Jowett *et al.*, 2008). Overseas and New Zealand studies have indicated that crayfish favour cobble-sized substrates in lakes (Capelli & Magnuson, 1983; Kirjavainen & Westman, 1999; Kusabs, 2015) and streams (Usio & Townsend, 2000), however, this relationship appears to vary with crayfish size.

Significant or “moderate” correlations were evident in the present study between embeddedness and total kōura and juvenile densities at most scales, suggesting that the level of deposited fine sediment encountered at the study sites was not adversely affecting kōura populations. Fine deposited sediment is becoming increasingly abundant in hill-country streams due to surrounding land practices (Blaschke *et al.*,

1992; Hicks *et al.*, 1996; Hughes & Quinn, 2019). A study by Dodd *et al.* (2008) showed sediment yield per hectare was approximately 5 times higher in a pastoral catchment compared to a catchment in native forest, and 18 times higher in a mixed catchment (50% pasture, 40% indigenous forest and 10% pine forest) when compared to native forest. Kōura are regarded as sensitive (Greenwood & Taylor, 2008) and vulnerable (Usio & Townsend, 2000) to increased sedimentation leading to embeddedness of the substrate. High levels of fine sediment can clog the fine gills of crayfish (Westman, 1985) and in lake benthic communities heavy sediment loads are known to clog interstitial spaces and decrease light penetration affecting zonation of plant communities upon which kōura feed (Kusabs *et al.*, 2015). High sediment yields can be consistent within pastoral areas undergoing a re-establishment phase from riparian planting, resulting in a period of stream bank erosion while the stream channel adjusts to increased shade from slow understorey recruitment (Davies-Colley, 1997; Quinn *et al.*, 1997), although this was not evident in the present study where excessively high fine sediment deposition was not apparent.

Pastoral streams in hill-country areas are known for increased algal epilithion growing primarily on stable inorganic substrates compared to shaded native streams (Quinn *et al.*, 1997; Quinn & Stroud, 2002). “Moderate” strength significant correlations were evident between algal growth and channel or wetted width in the stream studied here, presumably due to higher light levels in wider streams. Unsurprisingly, there was also a negative relationship with embeddedness since algae would find it difficult to grow on unstable fine sediment deposits which are limited in faster flowing streams. Although kōura are known to be consumers of filamentous algae (Hicks, 1997), and act as active grazers which can indirectly influence benthic community structure (Creed, 1994; Charlebois & Lamberti, 1996), in the present study they tended to be less common in streams with more algal cover. However, this result could be partly due to the small number of sites where algae was present (5 in total).

2.5.3 Kōura relationships with organic cover

The decline in wood volume from native to pastoral treatments was consistent with findings in other studies (Quinn *et al.*, 2009). Logs are regarded as good creators of pools within streams (Jowett *et al.*, 2008), and can trap CPOM and other debris used by kōura as habitat and food sources. Ponga logs showed significant or “moderate-strong” associations for some kōura variables across all scales, notably juvenile kōura; these logs were not present at pastoral sites and had low abundance at early riparian sites. The only strong relationships found between kōura and other large wood structures were at the reach scale, potentially due to increased depth variability providing habitat complexity (Usio & Townsend, 2000; Parkyn *et al.*, 2009). Large wood structures have been used as a restoration technique for in-stream habitat re-establishment as they can influence multiple stream geomorphic characteristics (Montgomery *et al.*, 2003). These characteristics can directly and indirectly influence kōura by providing cover and increased habitat heterogeneity (Parkyn *et al.*, 2009).

Stream-bank undercuts were associated with higher stream depth and grass root area, reflecting their prevalence in pastoral streams, but showed no relationship with any of the kōura variables assessed. This result was surprising as crayfish are known to be associated with streambank undercuts, especially in streams with limited substrate cover (Usio *et al.*, 2006). Undercut banks, along with leaf litter, tree roots and wood, have been reported to be more important than hydraulic and substrate variables for controlling daytime cover preference (Jowett *et al.*, 2008; Parkyn *et al.*, 2009). However, the present study suggests that this may not always be the case, although this result may have partly been driven by the absence of juvenile kōura from pastoral treatments due to other factors and the small number of areas with extensive undercuts at other sites.

Across all scales, total and juvenile kōura densities were associated with “other” root mats, but for juvenile densities the relationship with total root mat systems was much weaker suggesting grass and willow roots may not have provided suitable habitat for juvenile kōura. Increased availability of cover from fern/ponga and “other” tree roots in native areas is consistent with findings of Parkyn and Collier (2004) who reported tree roots, undercut banks, and stony substrates as the most commonly used habitats by kōura. These authors also found low percentages of

kōura in leaf litter and woody habitats that were abundant in forest streams, a finding supported in the present study where few kōura were found associated with CPOM. Nevertheless, relationships were evident between CPOM area and juvenile kōura density, suggesting accumulations of litter and small wood may provide juvenile habitat in some situations, although this may also partly have been due to CPOM abundance coinciding with cover by root mats and large woody debris.

In streams where a variety of habitats for kōura were present, kōura tended to be found amongst organic habitats and undercut banks (Jowett *et al.*, 2008; Parkyn *et al.*, 2009), a result also found in the manipulation study where kōura favoured artificial habitats simulating organic cover over cobbles (see Chapter 3). CPOM area showed no significant correlation with total kōura density, and this could be due to the instability of many CPOM deposits providing only short-term cover in hill-country streams. Focussed sampling of organic habitats detected only larger kōura in watercress patches, potentially due to the dominance tendencies and aggression known in larger crayfish in favoured habitats (Devcich, 1979; Capelli & Munjal, 1982; Wooster *et al.*, 2012). Brusconi *et al.*'s study of Italy's indigenous crayfish *Austropotamobius italicus* showed juveniles (carapace length < 24 mm) mainly used the benthic substrates for feeding, as indicated by periphyton and macroinvertebrates in their guts, while larger kōura preferred areas of vegetation including macrophytes, as well as patches of CPOM and woody debris confirmed by more vegetative material in their guts (Hollows *et al.*, 2002). The variability of habitat use evident in these results suggests kōura can be considered “opportunistic” and/or “adaptable” when it comes to habitat requirements in hill-country streams.

2.5.4 Ecological significance of variability across scales

Across-scale analyses in the present study examined inter-relationship patterns and responses between kōura and quantifiable stream habitat variables. The different scales comprised 5 x 2 m bands nested within 3 x 10 m sub-reaches per site, with 3 sites per treatment. Comparing results between the micro-scale (band), meso-scale (sub-reach) and macro-scale (reach) can highlight effects of differing stream and habitat characteristics which could inhibit or benefit the ability of kōura to find suitable habitat during the day. For example, the reach-scale comparison factored

in treatment type ($n = 3$ sites per treatment) and looked to identify important drivers of kōura responses to stream heterogeneity caused by land use and riparian management. Identifying habitats important to kōura across scales can help determine effective approaches for restoration managers, including iwi, community groups and regulatory authorities, to increase habitat suitability for in-stream biota of interest.

Influences and interactions between stream life and habitat are complex and there is scant information regarding the influence of stream edge treatment type on daytime habitat use by kōura across multiple scales. Identification of relationships with habitat variables across scales in this study provided valuable information that can be considered when selecting and implementing restoration practices aimed at enhancing kōura populations, particularly for juvenile recruitment. Relationships between kōura and undercut banks, wood, leaf litter, and substrates have been reported elsewhere for kōura in native and pastoral streams similar to those used in this study (Hicks, 2003; Parkyn & Collier, 2004; Jowett *et al.*, 2008; Parkyn *et al.*, 2009), but there have been no studies examining the effects of different riparian planting stages across multiple spatial scales.

When comparing variability between scales within sites, consistent responses were evident for the effects of embeddedness, “other” root mat cover, ponga logs and CPOM. This highlights the importance of reach-scale riparian planting in pastoral settings and smaller meso- and micro-habitats where kōura reside in native forested streams, and emphasises the significance of in-stream habitat associated with riparian vegetation to juvenile kōura (Usio & Townsend, 2000; Parkyn & Collier, 2004). The significant inverse relationships between velocity and grass with juvenile densities at the band scale potentially highlights the lack of micro-habitat flow refugia for juveniles in pastoral streams, which may also explain positive relationships with CPOM and other root mat cover across scales. These relationships with small kōura density were often reflected by corresponding significant relationships with mean size (Figure 2-3 B&E), although as expected these were in the opposite direction. This supports the preference of juvenile kōura for slower-flowing micro-habitats and the importance of cover habitats for juveniles across scales (Usio & Townsend, 2000; Jowett *et al.*, 2008).

Between-site comparisons showed significant variability of hydraulic and substrate variables highlighting the complexity of individual streams, partly due to the interaction of geographic area and surrounding land uses. Some of this variability could nonetheless still be explained by treatment based on location in each of pasture, native and early or late riparian sites. Although this analysis was limited statistically by low sample size, it suggested that kōura size and possibly juvenile density could potentially be influenced by factors associated with riparian vegetation, likely to involve the area of cover available as discussed earlier. This is in accordance with the studies of Hicks and McCaughan (1997) on New Zealand fish species and *P. planifrons*, and Hicks *et al.* (1991) on salmonid fish populations which indicated streamside or riparian vegetation influenced biota through light availability, water temperature and channel stability.

Variability of kōura abundances, particularly for juveniles, increased with riparian planting age or native land use. These results highlight the roles of different types of habitat cover with hydraulic and substrate variability suited for juvenile kōura habitat demands. Consistent with the results in this study, Whitmore (1997) also found native forested sites to have high productivity and density of *P. zealandicus*, while pastoral sites generally had little available in-stream habitat from vegetation cover (with the exception of roots from pastoral grasses, and the occasional willow tree or fern). The lack of cover was associated with the general absence of juvenile kōura, leading to pastoral and early riparian streams being dominated by larger kōura that are physically more able to withstand pressures from changes in stream processes and inadequate stream bank cover induced by land use change (Parkyn & Collier, 2004).

Overall variability within the streams sampled contributes to the heterogeneous habitat that crayfish require for survival over different life stages (Reynolds *et al.*, 2013). In streams where there was less habitat variability due to surrounding vegetation type, as well as other physicochemical and hydraulic factors influenced by stream edge treatment, the persistence of kōura can decrease because niches are only available for a narrow range of size classes (Usio & Townsend, 2000; Whitmore *et al.*, 2000; Parkyn *et al.*, 2002). The fact that strong associations were attributed to established and regenerating native forest underscores the need for greater consideration and care towards hill-country streams with forest remnants,

and for action to improve the quality of water and habitat for resident species. The results from this study provide restoration managers with general information on habitat features to enhance in-stream and stream edge structures for kōura, particularly juvenile kōura.

