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# Responses of the fish community and biomass in Lake Ohinewai to fish removal and the koi carp exclusion barrier

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# Executive summary

The objectives of this research were to determine the biomass of koi carp (*Cyprinus carpio*) and other fish species in Lake Ohinewai in 2016 by two-sample mark-recapture methods and to compare these estimates with similar studies conducted in 2011, 2012, and 2014. In May 2011 the University of Waikato installed a one-way barrier on the outlet of Lake Ohinewai that was designed to prevent adult koi carp moving upstream into the lake, while allowing fish to pass downstream out of the lake, thereby attempting to passively reduce fish biomass in the lake. In addition, an invasive fish removal programme was undertaken in Lake Ohinewai with the aim of reducing the koi carp population from the estimated original biomass of 308 kg/ha (211–466, 95% CL) to below 100 kg/ha. In previous mark-recapture studies it was estimated that the koi carp biomass had been reduced to 39 kg/ha (24–67, 95% CL) in 2012 and 14 kg/ha (7–27, 95% CL) in 2014 by a combination of fish removal and the one-way gate. In 2016, we estimated that the koi carp biomass had increased to 94 kg/ha (49–197, 95% CL).

A mark-recapture study was conducted on the fish community in Lake Ohinewai from 21 November to 7 December 2016. Capture method included fyke net sets for a total of 120 net nights and boat electrofishing for 12 h. Species included in the study were the invasive species koi carp, brown bullhead catfish (*Ameiurus nebulosus*), rudd (*Scardinius erythrophthalmus*), goldfish (*Carassius auratus*) and koi carp-goldfish hybrids, and the native species shortfin eel (*Anguilla australis*) and longfin eel (*Anguilla dieffenbachii*). In addition, water samples for nutrient analysis and suspended solids, Secchi depth, CTD (conductivity, temperature, depth) profiles and zooplankton and phytoplankton samples were taken from Lake Ohinewai on three occasions between 21 November 2016 and 20 January 2017.

A total of 1680 fish were caught in the marking phase (21–24 November 2016) and 2058 fish in the recapture phase (5–8 December 2016); 479 of fish caught in the recapture phase were marked. The estimated koi carp population in Lake Ohinewai more than quadrupled in size from 454 (251–889, 95% CL) fish in 2014 to 2063 (1070–4328, 95% CL) fish in 2016. Similar increases in the estimated populations of catfish (925 to 4010), goldfish (512 to 1927) and koi carp hybrids (43 to 252) were also observed. Eels also increased in abundance; between 2014 and 2016 shortfin eels increased from 2305 to 3456 and longfin eels increased from 44 to 100. Total invasive fish biomass also increased from 29 kg/ha (18–50, 95% CL) in 2014 to 154 kg/ha (78–311, 95% CL) in 2016. This change was primarily due to an increase in koi carp biomass, but increases in catfish and goldfish biomasses have also occurred since 2014. Goldfish showed a strong pulse of recruitment in 2016.

The large-scale removal of invasive fish and installation of the one-way barrier resulted in significant changes to the invasive fish community composition. The fish removal programme reduced the proportion of larger (>275 mm fork length) koi carp and goldfish, which can be attributed to size selectivity of the removal methods and emigration of adult koi carp from the lake. Recruitment of smaller koi carp was observed in 2014 when they had bimodal size distribution, comprising juvenile fish (<250 mm FL) and adult fish (>300 mm FL).

Shortfin eels increased significantly in mean weight following carp removal. Changes in the longfin eel population appeared similar to those of shortfin eels, with an increased proportion of larger eels following removal of koi carp and other invasive fish, but the low sample size hampered comparisons of mean weight.

Water quality indicators such as nutrient concentrations, Secchi depth and total suspended solids showed no improvement in the 5 years following the reduction in invasive fish biomass, except for chlorophyll *a* concentration, which declined with decreasing biomass of invasive fish from 2011 to 2014, and returned to previous concentrations as invasive fish biomass increased by 2016. It is not entirely clear that this was caused by changes in the fish biomass as total nitrogen also declined from 2009 to 2013. Total phosphorus remained largely unchanged throughout the study period. In addition, phytoplankton species and abundance appear consistent with other hypereutrophic lakes in the Waikato region. The annual mean TLI3, which excludes Secchi depth, ranged from 6.1 to 6.6 between 2006 and 2017, indicating that the lake remained hypertrophic during fish removal. Chemically-driven internal nutrient cycling and catchment nutrient inputs are likely to maintain the hypereutrophic condition and low water clarity will continue to inhibit re-establishment of submerged macrophytes, the absence of which can exacerbate wind resuspension of sediment.

The increase in the koi carp abundance indicates that at least one successful recruitment event occurred following the removal programme and installation of the one-way barrier, either by spawning in the lake or by upstream migration of juvenile young-of-the-year fish from spawning areas lower in the catchment. In addition, reduced interspecific competition has likely contributed to increased recruitment of the catfish and goldfish populations. Therefore, while the Lake Ohinewai one-way barrier appears effective in preventing immigration of adult koi carp into an area, it should not be considered as a mechanism to exclude both adult and juvenile koi carp nor as a sole measure of control.

In Lake Ohinewai, reductions in koi carp biomass were not long lasting, and during the period of low carp abundance there was no convincing evidence for a corresponding improvement in water quality and zooplankton and phytoplankton community composition. Koi carp removal did appear to increase the abundance and size of shortfin eels. Before any restoration programme is initiated it is recommended that a complete assessment of the system is undertaken to determine which factors are driving the decline in water quality. Ecological models can be helpful in determining these driving factors but they are reliant on substantial data for parameterisation and calibration. If reductions in invasive fish biomass are deemed necessary for ecosystem restoration, repeated removal programmes appear to be the only viable way of ensuring low biomasses of target invasive species are maintained.

