Reproductive biology and spawning substrate preferences of European Perch (*Perca fluviatilis*) from two New Zealand lakes

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ABSTRACT

European perch (*Perca fluviatilis*) has dominated freshwater systems in New Zealand since its introduction in 1868. This introduced species has established itself by outcompeting native species and altering the physicochemical properties of habitats. Eradication and control efforts in New Zealand seldom focus on initiating management at spawning, with little attention to their reproductive biology and plasticity. Despite many studies across the world focusing on these aspects, most are in the context of population protection within their native territories or in fisheries. Lake Rototoa and the Hamilton Lake (also known as Lake Rotoroa) are two lakes within the North Island of New Zealand that vary considerably in size and quality, and host populations of European perch that have dominated both systems.

Sampling from both lakes occurred over a 12-month period, where measurements of body size, gonad development, fecundity and condition were collected to provide insight into each population's health and reproductive biology. An artificial spawning substrate experiment over six weeks consisted of three different substrates at five sites in both lakes and in laboratory tanks to investigate the potential for spawning substrate preferences.

A total of 159 perch were caught and dissected from the Hamilton Lake, and 126 were caught and dissected from Lake Rototoa. Spawning appeared to be asynchronous at Lake Rototoa from condition and GSI results, and synchronous at the Hamilton Lake. Size and condition indices were higher at the Hamilton Lake and displayed some seasonal patterns. Fecundity at the Hamilton Lake ranged from 71,202 to 80,400.96 compared to 40,844 to 73,232.21 eggs per female at Lake Rototoa during the spawning season. Oocyte diameters were slightly larger at the Hamilton Lake, with a range of 0.836 mm and 2.019 mm compared to 0.839 mm and 1.886 mm at Lake Rototoa. Perch did not use any artificial spawning substrates at all three sites.

Results suggested a more stunted population at Lake Rototoa, likely due to different water qualities and resource availability. These results provide a solid foundation for control methods targeting spawning strategies in European perch. However, improved techniques for artificial spawning substrates are necessary, particularly focusing on the location and timing of where and when they are deployed.

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Chapter 1: Introduction and Literature Review

1.1 General introduction and study objectives

Whether on purpose or accidentally, non-native fish species have been introduced by humans to ecosystems exceeding their native range for many years, with freshwater fish having the most documented invasions (Bernery et al., 2022). In 1868, European perch (*Perca fluviatilis*) were introduced to New Zealand freshwater systems, initially for the purpose of game fishing in the South Island (Sabetian et al., 2015) but are now present in both North and South Island lakes and rivers (Jellyman, 1980) (Figure 2). They belong to the family *Percidae* and are native to the Northern parts of Europe and areas in Asia (Ning et al., 2025), where they are a desired farming species. They can be identified by their bright orange/red caudal, pelvic and anal fins, and darker coloured stripes along the side of their body (Figure 1). They are sexually dimorphic, with females typically appearing larger than males of the same age in both length and weight (Prchalova et al., 2022). The morphology and size of both sexes can be influenced by environmental factors, with temperature being the most significant variable (Ning et al., 2025).

Figure 1 European perch (Perca fluviatilis), showing its distinct physical characteristics (stripes and bright fins). https://www.ikijime.com/fish/perch-european/

Perch at different life stages inhabit different parts of their habitats. Larvae are typically within open waters, once fins are grown, they move closer to the shore (Ning et al., 2025). There appears to be no literature reviewing habitat preferences in native and non-native areas, or whether they differ. However, European perch are known as a plastic species and are able to adapt and adjust to environmental conditions, which is likely why they are able to successfully establish themselves in non-native territories (Saemi Komsari et al., 2014 & Sabetian et al., 2015).

Since their introduction into New Zealand, European perch have taken over freshwater systems, greatly affecting the native species already inhabiting them. This has been predominantly through competition for food and habitat, and predation of smaller native or endemic species, such as the Common Bully (*Gobiomorphus cotidianus*) (Sabetian et al., 2015). Diets vary at each life stage of European perch, where larvae consume zooplankton and other pelagic organisms, juvenile perch consume invertebrates such as insect larvae, and adults eat other fish species; in some cases, their own (Ning et al., 2025). The increase in the abundance of European perch has also contributed to declines in water clarity in some lakes in New Zealand. Not only do the perch larvae consume zooplankton, but adults prey on planktivorous fish, thus initiating a top-down disruption that directly and indirectly impacts species that help to contain and manage algal blooms (Rowe, 2007). Adult perch then shift to a more piscivorous diet; this change can depend on the abundance of prey fish in their habitat (Ning et al., 2025). Cannibalism has also been seen occurring within perch populations, likely when prey availability is low (Ludgate & Closs, 2003 & Ning et al., 2025).

Despite European perch holding an invasive status in New Zealand, it is native to parts of Europe and Asia, where it is eaten and also used as a biomarker for environmental impact (Hanson, 2009), it is also a popular recreational and commercial fishing species (Ning et al., 2025). The impacts of perch introductions in non-native territories have been well researched, from direct impacts on naive fish species to effects on water quality (Ludgate & Closs, 2003; Rowe, 2007 & Smith & Lester, 2006). Efforts have been made in New Zealand to control these populations, and research has been conducted to assess the effects of their removal on other freshwater species (Closs et al., 2001). Complete eradication of this species in New Zealand would be difficult due to its wide distribution and abundance, and control methods have the likelihood of impacting other native species. Previous and current methods of control in New Zealand have included physical removal using nets, traps and electrofishing, and also the input of poisons into freshwater systems; however, these methods run the risks of also affecting non-target species, especially native species (Closs, et al., 2001).

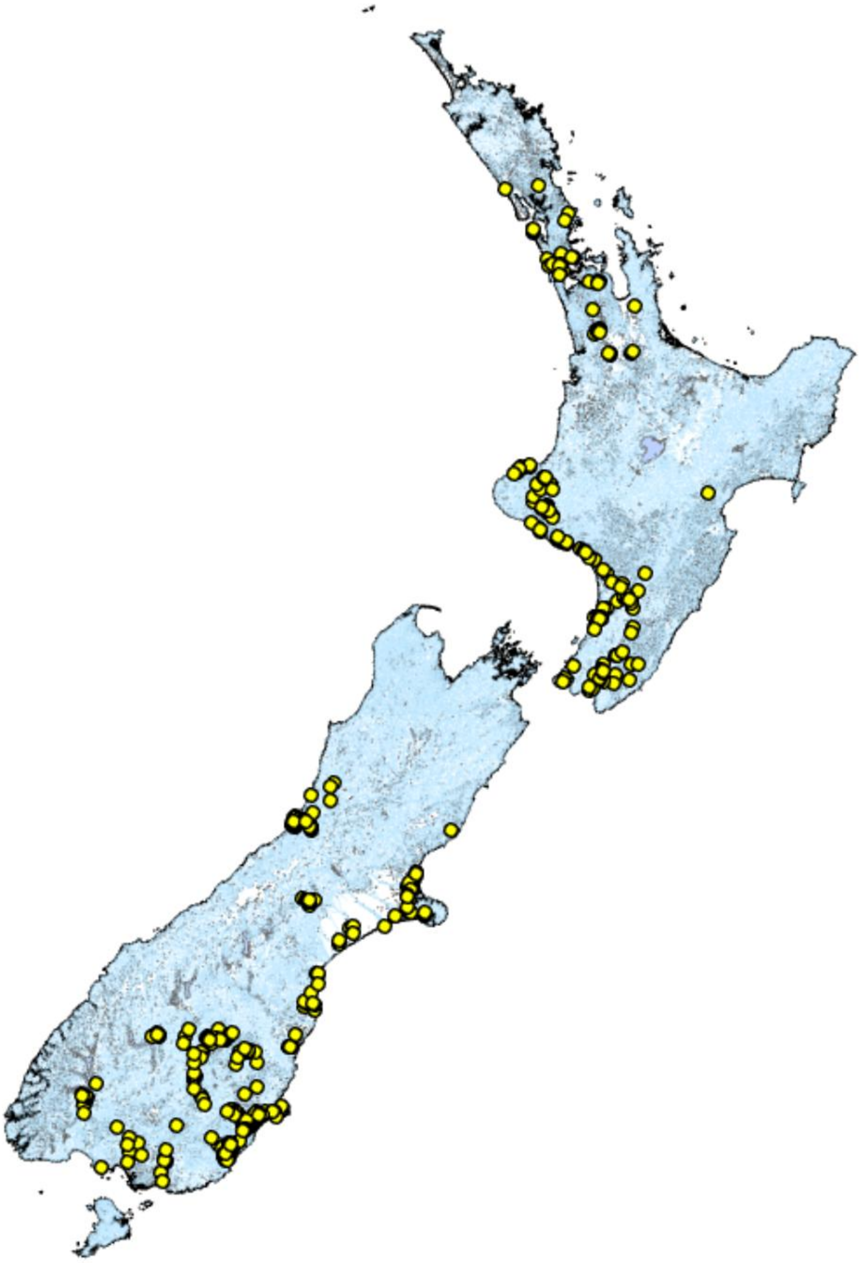


Figure 2 European perch distribution in New Zealand from NZ Freshwater Fish Database (Earth Sciences New Zealand). Map created using ArcGIS Pro.

It is important to develop non-invasive methods for controlling and, if possible, eradicating European perch in New Zealand to minimise the risk of further damage to native species and ecosystems. Here, we explore the potential to initiate removal from early life stages of European perch, where their reproductive cycle is influenced by abiotic and biotic factors, and therefore, differs across locations (Ning et al., 2025). Spawning strategies, such as the timing and location of spawning and fecundity, are heavily influenced by environmental cues such as temperature (Koenigbauer et al., 2024; Čech et al., 2011; Gillet & Dubois, 2007 & Migaud et al., 2004).

The objectives of this study were to examine the reproductive biology, condition and spawning substrate preferences of European perch in two different New Zealand lakes, which vary considerably in quality and size, but are both affected by the presence of this invasive species. This information provides insight into the populations inhabiting each lake and could contribute to the improvement of existing removal and control techniques or aid in the creation of potential new techniques.

In order to evaluate the real impact of European perch and potential management of this species in New Zealand, it is important to review literature collected from around the world focusing on their reproductive biology, the impacts of their presence on ecosystems, and spawning patterns and behaviours. Upon searching for and reviewing literature, this review did not have constraints on the year of publication, as it is important to consider changes in reproductive characteristics and population dynamics of European perch over the years to note changes and adaptations they may have had. Literature from outside New Zealand was included, even in places where this species is not considered "non-native", as parts of this review do not focus on that aspect and are purely from a biological perspective. Methods used to assess perch health and population status can be applied to both conservation and population control contexts.

1.1.1 Measurements and condition indices

Fulton's Condition Factor, somatic condition and gonadosomatic index (GSI) were calculated using fork length, total weight, and gonad weight of each perch caught. These metrics also provide insight into fish health and well-being (Froese, 2006; Morton & Routledge, 2006), which is useful when comparing perch from two lakes with different quality levels. In this study, Fulton's Condition Factor and somatic condition use length-weight relationships to evaluate the health of each fish and provide insights into the overall health of the population and the environment they live in.

Somatic condition uses eviscerated weight, where the weight of the gonad is removed from the total weight of the fish (Craig, 1977), and Fulton's Condition Factor includes the gonad weight in the total weight (Christophe, et al., 2015). Somatic condition is a valuable indicator of energy reserves and energy expenditure; changes in this are typically seen during spawning periods (Craig, 1977).

Gonadosomatic index is used to calculate the portion of gonad mass relative to the total body weight (Parker et al., 2018). This can provide valuable information into the reproductive condition and sexual maturity of perch at each lake.

Fecundity is the potential of reproductive output, or the maximum number of eggs one can produce (Bradshaw & McMahon, 2019). It can be used to predict reproductive performance and capability within perch, and a comparative analysis at both lakes can provide information on environmental factors, as well as the reproductive condition of perch when related to GSI.

1.2 Study sites

This study focuses on two lakes in the North Island of New Zealand that differ in quality and size, but both contain introduced European perch populations and have been greatly affected by their presence. Lake Rototoa (previously known as Lake Ototoa) in South Head, Auckland, and Lake Rotoroa (Hamilton Lake) in the Waikato region. In order to avoid confusion throughout this thesis, Lake Rotoroa's English name, Hamilton Lake, will be used.

1.2.1 Lake Rototoa

Lake Rototoa is a rectangular-shaped, sand-dune lake located in the Kaipara Harbour just 80km North of Auckland (Green, 1975). It has a maximum depth of 27.5 meters (Wilson, 2006) with its deepest parts located on the Eastern side of the Lake (Green, 1973). It has an area of 1.39km² and a catchment area of 5.61km² (Livingston et al., 1986). The lake has been considered "high quality" and its trophic status shifts between oligotrophic and eutrophic (Gregersen et al., 2022). The lake is surrounded by hills and dunes, with vegetation including *Chara australis,* mostly at the Southern part of the lake, and *Eleocharis sphacelata* in the Northern, Western and Eastern parts of the lake (Green, 1975). Exotic fish introductions, including European perch, introduced in 1999, are one potential cause of this shift in trophic level; however, they have also impacted the abundance of other important freshwater species including common bully (*Gobiomorphus cotidianus*), koura (*Paranephrops planifrons*) and dwarf inanga (*Galaxias divergens*) (Barnes & Burns 2005).

1.2.2 The Hamilton Lake

The Hamilton Lake (Lake Rotoroa) is a 54-ha lake in Hamilton at 38.799° S, 175.274° E, which has a maximum depth of around 6 m (Tanner et al., 1990). The lake was previously used for recreational purposes, as it is situated within Hamilton City (Figure 5) but is now plagued with high nutrient levels and cyanobacterial blooms, partly due to previous herbicide use, low aquatic macrophyte abundance and stormwater (Rumsby et al., 2011, Kane, 1995). European perch were successfully introduced to the Hamilton Lake in 1907 for game fishing, introducing a new threat to natives inhabiting the lake including common bully, shortfinned eel (*Aguilla australis*), longfinned eel (*Anguilla dieffenbachii*) and common smelt (*Retropinna retropinna*) (Kane, 1995).

1.3 Spawning strategies and preferences

Female perch typically spawn their eggs at the beginning of spring, and can continue for months after (Ceccuzzi et al., 2011). Mature females will lay strands of eggs on a substrate of their preference, typically something such as underwater vegetation, and a male will follow and fertilise the egg strand – creating a ribbon-like strand of eggs, which is relatively unique to species of perch (Ning et al., 2025). The selection of substrate is important, as anything that may impact the survival or early life stages of offspring will not be considered. Environmental conditions, such as temperature, location, and substrate strength (Probst et al., 2009; Čech et al., 2011 & Gillet et al., 2013), should be considered in spawning substrate experiments to encourage spawning activity and produce egg strands for population-level reproductive analysis. The width and length of each strand correlate to the length of the female and are a good indicator of some morphometrics (Gillet et al., 2013 & Olin et al., 2012), which provides insight into the size structures of a current and future population. Due to the physical characteristics of European perch egg strands, it is easy to identify and observe in spawning substrate experiments. Perch eggs can be used to calculate estimates of fecundity, as well as predict the survival and characteristics of future spawn. They can also provide insight into other conditions and changes within the habitat (Koenigbauer et al., 2025 & Zeh et al., 1989).

The width of egg strands can be used as an indicator of population dynamics in perch and microclimatic variables in their environments, as Gillet et al. (2013) found that perch egg strands from Lake Geneva at the French shore (collected from artificial substrates) and the Swiss shore (collected from transects at the natural lake bottom) varied considerably on either side. They assumed that the same female population was using both the artificial spawning substrates and the natural ground, and was attracted to either substrate in the same way each year in the time series. Mean egg strand widths appeared to be slightly higher in transects on the Swiss shore, where wind intensity is lower. This suggests that environmental conditions play an important role in spawning preferences for European perch. Probst et al. (2009) found that large perch strands were more common in areas where there were fewer waves, and Čech et al. (2011) also observed how strong winds can affect egg strand distribution in a lake in the Czech Republic. From this study, it appears that perch are relatively sensitive to environmental conditions for their spawning strategies, likely to ensure survival of their offspring. This study raises the consideration of external variables in control methods focused on spawning substrates, as this would heavily influence where perch would prefer their spawn to grow. These variables should all be considered when using artificial spawning substrates.

Spawning substrates allow for a more controlled observation of spawning behaviours, and the size and location of these substrates are crucial. Čech et al. (2011) found that artificial spawning substrates made of common stonewort held smaller egg strands than those of sunken trees, as the larger female perch could not spawn their eggs within the dense stonewort. Čech et al. (2012) found that in the Chabařovice Lake in the Czech Republic, temperature, waves and length of daylight had the most influence on the depth of egg strands for perch. The selection of sites for artificial spawning substrates took into account the instability of temperature in water columns, internal seiches, and the wind-influenced current. Using areas that contained artificial substrates and areas without, they noticed that the depths of perch egg strands increased in both areas during the spawning period (3rd of May to the 3rd of June). The depth of the egg strands correlated with the location of the 10-12°C layers of the lakes' water column. Nevertheless, by the third week, the egg strands were found in colder water. They discussed this as likely being due to their "inner clock", where the shallower layers of the lake are still too warm for embryo development. Embryonic development is crucial for offspring survival, therefore, water temperature appears to be incredibly important in perch spawning strategies and varies at different parts of a lake. In the Chabařovice Lake, the optimal temperature for spawning was around 10-12°C, and is likely true in most places. However, this preference may differ in other locations, which should be considered in spawning substrate control methods.