Chapter 3

Comparison of ponga and root mat substrates with cobble habitats for kōura in a pastoral hill-country stream

3.1 Introduction

Pastoral streams throughout New Zealand lack diverse native riparian plant communities, characteristic of native forest streams (Quinn *et al.*, 1997; Collier *et al.*, 2000; Quinn *et al.*, 2009). Deforestation and agricultural development have led to pastoral streams dominating lowland and hill-country landscapes within the Waikato region, directly and indirectly affecting stream physical and chemical characteristics (Quinn & Stroud, 2002; Hughes *et al.*, 2012). These characteristics, in turn, influence in-stream habitat and associated biota (Quinn *et al.*, 1997; Collier *et al.*, 2000).

Crayfish living in pastoral streams are known to grow faster and larger than in native forest streams due to increased moult frequency of juveniles, caused by lack of shade and a resulting increase in water temperatures (Jones, 1981b; Musgrove & Geddes, 1995; Whitmore, 1997). A study by Parkyn *et al.* (2002) on growth and production rates of kōura in Waikato hill-country streams showed similar levels of production between native and pastoral streams, but higher densities in native streams possibly due to greater longevity and higher recruitment of juveniles compared to pastoral sites. In contrast, high production of *P. zealandicus* in a cool Otago stream was attributed to high densities and longevity rather than high growth rates (Whitmore & Huryn, 1999). A shorter lifecycle than *P. zealandicus* has been observed for *P. planifrons* in Waikato hill-country pastoral streams, with higher mortality rates over winter (Parkyn *et al.*, 2002). High mortality may be due to the increase in moult frequency leaving juvenile kōura vulnerable to predation and environmental change in pastoral streams, and/or unsuitable habitat and diet related to land use type. Land use change can make kōura more vulnerable to major flood events and can significantly impact kōura more in pastoral streams than native forested streams (Parkyn & Collier, 2004). Parkyn *et al.* (2009) examined coarse

particulate organic matter (CPOM), root mats, cobbles and stream bank undercuts associated with kōura in native forest environments, but little is known around habitat types suitable for kōura in pastoral areas, particularly those that have undergone riparian management.

Restoration of riparian areas by fencing and planting native species to reduce land use impacts is gaining in popularity among farmers, community groups and iwi stakeholders. Although usually aimed at water quality improvements, such restorative measures can also enhance habitat for freshwater species, however, little is known what plant species contribute most towards kōura habitat enhancement. Kōura are known to congregate towards specific habitat types for shade, protection, and food, including leaf litter, woody debris, tree roots, bank undercuts and holes, and a range of inorganic particle sizes from fine sediment to large boulders (Grace, 1959; Usio & Townsend, 2000; Hicks, 2003; Parkyn & Collier, 2004; Jowett *et al.*, 2008; Parkyn *et al.*, 2009). Parkyn and Collier (2004) reported that native kahikatea (*Dacrycarpus dacrydioides*) and exotic willow (*Salix* spp.) tree roots on stream edges were important habitat for kōura, particularly juveniles. Knowledge is generally lacking around habitat preference for juvenile kōura with OCL < 8 mm, especially which habitats most suit very small individuals that have recently become free-living (c. 3-4 mm OCL).

The study presented in this chapter focused on manipulating habitat in a pastoral stream by simulating ponga (tree ferns; *Dicksonia* and *Cyathea* spp.) frond accumulations and dense root mats that are evident in native forested streams and known to accommodate kōura. The study assessed whether kōura would gravitate towards such structures as shelter during the day when kōura are most inactive and require safe housing. Ponga are a native woody tree with large, hard leaves and come in a variety of species common along stream edges in the Waikato region. Dependent on the species, ponga can be slow- to fast-growing and short- to long-lived (Crowe, 2009), but all species can provide important retention structures in small streams (Wardle, 1995), and are highly suited to riparian plant restoration. The smaller rārahu (bracken fern; *Pteridium esculentum*) was traditionally used as a harvesting method of kōura by Māori (Best, 1929; Kusabs, 2015), and today is used as a representative sampling tool to monitor lake kōura by local iwi in the North Island, New Zealand (Kusabs & Quinn, 2009).

3.1.1 Study aims and objectives

The aim of this study was to determine whether two constructed habitat types could simulate natural habitats found in hill-country streams lined with established and regenerating vegetation by providing suitable habitat for kōura. The study aimed to provide information that would determine the value of ponga in riparian restoration, and potentially highlight the value of introducing constructed ponga habitats as an interim measure to increase in-stream habitat for kōura until plantings become established. This aim was achieved by introducing ponga frond bundles and natural coconut fibre bundles to simulate ponga root mats into a pastoral hill-country stream, and then measuring colonisation over time by kōura and toi toi (bully, *Gobiomorphus* spp.) which both shared the constructed habitats. Nearby cobble habitats were also sampled to provide a naturally-occurring inorganic substrate comparison.

The study had the following objectives: (i) measure densities of kōura and toi toi per unit area of substrate type over time; and (ii) understand how other environmental factors (e.g., water velocity and depth) might affect colonisation patterns; (iii) determine organic matter decay times to understand how long ponga frond bundles and root wad surrogates last. The null hypothesis was there would be no effect of habitat type on kōura and toi toi densities over time in response to habitat degradation.

3.2 Study area

The study site was selected to represent a typical North Island hill-country stream within a working pastoral farm. The site was located on an unnamed tributary of the Mangaotama Stream at the Whatawhata Research Centre, within the Mangaotama catchment draining the Hakarimata Ranges 15 km west of Hamilton City. The station was developed from native forest to pastoral land before 1940, and became the Ruakura Hill Station research centre in 1949 (Quinn & Cooper, 1997). By 1969, the station had 380 ha of well-developed land typical of the 1.2 million ha of farmable hill-country throughout the North Island at the time (Farrelly, 1986). Throughout the 1970's and 1980's, the facility continued to develop and produce information for the improvement of agricultural research

programmes, and by 1984 it was the only station in the MAF Research Division directly servicing the 5.3 million ha of North Island hill-country (Farrelly, 1986). The Whatawhata Research Centre is also known as Te Rauputiputi by the Waikato-Tainui land owners and is managed by Tainui Group Holdings who continue to use it as a research facility.

The upper Mangaotama catchment has an area of 268 ha, and the present land use is 38:58:4% pasture:pine:native, within mostly steep (mean slope $22.5^{\circ} \pm 8.9$ SD) hilly terrain (Hughes *et al.*, 2012). The area is comprised of Mesozoic sedimentary sandstones and siltstones made up of greywacke and argillite, with weathered yellow brown earth soils (Quinn & Stroud, 2002). The climate is humid temperate with a mean annual rainfall of 1663 mm (1993-2010; NIWA, unpublished data for Whatawhata Research Station climate station) and a mean annual temperature of 13.7°C (Hughes *et al.*, 2012). River Environment Classification (2010, REC v2.4, NIWA) attributes of the Mangaotama Stream reach used in this study are summarised in Table 3-1. Monthly water quality data previously recorded at site PW5 (c. 250-300 m upstream from the manipulation study site) by NIWA from 1998-2018 is shown in Table 3-2.

Table 3-1 River Environment Classification (REC) data summary for the Mangaotama Stream reach where the stream manipulation study site was located.

REC attributes		Values
Watershed area (m ²)		683306
Reach length (m)		1272
Reach distance to coast (km)		119.45
Stream order		2
Top reach elevation (m)		80.10
Bottom reach elevation (m)		60.03
Mean slope of reach (°)		1.02
Upstream coordinates (NZTM)	Easting	1782480.20
	Northing	5815551.74
Downstream coordinates (NZTM)	Easting	1782688.55
	Northing	5816662.22

Table 3-2 Water quality data taken monthly shown as ten-year averages and limits (1998-2018, NIWA, unpublished data for Whatawhata Research Station) at site PW5. DOC = dissolved organic carbon; EC = electrical conductivity; max = maximum; min = minimum; SD = standard deviation; SS = suspended solids; TN = total nitrogen; TP = total phosphorus.

	Temp. (°C)	pH	EC (µS/cm @ 25°C)	Turbidity (NTU)	SS (mg/L)	TN (µg/L)	NH ₄ -N (µg/L)	DOC (mg/L)	TP (µg/L)	Black disc (m)
min	5.30	6.69	64.50	2.80	0.90	204	0.50	0.67	13.00	0.05
max	25.20	7.66	128.00	386.00	722.00	2920	833.20	6.27	647.00	2.21
mean	13.70	7.20	101.27	14.20	19.42	972	12.93	1.92	52.66	0.84
SD	3.03	0.18	10.21	28.89	67.23	477	20.80	0.95	47.12	0.32

The habitat manipulation site (NZTM 5816333.160 N, 1782583.160 E) had a mean stream width of 2.06 m (± 0.5 SD, $n = 44$) with substrate predominantly composed of gravels between 2-60 mm (across the b-axis) and finer sediment < 2 mm measured on 10 substrate elements across 45 stream transects (Wolman, 1954). Small to large cobbles were abundant enough (14% of substrate elements in total) to allow comparisons of natural in-stream habitats utilised by kōura (Parkyn *et al.*, 2009) with artificial structures.

Table 3-3 Substrate composition of habitat manipulation study area including size classification and percentage of substrate.

Substrate	Size mm	% of substrate
Bedrock		2%
Boulders	> 250	5%
Large cobbles	120-250	3%
Small cobbles	60-120	11%
Gravels	2-60	44%
Sand/silt/mud	< 2	30%
Clay		1%
Root mat		5%

The stream bank vegetation was dominated by pasture grass with the occasional willow, sedge (*Carex* spp.) or fern, creating cover and in-stream root mats. The stream was unfenced and adjacent pastoral land often grazed by stock. The study reach was downstream of a fenced, retired area of regenerating native trees 50-80 m upstream. Regenerating vegetation included a mix of shrubs and small trees such as tree ferns (*Cyathea* and *Dicksonia* spp.), *Coprosma* spp., parataniwha

(*Elatostema rugosum*), koromiko (*Hebe* spp.) and māhoe (*Melicytus ramiflorus*), as well as occasional remnant forest canopy trees (e.g. *Dacrydium cupressinum* and *Agathis australis*). This native area, situated upstream of the pasture site, was used to source ponga fronds for construction of in-stream substrates, and was also sampled for kōura as part of a pilot study to determine patterns in abundance downstream (see below). Three 50-m long reaches that included representative pools and slow flowing habitats were identified in the pasture area for the present study.

3.3 Methods

3.3.1 Electrofishing

On 11 September 2018, electrofishing was conducted in the three pastoral stream reaches and in the upstream fenced reach (also 50-m long) lined by regenerating native trees to determine kōura abundances prior to the substrate manipulation study. Electrofishing is considered the most effective means for targeting kōura in specific habitat types during the daytime when they are mostly inactive (Rabeni *et al.*, 1997; Parkyn *et al.*, 2002; Jowett *et al.*, 2008; Price & Welch, 2009). For this study, a Kianga back-pack electric fishing machine (EFM300; NIWA Instrument Systems) was used, in accordance with *New Zealand Freshwater Fish Sampling Protocols for Wadeable Rivers & Streams* (Joy *et al.*, 2013). The method was modified to target kōura by combining the electrofishing with use of a long-poled scoop net (with a metal sieve mesh) to create flow via a sweeping action behind the electro-fishing wand toward a downstream stop-net, similar to the approach of Engelbert *et al.* (2016). A further c. 20 second sweeping effort with the sieve net concentrated on CPOM, woody debris, root wads and undercuts to dislodge any remaining kōura, continued after the electrical current from the EFM was turned off. Where large cobbles were present on the substrate, the c. 20 second effort included turning and moving cobbles to free any trapped kōura. Size and abundance of kōura were recorded for each sub-reach. Kōura orbital carapace length (OCL) from the back of the eye socket to the posterior end of the carapace was measured using Vernier callipers to the nearest 0.5 mm.