# 1 Introduction

Invasive freshwater fish species such as koi carp (*Cyprinus carpio*), brown bullhead catfish (*Ameiurus nebulosus*), rudd (*Scardinius erythrophthalmus*), European perch (*Perca fluviatilis*) and goldfish (*Carassius auratus*) have been implicated in the decline of the overall ecosystem health of New Zealand's aquatic ecosystems (Rowe 2007, Collier and Grainger 2015). Koi carp, goldfish and brown bullhead catfish are the three most abundant invasive fish species in the Waikato region (Collier et al. 2015, Hicks et al. 2015). The effects of these species include sediment resuspension, submerged macrophyte disturbance, increased nutrient cycling and predation of native species resulting in reduced water quality and biodiversity (Rowe 2007, Collier and Grainger 2015). Species-specific impacts by invasive fish, particularly koi carp, have not been well documented in New Zealand and their influence on water quality can be difficult to discriminate from catchment and intrinsic limnological processes, such as nutrient loading and wave resuspension of sediment. However, numerous overseas studies have demonstrated negative impacts by koi carp on water quality and submerged aquatic macrophytes under both artificial conditions (Crivelli 1983, Roberts et al. 1995, Driver et al. 2005) and natural conditions (King et al. 1997, Zambrano et al. 2001, Miller and Crowl 2006, Bajer et al. 2009, Kaemingk et al. 2017). The impacts of brown bullhead catfish and goldfish are considerably less well documented but appear to be more related to predation and competitive exclusion of native species, rather than macrophyte disturbance or water quality effects (Barnes and Hicks 2003, Hicks 2007, Cucherousset and Olden 2011, Nowosad and Taylor 2012).

Generally, reduced water quality and macrophyte loss starts when the population density of koi carp exceeds 100 kg/ha, with significant impacts occurring at densities >400 kg/ha (Crivelli 1983, Roberts et al. 1995, King et al. 1997, Chumchal et al. 2005, Driver et al. 2005, Bajer et al. 2009). In the lower Waikato region, boat electrofishing estimates of koi carp population densities exceed 200 kg/ha for many lakes (Hicks et al. 2006, Hicks et al. 2015), and spawning aggregations of over 4,000 kg/ha have been observed (Hicks and Ling 2015). Therefore, control or eradication of koi carp populations has been identified as a priority for governmental and community agencies and such as the Waikato Regional Council, Department of Conservation and the Waikato River Authority (Chadderton et al. 2001, WRC 2014, Collier and Grainger 2015).

One method that has been employed to manage koi carp populations is the installation of physical barriers to exclude koi carp from localised areas. Variations on this method have been employed overseas, with success varying from a 95% reduction in biomass in the targeted area (Lougheed et al. 2004) to no difference (Hillyard 2011). Physical barriers typically exploit lateral movement behaviour from riverine or lacustrine areas into wetlands and inundated areas to forage or spawn (Lougheed et al. 2004, Daniel et al. 2011, Taylor et al. 2012). Barriers are typically installed on movement choke points between systems and are either designed to be completely impermeable to fish (Taylor et al. 2012) or allow limited movement of juveniles and smaller native species while excluding adults (Hillyard et al. 2010).

An alternative exclusion approach was employed at Lake Ohinewai in 2011, based on results obtained during radio telemetry tracking of koi carp in the lower Waikato River and riverine lakes. Up to 75% of adult koi carp leave lakes adjacent to the Waikato River at some point in their life history and many attempt to re-enter later (Daniel et al. 2011). This behaviour was exploited at Lake Ohinewai by installing a one-way barrier that allowed the adult koi to leave, but prevented their re-entry to the lake at a later time. Potentially, this passive control method would be a comparatively low cost and persistent way of reducing koi carp biomass within the lake.

The permanent one-way barrier designed by the University of Waikato (Figure 1) was installed on the culvert under Tahuna Road, the only outlet for the lake, during May 2011 with the aim of preventing adult koi carp from recolonising the lake following large-scale invasive fish removals from Lake Ohinewai between January – May 2011. The barrier was designed with horizontal bars to allow debris <30 mm to pass through unobstructed and was hinged at the top to allow for easy cleaning in the case of blockage. The bar spacing and pushing mechanism of the one way gate installed in the barrier was based on the fish trap design of Thwaites et al. (2010). A design requirement was that the spacing between the push elements had to allow upstream passage of juvenile native fish species such as shortfin and longfin eels, it was still possible for juvenile koi carp (estimated <150 mm FL) to pass upstream through the barrier. Testing of native eel passage employing tagged eels released downstream of the barrier and subsequently recaptured upstream of the barrier found the 30 mm vertical bar spacing did not inhibit the passage of eels (size <300 mm TL) through the barrier (Daniel and Morgan 2011), with the assumption that larger adult eels will only be passing in the downstream direction (out of the lake) as they undertake spawning migration.

**Figure 1.** Installation of the Lake Ohinewai one-way koi carp barrier on the downstream side of the culvert running under Tahuna Road in May 2011. The barrier was designed to allow fish passage downstream out of the lake, but prevent upstream movement of adult koi carp.

Maintenance and debris clearing of the one-way barrier was initially conducted by University of Waikato staff and then by the Department of Conservation (DOC) from April 2015. The barrier was inspected monthly and accumulated debris cleared as required. There were no observed instances of debris impairing the operation of the barrier (J. Gumbley and J. Whanga, DOC, Hamilton, pers. comm.).