Gillet & Dubois (2007) investigated the impact of water temperature and the size of female European perch on spawning in Lake Geneva, in the context of accelerating temperatures due to climate change. Their results revealed that spawning in Lake Geneva was delayed if the water temperature was less than 10°C, and spawning was stimulated at temperatures of 12°C and above. However, when temperatures reached 14°C, the females were spawning in deeper areas where the temperature was lower and back around 12°C, likely because the water temperature also encourages healthy egg development, as seen in yellow perch (*Perca flavescens*) (Hokanson & Kleiner, 1974). Perch that spawned later also appeared to be larger; therefore, the egg ribbons were larger as well, however, the width of these ribbons fluctuated yearly, likely due to the succeeding year classes being weaker or stronger. The larger perch spawning later may be attributed to the different times of spawning migration, as larger fish appear to inhabit deeper parts of the water. The results of this study show that European perch have relatively specific water temperature preferences for spawning, and this is especially significant in the context of climate change. Control methods focusing on European perch spawning should consider changes in water temperatures over time in any location, as climate change could be increasing or decreasing these temperatures, and perch may be adjusting. The water temperature could drive the spawning period, and as water temperatures change, the spawning period may as well.

Temperature appears to be the most significant cue in the reproductive cycle and spawning period of European perch. Extended periods of low temperatures have been seen to correlate with high oocyte diameters and higher GSI, as well as increased plasma testosterone and protein phosphorus (Migaud et al., 2004). In an attempt to test the effects of warming periods on the reproductive cycle of European perch, Migaud et al. (2004) observed gonadogenesis, spawning and plasma steroid levels in European perch of two different body size classes at a one-month-long warming period, and a two-month-long warming period. Their experiment confirmed the importance of water temperature on gonadogenesis and spawning. Temperature changes during a spawning season, initiating out-of-season spawning, affect the last stage of gonadogenesis and the release of spawn. Quicker warming periods also affect spawning rates, in which spawn rates were higher in order to accommodate for that last stage of gametogenesis. They also found that smaller perch had “better” gonadogenesis, where the reason was not confirmed. However, they questioned whether this was due to smaller fish being more sensitive to environmental conditions. They concluded that despite temperature having a significant role in reproductive performance, fish weight had the most considerable influence. The context of this study was for the purpose of breeding, but it can also be applied to control methods targeting spawning periods and spawning strategies of perch.

1.4 Reproductive biology

Male European perch have two testes found in the peritoneal cavity of their body, and females have a single ovary, originally two, which fuses into one during gonad maturation (Fontaine et al., 2016). Females typically spawn their offspring in the springtime in both Northern and Southern Hemispheres, and can last up to three months (Ning et al., 2025). In the Autumn, Winter and early spring, before spawning, both females and males undergo gametogenesis, or the creation of sex cells (Ceccuzzi et al., 2011). They are an oviparous species, meaning they spawn their eggs once a year (Ning et al., 2025). Females reach sexual maturity at around two to four years, whereas males reach sexual maturity at one to two years, however, this depends entirely on growth rates within a specific population (Ning et al., 2025). Certain environmental factors can also influence the rate at which the perch reach sexual maturity, as some studies show sexual maturity rates differ in different water temperatures (Ning et al., 2025). Understanding the general reproductive biology of perch can assist in non-invasive control methods, particularly when they focus on the early life stages and reproductive cycle of perch, and these variables may differ in different locations.

Jellyman (1980) captured 1052 adult European perch from Lake Pounui, in the Wairarapa, from July 1974 to November 1975 using a mix of gill nets, fyke nets and electrofishing. Maturity stage of each gonad was classified and weighed. Along with the classification and age data (using opercular bones), they found that 86% of the male fish spawned in their first year, and all females in their first year were virgin fish. The smallest “ripe” male and female were 9.9cm and 14.0cm, respectively. Monthly GSI values were calculated in order to investigate seasonal gonad development, where the lower GSI values of both males and females were seen around the summer months (November, December and January), and peak values were seen in late winter and early spring months, with female GSI values dropping significantly in November. GSI valuable for identifying the duration and time of the year for spawning in a species and to determine a fish's maturity stage (Flores et al., 2019). The study provides valuable information on the sexual maturity of European perch, as well as seasonal gonad development using GSI, which can be used to identify spawning periods. Since this is a New Zealand-based study, it can be used alongside newer studies to pick up potential trends in gonad weight and GSI values of European perch in today’s ecosystems or changes in reproductive cycles.

In a study by Castets et al. (2012), 14 parameters surrounding spawn, embryonic/larval development, breeders and oocyte were monitored in 20 European perch spawns, originally bred in France, and then grown in a laboratory, to understand which the most important and reliable criteria are to assess and predict reproductive performance. Of the 20 female spawn used in this study, 14 grew to larval stages, and the results showed that most of the parameters monitored were not entirely relevant to the prediction of deformities, development of embryos and larval features. However, after proteomic analysis, they found several proteins that were expressed differently between the clusters, which were better markers for reproductive performance predictions. While the parameters did not produce significant results in this study, it emphasises the use of molecular markers and protein analysis to understand and predict the reproductive performance of European perch, which could be something worth investigating further on perch residing in New Zealand. These markers can likely contribute to the condition of perch, which can provide insight into their health and well-being.

Reproductive traits such as fecundity, GSI and spawning behaviours of geographically distributed fish can vary due to the different environmental variables, including water temperature, length of daylight, feeding and other physico-chemical properties in the water (Saemi Komsari et al., 2014). Saemi Komsari et al. (2014) investigated the temporal variation of reproductive characteristics and their plasticity in 324 European perch from the Anzali wetland in the Caspian Sea from 2008 and 2009. Specifically, this study area is located at a lower latitude than fish that have previously been studied in this area. The authors quantified reproductive traits such as spawning, fecundity, gonad development and the occurrence of atresia, which is degeneration of somatic and germ cells in the ovarian follicles (Correiro et al., 2021), to determine the variance in European perch. They found that the spawning season occurred earlier compared to regions higher in latitude, and the season only lasted from January to February for approximately two weeks, which is shorter than most spawning seasons, likely due to an increase in water temperature and a change in the duration of daylight in February.

The female perch displayed “group-synchronous” development of the ovaries, and only one clutch of oocytes was developed. Water temperature appeared to have the most significant effect on gonad development and vitellogenesis (yolk formation in female oocyte). GSI increased in October, when days were shorter and temperatures were low. From the results of this study, we can understand how significant temporal variation can be within different geographical regions, despite the Hamilton Lake and Lake Rototoa sitting at the same latitude. This study still provides valuable information on the plasticity of European perch, and how they adjust their reproductive cycle and reproductive biology to different conditions and environments.

Perch are found in many parts of the world, spanning both the Northern and Southern hemispheres. Because of this, it is possible that European perch are a well-adjusted, plastic species that can adapt easily to any environment in order to survive and continue population growth. Specifically, adjusting reproductive effort can help with population and offspring survival in new environmental conditions (Heibo et al., 2005). At Lake Wainamu, Sabetian et al. (2015) investigated the biological plasticity and population dynamics of European perch in the context of eradication and population management using size and age data and oocyte development analysis. Their findings showed that the population dynamics of European perch were plastic and also showed asynchronous egg cell development each year in parts of the population at Lake Wainamu. They suggested that the asynchronous egg development was likely temperature-induced, as was the increased growth rate in juvenile and young perch, ultimately increasing population turnover through mechanisms such as cannibalism. When compared to European studies, they found that Lake Wainamu perch grew faster in their first year, however remained smaller sizes thereafter. Plasticity allows European perch to acclimate and adjust well to new conditions, in this case, being introduced to New Zealand ecosystems. The findings of this study could influence current control and management approaches in New Zealand, as a high turnover rate within populations may require more eradication effort.

1.4.1 Condition

Condition indices such as Fulton’s condition factor and somatic condition provide valuable insight into the health and well-being of fish, by using length-weight relationships which provide information on population dynamics, resources in an environment, seasonal changes in body size and mortality (Kozłowski et al., 2025), typically as a result of changes in energy storage (Persson et al., 2011). Abiotic and biotic factors have a significant effect on growth in fish and, in in turn, reproductive condition (Gauthier et al., 2008), and these conditions vary geographically.

From 38 lakes in Poland, Kozłowski et al, (2025) measured the condition of 8,904 European perch using Fulton's condition factor. Most lakes were eutrophic, and some were oligotrophic and hypereutrophic, so some had different qualities. They found that Fulton's condition factor varied between lakes, suggesting different growth rates at all lakes, likely due to resource availability and varied feeding activity, which could be influenced by the depth of each lake, habitat diversity and primary production. However, Fulton's condition showed a weak negative relationship with lake depth. However, depth does seem to affect food resources and foraging techniques as they found that it altered niche partitioning with cyprinid species, as in shallow lakes, perch mostly consume benthic macroinvertebrates, whereas perch in deep lakes develop a piscivorous diet. The Hamilton Lake and Lake Rototoa vary considerably in depth; therefore, we may see differences in condition between populations, and our results could show insight into resource availability at each lake. Characteristics and morphometrics parameters of lakes can influence length-weight relationships and therefore, perch condition. Condition may have an effect on reproductive effort and is important to consider in efforts to manage perch populations from spawning, as these can also affect the spawning period and fecundity.

Somatic condition was used in a study by Persson et al., (2011) to observe changes in energy reserves and growth in young-of-the-year (YOY) European perch as a response to the presence of cyanobacteria on in the East coast of Sweden. Specifically, whether prolonged exposure to non-toxic and toxic cyanobacteria species (*Nodularia*) impacted feeding behaviour and growth. They found that both non-toxic and toxic *Nodularia* caused a decline in somatic condition and growth; toxic *Nodularia* had a greater negative effect on these responses. This was likely due to the extra energy costs for relocation, foraging and health maintenance within the cyanobacterial conditions. The high nutrients at the Hamilton Lake are likely affecting the perch population there and cyanobacterial blooms are not foreign there. Although *Nodularia* may or may not be the cyanobacterium present there, other species may be at play. Impacts to earlier life stages in fish may affect the overall strength of the following classes, and how these populations adapt to conditions where nutrients are high and cyanobacterial blooms are prevalent can assist in understanding the overall health of a population. YOY perch are also much more sensitive to environmental variables than their preceding age classes (Ning et al., 2025). Somatic condition provides this information and is useful in control techniques to different populations where environmental conditions may differ, and energy expenditure varies.

Changes in condition in fish are evident during the spawning period due to increases in energy reserves for reproductive cycles and health. This is typically seen in the size of the fish, but also in their chemical composition (Craig, 1977). Perch were collected from Windemere in England to evaluate the changes in condition and gonads in sexually mature perch with reference to seasonal and reproductive cycles. Craig (1977) examined somatic fat and gonad fat to measure and calculate ash, protein, water and fat as well as length-weight relationships for two years, monthly. They found that females had the most significant decrease in energy reserves during sexual maturation and loss of gonad mass. Males also went through similar energy changes but was thought to be due to increased activity rather than a loss of gonad mass. Older perch have a lower energy reserve, likely due to needing more energy for sexual maturation and compensating for slower somatic growth. This study highlights the changes in perch condition through the reproductive cycle, and the distribution of energy at each stage. As females lose energy through sexual maturation and spawning (gonad mass loss), it leaves them with less energy for other basic needs, such as foraging and predator protection. Control and management methods should consider changing body conditions around the time of spawning, as it can aid in the timing of when to apply these efforts and predict reproductive activity.

1.5 Fecundity and oocyte size

Previous studies have shown European perch to have relatively high fecundity in some locations, where males can produce up to 127 billion mL of sperm, and females can produce up to 100,000 and 200,000 eggs/kg body weight (Ning et al., 2025). The variation of these outputs is generally reliant on the abiotic and biotic factors of their environment, affecting reproductive characteristics and the size of each perch (Koenigbauer et al., 2024). The size of the perch can be used when estimating fecundity, as larger-sized fish typically hold more eggs or larger eggs (Saemi Komsari et al., 2014). Larger eggs may also indicate extra efforts into offspring and juvenile perch survival (Heibo et al., 2005). Fecundity is typically the most commonly used measurement of reproductive capacity in fishes (Saemi Komsari et al., 2014).

The size and quality of the oocyte produced by the perch can be used as an indicator of fecundity, as it can provide insight into the environmental conditions and changes in conditions (Zeh et al., 1989), and the age and size of the female (Olin et al., 2012). These observations can be used to predict future population growth or other changes in population dynamics.

In a study by Treasure (1981), European perch were collected from two shallow lakes in Scotland, using data on size and abundance of females to measure estimates of fecundity, and later measuring absolute fecundity. From the females caught at both lakes, ovaries were removed and preserved from mature females around one to two weeks before spawning. To test absolute fecundity, they used a dry gravimetric method and measured the maximum diameter of the eggs along two axes. Fecundity in females ranged from 5,480 to 77,987, depending on the length of the fish, with the smaller number of eggs from a fish of 13.5 cm, and the larger number of eggs from a fish of 34.5 cm. Mean egg diameter ranged from 0.94 mm to 1.62 mm in eggs preserved before spawning, consistent with similar diameters recorded in earlier studies. The eggs were taken from fish with lengths ranging from 17 cm to 32 cm. Although this is an older study, the results show how length aligns with fecundity, as we can see fecundity increases as length increases. Egg diameter appeared to be similar to that of previous studies. Earlier studies, such as this one, allow us to monitor changes in these outputs throughout the years. Oocyte size can provide valuable information on the morphometrics of a population, as well as fecundity and spawning periods. This insight is useful on control methods focused on spawning strategies, as it provides information on spawning timing and population dynamics.

Saemi Komsari et al. (2014) sampled ovaries from European perch caught in the Anzali wetland, using sub-samples from the middle of each ovary to estimate both potential fecundity and realised fecundity. The findings of their study revealed that realised fecundity had a positive relationship with fish length, potential fecundity increased with fish length, and both realised and potential fecundity had a weak positive relationship with age. Total length had a stronger relationship with potential fecundity than with realised fecundity, likely due to the different stages of maturation in the egg samples used. Fecundity appeared to increase in females aged six and under, and declined in females aged seven, suggesting that fecundity may drop in European perch after a particular age class. These results suggest that reproduction and fecundity can be influenced by age and size, which is useful for understanding population dynamics and overall reproductive characteristics of a particular population. Population trends of age and size can provide insight into population growth and health, which is important to consider in management and control methods in New Zealand, as different environmental factors may influence the morphometrics of perch and their reproductive strategies.

In Lake Pounui, Jellyman (1980) measured fecundity from 66 female perch using absolute and relative fecundity measurements against fish lengths and body weight. They found that absolute fecundity ranged from 2,657 to 63,858 in females ranging from 14.5 cm to 42.2 cm in length. Relative fecundity is the number of eggs in a fish per gram of total weight, which ranged from 141 to 33. Egg diameters ranged from 0.86 mm to 1.31 mm. Compared to other literature in his study, Treasure (1981) notes that fecundity results from Lake Pounui are lower than other populations, believing that this was due to unfavourable environmental conditions in Lake Pounui. Lake Pounui is described in this study, in 1980, as a mesotrophic lake with a mean depth of 5.1 m and annual temperatures at the surface of 6.7 - 24.2°C. While there is no in-depth connection to lake morphometrics and environmental conditions to fecundity in this study, we can infer that they all may be contributing to the lower fecundity. Environmental conditions should be considered when studying the fecundity or reproductive capacity of perch, especially in the context of management from the time of spawning, and also for predicting potential population growth.

In a study by Hanson (2009), he noted a 40% decline in European perch gonad size in Kvädöfjärden of the Swedish Baltic coast. Despite this decline, there were no changes in population size in the study area over these years; therefore, the smaller gonads may not be causing a decrease in fecundity. The author aimed to examine the potential long-term effects of a decrease in fecundity on the survival of perch populations and to investigate whether using abundance estimates could detect these effects. The author used an age-structured matrix model, and they found that, in Kvädöfjärden, a decrease in fecundity that aligns with a decrease in gonad size creates a risk of extinction of European perch. The study emphasises the use of fecundity and size as an indication of population abundance, which, although it is being used in this context for the purpose of conserving European perch populations, can also be applied to population control and management of unwanted European perch populations such as those present in New Zealand.

Environmental conditions can shape and change reproductive output and reproductive energy for female fish species in order to encourage and ensure the survival of their offspring (Koenigbauer et al., 2024). Larger eggs have an increased survival rate than smaller eggs, due to elements such as the reduced risk of hunger, increased growth rate, greater avoidance of predators and greater foraging potential (Koenigbauer et al., 2024). In the United Sates, Koenigbaur et al. (2024) sought to test this on Yellow perch (*Perca flavescens*), as they have similar morphological traits to European perch (Ning, et al., 2025). They hypothesised that egg size would vary at different populations, and egg size would increase as the size of the lake decreases, and vice versa. They also expected a correlation between size of the female, and size of the eggs, where the larger the female, the larger the eggs. They found that total length and egg diameter had a significant correlation, and it was the greatest prediction method of egg diameter. They also found that lake size and egg size were correlated, in that smaller lakes had larger eggs and vice versa. As Lake Rototoa is larger than the Hamilton Lake, we could likely see a difference in egg diameter, factors influencing this could also include resource abundance and predators.