3.3.2 Habitat manipulation

Construction of habitats

The common occurrence of numerous ponga (*Cyathea dealbata*) within the upstream native site was observed to create temporary in-stream habitat structures from trapped fallen fronds, and more permanent habitats along stream banks in the form of tightly condensed root wads, an attribute of ponga root systems. Pilot sampling of these habitats using a rectangular kick net (0.5 mm mesh) confirmed they sheltered kōura. Thus, constructed ponga frond bundles and manufactured biodegradable coconut fibre matting (*Cirtex BioCoir™*) were used as introduced habitats to simulate these natural habitat structures.

The coconut fibre matting was cut from a roll into 3 m x 1 m lengths which were rolled along the 3 m edge then folded in half for an approximate planar area of 0.5 m² (Figure 3-1). The ends were tied with zip ties to maintain this shape. Fresh ponga fronds were collected from the native site and each frond was trimmed to an area of approximately 1.7 m x 0.6 m (approx. planar area of 1 m²) with a stalk length of 0.5 m. Six ponga fronds were layered into a 'bundle' tied together with zip ties at the stalk end. Nineteen ponga bundles and root mat surrogates were constructed, 16 for introduction to the stream and three for "fresh weight:dry weight" conversion analysis (Figure 3-1). All substrates were weighed prior to introduction to the stream to the nearest 0.001 kg using a digital bench scale (Wedderburn WS 202), to enable determination of degradation rate over time. The three bundles for fresh weight:dry weight conversion were later dried at 60 °C and reweighed (see below).

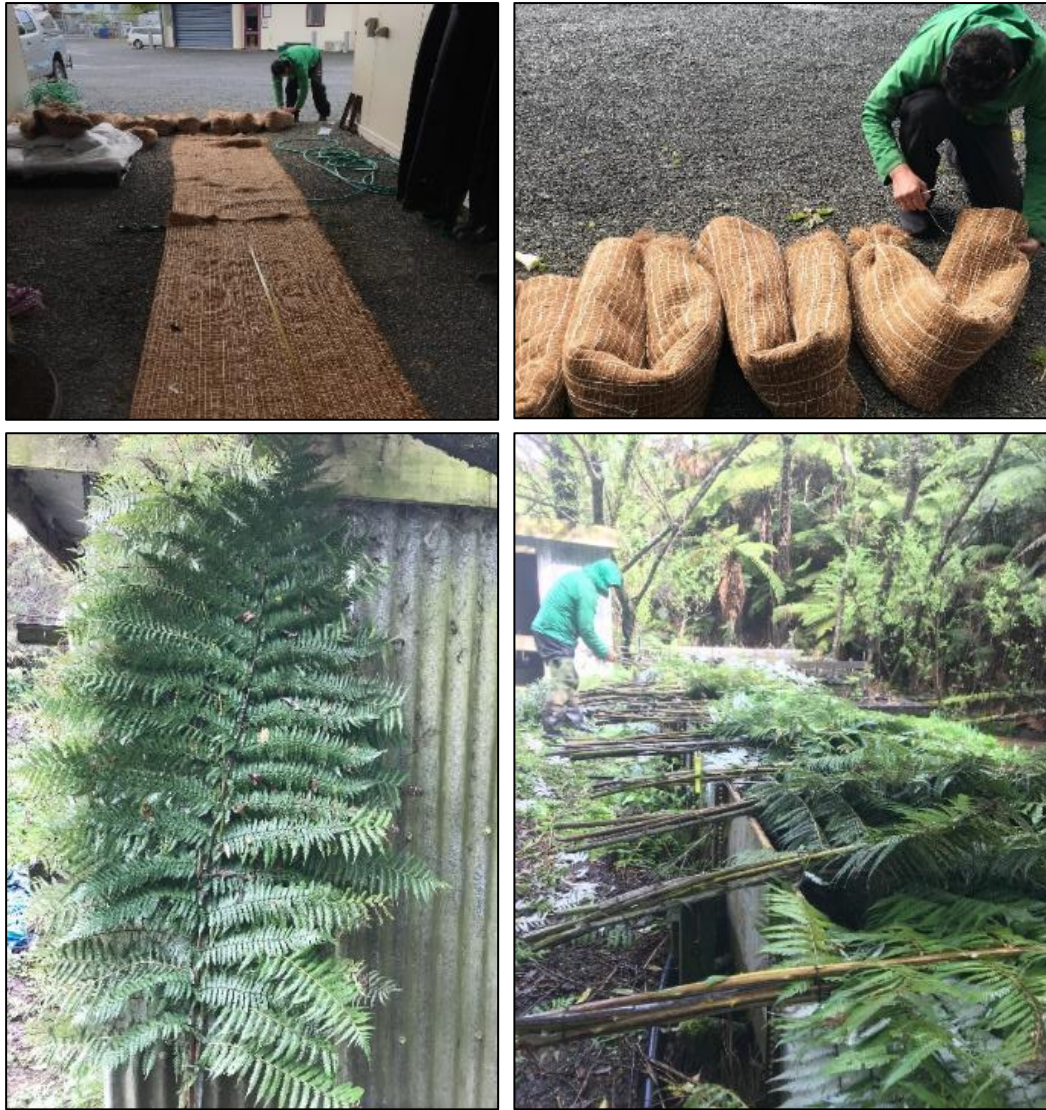


Figure 3-1 Artificial habitat construction. *Top left* – construction of artificial habitat to simulate ponga root mats from rolled out coconut fibre weed matting. *Top right* – finished tied weed mat habitats before stream placement. *Bottom left* – finished ponga bundle constructed from fresh fronds. *Bottom right* – ponga frond bundles lined up ready for stream placement.

In-stream incubation of constructed habitats

The sixteen ponga bundles and root mat surrogates were paired and secured in-stream using metal standards on 25 November 2018. The three pasture reaches were moved 5-10 m downstream from the initial electro-fished sub-reach areas to accommodate artificial habitat placement in pools and areas of low flow, and to avoid a deceased cow within the stream. The top reach was located c. 30 m downstream from the native site fence line. The total pasture reach length used in this experiment therefore was 223 m.

Five or six habitat pairs were deployed in pools with slow flow in each of the three pasture reaches (Figure 3-2) on 25 November 2018. All habitat pairs were positioned < 5 m apart and > 5 m from next set of pairs. A coin was tossed to determine whether ponga bundles or root mat surrogates were placed on true left or true right sides of the stream. The habitats were completely submerged on the streambed. For each artificial habitat, the distance from top of the reach, position in channel (straight or bend, true left or true right), presence of bank undercut, or any other adjacent habitat of note was recorded.



Figure 3-2 Artificial stream habitat installation. *Top left* – Coconut fibre “root mat” placement with frayed ends facing downstream. *Top right* - An example of ponga bundle placement with a metal standard attached at the stalk end facing upstream. *Bottom* – Coconut fibre “root mat” (left) and ponga bundle (right) artificial habitat pair secured in-stream.

Because initial kōura sampling indicated declining abundance with distance downstream (see Results), the 16 artificial habitat pairs were divided into four equidistant groups. One or two pairs were selected at random from each group on

four occasions over a 19-week period, yielding soak times of 14, 44, 66 and 133 days. Before removal, stream width (m), water depth (m) and velocity (m/s) at 40% depth (0.01 m/s accuracy) were measured on the middle inside edge of each habitat using a Marsh-McBirney™ Flo-Mate 2000 or Hach™ FH950 velocity meter and metric wading rod to characterise hydraulic conditions associated with the deployment site. Any observations of artificial habitat condition and surroundings were noted (e.g., adjacent macrophyte presence, periphyton and sediment coverage).

Collection of kōura and toi toi

Each habitat was removed using a kōrapa (landing net) to ensure any associated kōura and fish were caught (Kusabs *et al.*, 2018). The kōrapa was made from shade cloth 1.5 m wide x 1.3 m high, with mesh size 3 mm, and secured by 2 x 1.8 m poles on each end with a galvanised chain attached to the bottom as a weight (Figure 3-3, bottom panel). The kōrapa was slid underneath each artificial habitat which was then lifted out onto the bank where it was searched for kōura and toi toi (Figure 3-3, top left panel). Each habitat was washed with stream water in 70 L fish bins to remove excess silt and deposited in 60 L rubbish bags for transportation to the laboratory. The remaining wash water was sieved through the kōrapa for any missed kōura and toi toi.

In-stream cobble habitats adjacent to (within 5 m of) each substrate pair were sampled concurrently to compare abundances of kōura and toi toi among natural inorganic substrates. A 1 m x 0.5 m quadrat sampler with 0.4 m high, 3 mm mesh sides, and a catch net at one end (0.5 m x 0.4 m open face by 0.6 m long, 0.5 mm mesh) was used to sample large (12-25 cm b-axis diameter) and small (6-12 cm) cobbles (Figure 3-3, top right panel). Cobbles were disturbed for c. 30 seconds while creating flow into the catch net. If cobbles were absent large gravels up to 6 cm across were sampled, but this was seldom necessary.

Abundance and sex of kōura with recognisable gonads were recorded from all samples. Size (OCL) of kōura was measured to the nearest 0.5 mm using Vernier callipers. Toi toi were also counted.



Figure 3-3 Tools used for sample collection. *Top left* – artificial root mat on bank once lifted from stream using kōrapa. *Top right* – 1 m x 0.5 m quadrat sampler used for sampling cobbles. *Bottom* – kōrapa (landing net) made from shade cloth, wooden poles and galvanised chain.

Laboratory dry weight methods

After each sampling interval the artificial habitats were taken to the laboratory at The University of Waikato where they were washed again and rinsed to remove other trapped CPOM and sediment. Each habitat was then placed on foil trays before being placed in oven at 60 °C until a stable dry weight was achieved to the nearest 0.001 kg using a digital bench scale (Wedderburn WS 202). The artificial habitats were reweighed, and percent of initial dry weight (A) calculated as;

$$A = \frac{B}{C \times D}$$

B: Final dry weight

C: Initial fresh weight

D: Fresh:dry weight conversion (root mat = 0.89%, ponga = 25% of original weight left after drying).

The number of kōura and toi toi per kilogram of remaining habitat dry weight was calculated to provide numbers per kg dry weight. Kōura and toi toi abundance per m² of remaining habitat planar area was also calculated by counting the number found in each habitat and estimating the remaining area of habitat from the original areal measurements of root mat (0.5 m²) and ponga (1 m²) (cobbles were always 0.5 m²). Day 133 was excluded from the areal analysis as the ponga frond habitats were too degraded for area estimation.