The initial fish removal programme conducted by the University of Waikato removed 3.12 tonnes of invasive fish biomass (primarily koi carp, catfish and goldfish) from Lake Ohinewai from January to June 2011. Koi carp comprised >79% of the biomass removed during this period, reducing the koi carp biomass of Lake Ohinewai that was estimated at the time from 374 kg/ha to below 100 kg/ha (Tempero et al. 2015). A follow-up mark-recapture study in December 2011 found the koi carp biomass had further declined to an estimated 45 kg/ha 6 months after the installation of the one-way barrier and cessation of the removal programme (Tempero et al. 2015). Follow-up surveys in 2012 and 2014 also found koi carp biomass at comparatively low levels (<40 kg/ha; Tempero unpublished data, Tempero et al. 2015) with some evidence for continued decline in the koi carp population.

## 1.1 Objectives

In November 2016 the University of Waikato was contracted by the Waikato Regional Council to conduct a mark-recapture study of invasive fish and native eels (*Anguilla* spp.) in Lake Ohinewai. The primary objective of the study was to determine the current population sizes of invasive fish and native eels in the lake >5 years after the installation of the one-way barrier. Population estimates were compared to previous mark-recapture estimates to determine whether the one-way barrier had continued to control koi carp biomass in the lake. Changes in abundance and population size structure of other resident fish species were also of interest, as the removal of koi carp had the potential to increase food availability.

To examine the effects of previous removals on the lake's ecology, previous biomass estimates of invasive and native fish were reanalysed using the statistical techniques provided in the R statistics package Fish Stock Assessment (Ogle 2016) based on the two-sample capture-recapture Lincoln–Petersen model. The package optimises error calculation procedures according to recapture rates. The current water quality status of Lake Ohinewai was also determined and compared to previous historical water quality data in the context of these estimates.

# 2 Methods

## 2.1 Study site

Lake Ohinewai is a shallow, riverine lake on the Waikato River floodplain with a maximum depth of 4.5 m and a surface area of 16.8 ha (Figure 2). The lake has a 331 ha catchment that is primarily flat with several inlet drains and is dominated by intensive pastoral farming. A single outlet drain leads to Lake Waikare via Lake Rotokawau and passes through a circular road culvert (length 33 m) that is 930 m downstream from the lake outlet. Lake Ohinewai deteriorated during the 1980s from a historically macrophyte-dominated state to a highly eutrophic algal-dominated state and currently lacks aquatic macrophytes. In 1981, 80% of the lake was covered by aquatic macrophytes but by 1991 none remained (Edwards et al. 2005).

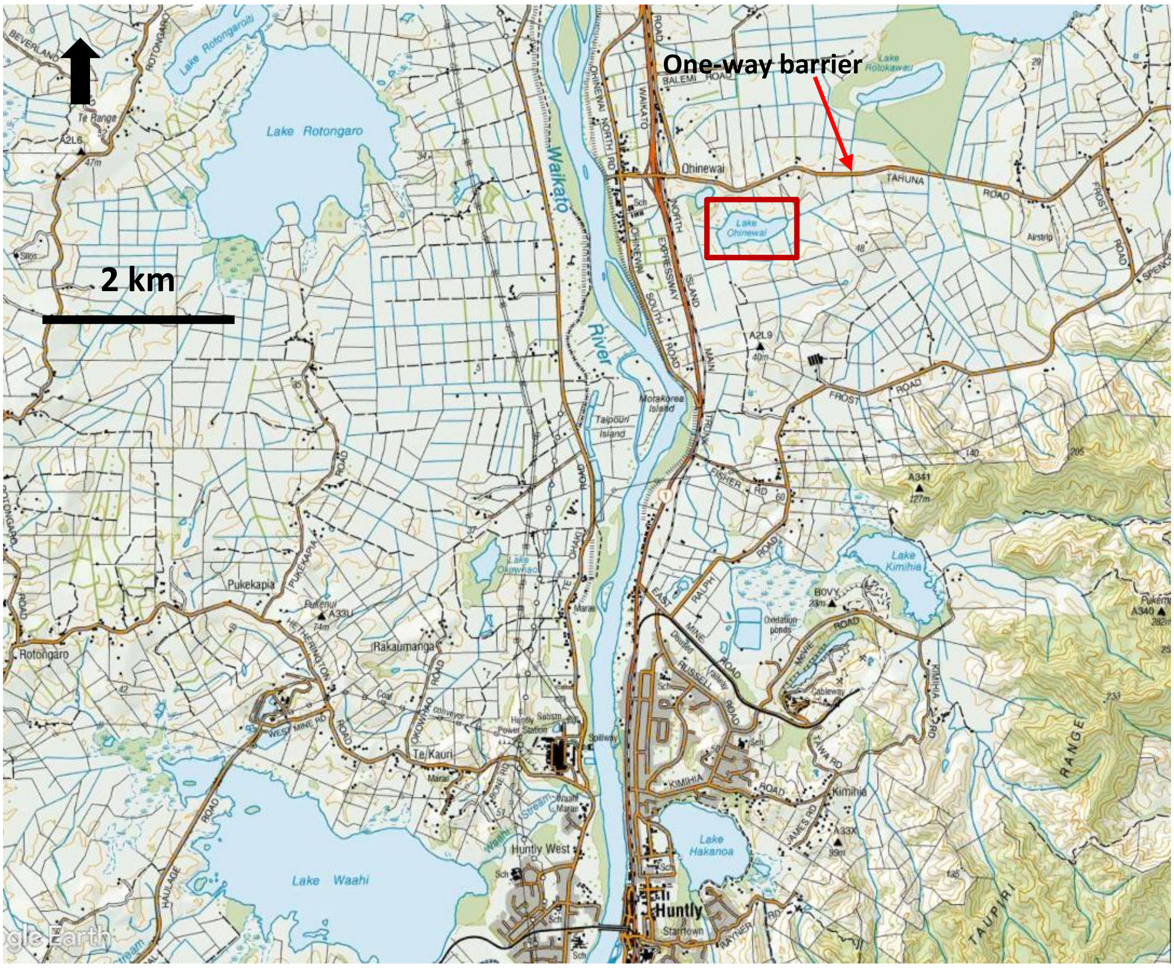



**Figure 2.** Location of Lake Ohinewai on the lower Waikato floodplain shown by the red rectangle. A single outflow drains the lake, passing under Tahuna Road to Lake Rotokawau and then to Lake Waikare. Location of one-way barrier is indicated by the red arrow.