1.6 Environmental influences

The introduction of exotic or invasive fish species into freshwater systems can have significant impacts on the existing ecosystem, from water quality changes, to disruptions of the food web (Bernery et al., 2022). Their effects on water quality are a result of the juvenile perch feeding on filter-feeding species, which promotes algal blooms (Ning et al., 2025). In New Zealand, perch negatively impact the abundance of other freshwater fish species, such as the Common Bully (Ludgate & Closs, 2003). European perch have also been noted to spread diseases and viruses to other animals, which can threaten other animals within the same ecosystem (Ning et al., 2025). Understanding these environmental responses can provide insight into the extent of damage caused by European perch, and how they are able to dominate ecosystems. Some research in New Zealand has delved into the responses of perch removal in systems they inhabit (Ludgate & Closs, 2003), which demonstrates how out native biodiversity can recover. The environmental damage caused by European perch shows why control and management of this species is so important.

As an introduced species of fish in New Zealand, European perch poses a significant threat to our native flora and fauna, and understanding these impacts is crucial when considering management of populations or conservation of the systems they inhabit. Ludgate & Closs (2003) conducted a comparative study of six similar ponds in Otago, where three had regular removal of perch, and three had no removal (control ponds). The aim was to investigate the impact of European perch on native fish species in the same ecosystem and assess the feasibility of eradicating European perch from these ponds using nets and traps. They also wanted to investigate whether successful eradication or reduced populations would affect the recruitment and survival of juvenile perch, as well as the Common Bully populations. They found that physical removal of European perch worked effectively to control the abundance of adult perch, but that cannibalism was the most significant factor controlling population abundance. The abundance of the Common Bully in two of the small and medium-sized removal ponds increased significantly. These results demonstrate the effectiveness of European perch removal in managing native populations and its impact on common bully populations in shallow lakes. This study provides insight into effective management and control of European perch with the use of gill nets and fyke nets that can be applied to other smaller lentic systems where they may be a problem. This may be true for other native species living in the presence of European perch.

Cyanobacterial blooms are a universal problem in freshwater systems; the toxicity of these blooms can cause significant risks to wildlife and even humans (Smith & Lester, 2006). European perch have been reported to play a role in some of these blooms. Smith & Lester (2006) investigated this in the Karori Wildlife Sanctuary in Wellington, where cyanobacterial blooms are prevalent and European perch are present. The study aimed to describe bottom-up versus top-down effects in the Lower Karori Reservoir. In this study, bottom-up refers to the role of nutrients in the lake, and top-down refers to zooplanktivorous fish, in this case, European perch, that consume the cyanobacteria. Their results showed that European perch impact cyanobacteria levels within the Lower Karori Reservoir, as enclosures containing European perch were high, and that enclosures containing added nutrients had no significant impact on cyanobacteria levels. In treatments without perch, zooplankton species were more diverse, and these enclosures also had high densities of large crustaceans, which are one of the main preys of European perch. This study highlights how European perch not only affect other species of fish, but also the physicochemical properties of their environment, likely due to their impact on food webs (Rowe, 2007). Locations in New Zealand affected by cyanobacterial blooms may benefit from the eradication or control of European perch populations, as an improvement in water quality and nutrients is crucial in maintaining and conserving native species inhabiting the same lakes. Although this may require the eradication of perch and other introduced species.

Despite many documented adverse effects of the introduction of non-native species to freshwater systems in Aotearoa, little research has been done on potential positive effects, including predator-prey dynamics that benefit native species. Stewart et al. (2023) investigated how the presence of European perch could positively impact the longfin eel (*Anguilla dieffenbachii*) and the shortfin eel (*Anguilla australis*) at the Rakatu-Redcliff wetlands in the Southland region, an endemic species and a native species to Aotearoa, respectively. At the Rakatu site, the fish community contained native fish and non-native fish, and the Redcliff site contained only native fish. They found that eel population density, including juvenile density, was higher at the Rakatu site compared to the Redcliff site. From isotope analysis, YOY European perch made up ~40% of both species of eel's diet at the Rakatau site. These results also suggest potential cannibalism occurring in eels at the Redcliff site to support adult populations. Condition and size results at both sites were not significant, but this finding is interesting given the difference in diets. This study highlights the potential benefits of non-native fish introductions, particularly in the context of conservation management and specific predator-prey dynamics, and how systems within an ecosystem can be disrupted when a species is removed. If this study were to be replicated, it would be interesting to see how the results would differ if there were any other species at the sites.

Chapter 2: Materials and methods

2.1 Fish capture and sampling sites

Fish capture at the Hamilton Lake occurred over 12 months from June 2024 to May 2025, and at Lake Rototoa over 9 months from August 2024 to May 2025, excluding April 2025 due to technician availability. Methods of capture included a mix of fyke nets, gill nets and night electrofishing using an electrofishing boat. The electrofishing boat was only used at the Hamilton Lake but was out of order from September 2024 until March 2025; therefore, gill nets were set as a replacement. Visits to each lake for fish capture occurred once every month. There were no concrete goals for the number of perch caught at either lake. Some nights, electrofishing was highly successful in a short time, and others yielded only a few perch over several hours. Due to preparations for trips to Lake Rototoa, we were unable to reset nets for another night if unsuccessful.

For the first two months of field work at Lake Rototoa, both gill nets and fyke nets were deployed overnight and collected the following morning. Initially, around 10 fyke nets and two or three gill nets were deployed around the northern parts of the lake. The fyke nets proved to be significantly more effective at catching perch than the gill nets at Lake Rototoa. As a result, around 30 fyke nets were deployed, and no gill nets were used. Fyke nets were either tied to trees by shorelines or tied to wooden stakes if the water was deeper. At the Hamilton Lake, fish capture was mainly carried out using an electrofishing boat; however, when this was out of order, two to three gill nets were deployed as a replacement. Fyke nets proved to be unsuccessful and difficult at the Hamilton Lake due to the presence and abundance of catfish and shortfin eel. Once fish were caught in both locations and with all methods, they were euthanised by an anaesthetic overdose of benzocaine and transported back to the university, where they remained refrigerated until dissection.

Electrofishing was carried out at night, with successful catches on the Southern, Western, and Eastern edges of the Hamilton lake, particularly within reeds and fallen trees. Fyke nets at Lake Rototoa were situated towards shorelines and shallow edges. Fyke nets were either tied to trees and branches close to the shore or tied to a stake in deeper parts still below 5 m, ensuring the net was as close to the lake floor as possible. Typically, three gill nets were deployed at Hamilton Lake when used, around the eastern side of the lake in deeper parts, parallel to the edge of the lake, about 1 m from the reeds, and perpendicular to the side of the lake and were around 50–100 m in length by tying two together. Gill nets, when used at Lake Rototoa, were longer (more tied together), and set much deeper due to the different depths of the lake.

Figure 3 Fyke net deployed on a shore at Lake Rototoa, emptying the fyke net the following day & catch from one fyke net.

2.2 Dissection

For each fish caught, their fork length (mm) and their total weight (g) were recorded prior to dissection. A careful incision was made from the cloaca of the fish towards the sternum, and each gonad was carefully removed and examined for each sex. For male perch, the testes were removed, weighed (g), and recorded, and any cysts or unusual characteristics were noted. For female perch, the ovary was removed, weighed (g), and recorded. It was then cut into three samples (front, middle, and rear), and each sample was weighed (g), recorded, and stored in Davidson's fixative solution for three to six days. Samples were then removed from the fixative solution and preserved in 50% ethanol until used for oocyte analysis. Immature fish were identified by their much smaller, underdeveloped gonads, as well as females whose ovary contained no eggs; these were noted as 'MT', and their ova were weighed, kept and fixed.

2.3 Data

Fork lengths of each fish were measured flat on a 1 m measuring board to the closest millimetre. All fish were weighed using the same scale. Gonads were weighed on a smaller scale with a maximum weight capacity of 100 g; therefore, gonads weighing over 100g were split in half and weighed separately. Gonad samples were weighed using a precision scale.

From the fork length, weight and gonad weight measurements for each individual fish, calculations were made to determine condition indices and GSI, all of which provide insight into the overall health and well-being of each fish.

Somatic condition (S) was calculated as:

W = total weight (g), GW = gonad weight (g) & L = fork length (mm)

$$S = \frac{(100 \times (W - GW))}{((L \div 10)^3}$$

Fulton's Condition Index (*K*) was calculated as:

W = total weight (g) & L = fork length (mm)

$$K = 100 \times (\frac{W}{L^3})$$

Fulton's condition calculations for each fish were graphed using R Studio as box plots per sex, per lake. Differences in mean index values were calculated in R Studio using two-sample t-tests between lakes.

Gonadosomatic Index was calculated as:

W = total weight (g) & GW = gonad weight (g)

$$GSI = (\frac{GW}{W}) \times 100$$

GSI results were graphed in R Studio as box plots per sex, per lake. Spearmann's correlation tests between GSI and fork length for each sex were calculated using R Studio, and two-sample t-tests were also calculated in R Studio for differences in mean index values.

Calculations were recorded in Excel spreadsheets for each lake. Some graphs were also plotted using GraphPad.

2.4 Analysis of oocytes

Photos of oocytes were taken using a Nikon D7000 digital camera of smaller sub-samples from the ovary samples of each female perch. The weight of the sub-sample was recorded, as well as the whole sample. All samples at this point were fixed, and ethanol was removed and replaced with water. The oocytes of each sample were poured into small plastic balance trays, which were spray-painted black prior to photos. The camera was hooked to a stand, with the lens facing down at the trays. Throughout the analysis, the focus and zoom were not adjusted, but a photo including a ruler for scale was taken at every session as a precaution.

The photos were then uploaded to the application '(Fiji is just) Image-J' where diameter was measured using Feret's diameter, and eggs were counted. This was to provide insight into fecundity and the average size of eggs through the months prior to spawning. Ova after the spawning season were typically empty, or eggs were too small to be measured.

2.4.1 Statistical analysis of oocytes

Histograms of oocyte diameters for each month were created using the data analysis function on Excel. Skewness and kurtosis were calculated on Excel using the =SKEW and =KURT functions, which returned excess kurtosis. Violin graphs of oocyte diameters were created in R Studio, and bimodality coefficients for each month (Pfister et al., 2015) were calculated using:

$$m_3 = skew, m_4 = kurtosis\ \&\ n = no.\, oocytes\ in\ monthly\ sample$$

$$BC = \frac{m_3^2 + 1}{m^4 + 3\frac{(n-1^2)}{(n-2)(n-3)}}$$

2.4.2 Fecundity

The number of eggs per sub-sample was counted in ImageJ. Sample weight refers to the original sample taken from the ovaries (Front, middle or rear), and sub-sample weight refers to the sample taken out of either of those three samples for each fish. Eggs per gram of wet weight (eggs/g WW) was calculated using the original weight of the sample from when the fish were first dissected, and the percentage of weight loss. From this, calculations were made for the mean egg count for all three sub-samples. Calculating the total fecundity of one ovary was done using:

$$Fecundity = \frac{Total\ gonad\ weight}{Mean\ egg\ count}$$

The fork length of each fish sampled was compared with the fecundity calculations in a scatterplot using RStudio. Calculations were also made to find the mean fecundity for each month at each lake using Excel.

2.5 Artificial spawning substrates

Bundles of bracken fern, kānuka and manually frayed natural fibre rope at ~0.5m in length were deployed in three locations: Lake Rototoa (Figure 4), Hamilton Lake (Figure 5) and in six enclosures at the University laboratory, two of which were inside the lab, and three were outside. At each study site, 15 substrates were deployed —three of each substrate —in five different areas. Each substrate was positioned around the middle layer of the water, at lakes, they were placed near the edges and some near aquatic fauna such as reeds. In the lab tanks, fish were caught from the Hamilton Lake, with each tank containing one female and one male. The identification of sex in these fish was mainly through size, where heavier and longer fish were suspected to be female. This was not the most accurate identification method for fish, and only two of the fish caught ended up being females; however, this was only realised upon dissection after the experiment.

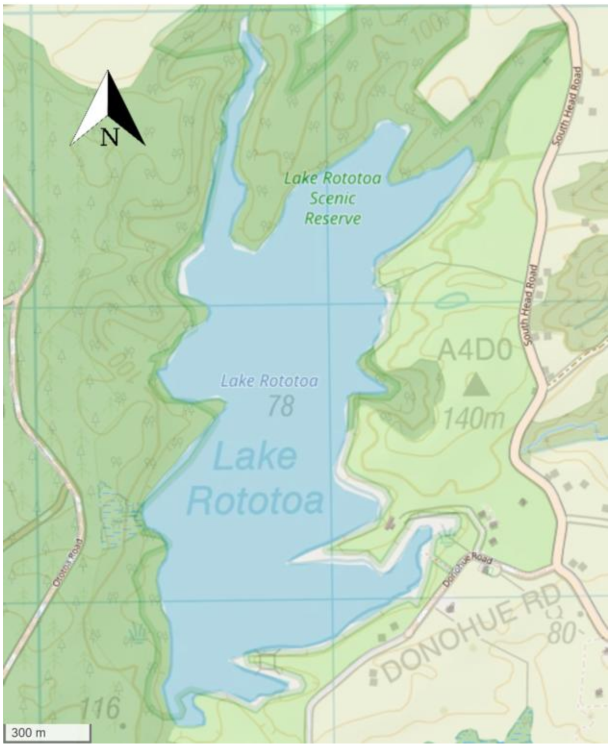


Figure 4 Map of Lake Rototoa with scale and North arrow. (https://www.topomap.co.nz/)

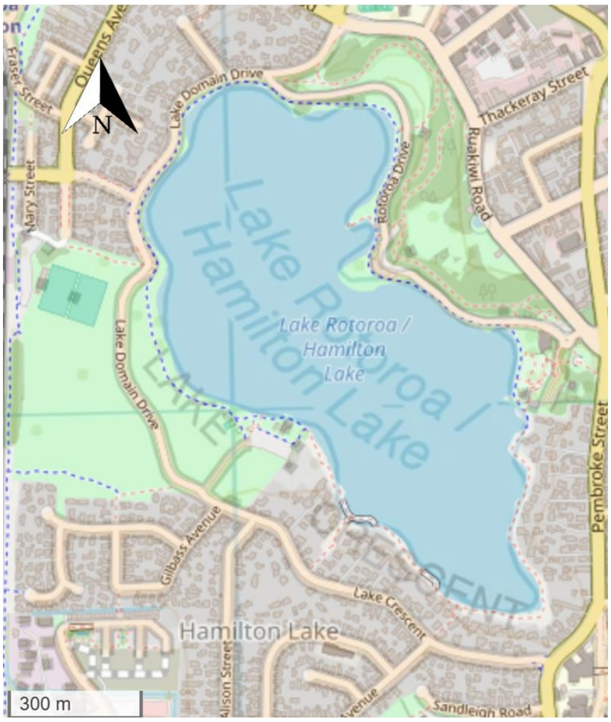


Figure 5 Map of the Hamilton Lake with scale and North arrow. (https://www.topomap.co.nz/)

These sites were monitored weekly in all locations for six weeks from September 2024 to early November 2024 to determine if the perch were using any of the substrates for spawning their eggs (Figure 6). Substrates were carefully pulled out of the water, making sure any hard pulling would not affect any egg ribbons, if any. Fish were also fed at the laboratory tanks.

An ethics application was submitted to the Animal Ethics Committee at the University of Waikato for the capture and use of live fish prior to this experiment, specifically, the fish used and kept in the laboratory tanks.

Figure 6 Monitoring of artificial substrates at Lake Rototoa.

Chapter 3: Results

3.1 Overview

A total of 159 European perch were caught at the Hamilton Lake between June 2024 and May 2025, and a total of 126 European perch from Lake Rototoa were caught between August 2024 and May 2025. Due to technician availability, no fish were caught at Lake Rototoa in April 2025. An additional 19 European perch were caught from the Hamilton Lake in September 2024 and 10 were used for the artificial spawning substrate experiment. For each fish caught at both locations, fork length (mm), weight (g), sex, gonad weight (g), and sample weight (g) of female gonads were recorded in Excel. Condition indices were then calculated using these measurements to examine overall fish health and sexual maturity. Samples of female gonads were used to measure oocyte diameter and fecundity.

Methods for fish capture differed at each lake, with fyke nets most successful at Lake Rototoa, and electrofishing most successful at the Hamilton Lake. Gill nets at Lake Rototoa were used at two trips, but were not as efficient as fyke nets, and were therefore not used. Gill nets were used for a short period of time at the Hamilton Lake while the electrofishing boat was out of order and these worked sufficiently for the time being.

3.2 Size structures and sex ratio

Larger European perch were caught more frequently at Hamilton Lake than at Rototoa (Figures 7 & 8); however, the biggest and smallest fish were caught at Lake Rototoa. At the Hamilton Lake, the largest caught was 378 mm, and smallest was 202 mm. At Lake Rototoa, the largest caught was 404 mm and the smallest was 101 mm. Females appeared to be larger than males, and this was true at both lakes. Perch caught from the Hamilton Lake had a mean fork length of 319.43 mm, and perch caught from Lake Rototoa had a mean fork length of 228 mm. Combined male and female lengths from the Hamilton Lake show a unimodal, normally distributed curve and combined lengths from Lake Rototoa show a bimodal distribution. Both weights and lengths were consistent at each lake, with perch from the Hamilton Lake appearing bigger in both measurements; however, the longest and heaviest from the entire sample were from Lake Rototoa (Figure 9).

At Lake Rototoa, there was a female dominance in catches, with 105 females and 21 males caught. The Hamilton Lake had a male dominance in catches, with 104 males and 56 females (Figures 7 & 8).