3.3.3 Statistical analysis

Organic matter decay

The decay of organic matter per artificial habitat per day was predicted for 50% organic matter loss over time (T₅₀) and 95% organic matter loss over time (T₉₅) by using a linear exponential decay equation between mass loss and days in the stream (Bärlocher, 2005);

$$y = kx + a$$

Where;

x = number of days in the stream

y = percent of organic matter remaining

k = slope

a = intercept (calculated mass at time 0), i.e. 100%

This was transposed to find x for T₅₀ and T₉₅;

$$x = \frac{y - a}{k}$$

The slope k represents the decay coefficient (Bärlocher, 2005). The coefficients of determination (R²) for the linear regressions were calculated for both root mat and ponga habitat decay over time, including day 0.

Comparisons of substrate types

All statistical tests were performed in Statistica 64™ (v. 13, TIBCO Software Inc. 2017). Shapiro-Wilks test was used to test for data normality which was confirmed

only for log-transformed toi toi abundance per m². Accordingly, for this response variable, a factorial ANOVA was used to analyse differences in abundance for substrate type (cobble, root mat, ponga frond) and soak time. This analysis tested the null hypotheses that the mean toi toi abundance per m² was the same between habitats over time. If main effect differences were identified, a Tukey's post-hoc test was used to examine pairwise differences.

For kōura abundance per m², Kruskal Wallis non-parametric analysis was used to compare between habitat types for each sampling interval. This analysis tested the null hypothesis that abundances were the same in all habitat types. Data were untransformed, but the effects of outliers was reduced by converting data into ranks.

For kōura and toi toi abundance per kg of dry weight remaining, Wilcoxon non-parametric analysis was used to compare the location of the population median between root mat and ponga habitats. This analysis tested the null hypothesis that the median kōura abundance per kg was the same between pairs of habitat types.

Relationships with co-variables

Correlations between habitat co-variables and species abundances per unit area and weight of habitat remaining were analysed using non-parametric Spearman rank test to explore whether other factors could be influencing differences between habitat types. The habitat variables tested were water depth, velocity, channel width and distance from the top of reach. This analysis tested the null hypothesis that there was no significant effect of the independent co-variables on species densities among habitat types.

3.4 Results

3.4.1 Organic matter decay

Decay of the artificial habitats increased gradually over the 133 days when 40% of ponga bundle and 63% of root mat habitat dry weight remained (Figure 3-4). On day 44, dry weight analysis results for both root mat and ponga habitats showed an increase in percent of initial weight (Figure 3-4), this is thought to have been due to sediment remaining within the habitats after insufficient washing. Day 44 data

was removed when linear regression analysis was performed. This was rectified by more thorough washing on the two subsequent sample times. Both root mats and ponga exhibited similar decay rates from days 14 to 66, however, root mat decay rates showed overall slower decline compared with ponga (Figure 3-4).

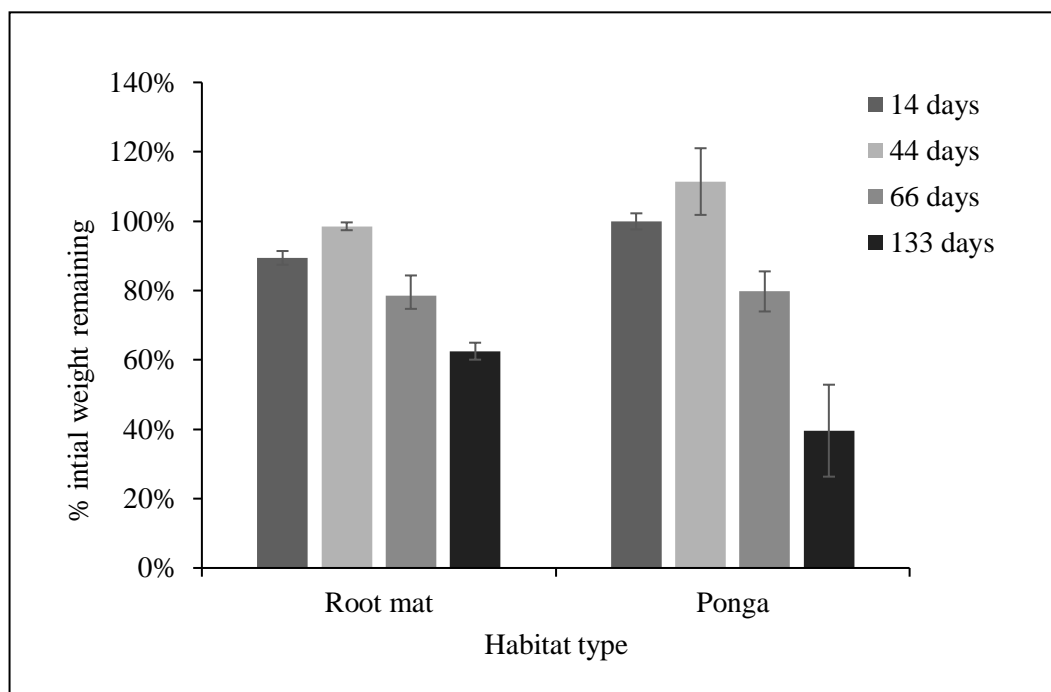


Figure 3-4 Percent of initial dry weight remaining for artificial habitats of root mat and ponga fronds after soak times of 14, 44, 66, and 133 days (mean \pm SE, n = 4).

Predictions for 50% organic matter loss over time (T_{50}) was 56 days longer for root mat than ponga fronds, and 107 days longer for 95% loss (T_{95}) (Table 3-4). Both root mat and ponga had decay coefficients < -0.005 , (k; Table 3-4) which indicates a “slow” decay rate when compared with a range of leaf pack species (Bärlocher, 2005). The coefficient of determinations for the root mat and ponga frond linear regressions showed a strong effect of soak time with $R^2 > 0.93$ (Table 3-4).

Table 3-4 Summary of organic matter decay of artificial habitats over time; k = decay coefficient derived from the linear relationship between mass loss and time, R^2 = coefficient of determination for the linear regressions, T_{50} and T_{95} = predicted time (days) for loss of 50% or 95%, respectively, of initial dry mass (see Statistical analysis for explanation of calculations).

	k	R^2	T_{50}	T_{95}
Root mat	-0.003	0.938	172	328
Ponga	-0.004	0.966	116	221

3.4.2 Habitat effects on kōura

Numbers found in all habitat types was 67 kōura in total; of these 21% were juveniles (≤ 8 mm OCL) with 29% of the juveniles less than 5 mm OCL. Kōura numbers ranged from a minimum of 0 up to 10 per m² after 66 days, and 0 up to 62.5 per kg dry weight remaining after 133 days across all habitat types. Kōura were more abundant overall per m² in ponga frond bundles over three sampling intervals compared to root mats, while cobbles consistently exhibited the lowest kōura abundance per m² at all sampling intervals (Figure 3-5). Over half of the kōura were found in habitats inserted near the true left bank (57%) of the study stream compared to 34% in habitats near the true right bank, with the remaining in mid-channel cobble habitat (9%).

Kruskal-Wallis tests showed significant difference between ranked abundances of kōura per m² on day 14 between all habitats ($p < 0.05$), however, pairwise differences between ponga fronds and root mat ($p = 0.082$) and ponga fronds and cobbles ($p = 0.082$) were not statistically significant at $p < 0.05$ (Table 3-5). No statistically significant differences were observed between habitats during the remaining sampling period ($p > 0.1$). There were no female kōura found in sampled cobble habitats, whereas on average 53% of kōura found in ponga habitats were female compared to an average of 33% female in root mats.

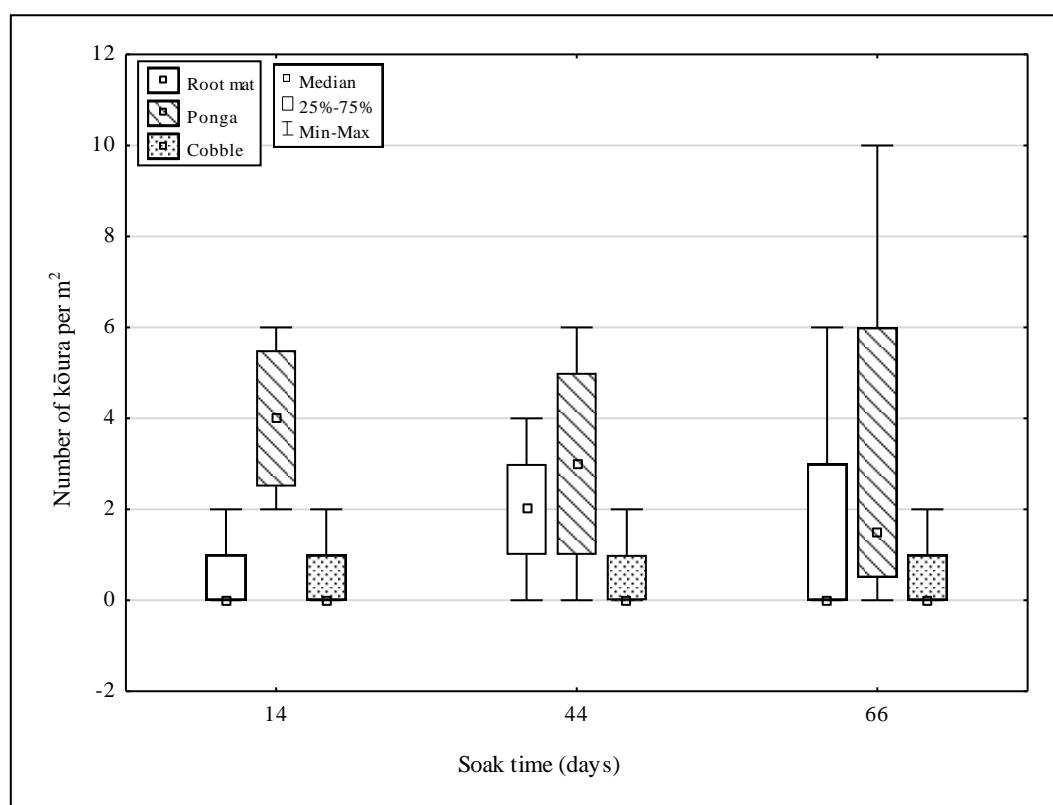


Figure 3-5 Comparison of kōura abundances per m² between root mat, ponga frond and cobble habitats over three sampling intervals (n = 4). Area of substrate remaining on day 133 was not determined for ponga due to advanced decay.

Table 3-5 Summary of Kruskal-Wallis results comparing kōura abundances per m² across three habitat types over three sampling intervals (n = 4 per habitat type on each date). H = Kruskal-Wallis statistic (degrees of freedom = 2), z values = pairwise comparisons, **bold** = probability (p) < 0.05.