## 2.2 Mark-recapture

Fishing in 2016 was divided into a marking phase (21–24 November) and a recapture phase (5–8 December). Fishing effort and techniques were consistent with previous mark-recapture studies of Lake Ohinewai. During each phase 20 unbaited 5-mm mesh exclusion-chamber fyke nets were set overnight around the perimeter of the lake for three consecutive nights (Figure 3). Following each overnight set, captured fish were cleared from the net, which was then reset in the same location. Fish were placed in numbered catch bags and transported back to the shore station for processing.

Boat electrofishing was conducted using a 4.5-m long, custom-made aluminium electric fishing boat equipped with a 5-kilowatt gas-powered pulsator (GPP, model 5.0, Smith-Root Inc, Vancouver, Washington, USA) that was powered by a 6-kilowatt custom-wound generator. Two anode poles, each with an array of six electrode droppers, created the fishing field at the bow, with the boat hull acting as the cathode. We assumed from past experience that an effective fishing field was developed to a depth of 2-3 m, and about 2 m either side of the centre line of the boat. The boat thus fished transects approximately 4 m wide, which was generally consistent with the behavioural reactions of fish at the water surface. This assumption was used to calculate area fished from the linear distance measured with a Garmin GPSmap 60CSx global positioning system (Hicks et al. 2006). A total of eighteen 20-minute electroshocking transects were conducted around the littoral zone of Lake Ohinewai during each fishing phase. This totalled 360 minutes of boat electrofishing, covering the lake's perimeter 2.2 times during each phase. Transect locations were selected to include the widest range of littoral habitats possible; however, mid-lake transects were not performed as previous fishing of this habitat has resulted in low capture rates. Following capture, fish were placed in numbered catch bags and transported back to the shore station for processing.

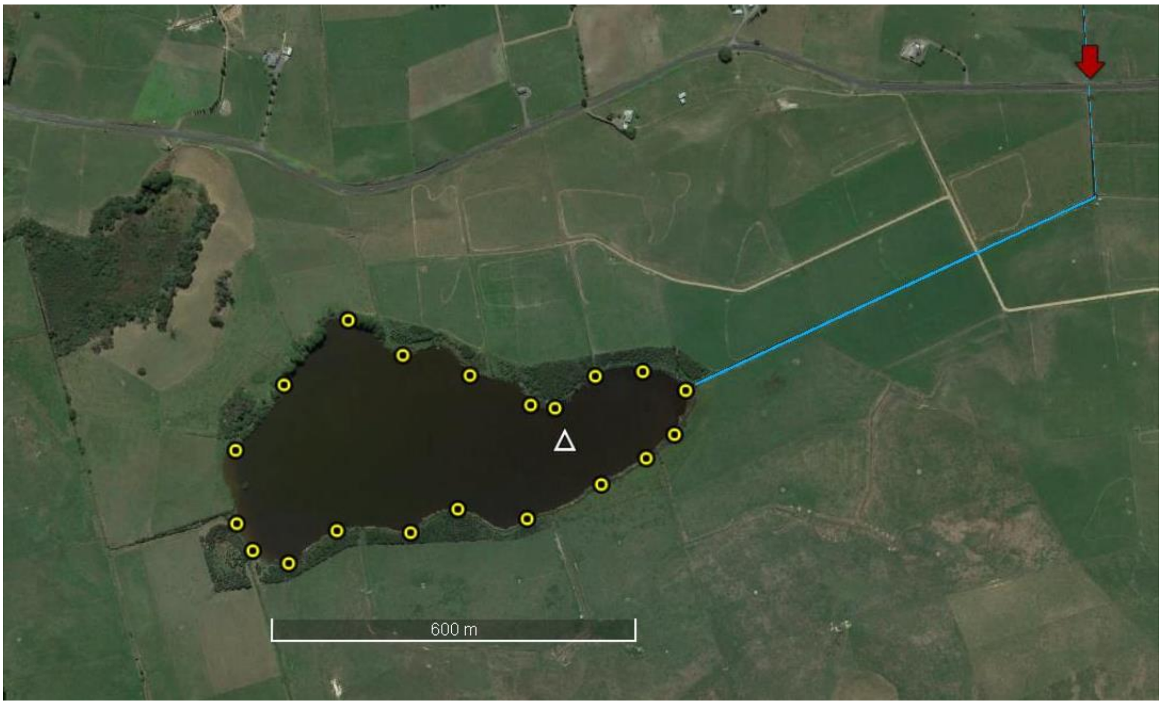



**Figure 3.** Lake Ohinewai fyke net locations (yellow circles) set on three consecutive nights during mark (21–24 November 2016) and recapture phases (5–8 December 2016). The lake outlet is indicated by blue line and location of one-way barrier by red arrow. Location of water quality sampling and CTD cast is indicated by white triangle.

University of Waikato Animal Ethics Committee approved Standard Operating Procedures (SOPs) 6 (Euthanasia and anaesthesia of fish), 7 (Capture, handling, and captive maintenance of fish) and 8 (Marking and tagging of fish) were adhered to during this research (http://www.waikato.ac.nz/research-enterprise/ethics/animal-ethics/sops). During the marking phase, captured fish were anaesthetised with Aqui-S (Aqui-S New Zealand Ltd) before being weighed (± 1 g), measured (fork length or total length ± 1 mm) and then marked. Koi carp, goldfish and koi carp-goldfish hybrids were marked by hole-punching of the first dorsal spine, catfish were marked by removal of the adipose fin and eels and rudd by clipping of the left pectoral fin. Following marking, fish were placed in continuously aerated recovery tanks and allowed to regain equilibrium before being released back to the lake. Invasive fish caught during the recapture phase were examined for marks, weighed, measured, and then euthanised with an overdose of anaesthetic. Eels were also weighed, measured, and examined for fin clips before being released into holding nets in the lake. Following the end of the study, eels were released from the holding nets back into the lake.