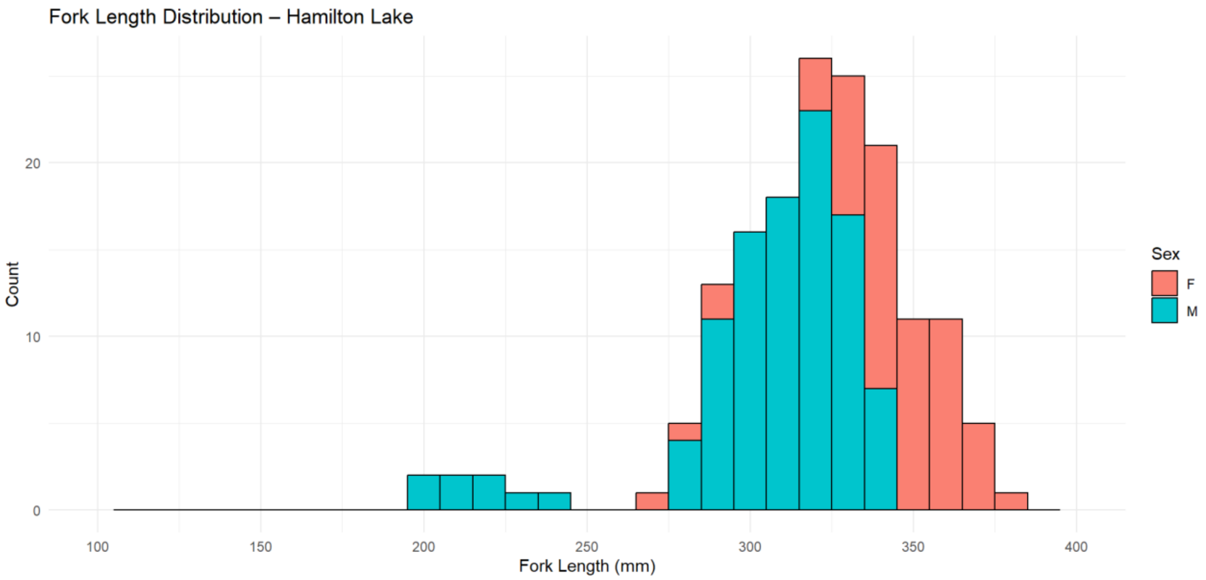


Figure 7 Fork length of male and female European perch caught at the Hamilton Lake, included key to distinguish the sex of the fish.

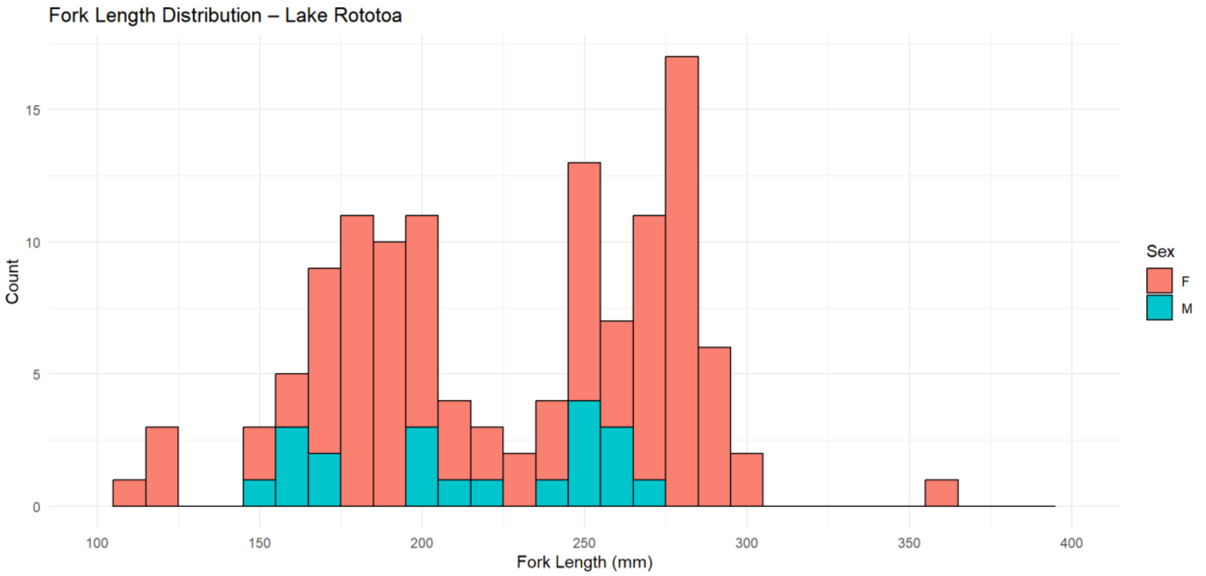


Figure 8 Fork length of male and female European perch caught at Lake Rototoa, included key to distinguish the sex of the fish.

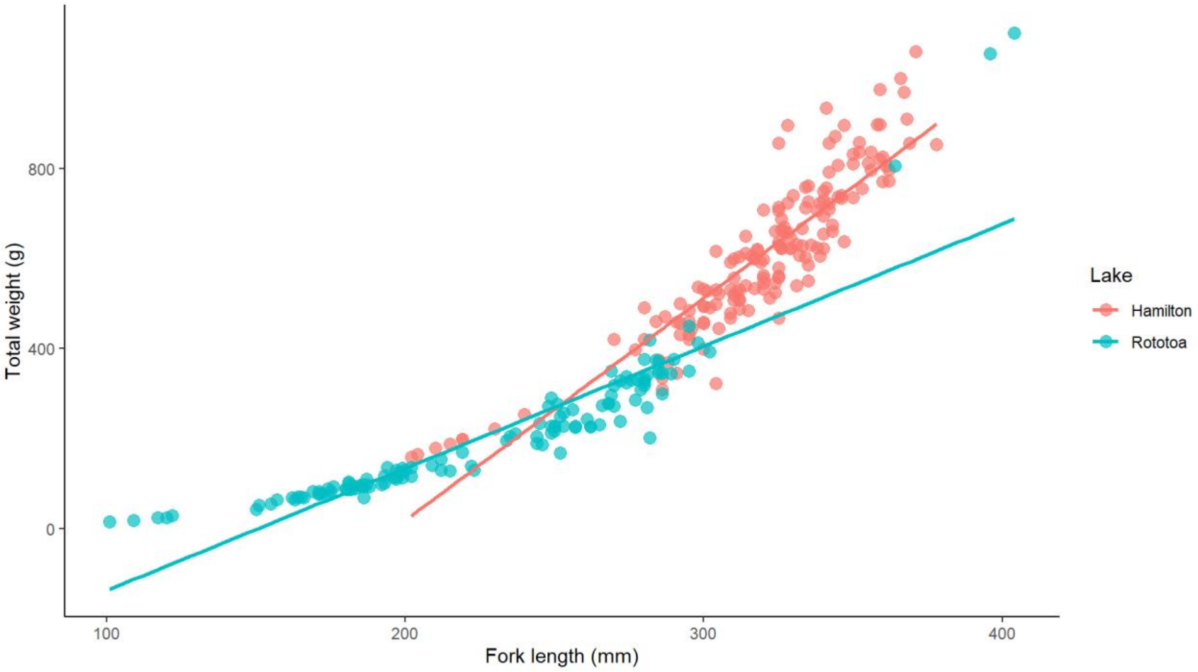


Figure 9 Total weight and Fork length of all perch caught at both lakes, included key to distinguish each lake.

3.3 Gonadosomatic index and reproductive status

GSI values for females at both lakes were the highest in September (start of spring) and both drop in October, however this drop was much steeper at the Hamilton Lake, and GSI from females at Lake Rototoa had a much steadier drop through October, December and January (Figure 10). The highest GSI values from the Hamilton Lake and Lake Rototoa were 23.72% and 22.71% respectively, both were females caught in September 2024. A Welch two sample t-test in RStudio showed a significant difference in mean GSI values between females (p-value = 0.003, t = -2.980), with females from the Hamilton Lake having a mean GSI of 7.38. GSI values for males at the Hamilton Lake and at Lake Rototoa peaked in August (end of winter) (Figure 11). However, Rototoa had a significantly steep jump from March to May, it was also the only male caught at Lake Rototoa in May. A two-sample t-test on males from both lakes also showed a significant difference in mean GSI values (p-value = 1.602 e-06, a t = -5.809) and males from the Hamilton Lake had a higher mean GSI of 8.32.

Spearman's rank correlation tests in RStudio showed females and males from the Hamilton Lake had no significant correlation between GSI and fork length (p-value = 0.442, rho = 0.104 & p-value = 0.530, rho = 0.062 respectively). Males and females from Lake Rototoa also had no significant correlation (p-value = 0.935, rho = 0.018 & p-value = 4.067e-07, rho = 0.471) between GSI and fork length.

Atresia was observed in two females at the Hamilton Lake in June and September, these gonads were not weighed. Cysts were also found on several testes at the Hamilton Lake and were weighed.

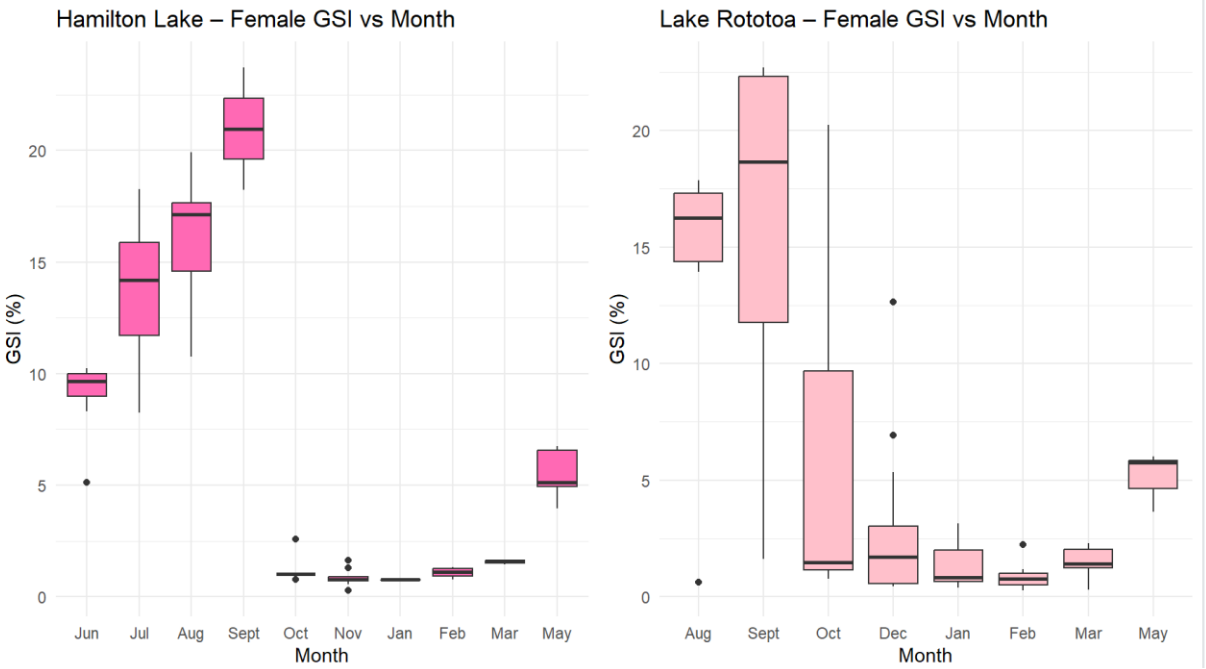


Figure 10 Gonadosomatic index of females caught at the Hamilton Lake and Lake Rototoa from June 2024 to May 2025.

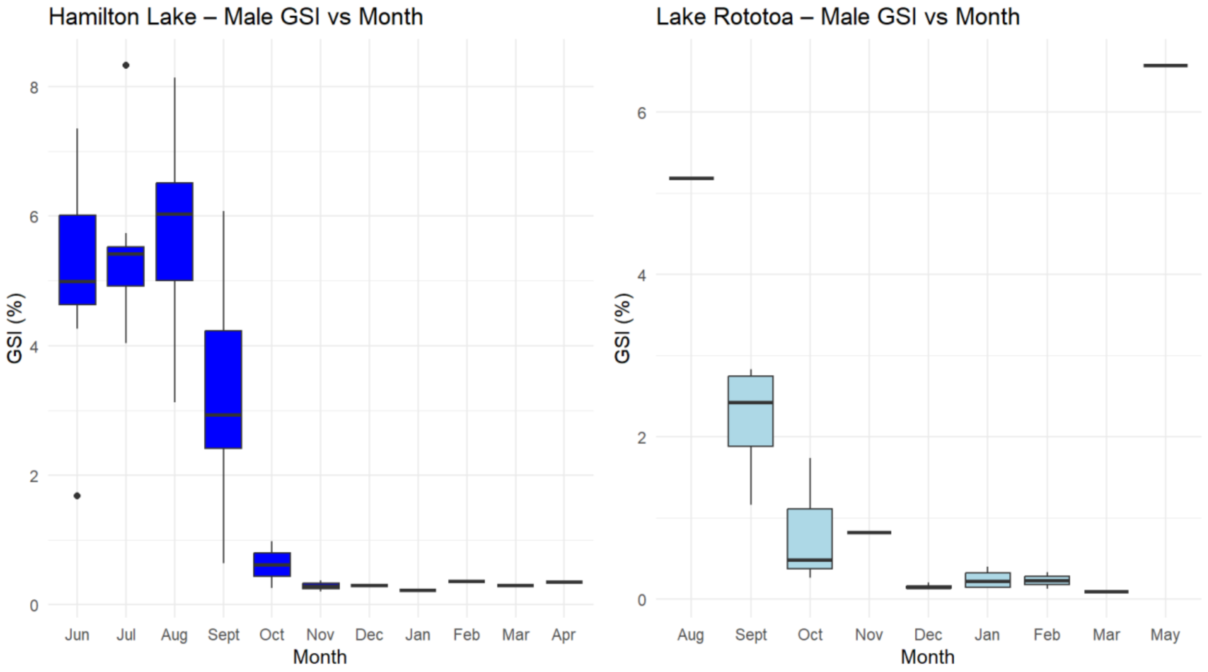


Figure 11 Gonadosomatic index of males caught at the Hamilton Lake and Lake Rototoa from June 2024 to May 2025.

3.4 Condition

Fulton's Condition factor (*K*) varied considerably in both sex and at both locations, there did not appear to be any significant seasonal patterns (Figures 12 & 13). However, perch caught at the Hamilton Lake had higher *K* values than those caught at Lake Rototoa and females at the Hamilton Lake appear to decrease after the spawning period. *K* increased after spawning period at the Hamilton Lake the spawning period in males. Both males and females at Lake Rototoa did not show any significant patterns.

A two-sample t-test on female condition at each lake showed a difference in mean *K* values (p-value = 2.2e-16, t = -10.979), with females at the Hamilton Lake having a higher mean index of 1.87. A t-test on males showed a significant difference of male *K* values at each lake (p-value =9.001e-10, t = of -8.351), with the males at the Hamilton Lake having a higher mean index of 1.78.

A Spearman's correlation test on fork length and *K* revealed no correlation in males or females at Lake Rototoa (p-value = 0.068, rho = -0.405 & p-value = 0.840, rho = 0.019 respectively). There was also no correlation in males or females from the Hamilton Lake (p-value = 0.405, rho = -0.082 & p-value = 0.1075, rho = -0.217). Negative rho values indicate a negative monotonic relationship between *K* and fork length, which was seen in males and females from the Hamilton Lake, and males from Lake Rototoa.

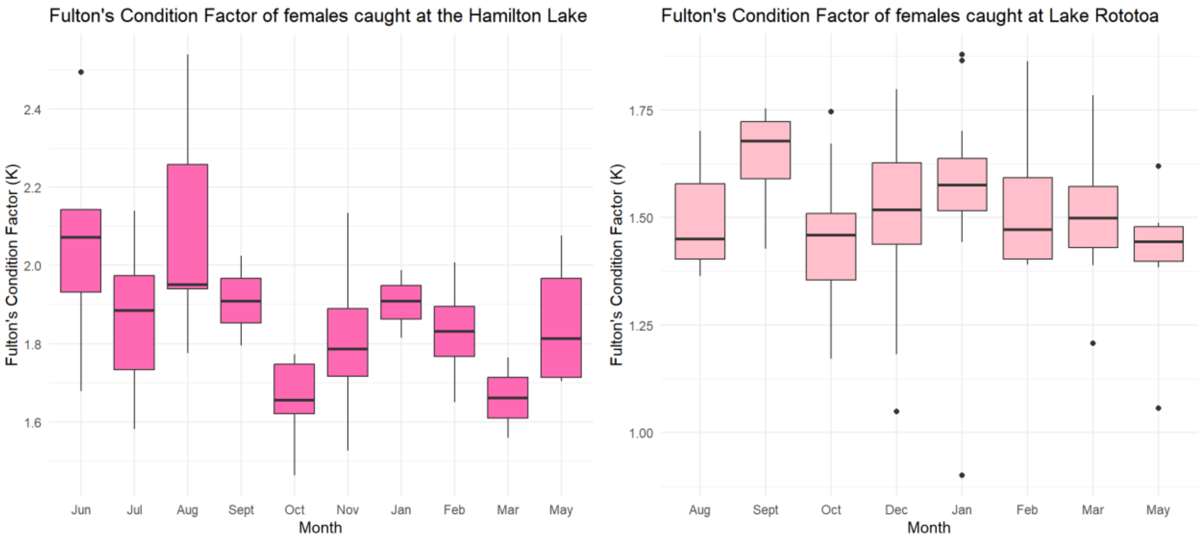


Figure 12 Fulton’s Condition Factor of females caught at the Hamilton Lake and Lake Rototoa from June 2024 to May 2025.