Paired comparison	Day 14		Day 44		Day 66	
	H = 7.52	p = 0.023	H = 3.14	p = 0.208	H = 2.05	p = 0.358
	z' values	p	z' values	p	z' values	p
Root/Ponga	2.206	0.082	0.441	1	1.030	0.910
Ponga/Cobble	2.206	0.082	1.618	0.317	1.177	0.718
Cobble/Root	0	1	1.177	0.718	0.147	1

Wilcoxon analysis showed there were significant differences in kōura abundance per kg of dry weight remaining between root mats and ponga across all sampling intervals ($p < 0.05$). However, when pairwise comparisons were made for each interval there was no statistically significant differences between root mat and ponga (Wilcoxon; day 44, 66, 133, $p > 0.1$), although the p value for day 14 was $p = 0.07$ which was close to the statistical significance level of $p < 0.05$ (Figure 3-6).

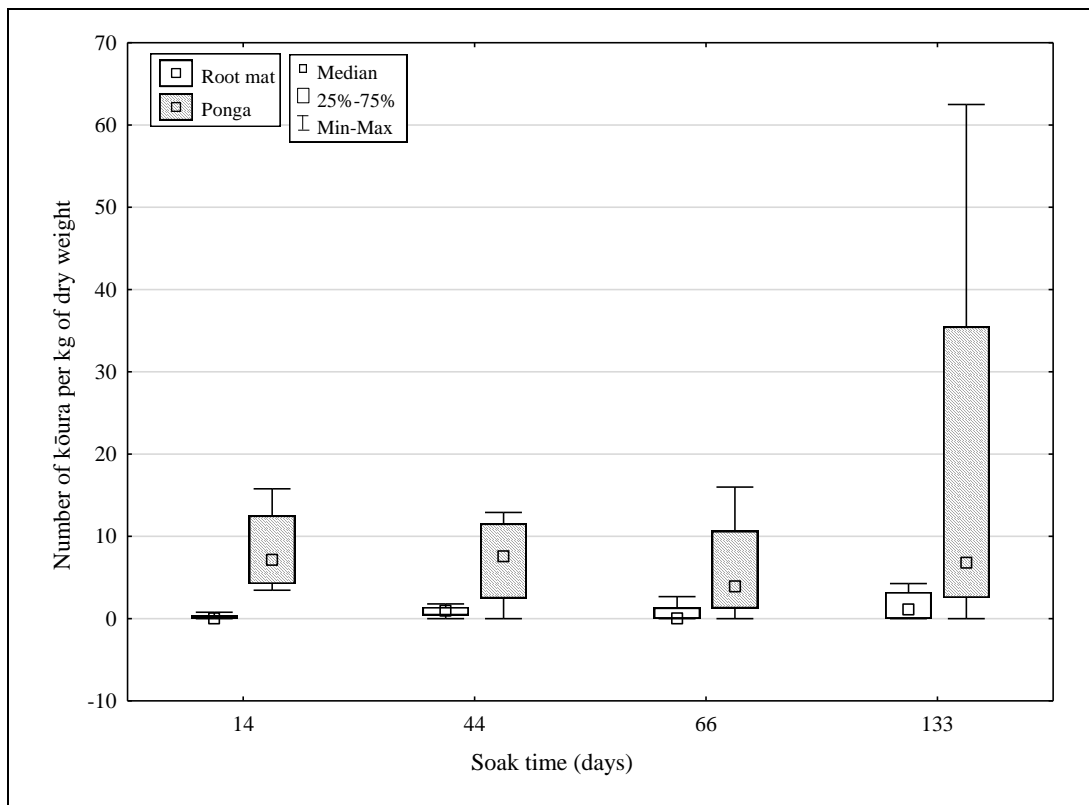


Figure 3-6 Comparison of kōura abundances per kg of initial dry weight remaining between root mat and ponga artificial habitats over four sampling intervals (n = 4).

3.4.3 Habitat effects on toi toi

Two species of toi toi occur in Mangaotama Stream – common bully (*Gobiomorphus cotidianus*) and Cran’s bully (*Gobiomorphus basalis*). Due to difficulties telling these cryptic species apart, particularly for small fish, the numbers of each were combined for the purposes of analysis. The total number of toi toi sampled across all habitat types was 197, with a size range of 21 mm to 77 mm. Toi toi densities ranged from a minimum of 0 to 20 per m² after 66 days, and 0 to 62.5 per kg dry weight remaining after 133 days across all habitat types. As with kōura, numbers were highest in habitats near the true left bank (46%) compared to those near the true right bank (26%) and in mid-channel cobbles (28%).

Two-way factorial ANOVA showed no significant effect of habitat type on toi toi abundance per m² ($p > 0.05$, Table 3-6). However, there was a statistically significant effect of soak time with a 62% increase in toi toi numbers from day 14 to day 44, then a 60% decrease between day 44 and day 66 (Figure 3-7). There was

no interaction between habitat type and soak time, indicating consistent temporal patterns among habitats.

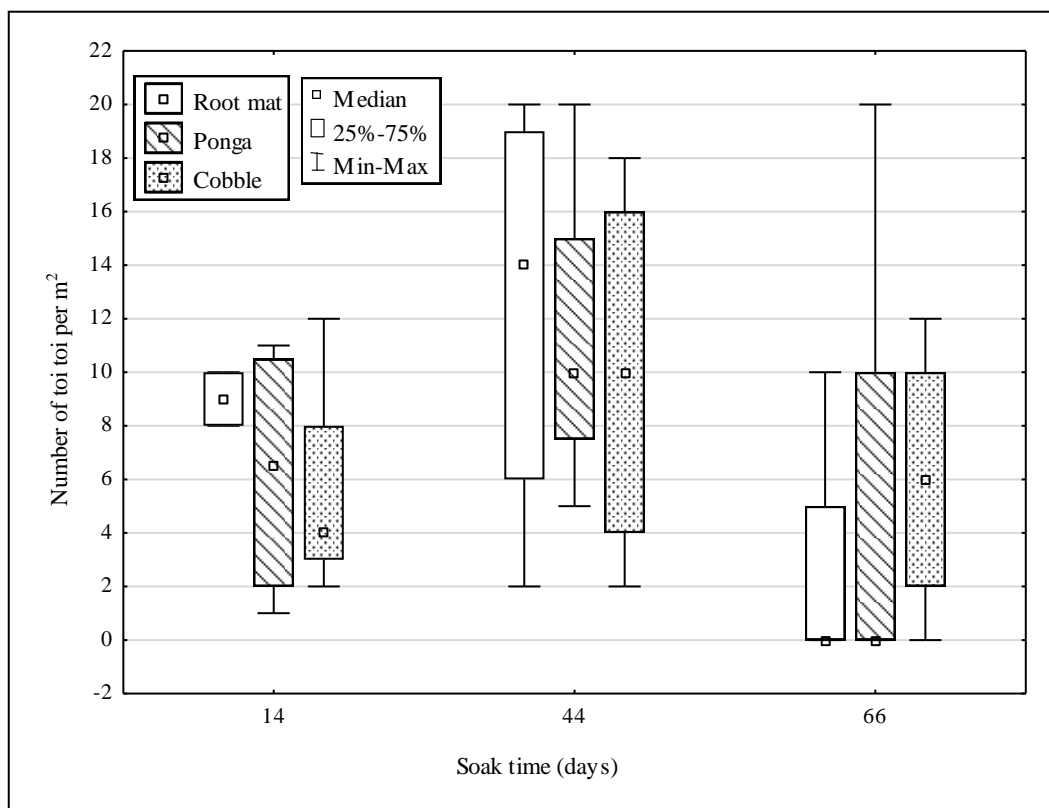


Figure 3-7 Comparison of toi toi abundances per m² between root mat, ponga frond and cobble habitats over three sampling intervals (n = 4).

Table 3-6 Summary of two-way factorial ANOVA results for toi toi abundances per m² measured over three sampling intervals for the habitat types root mat, ponga fronds and cobbles. SS = sums of squares, df = degrees of freedom, MS = mean squares, F = ANOVA statistic, **bold** = probability (p) < 0.05.

Effect	SS	df	MS	F	p
Intercept	20.57	1.00	20.57	123.95	0.00
Habitat type	0.04	2.00	0.02	0.13	0.88
Soak time	2.12	2.00	1.06	6.39	0.01
Habitat type*Soak time	0.57	4.00	0.14	0.86	0.50
Error	4.48	27.00	0.17		

Wilcoxon analysis showed significant differences in toi toi abundance per kg of dry weight remaining between habitats across all sampling intervals (p < 0.05), with consistently higher median densities on ponga fronds (Figure 3-8). However, for pairwise comparisons at each sampling interval there was no significant difference

found between root mat and ponga (Wilcoxon; day 14, 44, 66, 133, $p > 0.1$), reflecting high variability in toi toi densities among replicates on the same removal date.

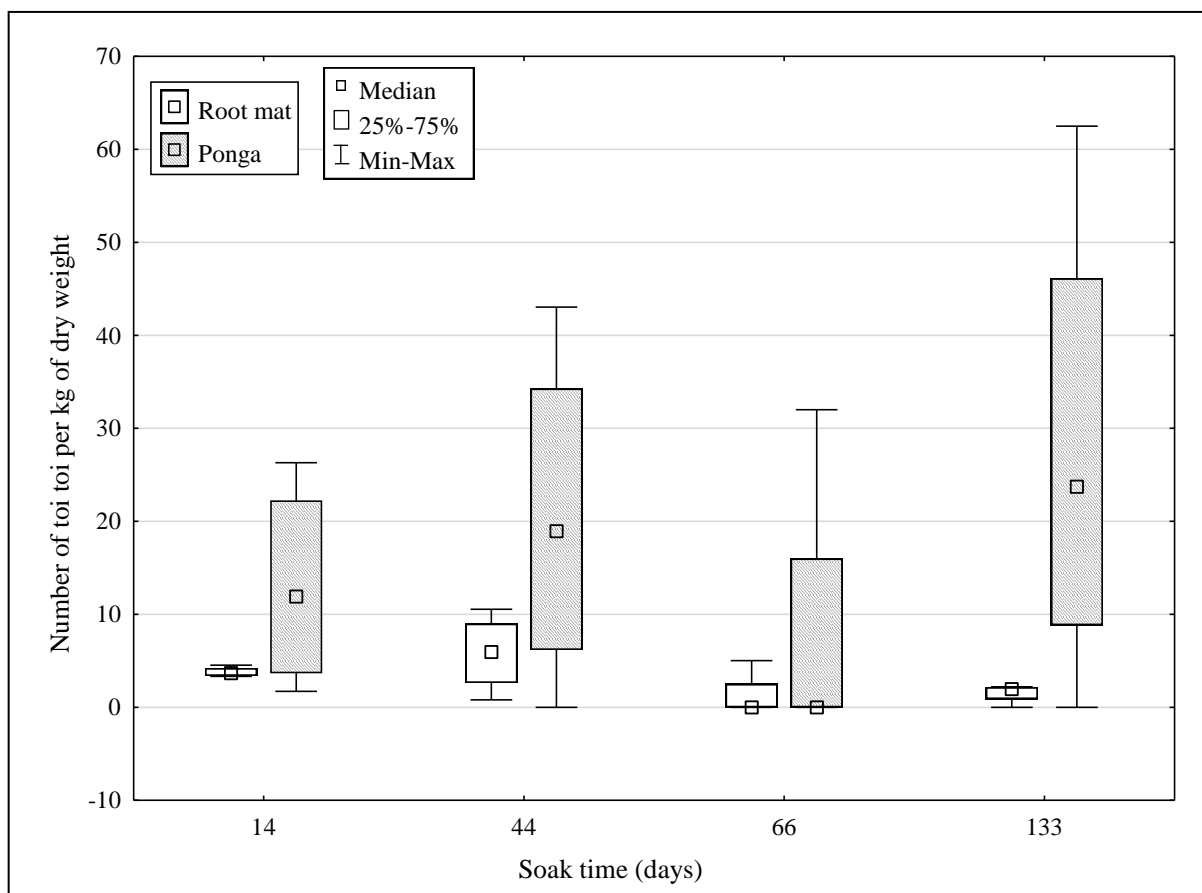


Figure 3-8 Comparison of toi toi abundance per kg of initial dry weight remaining between root mat and ponga frond artificial habitats over four sampling intervals ($n = 4$).