## 2.3 Water quality sampling

Water quality sampling was conducted on three occasions 21 November 2016, 7 December 2016 and 20 January 2017 at the deepest point (3.5 m) of the lake that could be found (Figure 3). Water sampling included conductivity, temperature and depth (CTD) profiles (SBE 19 plus SEACAT Profiler, Seabird Electronics Inc, USA), measurements of Secchi depth, surface (0.5 m) suspended solids, surface and bottom (3 m) nutrient concentrations, chlorophyll *a* concentrations, and zooplankton and phytoplankton samples. Total suspended solids (TSS) were determined by filtering (Advantec GC 50 filters) drying for 12 h at 100°C followed by gravimetric determination. Samples were then combusted at 550°C for 1 h and inorganic suspended solids (ISS) determined by gravimetric analysis. Volatile suspended solids (VSS) were determined as the difference between TSS and ISS. Nutrient and plankton samples were retrieved using a 10-L Schindler trap. Nutrient concentrations (total nitrogen, total phosphorus, nitrate, nitrite, ammonium and dissolved reactive phosphorus) were analysed using a Flow Injection analyser 8500 Series II. Phosphate was analysed using LACHAT QuickChem method 31-115-01-1-H; ammonium was analysed using LACHAT QuickChem method 31-107-06-1-B and LACHAT QuickChem Method 31-107-04-1-A was used to analyse nitrate/nitrite. Concentrations of chlorophyll *a* were determined by fluorometric analysis following maceration and extraction with 90% buffered acetone.

Unfiltered 400-mL phytoplankton samples were preserved with Lugol’s iodine and zooplankton were collected by filtering 10 L of lake water through a 40-µm net and subsequent preservation in 70% ethanol. Phytoplankton analyses were carried out using Utermöhl settling chambers (Utermöhl, 1958) and an inverted microscope (Olympus, Ix71, Japan). Phytoplankton was identified to genus level, and abundance was determined for each genus. Enumeration of phytoplankton density (cells/mL) used methods adapted from Hötzel & Croome (1999) and US Environmental Protection Agency (2007). A 10-mL subsample was settled in an Utermöhl chamber for 12-24 h and enumerated to genus level through microscopy. Phytoplankton were counted at 4009 or 2009 magnification in a single transect, including at least 100 planktonic units (cells, colonies and filaments) of the dominant species. Zooplankton were identified and enumerated by passing samples through a 40-µm mesh to remove ethanol and to attain a final known volume, dependent on the density of algae. Samples were enumerated in 5 mL aliquots in a gridded Perspex tray until counts of at least 300 cells were obtained, or the entire sample was enumerated. Species were identified using standard guides (e.g. Chapman & Lewis, 1976; Shiel 1995).

The vertical light attenuation coefficient of down-welling irradiance, *Kd*, was calculated from PAR data collected during CTD casts using the modified version of Beer’s Law:

$$Kd = \frac{[\ln\left(\frac{Ez1}{Ez2}\right)]}{Z}$$

eqn 1.

where *Ez*1 is the down-welling irradiance at depth *z*1, *Ez*2 the down-welling irradiance at depth *z*2 and *Z* the vertical interval between the measured layers.

## 2.4 Data analysis

Because our data has only a single recapture for each year model selection is limited to a few simple options for population estimates. We used the code provided in the R statistical package Fish Stock Assessment (Ogle 2016) and Chapman’s (1951) version of a two-sample Lincoln–Petersen capture-recapture model to estimate fish abundance in Lake Ohinewai on four occasions between 2011 and 2016 (Appendix 2). The simplest and most common capture-recapture study occurs when fish are collected from a closed population and *M* fish are marked (with either a batch or individual-mark) and returned to the population. After allowing time for mixing of marked and unmarked fish a subsequent sample is taken and the total number of fish (*C*) and the number of previously seen or marked fish (*R*) in the second sample are recorded. Under the assumptions listed below, the ratio of *M* to the unknown total population size $\widehat{N}$ is equal to the ratio of *R* to *C* (Pine et al. 2012). Equating the two ratios produces the standard Lincoln–Petersen estimator:

$$\hat{N} = \frac{MC}{R}$$ eqn 2.

The simple Lincoln-Petersen estimate (eqn 2) is biased for small samples. However,

$$\hat{N} = \frac{(M+1)(C+1)}{(R+1)} - 1$$ eqn 3.

is an unbiased estimator of *N* when (M+C) ≥ $\widehat{N}$ (Chapman 1951), or is nearly unbiased when $R > 7$ (Chapman 1951; Krebs 1999; Ogle 2015). Ogle (2015) substituted *n* for *C* and *m* for *R* in an otherwise identical equation. The estimated variance of $\widehat{N}$ is

$$\hat{\mathrm{var}}\,\hat{N} = \frac{(M+1)(C+1)(M-R)(C-R)}{(R+1)^2(R+2)}$$ eqn 4.

Ricker (1975) regards the −1 in eqn 3 as of no practical significance, which is true for most population estimates of > 20 fish, and reformulated eqn 3 as

$$\hat{N} = \frac{(M+1)(C+1)}{(R+1)}$$ eqn 5.

We used eqn 3, retaining the −1, as some fish population estimates were small but fish mean weights were large (e.g., for koi carp-goldfish hybrids).