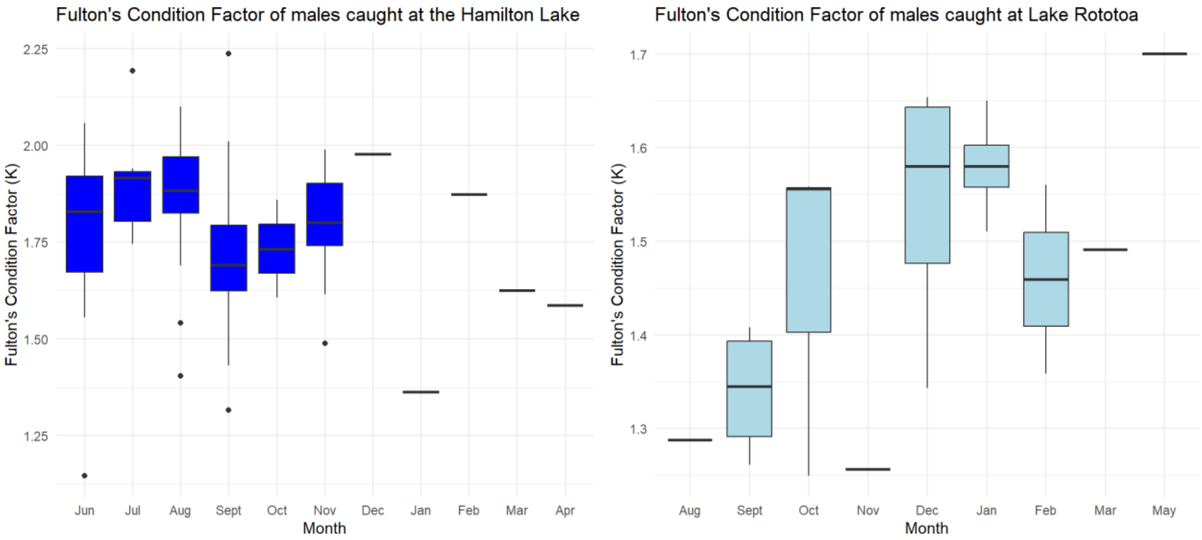


Figure 13 Fulton’s Condition Factor of males caught at the Hamilton Lake and Lake Rototoa from June 2024 to May 2025.

Somatic condition appeared to have some seasonal pattern, with increases after the spawning period at all lakes (Figures 14 & 15). Condition was higher in both sexes at the

Hamilton Lake than at Lake Rototoa. Males at Lake Rototoa had the least significant pattern in condition.

Spearman's rank correlation tests on fork length and condition were completed on each sex at each lake. Both males and females from the Hamilton Lake showed no correlation (p-value = 0.327, rho = -0.097 & p-value = 0.105, rho = -0.218 respectively). Males and females from Lake Rototoa also showed no correlation (p-value = 0.083, rho = -0.487 & p-value = 0.060, rho = -0.184 respectively). Negative rho values were seen in both sexes and at both lakes, suggesting negative monotonic relationships between somatic condition and fork length.

Two-sample t-tests revealed a difference in somatic condition in females (p-value = <2.2e-16, t = -10.177) with females at the Hamilton Lake having a higher mean index of 1.747. In males, there was also a difference in somatic condition (p-value = 5.573e-08, t = -7071) with males at the Hamilton Lake having a higher mean index of 1.713.

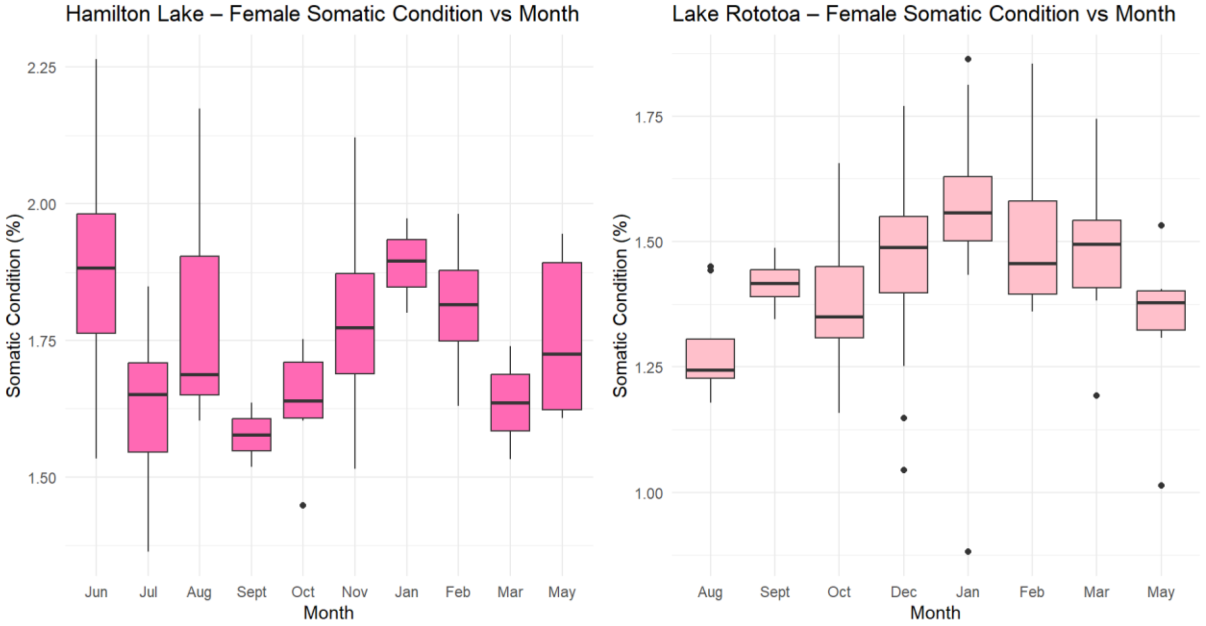


Figure 14 Somatic condition of females at the Hamilton Lake and Lake Rototoa from June 2024 to May 2024.

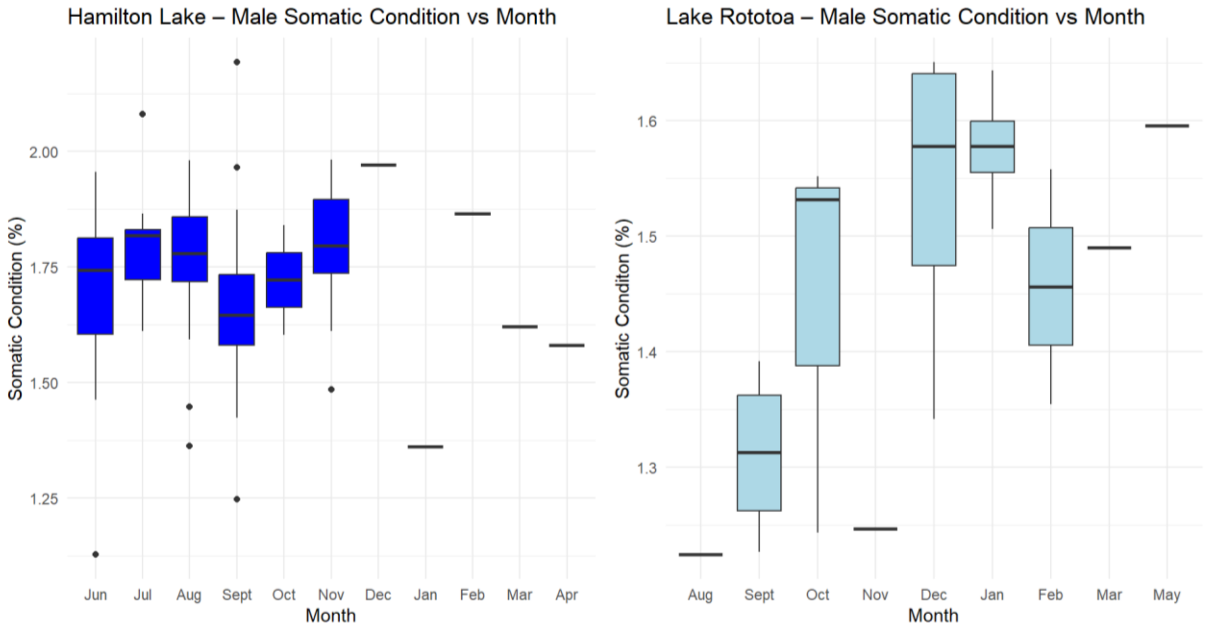
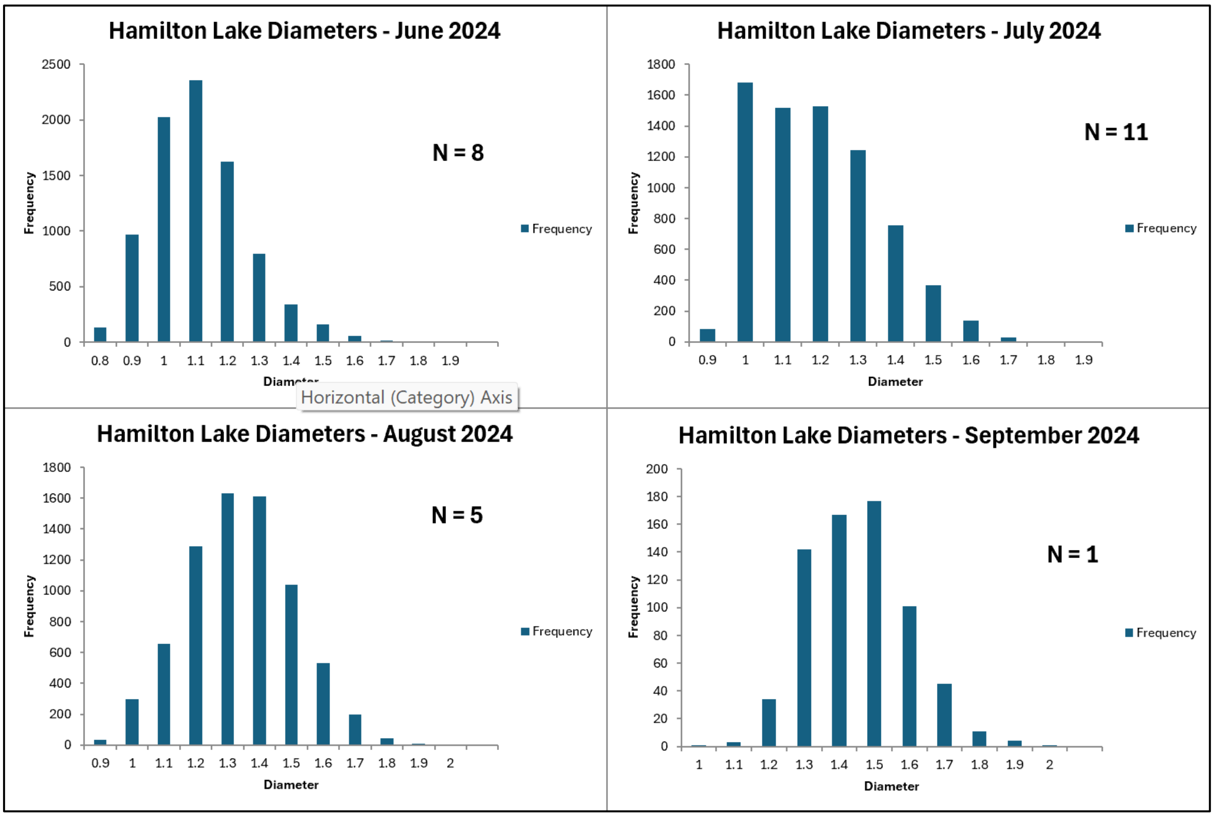


Figure 15 Somatic condition of males at the Hamilton Lake and Lake Rototoa from June 2024 to May 2024.

3.5 Oocyte diameter

A total of 75 oocyte samples from Hamilton Lake and 33 from Lake Rototoa were analysed in ImageJ for diameters. Histograms of diameters from the Hamilton Lake displayed unimodality, with June, August and September having normal distributions (Figure 16). Histograms of diameters from Lake Rototoa were all unimodal and normally distributed (Figure 17). All distributions at the Hamilton Lake and Lake Rototoa were right-skewed. Leptokurtic distributions were shown in June and September from the Hamilton Lake, and September at Lake Rototoa. July and August from the Hamilton Lake displayed platykurtic distributions, as did August and October at Lake Rototoa.



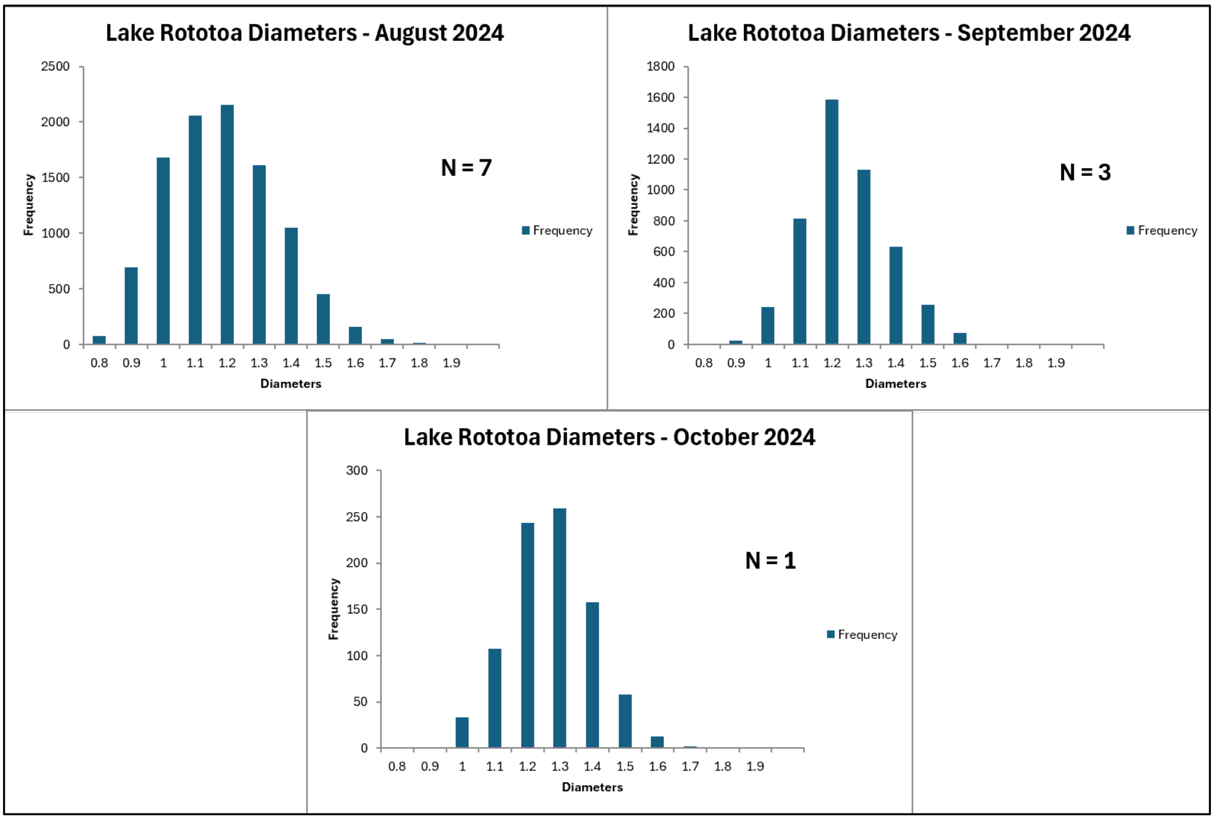
Hamilton Lake Diameters - June 2024

Hamilton Lake Diameters - July 2024

Hamilton Lake Diameters - August 2024

Hamilton Lake Diameters - September 2024

Figure 16 Histograms representing oocyte diameters from perch caught at the Hamilton Lake from June 2024 to September 2024.



Lake Rototoa Diameters - August 2024

Lake Rototoa Diameters - September 2024

Lake Rototoa Diameters - October 2024

Figure 17 Histograms representing oocyte diameters from perch caught at Lake Rototoa from August 2024 to October 2024.

A total of 28,889 oocytes were measured from the Hamilton Lake. Oocyte diameters appeared to increase from June to September (Figure 18), with a mean of 1.16mm in June and a mean of 1.5mm in September (Table 1). Bimodality coefficients were below three for all months, suggesting unimodality in oocyte diameters, with right-skewedness. Kurtosis calculations revealed June and September were leptokurtic, and July and August were platykurtic. A total of 15,627 oocytes were measured from Lake Rototoa. Diameters here appeared to increase slightly from August to October (Figure 19), with a mean of 1.23 mm in August and 1.32 mm in October (Table 2). Bimodality coefficients were also all below three for each month, suggesting unimodality (Tables 1 & 2). All distributions were right-skewed, and kurtosis was leptokurtic in June and September at the Hamilton Lake, and September at Lake Rototoa; and platykurtic in July and August at the Hamilton Lake and in August and October at Lake Rototoa (Tables 1 & 2).