Correlation of co-variables

Statistical analysis showed a significant inverse correlation between velocity (m/s) and toi toi abundance per m^2 ($r_s = -0.36$, $p < 0.05$), however, there was no correlation between velocity and number of toi toi per kg dry weight or either measure of kōura densities (Table 3-7). Other factors investigated in this study that exhibited no correlations with kōura and toi toi densities were depth, channel width and distance from the top of the reach, indicating these factors did not influence observed patterns in relation to substrate type or soak time. Significant correlations were detected between kōura per m^2 and toi toi per kg ($p < 0.05$), and between kōura per kg dry weight habitat remaining compared with toi toi per kg dry weight habitat remaining ($p < 0.05$; Table 3-7).

Table 3-7 Matrix of Spearman rank correlation coefficients (r_s) for co-variables measured at each artificial substrate on removal, and kōura and toi toi abundances. **Bold** indicates significant at $p < 0.05$.

	Depth	Velocity	Channel width	Distance from reach top	Kōura per m ²	Toi toi per m ²	Kōura per kg
Kōura per m ²	0.23	-0.14	0.02	0.23			
Toi toi per m ²	0.15	-0.36	0.30	0.01	0.33		
Kōura per kg	0.29	0.05	-0.13	0.03	0.92	0.30	
Toi toi per kg	0.34	-0.27	0.28	-0.05	0.61	0.81	0.68

3.5 Discussion

Natural decay of organic matter in streams varies considerably dependent on the size of the vegetation (as smaller leaves break down quicker), and the type of vegetation (as certain plant species break down faster). These characteristics determine the ability of the organic matter to withstand degradation pressure from naturally occurring events that may be exacerbated due to surrounding land use (Bird & Kaushik, 1981; Jenkins & Suberkropp, 1995; Graça, 2001; Kusabs *et al.*, 2018). In pastoral streams stock trampling, erosion, nutrient inputs, altered hydrology and lack of riparian vegetation can have major influences on in-stream habitat and the durability of organic matter accumulations (Quinn *et al.*, 1997; Parkyn *et al.*, 2002; Jowett *et al.*, 2009; Kusabs *et al.*, 2018). The hydrological processes associated with pastoral development influence the stream's ability to form deep pools in which organic matter accumulates (Jowett *et al.*, 2008; Rosenfeld *et al.*, 2011) and to retain organic material for long enough to form enduring habitat. This manipulation study aimed to understand how artificial structures constructed to simulate naturally-occurring habitats created by ponga, could provide habitat in a representative pastoral hill-country stream. A key focus was on how long the artificial habitats would last in-stream and the interactions between decay time and colonisation. Although the key focus of the study was kōura, toi toi numbers were also often high in the substrates sampled and correlated with kōura densities, so they were also analysed to highlight the multiple benefits of ponga frond and root wad habitats

3.5.1 Effects of organic matter decay

It is known that shredders, such as kōura, can discriminate differences in leaf toughness and nutrient value (Graça, 2001). These characteristics can be mediated by microbial communities which can make the leaf matrix more palatable as it decays and adds to its nutritive value (Graça, 2001; Kusabs *et al.*, 2018). Nonetheless ponga (*Dicksonia squarrosa*) leaves have been found to be an unreliable food source for kōura particularly juveniles, which cannot be sustained on ponga leaves alone (Parkyn & Collier, 2002). Therefore, the kōura found in the ponga frond bundles in this study may have been seeking daytime shelter or food directly from colonising microbial and invertebrate communities. Leaf material can become colonised by macroinvertebrate shredders soon after entering the stream (McArthur & Barnes, 1988). Kusabs *et al.* (2018) found by checking whakaweku (bracken bundles) 16 hrs after placement, then approximately every week, that kōura colonised whakaweku in a Waikato hill-country stream in high numbers within only 2 weeks of soak time. It was unclear in the present study if kōura inhabited the artificial habitats prior to two weeks as samples were withdrawn over longer time scales.

Ponga fronds are known to be hardy (Wardle, 1995), with ponga frond bundles predicted to last 221 days in-stream based on estimated 95% loss in mass. This may be an over-estimate, however, as a significant part of the total weight in a ponga frond is likely stalks and veins which are unlikely to provide adequate habitat for kōura in the absence of leafy material. In the present study after 116 days, half the frond mass remained, and visual observation confirmed intact leafy material was abundant suggesting there would still be substantial habitat remaining, dependent on in-stream conditions. Field observations also indicated that the most intact ponga bundles were in pools with low flow or completely submerged on bends where sediment was not settling, suggesting such locations could provide suitable sites for in-stream habitat enhancement while riparian vegetation grows.

Predicted longevity of root mat surrogates in this stream was greater than for ponga fronds, and in the right conditions they may provide enduring habitat for up to 328 days. Even with 5% of weight remaining at this time, the coconut fibre mats could still function as an adequate habitat supporting small numbers of kōura and toi toi as the material composition was homogenous and, unlike ponga fronds,

would not change in composition over time. The matting was bound together by string which added to its structural stability. However, it was very susceptible to sedimentation, a common occurrence associated with hill-country pastoral streams (Quinn *et al.*, 1997; Hughes *et al.*, 2012). As the matting began to break down and become loose, it was noted that more kōura were present within the rolls, whereas before kōura were only found on the outside. The effectiveness of the bundles as habitat might have been improved if they were not so tightly rolled together and the strings were cut in places to create interstitial spaces. This, however, may have resulted in quicker breakdown of the matting and would have little effect on susceptibility to sedimentation.

Similar to this study, bracken fern whakaweku was used to monitor kōura and toi toi in streams and showed species abundances declined after 9 weeks, apparently due to the decline in structural integrity from fern decay (Kusabs *et al.*, 2018). They noted that the whakaweku decay rate was much quicker in streams compared to lakes (6 months in eutrophic lakes, > 2 years in oligotrophic lakes), especially during the summer when water temperatures were higher. Faster decay rates can also be attributed to differences in water velocity and nutrient concentrations (Gulis & Suberkropp, 2003). It was unclear in the present study if these effects contributed to decay times of ponga fronds and root mat surrogates, however, the period from day 66 to day 133 was characterised by high rainfall and high flow events and marked decay in ponga fronds was evident over this time. Nevertheless, ponga fronds in particular, appeared to provide longer term habitat than bracken fern with no declines in kōura densities evident up to 133 days in the stream, although their suitability as kōura and toi toi habitat compared to bracken fern cannot be determined from these data.

3.5.2 Habitat relationships with kōura and toi toi

Results from Chapter 2 showed that in pasture streams kōura habitat can be limited to grass roots, the occasional exotic plant root system, in-stream substrates including CPOM accumulations, and undercut banks. In many pastoral streams draining hill-country, benthic substrate can be limited to finer sediments due to high erosion rates and low stream power (Harding *et al.*, 1999), while large undercut

banks can be too exposed to provide adequate habitat without root systems (R. Parata, personal observation). These conditions may expose kōura to a variety of pressures and threats, including predation, flood events, ongoing sediment inputs from erosion, and stock disturbing substrates and destroying banks. Nevertheless, kōura densities in the preliminary sampling were typical when compared to the average densities of the 12 sampled streams in Chapter 2.

This study found there were no statistically significant effects of habitat types, partly due to the number of kōura found among ponga fronds being highly variable compared to root mats and cobbles. There could be a number of reasons for this including variable sedimentation of some habitats and trampling by stock which regularly entered the study reach. Nevertheless, the plots highlighted that some ponga frond bundles at least were well colonised by kōura and generally did appear to be the preferred habitat across all sample times. Such a preference could reflect a wide range of factors including: (i) colonisation of macroinvertebrates and fungi which may have provided a food source for kōura; (ii) ponga frond material eventually providing some nutritional value to kōura through the decay process; and (iii) more appropriate habitat structure providing increased cover. Furthermore, there was no evidence to support a decline of kōura densities per habitat type over time, indicating they played a consistent role even as habitat area or mass decreased over the 133-day duration of the study.

Toi toi and kōura habitat are known to overlap (Hicks & McCaughan, 1997; Hicks, 2003), as confirmed in this study through consistent co-occurrence and significant correlations between densities of the two species. Results from my study showed a greater number of toi toi preferred ponga when compared to root mat per weight of habitat, but when comparing all habitat types based on density per area, results were similar with no statistical significance. This result could be due to the dense nature and compact structure of the root mat. Soak time and water velocity appeared to influence toi toi density with overall densities higher in slower flowing habitats. Toi toi numbers per m² of substrate were highest at 44 days and then declined across all substrate types. It was unclear why this decline occurred, however, the study took place at peak migrating and spawning time for toi toi (McDowall, 1995b; Boubee *et al.*, 2000) which probably affected toi toi movement relative to the habitats. Like kōura, toi toi are associated with cover in the form of cobble and gravel substrates,

undercut banks and vegetative cover (McDowall, 1990). The association of toi toi and kōura using the same habitat was similar to results from Kusabs *et al.* (2018).

The few kōura found in cobbles (9% of total numbers) underscores the lack of suitability of this habitat type. Cobbles that were sampled for kōura were mainly situated at the downstream ends of pools where there was higher flow and less deposited fine sediment. Kōura are known to be associated with low flow areas (Usio & Townsend, 2000; Jowett *et al.*, 2008) which is consistent with the low numbers found in cobbles, although there was no inverse correlation with water velocities detected as there was for bullies. However, preference for low velocity habitats by kōura is consistent with findings in the previous chapter. No female kōura were associated with cobbles, however, it was unclear if this was due to their low numbers or some unknown habitat separation with males during the daytime. If this study was to be repeated, it is recommended that more habitat replicates are installed and the frequency of sampling intervals is increased for a more comprehensive statistical analysis and reduce variability within results.