Valid application of Lincoln-Petersen population estimates and related modifications depends on six assumptions being met (Seber 2002; Hayes et al. 2007; Pine et al. 2012; Ogle 2015):

1. One or more marked fish are recaptured.
2. The population is closed both physically (i.e., no immigration or emigration) and demographically (i.e., no recruitment or mortality).
3. Marked fish that are returned to the population mix randomly with unmarked fish.
4. All fish within a sample have an equal probability of capture.
5. Fish behaviour or vulnerability does not change after being marked.
6. Marks or tags in recaptured fish are neither lost nor missed.

The most important of these assumptions is that some marked fish are recaptured and that the population is closed during the study. The consequence of assumption 1 not being met is that the population estimate fails. If any other assumptions are not met the population estimates will be unreliable. We believe that assumption 2 was met because Lake Ohinewai has a single small outlet and few surface inflows; combined with the 10-day interval between the marking and recapture phases, it is unlikely that migration, death or recruitment would have been substantial enough to influence the results. Assumptions 3 to 6 are difficult to test, but some marked fish were recaptured during the marking phase, showing that they were highly mobile, so the criterion of full mixing appears to have been fulfilled. The use of multiple fish capture methods (boat electrofishing and fyke nets) reduces the chance of assumption 4 failing, i.e., that there was unequal probability of capture within a species. Careful examination of all fish caught in the recapture phase validated assumption 6 in our opinion, and because of the marking methods used, marks could not be lost, e.g., by tag shedding. The fishing methods employed are biased against smaller fish, so our estimates are valid for fish > 100 mm in length.

Confidence intervals for $\hat{N}$ have been approximated from various distributions depending on characteristics of the data. Seber (2002) suggested that if more than 10% of fish in the second sample are recaptured fish (i.e., $R/C > 0.10$), then a binomial distribution should be used. Otherwise, if $R < 50$, then a Poisson distribution should be used, or if $R > 50$, then a normal distribution should be used. The *R* statistical code in the FSA package (Ogle 2016) selects the appropriate distribution based on R in the sample.

For a satisfactory population estimate from the Lincoln–Petersen model, the product of *M* and *C* should exceed four times the estimated population abundance, i.e., $MC > 4\hat{N}$. Also, multiple gears should be used for marking and recapture to reduce potential gear selectivity effects, which our sampling methods achieved, and seven or more recaptures (*R*) should be made (Robson and Regier 1964; Ricker 1975).

# 3 Results

## 3.1 Fish abundance and biomass

A total of 1680 fish were caught in the marking phase (21–24 November 2016) and 2058 fish in the recapture phase (5–8 December 2016) of these 479 were marked. Six fish species (koi carp, rudd, goldfish, catfish, shortfin eel and longfin eel) and one hybrid species (koi carp x goldfish) were included in the study, gambusia (*Gambusia affinis*) and common bully (*Gobiomorphus cotidianus*) were observed but not enumerated.

The abundance of koi carp declined in abundance from 8548 (5863 to 12937, 95% confidence limits) in January 2011 to 454 fish (251 to 889, 95% CL) in 2014 (Figure 4). By 2016, however, the number of koi carp had increased to 2063 (1070 to 4328, 95% CL) despite the continued operation of the one-way gate. Catfish and goldfish, which also declined in abundance by 2014 as a result of selective fishing, had increased in 2016 to 4010 catfish (2641 to 6373, 95% CL) and 1927 goldfish (1093 to 3659, 95% CL). Shortfin eels increased in abundance from 2305 in 2014 (2135 to 2497, 95% CL) to 3456 in 2016 (3186 to 3760, 95% CL) and the number of longfin eels also increased from 44 in 2014 (35 to 62, 95% CL) to 100 in 2016 (85 to 126 95% CL). Complete input statistics and population estimates using the Lincoln-Petersen model and the model distributions used in calculating confidence intervals are presented in Appendix 3.

Calculation of areal biomass depends on an estimate of the number of fish present multiplied by the mean weight of those fish. Comparison between years of the mean weights of fish caught during previous mark-recapture studies indicate that catfish weights have remained relatively constant while koi carp and koi carp hybrids have fluctuated reaching minima in 2012 and 2014 respectively, before increasing again in 2016 (Table 1). The mean weight of shortfin eels shows some indication of increase, however, no clear direction can be determined for rudd and longfin eels due to their low abundance. ANOVA tests for differences in mean weights between mark-recapture studies was conducted, with significant differences ($P<0.05$) for koi carp, catfish, goldfish and shortfin eels; a summary of the statistical analysis is presented in Appendix 4.

**Table 1.** Arithmetic mean weight of fish caught in Lake Ohinewai during the mark and recapture phases of four mark-recapture studies conducted between January 2011 and December 2016. Note that the number of captured fish are not directly comparable between studies due to differences in fishing effort.

| Sampling period | Mean weight (g) (*N in italics*) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Koi carp | | Catfish | | Goldfish | | Koi-goldfish hybrid | | Rudd | | Shortfin eel | | Longfin eel | |
| 17-28 Jan 2011 | 605 | *1464* | 128 | *797* | 250 | *421* | 623 | *6* | 200 | *37* | 172 | *800* | 362 | *18* |
| 17 Nov 2011-20 Jan 2012 | 468 | *86* | 151 | *288* | 144 | *132* | 739 | *20* | 244 | *6* | 141 | *1013* | 211 | *23* |
| 18 Nov-4 Dec 2014 | 505 | *134* | 181 | *333* | 121 | *214* | 571 | *22* | 116 | *2* | 186 | *1571* | 781 | *41* |
| 22 Nov-8 Dec 2016 | 763 | *316* | 153 | *646* | 125 | *327* | 743 | *70* | 207 | *20* | 197 | *2006* | 312 | *85* |