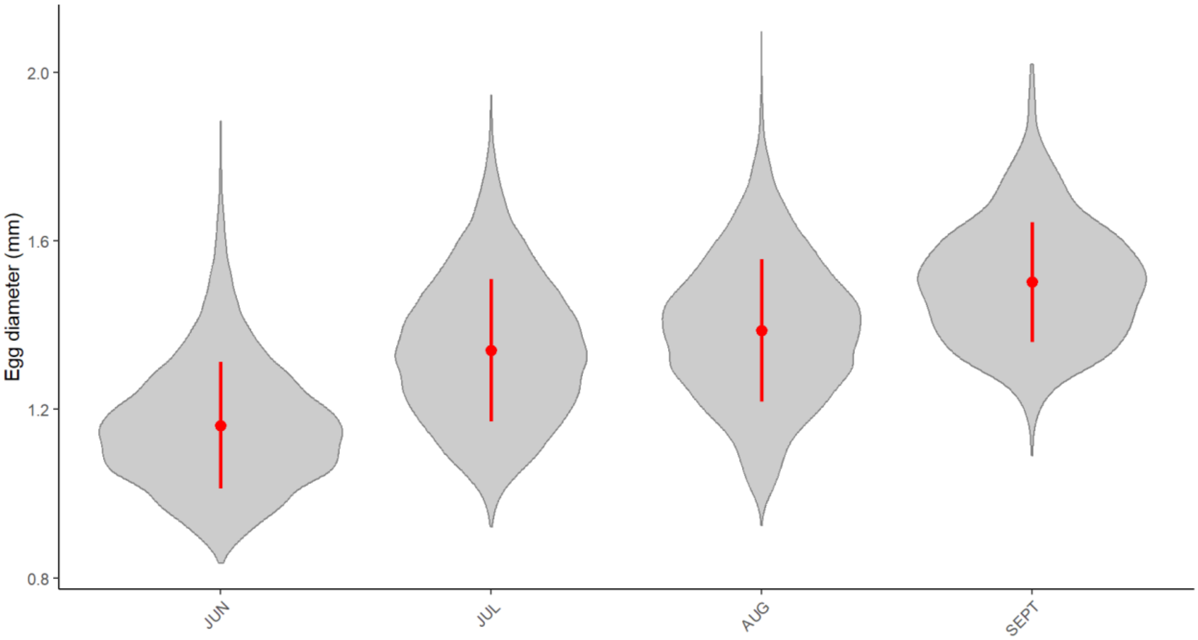


Figure 18 Oocyte diameter distribution from the Hamilton Lake from June 2024 to September 2024.

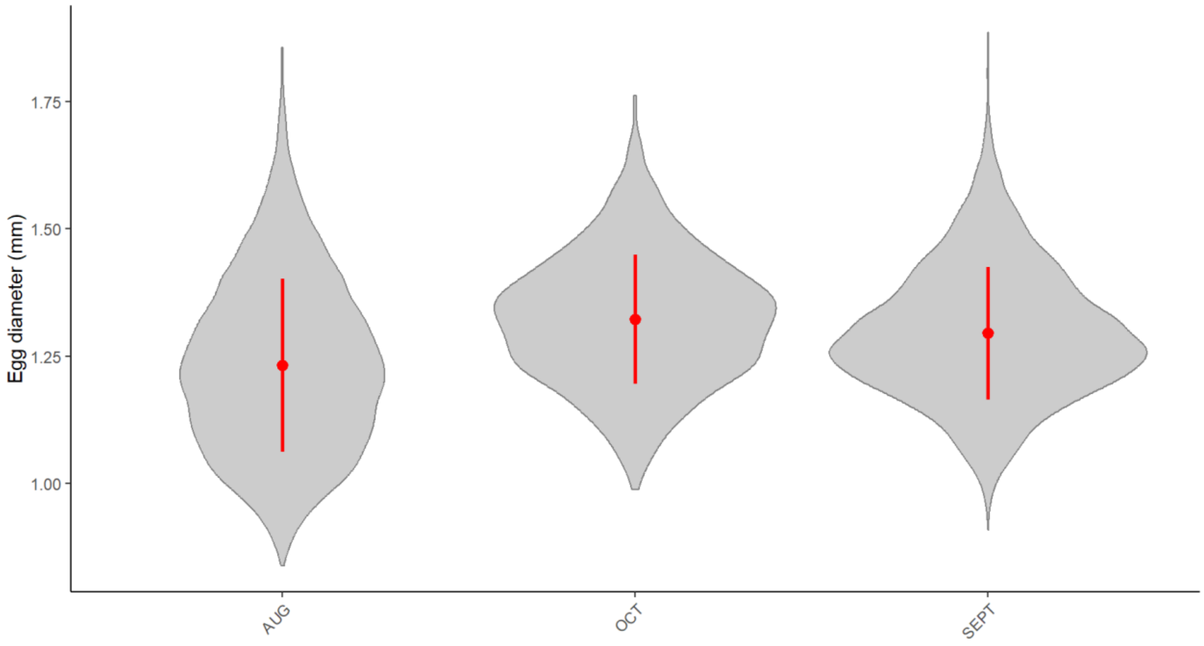


Figure 19 Oocyte diameter distribution from Lake Rototoa from August 2024 to October 2024.

Table 1 Mean, standard deviation, range, number of oocytes (N), skew, kurtosis and bimodality coefficient from the Hamilton Lake.

	Mean	*SD*	*Range*	*N*	*Skew*	*Kurtosis*	*BC*	*Min*	*Max*
JUN	**1.162318**	**0.149625**	**1.025**	**8477**	**0.706774**	**0.784077**	**0.251**	**0.836**	**1.885**
JUL	**1.340198**	**0.16915**	**1.025**	**13032**	**0.277324**	**-0.2983**	**0.188**	**0.921**	**1.946**
AUG	**1.388145**	**0.168857**	**1.172**	**7347**	**0.126135**	**0.149606**	**0.192**	**0.925**	**2.097**
SEPT	**1.502291**	**0.142021**	**0.928**	**684**	**0.376833**	**0.103742**	**0.225**	**1.091**	**2.019**

Table 2 Mean, standard deviation, range and number of oocytes (N), skew, kurtosis and bimodality coefficient from Lake Rototoa.

	Mean	*SD*	*Range*	*N*	*Skew*	*Kurtosis*	*BC*	*Min*	*Max*
AUG	**1.232205**	**0.169962**	**1.017**	**9985**	**0.359988**	**0.24078**	**0.235**	**0.839**	**1.856**
SEPT	**1.295168**	**0.129896**	**0.977**	**4768**	**0.410623**	**0.267785**	**0.357616**	**0.225**	**1.886**
OCT	**1.322548**	**0.126689**	**0.774**	**874**	**0.179924**	**-0.01012**	**0.345289**	**0.196**	**1.762**

3.6 Fecundity

Monthly average fecundity results were calculated for each month at each lake (Table 3). Perch from Lake Rototoa appeared to have higher fecundity than perch at the Hamilton

Lake, with an average fecundity of 59,294.23 from August to October. The Hamilton Lake produced an average fecundity of 79,079.17 from June to September. At both lakes, August produced the highest mean fecundity at 85,092 at the Hamilton Lake, and 73,232.21 at Lake Rototoa (Table 3). Fecundity appears to increase as fork length increases (Figure 20).

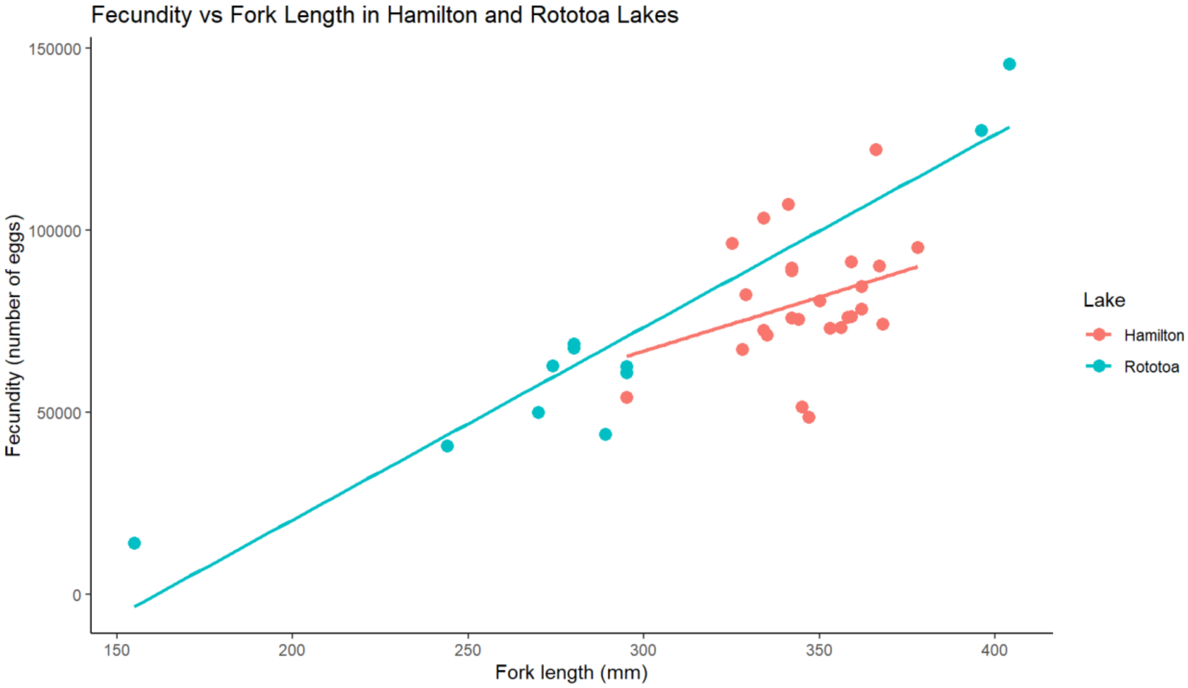


Figure 20 Distribution of fork length (mm) vs fecundity at both lakes.

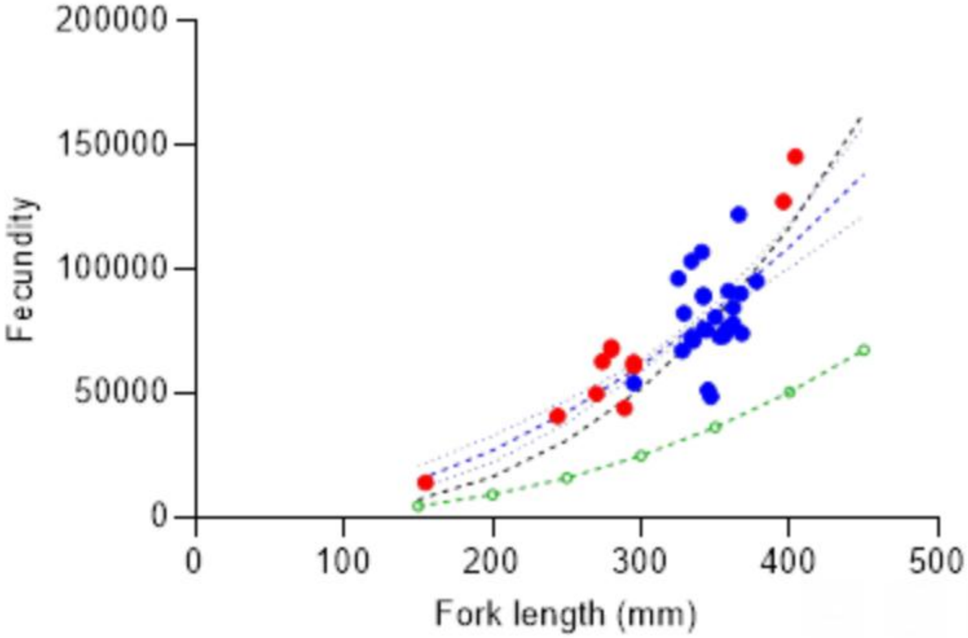


Figure 21 Distribution of fork length (mm) vs fecundity at both lakes and from the Treasure (1981) in Scotland (black dotted line) and absolute fecundity from Jellyman (1980) at Lake Pounui (green dotted line).

Figure 21 shows Lake Rototoa and the Hamilton Lake fecundity data, along with fecundity data the study by Treasure (1981), as a dotted line, to compare the different data sets. Lake Rototoa and Hamilton Lake fecundity are similar to that of Treasure's data from two lakes in Scotland, both increasing as fork length increases and at similar numbers of eggs. The green dotted line represents absolute fecundity results from Jellyman (1980) using the equation:

F = absolute fecundity L = fish length

$$\log_e F = 2.4527 \log_e L + 1.7839 \ (n = 66, r = 0.9179)$$

Which appeared to show much lower fecundity results than this study and Treasure (1981).

Table 3 Mean fecundity results per month at each lake.

Hamilton	*Fecundity*	*Rototoa*	*Fecundity*
June	**80,400.96**	*August*	**73,232.21**
July	**79,621.35**	*September*	**63,806.09**
August	**85,092**	*October*	**40,844**
September	**71,202**		
Mean:	**79,079.17**	*Mean*	**59,294.23**

3.7 Artificial substrates

Three different types of artificial spawning substrates were placed in both study sites, as well as in monitored tanks in a laboratory and outside of the laboratory on campus. At each site were five sets of substrates, each with one bundle of bracken fern, kānuka and natural fibre rope, each were anchored to the lake and tank floors. After six weeks of weekly monitoring at all locations, no eggs were found on any substrates placed at Lake Rototoa or in the tanks on campus at all weekly visits. A small cluster of eggs was found on one of the bracken fern substrates at the Hamilton Lake, however, these are yet to be tested to confirm if they were produced by European perch.

After dissection of the fish contained in the University tanks, it was discovered that only two of the five tanks contained a female fish. This was due to human error and difficulty in identifying female fish based on size. However, the female gonads did not contain eggs once dissected and there was no evidence of any spawn on any substrates.

3.8 Water temperature

Daily temperatures were recorded from mid-September to mid-November 2024 at Honeymoon Bay, Lake Rototoa, where most of the spawning substrates were placed (Figure 22). The mean temperature appeared to drop mid-October to around 16.5°C and increase again shortly after. Most mean temperatures remained above 17°C. Maximum and minimum results, shown through the blue ribbon, could indicate temperature fluctuations throughout the day.

Highest temperatures were seen between 18°C and 19°C, and minimum temperatures were as low as 16°C.

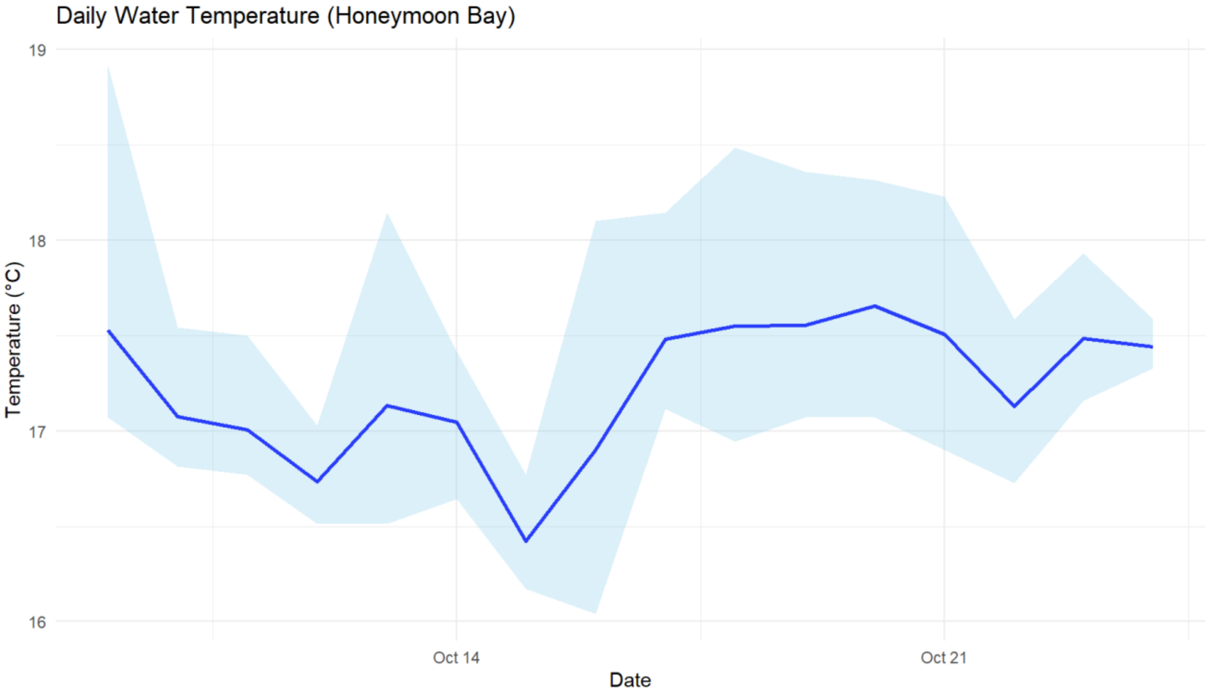


Figure 22 Daily water temperature from Honeymoon Bay at Lake Rototoa from October 2024. The blue line represents the mean temperature for that day; the blue ribbon represents the minimum and maximum temperatures.

At the Hamilton Lake (Figure 23), mean temperatures steadily increase through October, with a large spike after the 14th reaching around 22°C, which was the highest temperature. Minimum temperatures were seen around 15°C, but increased significantly towards the end of October sitting around 18°C and 19°C. Very similar to temperatures at Lake Rototoa.