3.5.3 Implications for stream restoration

Worldwide, there have been studies using a variety of structures made from metal, plastic and concrete, used as tools to enhance crayfish and lobster habitat with varying success (Sheehy, 1976; Huolila *et al.*, 1997; Jones & Ruscoe, 2001; Viau & Rodríguez, 2010; Mazlum *et al.*, 2017), however, there have been few studies concerning the use of natural organic materials for crayfish habitat. The matrix that ponga bundles provided in this study created a range of different-sized niches for multiple kōura of varying size, similar to results reported by Jones and Ruscoe (2001) who used mesh bundles made from onion bags in a study comparing 5 artificial habitats. Mesh bundles significantly improved ($p < 0.001$) survival rates when compared to pipe stacks, tires, flat or elevated cement/fibre board sheets, and no habitat as a control.

Riparian planting can improve in-stream habitat structure and provide refugia and food sources for aquatic biota, including for potential keystone species such as kōura, leading to improved ecosystem function with benefits for species diversity

and abundance (Graça, 2001). The study presented in this chapter has highlighted the effects that ponga species can potentially have as a riparian plant through fallen fronds and root mats which extend into the water, providing habitat for aquatic species. Through its extensive root network ponga can provide excellent stream bank stability (Ministry for the Environment, 2001), as well as acting as a nursery plant for other riparian species. Consequently, the tree fern varieties mamaku (*Cyathea medullaris*), whekī (*Dicksonia squarrosa*), ponga (*Cyathea dealbata*) as used in this study, and whekī-ponga (*Dicksonia fibrosa*) have all been recommended for riparian planting by territorial authorities and the Department of Conservation (Collier *et al.*, 1995).

Associations between riparian planting, and the in-stream habitat it provides, with kōura populations have received little attention in New Zealand. However, two riparian manipulation case studies described by Jowett *et al.* (2009) highlight the importance of riparian planting to fish habitat. The first study removed overhanging bank vegetation and in-stream wood deposits from a small pastoral stream with riparian margins and monitored its effects over 5 months. The second involved the riparian restoration of small sections in two pastoral streams over 10 years while fish species abundance, including redfin toi toi (*Gobiomorphus huttoni*), and habitat were monitored. The results showed the removal of cover decreased abundances of inanga (*Galaxias maculatus*) and large tuna (*Anguilla dieffenbachii*), whereas the riparian restoration sites showed increases in inanga, tuna, toi toi and macroinvertebrate numbers. Although kōura catches were not reported in those studies, the co-occurrence and positive density relationship between kōura and toi toi found in my study suggests that loss of riparian cover may also impact kōura habitat.

With the exception of Kusabs *et al.* (2018), artificial habitats constructed from natural materials have rarely been applied to aid in kōura habitat enhancement. The two artificial habitats tested in this study represent a first step towards designing a structure that provides a variety of interstitial spaces that accommodate a range of kōura sizes. The durability of the artificial habitats in the pastoral stream studied was dependent on in-stream conditions and management, in particular constant pressure from erosion, stock, and high velocities during frequent flood events. However, if used in a supporting role with riparian planting and fencing, then

artificial structures could provide long-lasting habitat to accelerate recovery of kōura populations, as well as providing benefits for other species such as toi toi. With time, the role of these structures would be superseded by growth of appropriate riparian species, including ponga, that would contribute organic matter and provide root habitat year-round. In the meantime, projects involving artificial habitats could focus on providing cover for kōura at key times of year in areas lacking adequate habitat.

Chapter 4

General Discussion

This study was motivated by the significance of kōura as a taonga species for Māori, and concern over the degradation of key habitat features known to be associated with kōura. Māori are concerned with ensuring strong taiao mauriora (environmental well-being) for the benefit of taonga species, and how the health of the environment also contributes to the health of the people. The New Zealand government has officially acknowledged the cultural, spiritual, historic, and traditional association many Māori have with taonga species in settlement claims (e.g. Ngāi Tahu Settlement 1997), enabling iwi to manage taonga species based on tikanga (customary practices and procedures). However, now that transfer procedures for moving kōura between locations is administered by the Ministry for Primary Industries and the Department of Conservation, the traditional practice of relocating kōura as a food source may be restricted for Māori, creating an incentive to enhance habitat to boost kōura numbers at existing locations.

Drivers of land use change can affect the characteristics of New Zealand streams and therefore kōura habitat requirements. While aquaculture of kōura, mainly *P. zealandicus*, has been successful in some locations, the current lack of specific kōura conservation measures means there is a gap in knowledge of how to enhance kōura habitat and improve survival and growth rates in natural settings, particularly for juvenile kōura. A focus of this research was to use both mātauranga Māori and western science methodologies to provide information for conservation managers, restoration practitioners and kaitiaki to enhance the survival of kōura through improved understanding of their habitat requirements.

The overall aim of this research was to identify and quantify instream habitat factors associated with kōura density and size in Waikato hill-country streams with a particular focus on juvenile kōura ≤ 8 mm OCL. Similar studies by Parkyn *et al.* (2009) and Jowett *et al.* (2008) focused on micro-habitat relationships with kōura in Waikato hill-country pastoral and native forested streams that helped define kōura relationships with particular habitats, including leaf litter, woody debris, tree roots, undercut banks, substrate size, and stream bank holes. My study builds on

these previous studies: (i) with the inclusion of riparian planting treatments at different stages of development; (ii) by investigating the scale at which particular hydraulic, substrate, and cover habitat features appear to exert an influence on kōura, and (iii) through finer scale analysis of habitat-associations involving targeted sampling and the use of constructed habitats to monitor colonisation. All sampling was conducted during the day, so the results reflect use of day-time refugia.

4.1 How the research was approached and designed

I used a field survey of 12 sites and conducted a habitat manipulation study at one site to address the thesis goals. Both studies had a focus on kōura relationships with micro-habitat, with a particular interest in juvenile kōura. The 12 streams in the field survey were at locations with four different stream edge treatment types – pasture, early riparian planting, late riparian planting and native forest – with three sites in each treatment. I selected different-aged stream edge treatments because they were expected to produce varying amounts of instream habitat available for kōura. I was particularly interested in the types of inorganic substrate cover and instream organic materials that were available for kōura to inhabit, and to determine what hydrological processes could interact with these habitats and therefore influence their suitability for kōura.

The field survey used a modified electrofishing technique to target kōura, with a specific focus on micro-scale habitats occurring within 2-m lengths of channel. The 2-m scale locations were replicated within five 10-m long sub-reaches which, when combined, represented 50-m long reaches at each site. This approach meant I could examine whether findings about kōura-habitat associations could be extrapolated across scales. This novel approach was intended to provide insights into the scale of management actions required to enhance populations, and to identify what role riparian management plays in influencing kōura populations. The field survey used both proven and modified electrofishing techniques to explore inter-relationships between kōura abundance and size and corresponding habitat variables across the range of scales. The modified electrofishing method targeted kōura by using soft bristled brooms to sweep electrofished areas into a net, which was less harmful to kōura with fewer loss of chelipeds than previous trials using only a plastic moulded,

metal lined sieve net (R. Parata, J. Kelly, personal observation.). Two electrofishing passes were conducted to improve capture efficiency, similar to effort used by Hicks and McCaughan (1997) for sampling fish and kōura populations. Rabeni *et al.* (1997) also used 2-pass electroshocking to produce kōura population estimates that were 76% of 5-pass electroshocking coupled with mark-recapture. Although this may indicate the present study did not capture c. 24% of the population, the combined 2-pass method provided a consistent and efficient approach for estimating densities to compare across scales and sites.

By incorporating a habitat manipulation study, I was able to test whether kōura would exploit artificial habitats (i.e., added ponga frond bundles or artificial root mats) in a pastoral stream starved of onsite organic inputs to create cover for kōura. I enlisted traditional mātauranga Māori approaches by using natural materials for habitat construction and by incorporating traditional sampling techniques with a kōrapa (or landing net) made of modern materials. The two artificial habitats, constructed to simulate naturally-occurring habitats observed in forested streams, were made from fronds of *Cyathea dealbata* which was common in the area or from rolled up coconut fibre matting to simulate the dense root structures of ponga found at the streams edge. If shown to be effective at providing habitat for kōura, the ease of construction and inexpensive cost of the materials used would enable cost-effective restoration by community groups, hapū and whānau.

It was observed in both studies that more juvenile kōura were being collected as time progressed from November 2018 to February 2019, consistent with juvenile kōura becoming free-living in pastoral streams from September to December and native streams from December to March (Parkyn *et al.*, 2002). This was most noticeable in the manipulation study as the final sample date in February produced the most juvenile kōura. To capitalise on this finding, I undertook targeted sampling of specific micro-habitat types to find out if these recently-released kōura were occupying habitats found to be important in the field survey, in particular, root wads.

4.2 Key findings of the research

The spatial variation of velocity and depth regimes within streams are key drivers of habitat heterogeneity (Rosenfeld *et al.*, 2011). The field survey indicated that hydraulic characteristics, including band-scale velocity, and sub-reach to reach scale velocity variability, influenced kōura densities in Waikato hill-country streams. Such effects of velocity may be direct by affecting the ability of kōura individuals to maintain position in faster flow (larger individuals more likely withstand faster flows), and/or indirectly by affecting organic matter build-up and persistence in streams and thereby affecting provision of micro-habitat. The breakdown of habitats caused by stream flow, particularly during high flow events, visibly contributed to the decay of artificial habitats in the manipulation study. Degradation of organic habitats can also be caused by water temperature increases and higher nutrient inputs associated with land use (Quinn *et al.*, 1997; Gulis & Suberkropp, 2003; Kusabs *et al.*, 2018). Although water velocity is a function of catchment size and channel gradient, logs and large organic matter accumulations may increase flow heterogeneity and create hydraulic refugia that may favour smaller kōura highlighting the importance of cover habitats and associated slower flowing areas for juvenile kōura (Usio & Townsend, 2000; Jowett *et al.*, 2008).

Even though crayfish are known to inhabit deep pools (Englund, 1999; Englund & Krupa, 2000; Usio & Townsend, 2000; Parkyn *et al.*, 2009), depth was not significantly or strongly associated with kōura in the present study, partly because of the lack of deep pools in these small hill-country streams. Pools were actively sought out for placement of the artificial habitats in the manipulation study because of this known association with kōura. The breakdown of ponga frond bundles was slower in pools with low flow and on bends where sediment was not accumulating rapidly (R. Parata, personal observation), suggesting that position of introduced habitat within a stream reach may affect how long they last.

Consistent relationships with embeddedness were evident across all scales in the field survey, suggesting erosion from the land and subsequent sedimentation in waterways (Quinn *et al.*, 1997; Hughes *et al.*, 2012) could have an ongoing negative impact on kōura, especially in pastoral streams where high sediment loading is more apparent (Dodd *et al.*, 2008). Although streams where embeddedness was greater seemed to favour smaller kōura, high sedimentation rates were not apparent within

the stream survey and this relationship may instead reflect the coincidence of sediment deposition in favoured slow-flowing areas. The effects of high concentrations of fine sediment on kōura can include loss of habitat, reduction of light penetration (Kusabs *et al.*, 2005), and direct obstruction of gills (Westman, 1985).