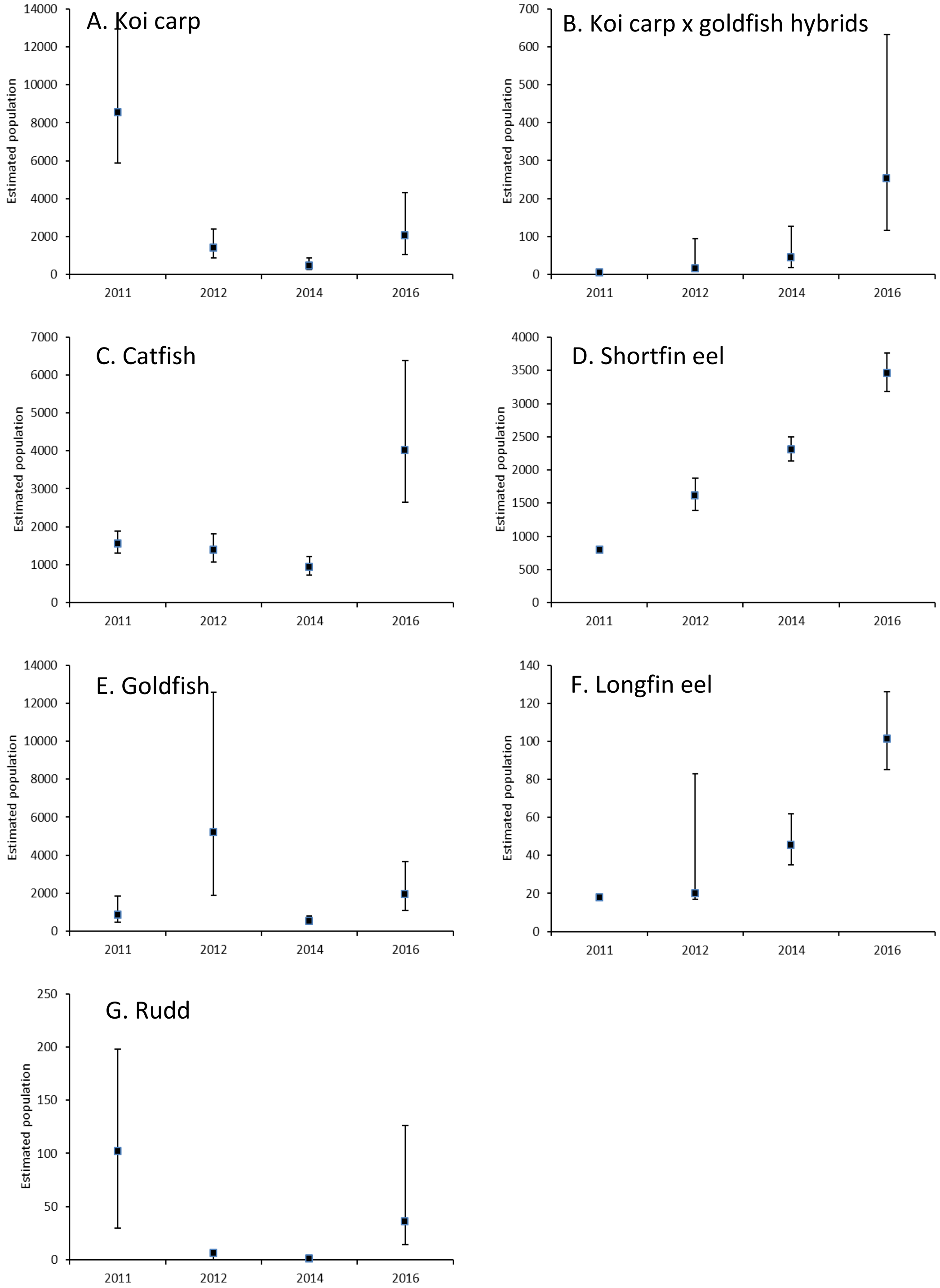



**Figure 4.** Two-sample capture-recapture fish population estimates in Lake Ohinewai from 2011 to 2016 ± 95% confidence limits. A. koi carp, B. koi carp x goldfish hybrids, C. catfish, D. shortfin eel, E. goldfish, F. longfin eel, G. rudd. Lincoln-Petersen model population estimates from the Chapman (1951) equation and Ricker-adjusted error distributions shown; full data presented in Appendix 3. Eel abundances in 2011 are actual catches as no recapture were made.

Changes in total and areal fish community biomass were primarily influenced by the removal of invasive species and the effect of the one-way barrier (Table 2). Between the end of January 2011 and June 2011 ca. 3 tonnes of invasive fish were removed from Lake Ohinewai by fishing, accounting for approximately 75% (178 kg/ha) of the decline in invasive species biomass between January 2011 and January 2012. The remaining 25% (59 kg/ha) may be attributed to either population loss through the one-way barrier or precision of population estimates. A further 505 kg (30 kg/ha) of invasive fish biomass was actively removed between January 2012 and December 2014, accounting for 43% of the decline in invasive fish biomass over this time. Invasive species were at their lowest abundance in 2014 (51% of total fish biomass), but had increased to 79% of total fish biomass by 2016.