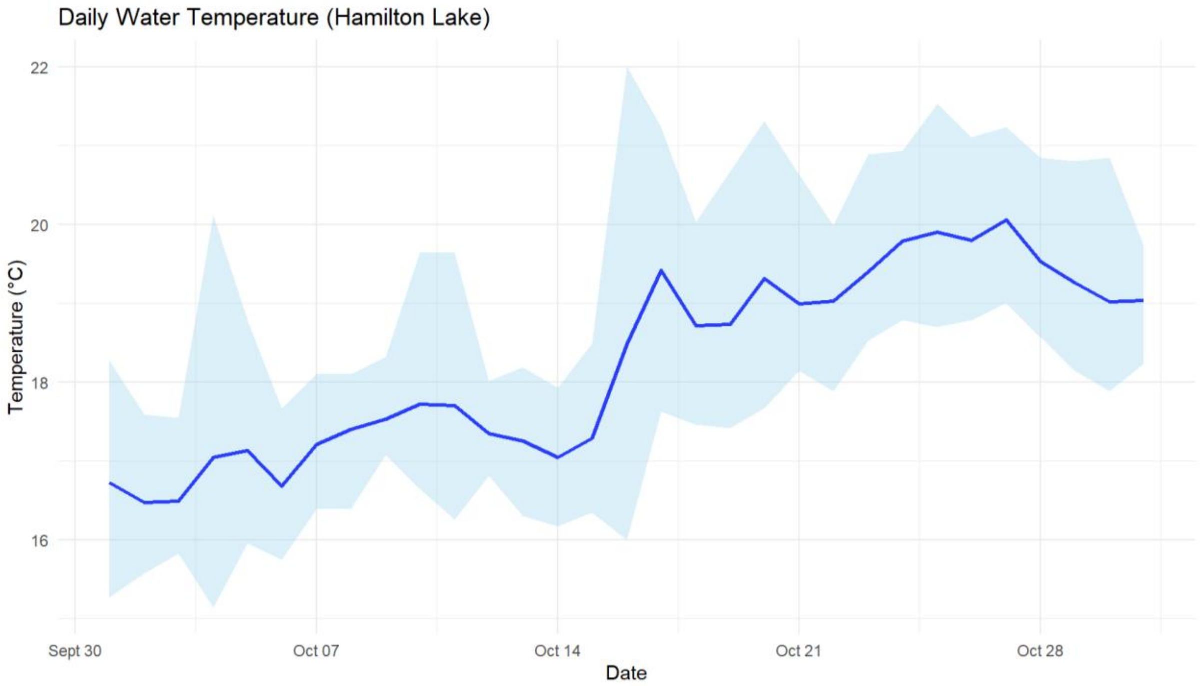


Figure 23 Daily water temperatures from the Hamilton Lake during October 2024. The blue line represents the mean temperature for that day; the blue ribbon represents the minimum and maximum temperatures.

The outdoor tanks (Figure 25) showed a steady increase throughout October, with peaks reaching around 22°C, and the lowest sitting between 15°C and 14°C. Minimum temperatures were seen at the start of the month between 14°C and 15°C. The indoor tanks (Figure 24) sat between 16°C and 17°C at the beginning of the month, then increased and remained around 17.5°C and 18°C towards the end of the month. The blue ribbon showing the maximum and minimum temperatures appeared to follow closely the mean temperature line, indicating little change during the day and night.

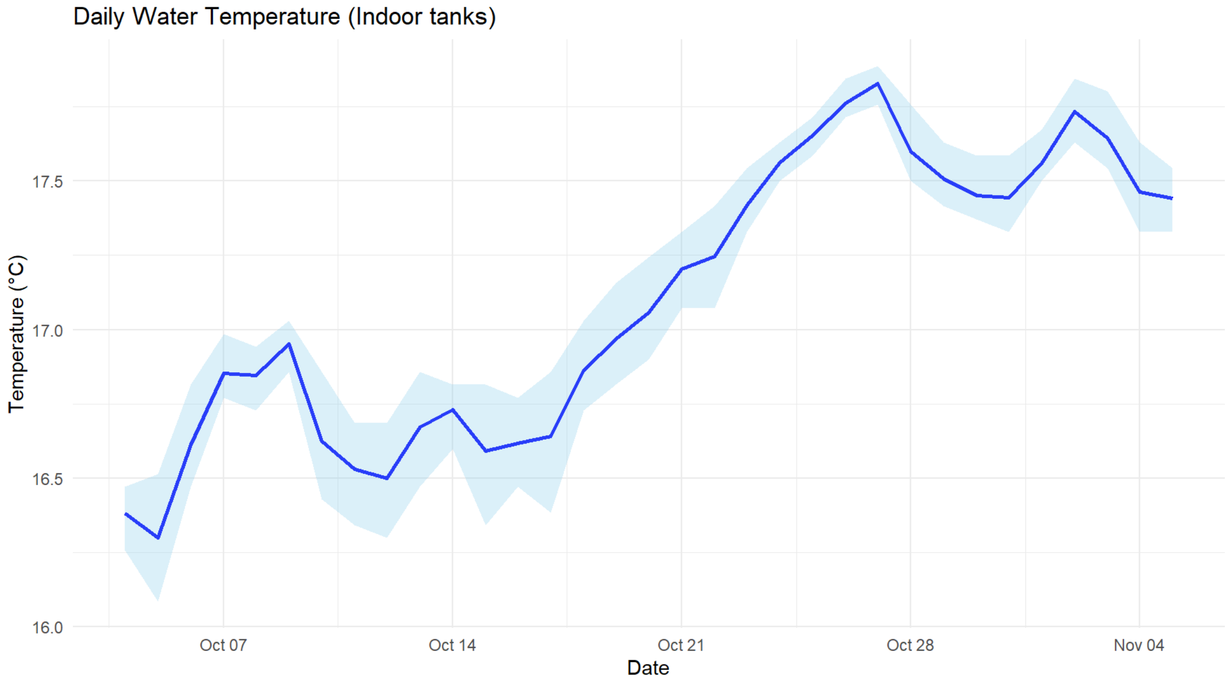


Figure 24 Daily water temperatures of the indoor tanks at the University from October 2024 to the start of November 2024. The blue line represents the mean temperature for that day; the blue ribbon represents the minimum and maximum temperatures.

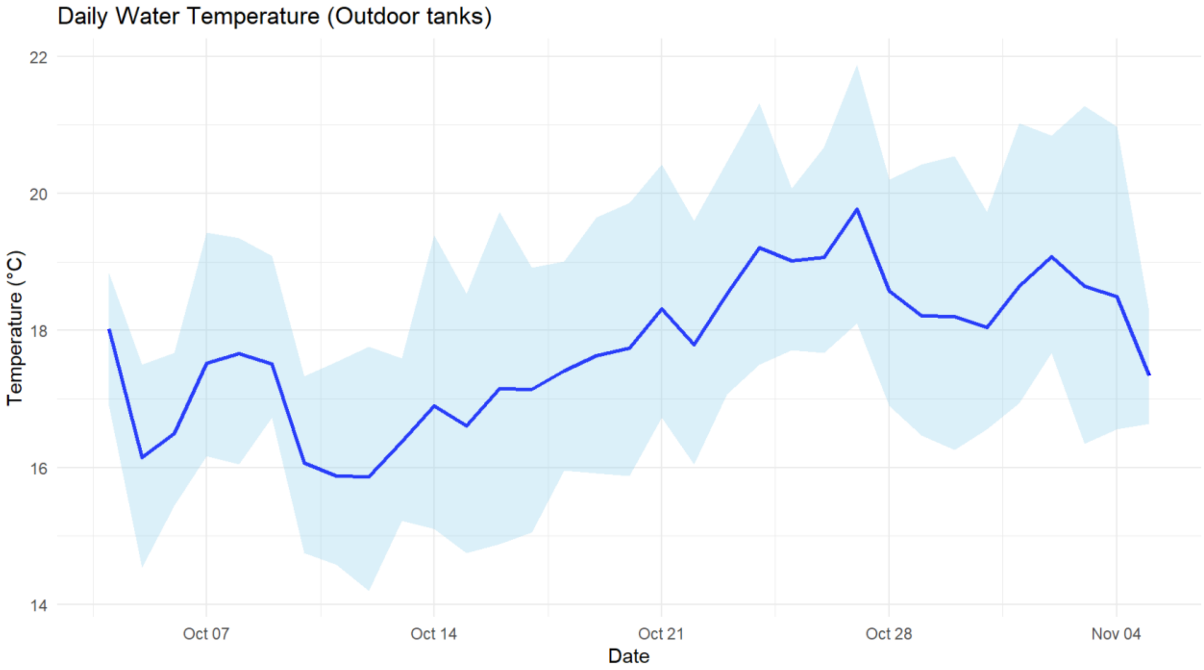


Figure 25 Daily water temperatures of the outside tanks at the University from October 2024 to the start of November 2024. The blue line represents the mean temperature for that day; the blue ribbon represents the minimum and maximum temperatures.

Chapter 4: Discussion

4.1 Morphometrics and size structure

Lake Rototoa catch had a female-dominated sample, with 105 of the 126 perch caught, a similar ratio to a 2014 study at Lake Rototoa (Banda, 2014) and Hamilton Lake had a male-dominated sample with 104 males and 56 females. Research has found links between warmer temperatures and male-dominated sex ratios in fish, as sex is heavily influenced and determined by the environment as well as genetics (Geffroy & Wedekind, 2020). While females dominated the sample from Lake Rototoa, the ratio was much more significant at the Hamilton Lake. Temperature data from both lakes showed the Hamilton Lake as slightly warmer than Lake Rototoa (Figures 22 & 23) in the month of October. Long-term temperature monitoring from both lakes would be valuable in observing trends in sex ratios, to see if they correlate with any potential warming. If this were the case, it is likely that climate change is what is driving these male-dominated sex ratios. This could potentially put constraints on reproduction in populations affected by warming water temperatures, as with only one spawning period per year and male sex skews, fewer females will be able to produce eggs and grow population sizes. The plasticity of perch may not reach sex determination; however, it would be interesting to monitor given the increasing concerns over global warming. Larger skewed sex at the Hamilton Lake could indicate different temperature thresholds within perch and their plasticity.

Males were smaller than females at both lakes, which is consistent with their known sexual dimorphism (Ning et al., 2025). European perch caught at the Hamilton Lake were larger on average than those caught at Lake Rototoa (Figures 7 & 8), despite the largest fish caught being from Lake Rototoa at 404 mm. The average fork length at the Hamilton Lake was 319.43 mm, and 228 mm at Lake Rototoa. Figure 8 shows the positive relationship between length and weight at both lakes and a comparison between the size structures. These results are consistent with the study by Koenigbauer et al. (2024), where larger lakes inhabited smaller-sized fish, and smaller lakes inhabited larger-sized fish. In the same study, they found that larger females spawned larger eggs and vice versa. This could explain the consistent size structures of perch from both lakes. Another reason could be that the quality of both lakes differs significantly, as the Hamilton Lake has higher levels of nutrients and is exposed to cyanobacterial blooms (Rumsby et al., 2011). At the Hamilton Lake, the invasive brown bullhead catfish and native eel species, which are also present (Kane, 1995) could also be part of adult perch diet, as adult perch are piscivorous (Kozłowski et al, (2025). Perch at Lake Rototoa are known to consume koura and common bully (Barnes & Burns, 2005), however the abundance of these may be lower, as both are protected species, and Lake Rototoa is larger in depth and area than the Hamilton Lake.

Size results suggest evidence of a potentially stronger top-down and bottom-up effect at the Hamilton Lake, where European perch feed off the abundance of nutrients and likely contribute to the cyanobacterial blooms by consuming beneficial zooplankton. Smith & Lester (2006) also noted this effect in their study at the Karori reservoir, where treatment areas containing European perch also had high levels of cyanobacteria. This would explain why perch caught at Lake Rototoa, were on average, smaller than those caught from the Hamilton Lake. Lake Rototoa is of higher quality and therefore may lack food sources, such as types of zooplankton, and other resources for the perch to thrive on. Interestingly, some male testes removed from the Hamilton Lake presented with cyst-like abnormalities. This was first noted in September. The cysts were small and protruded on all parts of the testes. Without proper testing of these cysts, it is hard to determine the cause of them. The quality of the Hamilton Lake could have some relations, as not only are there physiochemical quality issues, but there is a fair amount of litter and pollution also in the lake. There were also two cases of ovarian atresia in two females at the Hamilton Lake, one occurring in June and one in September. This phenomenon is common in female fish, which affects fecundity. Saemi Komsari et al. (2014) found atretic eggs in their study population from the Anzali wetland and found that it occurred in early egg yolk formation stages in mature females. They found that water temperature had the greatest effect on gonadogenesis. This process has been identified Hamilton Lake, where it is apparently (Jellyman, 1980). Although common, it is an important process to consider it affects reproductive output in females, and an investigation into why this is common in females at the Hamilton Lake could provide some new links into differences in reproductive biology and reproductive cycles of females. It would also be interesting if conditions affecting ovaries, are also the cause of the cysts found on male testes at the Hamilton Lake. From the Saemi Komsari et al. (2014) study, temperature could be the driving factor in these phenomena. However, the Hamilton Lake is also of poor quality in general which could also cause this.

Size structures can be used as an indicator of the overall health of a population, depending on environmental variables. Based on size structure, the perch population from Lake Rototoa appear to be more stunted than the population at the Hamilton Lake. Nutrient level differences are likely to be one cause for this, as the Hamilton Lake has a higher level of nutrients than Lake Rototoa, as well as an abundance of other fish species to consume. Juvenile perch are the main consumers of filter-feeding species (Ning et al., 2025), which are what could be aiding in the high nutrient levels at the Hamilton Lake. Survival in early life stages in perch only strengthens the preceding age classes, which helps in overall population survival (Persson et al., 2011). This highlights the need for control and management of perch at spawning or in early stages, as their survival and success pave the way for adult perch to continue to thrive and negatively impact ecosystems in New Zealand.

4.2 Condition indices

Condition was measured using length-weight relationships in each perch caught at both lakes. These relationships were used to calculate and observe trends in GSI, Fulton's Condition Index and somatic condition. All of which provide valuable information on the health and well-being of perch and reflect how their bodies change during spawning periods and recovery. They also reflect environmental variables and how each population is surviving and shifting its energy reserves. These shifts may be at the expense of their own body size but are usually a trade-off for whichever quality requires more energy and effort.

4.2.1 GSI

The highest GSI values in females from both lakes were in September, likely just before spawning (Figure 10), with a maximum of 22.71% at Lake Rototoa and 23.71% at the Hamilton Lake. Male GSI peaked in August at both lakes at Lake Rototoa (Figure 11), then decreased in September before females began spawning their eggs. Lake Rototoa also had one outlier in May with the highest male GSI value of 6.57%. Jellyman (1980) observed similar timing in perch at Lake Pounui from GSI results, which were the highest in late winter and early spring, and the lowest in the summer months. There appeared to be no correlation with size and GSI for either sex at either lake from a Spearman's correlation test. Before spawning, GSI increases, likely due to gametogenesis, making sure egg cells are ready for spawning and fertilisation (Ceccuzzi et al., 2011). GSI results showed that perch at the Hamilton Lake may exhibit synchronous spawning, where GSI was the highest in September, which then dropped significantly in October and onwards. Perch at Lake Rototoa also spawned at the same time but appeared to have some high GSI results after September, indicating more females spawning after September when it initially appears to begin. This could suggest a more extended spawning period and spawning asynchrony at Lake Rototoa. Another possibility is that the fish were larger; however, a Spearman's correlation test showed no correlation between GSI and fork length. Asynchrony was seen in perch eggs at Lake Wainamu (Sabetian et al., 2015), suggesting that temperature was one of the causes by observing asynchronous cell development in the spawned eggs. Migaud et al (2004) noted that temperature and perch size were considerable factors for reproductive performance, which was tested using two different warming periods in a laboratory setting. They noted that smaller perch had more efficient gonadogenesis, and that temperature changes during the spawning period impact the final part of gametogenesis and release of spawn. However, temperatures did not differ much at either lake (Figures 22 & 23). They also found that quicker warming periods resulted in higher spawning rates, however, temperature data from the Hamilton Lake and Lake Rototoa only provide one month of data (October), though it would be interesting to see how water temperatures fluctuate at both lakes before and after the spawning period. Sabetian et al (2015) also noted warmer temperatures increasing growth rate, where perch in Lake Wainamu had faster growth by year 1 than perch from the Northern Hemisphere; however, this growth rate did not continue after the first year.

Monitoring egg development in different temperatures, as seen in the Lake Wainamu study, could provide a better understanding of the causes of differences in spawning strategies at the Hamilton Lake and Lake Rototoa. Evaluating a longer temperature data set of both lakes could provide more information on the GSI and spawning responses of perch to temperature, which appears to play a significant role in spawning and gonad development. Despite the limitations in temperature data, results here lay a foundation for spawning periods which could assist in controlling perch populations during these periods and help predict future patterns that may occur. It may also be applied to other investigations on other potential influences to spawning strategy and reproductive effort.

4.2.2 Fulton's Condition Factor

Fulton’s Condition Factor results showed no seasonal patterns at Lake Rototoa, and slight seasonality at the Hamilton Lake, with a peak in August in both sexes, with a significant drop in September (Figures 12 & 13). At Lake Rototoa, the two lowest months were August and November for males; however, both months only had a sample size of one male, which is likely what caused these results. Two-sample t-tests between each sex showed a difference in mean *K* values at both lakes, with perch from the Hamilton Lake having a higher mean index. *K* appears to steadily increase after the spawning period in October at the Hamilton Lake, and in September in males at Lake Rototoa. Females at Lake Rototoa do not show much seasonality, as values at both lakes tend to fluctuate during and after the spawning season (Figures 12 & 13), with females showing more significant fluctuations. These results could further suggest evidence of asynchronous spawning at Lake Rototoa.