There tended to be fewer kōura in streams where algal growth was more common, which was a surprising result of the field survey as kōura are known to be consumers of filamentous algae (Hicks, 1997). This association could be due to the small number of sites where algae was present or its association with wider streams where kōura densities were low. Distinct relationships between kōura and organic matter was evident in both studies. In the analysis across scales and within streams, “other” root mat cover, ponga logs and CPOM all exhibited associations with kōura, in particular ponga logs with juvenile kōura. This was unsurprising due to the abundance of ponga at late riparian and native treatment sites compared to the absence of ponga in pastoral sites and few at the early riparian sites. Large wood structures mostly found at late riparian and native treatments were associated with increased depth variability and habitat complexity at the reach scale, reinforcing the importance of such habitat features for kōura (Usio & Townsend, 2000; Parkyn *et al.*, 2009).

Pastoral streams with no riparian planting lacked instream organic cover in the channel, with kōura apparently more reliant on undercut banks, inorganic substrates ranging from gravels to large cobbles, and submerged roots. No juvenile kōura ≤ 8 mm OCL were found when sampling pastoral and early riparian sites in the field survey, potentially because of lack of refugia. However, this finding could also partly have been due to the time of sampling (i.e., November to February), as according to Parkyn *et al.* (2002), free-living juveniles are typically present in pastoral streams within the Waikato hill-country as early as September, although juveniles were found in targeted habitat sampling as late as February. Also, free-living kōura of 3-5 mm OCL were difficult to sample and could have been easily missed without more targeted sampling, although juvenile kōura of c. 5-8 mm OCL were clearly visible at other locations, as evidenced by their high numbers at late riparian and native forest sites.

As part of this research, I also sampled individual habitats in a stream with native riparian forest and found low numbers of kōura in CPOM deposits, consistent with Parkyn and Collier (2004), but high numbers of juveniles among predominantly native tree roots along the stream edge. Watercress sampled along the streams edge had only larger kōura, potentially due to dominant and aggressive tendencies associated with large crayfish (Devcich, 1979; Capelli & Munjal, 1982; Wooster *et al.*, 2012). Interestingly, the field survey showed that grass and willow roots, along with undercut banks, supported no juvenile kōura in pastoral and early riparian treatments suggesting these habitat types may not provide adequate cover. This was surprising as crayfish are known to inhabit bank undercuts in streams with limited cover (Usio *et al.*, 2006). Although small sample size may have affected statistical analysis for both studies, overall results suggested that kōura size and density are influenced by instream habitat associated with riparian vegetation. Thus, reach-scale riparian planting in pastoral settings appeared to contribute important meso- and micro-habitats for kōura, supporting previous findings of a link between riparian vegetation and instream habitat used by juvenile kōura (Usio & Townsend, 2000; Parkyn & Collier, 2004).

The manipulation study investigated three habitats known to be associated with kōura. The small benthic fish toi toi (bully, *Gobiomorphus* spp.) was also used in this investigation as they are known associates of habitat cover shared by kōura (Hicks & McCaughan, 1997; Hicks, 2003; Kusabs *et al.*, 2018). From the manipulation study I wanted to determine finer-scale associations between kōura and specific habitat types in a stream dominated by surrounding pastoral land use, with a view to understanding how kōura populations could benefit from increased instream cover provided by riparian restoration and instream habitat additions. Only 9% of total kōura numbers were found in cobbles in the manipulation study suggesting that other types of habitat were more suited to kōura within pastoral streams.

The manipulation study also provided insight into the longevity of organic habitats. Almost all (95%) of the ponga fronds were predicted to have degraded by 221 days immersion in the stream, while at 116 days 50% remained. The coconut fibre matting lasted longer than the ponga fronds with 95% loss predicted by 328 days, although at the final sampling it was noted that the coconut fibre matting was

becoming frayed, so total degradation time may have been quicker from that point on. Nevertheless, even the remaining 5% coconut fibre matting could still provide a small amount of cover to both kōura and toi toi, in contrast to ponga fronds which were predominantly stalks after 95% weight loss.

4.3 Implications for management and future work

Results from this research indicate that the availability of instream habitat for kōura is highly dependent on instream processes and characteristics, surrounding land use type, durability of instream habitats, and stream edge planting. The importance of riparian vegetation for enhancing instream habitat structure is well documented (Ormerod *et al.*, 1993; Hicks & McCaughan, 1997; Abernethy & Rutherford, 2000; Parkyn & Collier, 2004; Brusconi *et al.*, 2008; Jowett *et al.*, 2009; Aarons & Gourley, 2013). Because kōura are primarily active at night, daytime habitat provided by riparian influences provides important refugia. Increasing riparian planting downstream from forested areas creates landscape connectivity along streams (Reynolds *et al.*, 2013). Pastoral streams near to native or restored headwater sources can exhibit high invertebrate community metrics reflecting good stream health (Jowett *et al.*, 2009; Quinn *et al.*, 2009), suggesting few physicochemical constraints exist for kōura in such streams. Recruitment of kōura from restored source areas to unrestored areas downstream suggests that habitat enhancement is best targeted close to forested areas or well-developed riparian treatments established along a connected catchment. Restoration managers may achieve greater gains in kōura productivity and longevity through riparian planting establishment and instream habitat enhancement by ensuring landscape connectivity.

Native riparian vegetation takes many years to mature, so an interim measure may be needed to provide habitat until instream habitat from logs and roots develops. Introduction of constructed habitats at key times of year, particularly when juvenile kōura recruit, provides one means of doing this. I found that ponga frond bundles were utilised by juvenile kōura and would last over the important summer months when juveniles were most vulnerable to predation. Coconut fibre matting root surrogates would last longer as kōura habitat, but would benefit from modification

(e.g., pleating or gathering into more complex layers) to provide more habitat spaces for juveniles. For best results, placement of these habitats would be most suited to instream areas: (i) with deep pools for complete submersion during low flows where sediment build up would be low; (ii) with less chance of destruction from flood events; and (iii) near or within undercut banks and overhanging vegetation for increased protection and chance of re-colonisation.

The information gained from this study can be used to aid restoration of streams for kōura by determining suitable vegetation for riparian planting, assessing what factors and drivers contribute to instream habitat availability and sustainability, and providing general information on habitat features to enhance instream and stream edge structures for kōura. Outcomes from this study highlight the importance of vegetation type for restoration (e.g., ponga) and, if constructing instream habitats for interim purposes, how to create habitat for kōura and other aquatic species to achieve multiple benefits using inexpensive natural materials. Mātauranga Māori and community science can also be used in determining reasonable goals and outcomes. If there are more kōura in greater abundance and densities in areas where there is late riparian and native forested streams compared to pastoral areas, then these simple understandings can lead to important decision-making regarding habitat restoration.

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Appendices

Appendix 2.1 Stream photographs of field survey sites



Left – Kiripaki Stream (K3), bottom of survey reach looking upstream. *Right* – Toreparu Stream (T1), bottom of survey reach looking upstream.



Left – Mangakara Stream (MK1), top of survey reach looking downstream. *Right* - Rangitukia Stream (R1), bottom of survey reach looking upstream.



Left - Te Pahu Stream tributary (TP6), bottom of survey reach looking upstream. *Right* - Te Pahu Stream tributary (TP5), bottom of survey reach looking upstream.



Left – Mangamauku Stream (MM1), bottom of survey reach looking upstream. *Right* – Te Pahu Stream tributary (TP1), bottom of survey reach looking upstream.



Left – Ahiawa Stream (AA1), bottom of survey reach looking upstream. *Right* – Rangitukea Stream (R2), top of survey reach looking downstream.



Left – Wainui Stream (W2), bottom of survey reach looking upstream. *Right* – Whakakai Stream (WK1), bottom of survey reach looking upstream.

Appendix 2.2 Matrix of band-scale pairwise comparisons (z values)

Multiple pairwise comparisons (z values) performed at the band scale between dependant kōura variables and sites. Shaded light to dark green to indicate pastoral, early riparian, late riparian and native treatments respectively. **Bold** = significant effect ($p < 0.05$).

Kōura per m ²											
Site											
K3	K3										
T1	1.74	T1									
MK1	2.52	0.78	MK1								
R1	0.84	0.90	1.68	R1							
TP6	1.39	3.13	3.91	2.23	TP6						
TP5	0.92	0.83	1.61	0.07	2.30	TP5					
MM1	0.04	1.79	2.57	0.89	1.34	0.96	MM1				
TP1	1.93	3.67	4.45	2.77	0.54	2.85	1.89	TP1			
AA1	1.12	0.62	1.40	0.28	2.51	0.21	1.17	3.06	AA1		
R2	1.84	3.59	4.37	2.69	0.46	2.76	1.80	0.09	2.97	R2	
W2	2.21	0.47	0.31	1.37	3.60	1.30	2.26	4.15	1.09	4.06	W2
WK1	0.14	1.89	2.67	0.99	1.24	1.06	0.10	1.79	1.27	1.70	2.36
Mean size (mm OCL)											
K3	K3										
T1	0.72	T1									
MK1	2.27	1.38	MK1								
R1	0.22	0.92	2.47	R1							
TP6	0.05	0.80	2.42	0.18	TP6						
TP5	0.04	0.63	2.02	0.23	0.08	TP5					
MM1	1.89	0.95	0.56	2.12	2.05	1.65	MM1				
TP1	2.23	2.72	4.39	2.00	2.31	2.02	4.25	TP1			
AA1	1.66	2.20	3.72	1.45	1.70	1.53	3.49	0.40	AA1		
R2	3.70	4.03	5.72	3.48	3.86	3.33	5.71	1.56	1.83	R2	
W2	2.17	2.65	4.15	1.97	2.23	2.00	3.95	0.18	0.53	1.21	W2
WK1	2.66	3.11	4.82	2.44	2.78	2.39	4.72	0.42	0.79	1.18	0.18
Juveniles per m ²											
K3	K3										
T1	0.00	T1									
MK1	0.00	0.00	MK1								
R1	0.29	0.29	0.29	R1							
TP6	0.78	0.78	0.78	0.49	TP6						
TP5	0.00	0.00	0.00	0.29	0.78	TP5					
MM1	0.00	0.00	0.00	0.29	0.78	0.00	MM1				
TP1	3.24	3.24	3.24	2.95	2.46	3.24	3.24	TP1			
AA1	0.94	0.94	0.94	0.64	0.16	0.94	0.94	2.31	AA1		
R2	4.20	4.20	4.20	3.91	3.42	4.20	4.20	0.96	3.27	R2	
W2	0.66	0.66	0.66	0.37	0.12	0.66	0.66	2.58	0.27	3.54	W2
WK1	2.50	2.50	2.50	2.21	1.72	2.50	2.50	0.74	1.56	1.70	1.84