Spearman’s test of correlation showed no correlation between fork length and K at either lake for either sex, and rho showed a negative monotonic relationship between the variables in both sexes at Hamilton Lake and males from Rototoa. Rototoa *K* values use the weight and length of a fish to provide some insight into their health, and of the environment it inhabits (Morton & Routledge, 2006), typically assuming that heavier fish are in better condition (Christophe et al., 2015). This is particularly significant when considering the different qualities of each lake and how that may be affecting the health of each population. Despite the quality of the Hamilton Lake being lower than that of Lake Rototoa, *K* values may suggest it has better conditions and resources for perch to thrive in, such as the abundance of zooplankton and other species of fish, being piscivorous in their adult stages (Kozłowski et al,. 2025) and zooplanktivorous in juvenile stages (Smith & Lester, 2006). In Poland, Kozłowski et al (2025) found that abiotic and biotic factors heavily influenced *K* in perch, with an emphasis on resource availability and food. Interestingly, in Kozłowski et al. (2025), lake depth showed a negative relationship with *K* but depth was thought to impact food sources and foraging in perch by affecting niche partitioning. In shallower lakes, perch diet mainly consisted of benthic macroinvertebrates, whereas perch in deeper lakes had a more piscivorous diet. However, the depth did not directly correlate to *K*, the results indicate more of a correlation with food abundance and feeding niches. The environmental conditions of a lake are what appear to drive length and weight relationships in perch, as these conditions are what influence production and activity. Growth rates are also affected by these conditions, where they are seen to increase in warmer temperatures (Ning et al., 2025), and as perch grow, their diet changes.

The possible top-down effect at the Hamilton Lake is likely contributing to higher *K* values in perch, as the high level of nutrients in the lake increases primary production and in turn, more food sources. This shows that perch from the Hamilton Lake are likely in better condition than those from Lake Rototoa, favouring the conditions of a eutrophic lake where food is abundant. It is a shallower lake, which is likely affecting the primary productivity within the lake. Fulton's Condition Factor considers the weight of the gonad, which is why we consider seasonal patterns, as they can provide insight into the timing of spawning and reproductive cycles of perch. The spawning period and health of a population can indicate certain spawning strategies of perch, where certain temperatures may influence the survival rates of offspring (Gillet et al., 2013; Čech et al., 2012; Migaud et al, 2004 & Gillet & Dubois, 2007). These variables are important to consider in management efforts and control of perch spawning, where the timing and even location of these efforts is crucial, and a combination of condition indices and GSI with leads on potential causes of these patterns can create successful management operations.

4.2.3 Somatic condition

There were some seasonal patterns in somatic condition at both lakes; however, this was much less significant at Lake Rototoa (Figures 14 & 15). Both populations showed an increase in somatic condition after the spawning period, indicating shifts in size after spawning. Spearman's correlation test showed no significant correlation between fork length and somatic condition at either lake for either sex. Despite the somatic condition solely focusing on length-weight relationships minus the gonad, we can still see some slight patterns at all lakes. Two-sample t-tests revealed differences in somatic condition between sexes, with somatic conditions at the Hamilton Lake being higher than those at Lake Rototoa. Craig (1977) explained that changes in somatic condition are due to changes in energy expenditure, where energy is lost, especially in females, during spawning. This energy loss impacts foraging abilities and other survival needs until that energy increases again. Which is why somatic condition is a great indicator of perch health and wellbeing, as the gonad weight is not included. At the Hamilton Lake, somatic condition is the lowest in September for females and males. When compared to GSI and *K* results, this is likely right before or during spawning, as GSI and *K* were lowest around October, indicating the end of the spawning period (Figures 10, 11, 12 & 13). At Lake

Rototoa, somatic condition was the lowest in August for males and females. *K* was lowest in August and September for males, and in October for females. GSI was lowest in December for both males and Females, but both began to drop in October. Somatic condition follows a similar pattern to *K*, but there is a bit more seasonality at the Hamilton Lake, where we can see that somatic condition in females falls before or early in the spawning season, likely when their energy reserves drop to ensure successful spawning. Male somatic condition at the Hamilton Lake drops in September, but has a greater increase again in September than *K* until both continue to increase. Hamilton Lake results are similar to what was found in the study by Craig (1977), where energy is depleted in females as they spawn, and at a larger expense than the male. The pattern at the Hamilton Lake also indicates synchronous spawning, as somatic condition follows a similar pattern to *K* and the inverse of GSI. Lake Rototoa results vary, with much less evidence of a seasonal pattern, similar to *K*. Thus, further suggesting asynchronous spawning patterns.

The overall health of perch appears to be better at the Hamilton Lake, again, likely due to a greater abundance of food resources. The study by Persson et al. (2011) examined the effect of toxic and non-toxic cyanobacteria in YOY perch, and found that those species caused a decline in somatic condition in YOY perch. Because of the higher somatic conditions at the Hamilton Lake, it is fair to assume that the species of cyanobacteria are not negatively affecting the somatic condition of perch. However, this would be interesting to investigate further. As the Hamilton Lake is exposed to cyanobacterial blooms, it would be interesting to see if the species there have any effect on somatic condition, or any effect at all on YOY, as they are more sensitive to environmental conditions (Ning et al., 2025).

The drop in Fulton's condition factor at Hamilton Lake coincides with the patterns in GSI, where GSI drops after the spawning period (October), and appears to drop in condition just before the spawning period ends (September). While there were seasonal patterns in GSI at Lake Rototoa, results suggested a prolonged spawning period and asynchronous spawning, which is also reflected in condition results. Higher conditions usually indicate higher energy reserves in fish, as more energy is needed for gonad maturation as age increases (Craig, 1977). *K* values further explain the synchronous spawning at the Hamilton Lake, driven by the peaks in August and drops in September and explain the asynchronous spawning at Lake Rototoa with no seasonal patterns. Condition and GSI results may also suggest some evidence of plasticity in perch, as Condition combined with GSI results can aid in management efforts focused on spawning periods by helping to predict future periods and track any changes in reproductive effort. Research into the energy storage of these populations could also provide new insight into the overall potential conditions of a population and potential reproductive effort. Although this was not part of this study, this provides some foundations to continue this research.

4.3 Fecundity and oocyte diameter

Mean fecundity was relatively similar at both lakes (Table 3), with August having the highest fecundity at both lakes (Table 3 & Figure 20). Overall, fecundity was slightly higher at the Hamilton Lake. Similar fecundity results were reported in the study by Treasure (1981) in Scotland, which ranged from 5,480 to 77,987 (Figure 21). At Lake Pounui, Jellyman (1980) reported relative fecundity results of 2,657 to 63,858 and relative fecundity as 33 to 141. Both studies showed a similar relationship with fork length to fecundity at the Hamilton Lake and Lake Rototoa, however, fecundity from Lake Pounui was much lower (Figure 21). Mean egg diameters from the Treasure (1981) study were also similar in range to the ones calculated in this study, at 0.94 mm and 1.62 mm. Diameters from Lake Rototoa ranged from 0.839 mm to 1.886 mm, and 0.836 mm to 2.097 mm at the Hamilton Lake (Tables 1 & 2). Egg diameters from Lake Pounui were also smaller at 0.86 mm to 1.31 mm. The fork lengths of fish used from Scotland and Lake Pounui (17 cm to 32 cm and 14.5 cm to 42.2 cm, respectively) were also similar to those used in this study (202 mm to 378 mm at the Hamilton Lake and 101 mm and 404 mm at Lake Rototoa). GSI results and condition indices were all higher at the Hamilton Lake, where slightly higher fecundity results were seen. However, Hanson (2009) noted in his Swedish population, that gonad size may not be causing declining fecundity numbers in perch, after he observed a 40% decline in gonad sizes and no changes in population size. Changes in gonad size could be a result of changing energy expenditure based on environmental conditions, which would encourage survival in offspring and all life stages, and could potentially be what we see at Lake Rototoa.

The diameters of oocytes from Hamilton Lake were slightly larger than oocytes from Lake Rototoa (Figures 18 & 19); although, the size difference is not incredibly significant. Perch caught at the Hamilton Lake were also, on average, larger than those from Lake Rototoa. The size of the perch is likely to affect the size and number of oocytes produced, as seen in the Yellow perch study by Koenigbauer et al (2024), where larger-sized fish typically spawned larger eggs. However, this was not the case here, as perch from the Hamilton Lake were larger, and their oocyte diameters were only slightly larger. The same study also investigated the correlation between the size of the lake and the size of the oocyte, where in Yellow perch, smaller lakes had perch spawning larger oocytes, and larger lakes had perch spawning smaller oocytes. This appears to be the case here, as the Hamilton Lake is smaller than Lake Rototoa, therefore, larger eggs would aid in the survival of juvenile perch to encourage population growth and abundance. Sample sizes for fecundity calculations and diameters were very different. The Hamilton Lake had a sample size of 25 fish, and almost 30,000 eggs total. Lake Rototoa had a sample size of 11 fish and 15,600 eggs. The difference in sample sizes was due to time limitations, and that fish collection at Lake Rototoa did not start until August 2024, instead of June 2024. Unimodal distributions (Figures 16 & 17) and bimodality coefficients (Tables 1 & 2) of oocyte diameter suggest singular spawning periods. Fecundity results were similar to those from Treasure (1981). At the Lake Wainamu study by Sabetian et al (2015), they note that warmer temperatures have been connected to earlier sexual maturation in perch, where younger perch are maturing faster.

Abiotic and biotic factors of the lake appear to influence oocyte diameter and fecundity, as well the size of the perch. This is likely a strategy of perch to ensure successful offspring and survival of larvae and juvenile perch. Koenigbauer describes the lake and size patterns as almost as if the females are giving their perch a good head start, as these strategies encourage better foraging potential, increased growth rate and strengthen avoidance of predators. These strategies then provide an understanding of the potential conditions within the lake, to explain why different strategies are used for offspring survival. For example, a lake with more predators, less food resources, or other abiotic and biotic factors. These variables should be applied to management efforts to help predict potential fecundity and spawning success.

4.4 Artificial spawning substrates

Females did not spawn their eggs on any artificial spawning substrate at Lake Rototoa or in the tanks at the University. A small cluster of eggs were found on a bracken fern bundle at the Hamilton Lake, which were not consistent with the characteristics of typical perch spawn and are yet to be DNA tested. Only two of the university tanks contained a female perch, both located in two separate outside tanks with a male to each, and these ova were empty upon dissection. This could be due to either catching them and transporting them after they had already spawned, or if there was consumption of the eggs by the fish in the tanks, as all substrates in all locations were only checked once per week for the six-week experiment. Gillet & Dubois (2007) and Čech et al. (2011) highlight the importance of water temperature on spawning substrate preference in European perch. Both studies found that perch preferred to spawn in temperatures around 10°C to 12°C and also noted temperature instability within the water columns. Efforts in deploying the artificial spawning substrates did not consider temperature differences in the water columns, and temperature data was not obtained until after the experiment. Temperature data showed that both lakes and tanks had much higher temperatures, with the lowest sitting at 14°C at the outdoor tanks, and the highest at around 22°C at the Hamilton Lake (Figures 23 & 25). However, as perch were still spawning around this time, particularly at Lake Rototoa, it begs the question of what temperature perch may prefer in a New Zealand climate, and whether their plasticity has allowed them to adapt to our different temperatures to continue repopulating. There was not much difference in temperature at Lake Rototoa and the Hamilton Lake, however, there was only one month of temperature data and it was from October. Extended temperature data from the entire spawning period would be useful for determining any changes in warming, and these results could be related back to condition indices and spawning results. It is also important to note that both lakes differ in depth, with Lake Rototoa being a much deeper lake, and therefore temperature may vary considerably at different parts and water columns of the lake. These studies were conducted in Europe, where temperatures will differ from those in New Zealand. The substrates were mostly deployed towards the edges or shores of the lakes, and some close to or within reeds and other vegetation. Čech et al. (2011) found that perch do have a preference for the size and location of the substrate, where larger substrates that were easier to access had larger egg strands than smaller, denser, harder to access substrates. Our substrates were all similar in size, but perhaps better, easier-to-access substrates were already naturally present in those locations. In the university tanks, the perch had no other substrate options other than the three provided, but no eggs were found on any during the six weeks. As the tanks were only monitored once a week, potential egg strands that spawned could have been missed. Another limitation of this study was the sex identification of the fish used in the lab tanks, where only two of the five tanks contained female perch, and both were in the outside tanks.

4.5 Catch methods

Methods of catchment varied between lakes between the use of nets and electrofishing. Night electrofishing was carried out at the Hamilton Lake, and mostly fyke nets were used at Lake Rototoa – gill nets had some success at Lake Rototoa but were not as effective. Gill nets were also successful at the Hamilton Lake during the months the electrofishing boat was out of order. Electrofishing was the most efficient at Hamilton Lake, as the lake has an abundance of catfish and eel that would dominate any deployed fyke nets. Interestingly, the larger perch caught at Lake Rototoa were caught using gill nets, and fyke nets brought in much smaller perch. This could be linked to the locations of the nets, as gill nets were set at much deeper parts of the lake, and fyke nets were located near the shoreline or edge of the lake at much shallower parts. Despite not having the electrofishing boat during some months of this study, gill nets were still successful as a replacement. It would be interesting to see if size structures change if this study was replicated and methods of catchment were limited to only electrofishing. Eradication and population control efforts of perch often involve fyke nets and gill nets; however, these methods can also affect other species present in the lake. On one occasion in this study, five fyke nets were deployed at the Hamilton Lake while the electrofishing boat was out of order, as opposed to gill nets. In the five nets, only one perch was caught, and the rest were filled with catfish and eels. The Hamilton Lake is much shallower than Lake Rototoa and has a large abundance of bottom-dwelling fish, hence why fyke nets were unsuccessful. At Lake Rototoa, very few common bully were caught in fyke nets, but koura would often also find themselves trapped in one, but this was not always the case. In order to measure important indices and morphometrics of perch to evaluate their health and condition, catch methods must suit the body of water, and the general size of the population.

Chapter 5: Findings from study and implications

The aims of this study were to evaluate and compare the reproductive biology of two European perch populations from two lakes in New Zealand with differing qualities and sizes in the hopes that this information can be applied to control and management efforts of this invasive species that is negatively impacting ecosystems and native species abundances. This study also incorporated an experiment on artificial spawning substrate preferences to provide insight into spawning strategies using bracken fern, kānuka and natural fibre rope. Fish collection was carried out over a 12-month period, providing one year of data on reproductive biology, condition and standard morphometrics of perch at both lakes which were analysed and compared provide valuable insight into the influence of environmental variables on spawning strategies and reproductive cycles within perch.

The study found that perch from Lake Rototoa were more stunted than perch at the Hamilton Lake, as perch were smaller on average at Lake Rototoa from fork length and weight results. GSI, Fulton's Condition Factor and somatic condition were also higher at the Hamilton Lake, suggesting more favourable conditions for perch survival, despite it being much a much lower quality lake. GSI and condition indices also indicated synchronous spawning at the Hamilton Lake, and asynchronous spawning at Lake Rototoa during the spring months and late winter months. Condition indices also highlight different energy reserves and expenditure between females and males at both lakes.

Fecundity was higher at the Hamilton Lake and at both lakes; fecundity correlated positively with fork length, and both lakes had the highest fecundity in August, likely right before the spawning period began. Oocyte diameters were slightly larger from perch at the Hamilton Lake, and all displayed unimodal distributions with higher. Both fecundity results and oocyte diameter results from both lakes matched ranges seen in other literature in other locations. Fecundity and oocyte diameter results provide insight into spawning strategies for optimal offspring survival and may reflect environmental variables at either lake.

The artificial spawning substrate experiment was unsuccessful at all locations. At the Hamilton Lake and Lake Rototoa, the location of the substrates could have impacted this result. In the laboratory tanks, only two females were caught and placed in a tank with their respective male; upon dissection, the ovaries were empty; however, the exact cause of this is unknown.

Results from this study highlight the differences in reproductive biology and spawning strategies of perch at both Lake Rototoa and the Hamilton Lake. Condition indices from perch provide a valuable foundation for control and management efforts by initiating control in those early life stages and slowing down population growth and perch abundance. The timing of these methods is crucial, and condition indices and continued monitoring can help to predict them. Environmental conditions have the greatest impact on growth and gonad development in perch, and it is equally important to continue to monitor these variables to observe any changes in reproductive output, particularly as climate change is on the rise. As European perch are a plastic species, they can adjust their needs and energy reserves to accommodate these changes and ensure the successful survival of offspring.

Artificial spawning substrate preferences of perch were not successful in this study; however, if replicated, it is important to carefully consider external variables such as temperature, which can vary within the water columns of lakes, as well as the size and location of the substrates, making sure they are optimal for perch spawning to ensure some success.

Further research into protein, lipid and fat changes in perch during seasonal cycles can allow for more thorough explanations of changes in energy reserves and somatic condition overall, as these can influence reproductive output and growth.

In closing, this study provides useful insight and data into the reproductive biology and spawning strategies of European perch, and will serve as a useful foundation for further research, and especially in current or future control methods on populations in New Zealand. Specifically, this information will aid in developing control methods targeting spawn and juvenile recruitment.

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