**Table 2.** Estimated total and areal biomasses of invasive fish (koi carp, catfish, goldfish, koi carp x goldfish hybrids and rudd) and eels (longfin and shortfin eels) in Lake Ohinewai in four capture-recapture occasions between 2011 and 2016.

| | Total | | Invasive | | | Eels | | |
|---|---|---|---|---|---|---|---|---|
| Sampling period | Biomass (kg) | Areal biomass (kg/ha) | Biomass (kg) | Proportion of total biomass | Areal biomass (kg/ha) | Biomass (kg) | Proportion of total biomass | Areal biomass (kg/ha) |
| 17-28 Jan 2011 | 5756 | 343 | 5612 | 0.97 | 334 | 145 | 0.03 | 9 |
| 17 Nov 2011-20 Jan 2012 | 1864 | 111 | 1633 | 0.88 | 97 | 231 | 0.12 | 14 |
| 18 Nov-4 Dec 2014 | 948 | 56 | 484 | 0.51 | 28 | 464 | 0.49 | 28 |
| 22 Nov-8 Dec 2016 | 3337 | 199 | 2623 | 0.79 | 157 | 714 | 0.21 | 43 |

From 2011 to 2016 the percentage contribution to total invasive fish biomass by individual species changed, with catfish, goldfish and koi carp hybrids all making larger contributions to total invasive fish biomass (Table 3). The percentage contribution of koi carp to the total invasive fish biomass declined from 90% in 2011 to 24% in 2014 before increasing again to 46% in 2016 as population abundance increased. Shortfin eel biomass increased in association with increasing abundance; however, the percentage contribution to total fish biomass decreased from 45% in 2014 to 20% in 2016 as invasive fish biomass increased during this period. The proportional contributions of longfin eel and rudd populations to total biomass in the lake have remained relatively unchanged.

We have made population estimates for rudd and koi carp-goldfish hybrids but suggest caution in comparing these population estimates with other results because of the failure of the estimate to meet the criterion that $MC > 4\widehat{N}$. The wide confidence limits also show the limits of reliability of these estimates. We could omit these results entirely, but they are informative about the limits of the technique in a mixed species fish community where not all species are equally abundant or equally caught by the range of capture techniques used. Low abundance of rudd, koi carp-goldfish hybrids and longfin eels most likely limit the recapture rates for these species and hence the reliability of some of the population estimates (Table 3).

**Table 3.** Lake Ohinewai biomass estimates calculated from Lincoln-Petersen fish population estimates from 2011 to 2016 (± 95% confidence limits). * indicates population estimate product of *M* and *C* did not exceed four times the estimated population abundance therefore estimate should be treated with caution or there were no recaptures so the population estimate failed.

| Species and date | Mean fish weight (g) | Total biomass (kg) | Areal biomass (kg/ha) | Errors for areal biomass estimate (kg/ha) | |
|---|---|---|---|---|---|
| | | | | Lower 95% CL | Upper 95% CL |
| **Koi carp** | | | | | |
| 17-28 Jan 2011 | 605 | 5170 | 307.7 | 211.1 | 465.7 |
| 17 Nov 2011-20 Jan 2012 | 468 | 659 | 39.3 | 24.4 | 66.9 |
| 18 Nov-4 Dec 2014 | 505 | 229 | 13.7 | 7.5 | 26.7 |
| 22 Nov-8 Dec 2016 | 763 | 1574 | 93.7 | 48.6 | 196.6 |
| **Catfish** | | | | | |
| 17-28 Jan 2011 | 128 | 200 | 11.9 | 9.9 | 14.3 |
| 17 Nov 2011-20 Jan 2012 | 151 | 210 | 12.5 | 9.7 | 16.3 |
| 18 Nov-4 Dec 2014 | 181 | 168 | 10.0 | 7.8 | 13.0 |
| 22 Nov-8 Dec 2016 | 153 | 613 | 36.5 | 24.0 | 58.0 |
| **Goldfish** | | | | | |
| 17-28 Jan 2011 | 250 | 219 | 13.1 | 6.8 | 27.4 |
| 17 Nov 2011-20 Jan 2012* | 144 | 751 | 44.7 | 16.3 | 107.9 |
| 18 Nov-4 Dec 2014 | 121 | 62 | 3.7 | 2.5 | 5.6 |
| 22 Nov-8 Dec 2016 | 125 | 240 | 14.3 | 8.1 | 27.2 |
| **Koi carp-goldfish hybrid** | | | | | |
| 17-28 Jan 2011* | 623 | 3 | 0.2 | 0.1 | 0.4 |
| 17 Nov 2011-20 Jan 2012* | 739 | 11 | 0.7 | 0.8 | 4.2 |
| 18 Nov-4 Dec 2014* | 571 | 25 | 1.5 | 0.6 | 4.3 |
| 22 Nov-8 Dec 2016* | 743 | 188 | 11.2 | 5.1 | 28.0 |
| **Longfin eel** | | | | | |
| 17-28 Jan 2011* | 362 | 7 | 0.4 | - | - |
| 17 Nov 2011-20 Jan 2012* | 211 | 4 | 0.3 | 0.2 | 1.0 |
| 18 Nov-4 Dec 2014 | 781 | 35 | 2.1 | 1.6 | 2.9 |
| 22 Nov-8 Dec 2016 | 312 | 32 | 1.9 | 1.6 | 2.3 |
| **Rudd** | | | | | |
| 17-28 Jan 2011* | 200 | 20 | 1.2 | 0.4 | 2.4 |
| 17 Nov 2011-20 Jan 2012* | 244 | 1 | 0.1 | 0.0 | 0.1 |
| 18 Nov-4 Dec 2014* | 116 | 0.1 | 0.0 | 0.0 | 0.0 |
| 22 Nov-8 Dec 2016 | 207 | 7 | 0.4 | 0.2 | 1.6 |
| **Shortfin eel** | | | | | |
| 17-28 Jan 2011* | 172 | 138 | 8.2 | - | - |
| 17 Nov 2011-20 Jan 2012 | 141 | 227 | 13.5 | 11.7 | 15.8 |
| 18 Nov-4 Dec 2014 | 186 | 429 | 25.5 | 23.6 | 27.6 |
| 22 Nov-8 Dec 2016 | 197 | 682 | 40.6 | 37.4 | 44.1 |

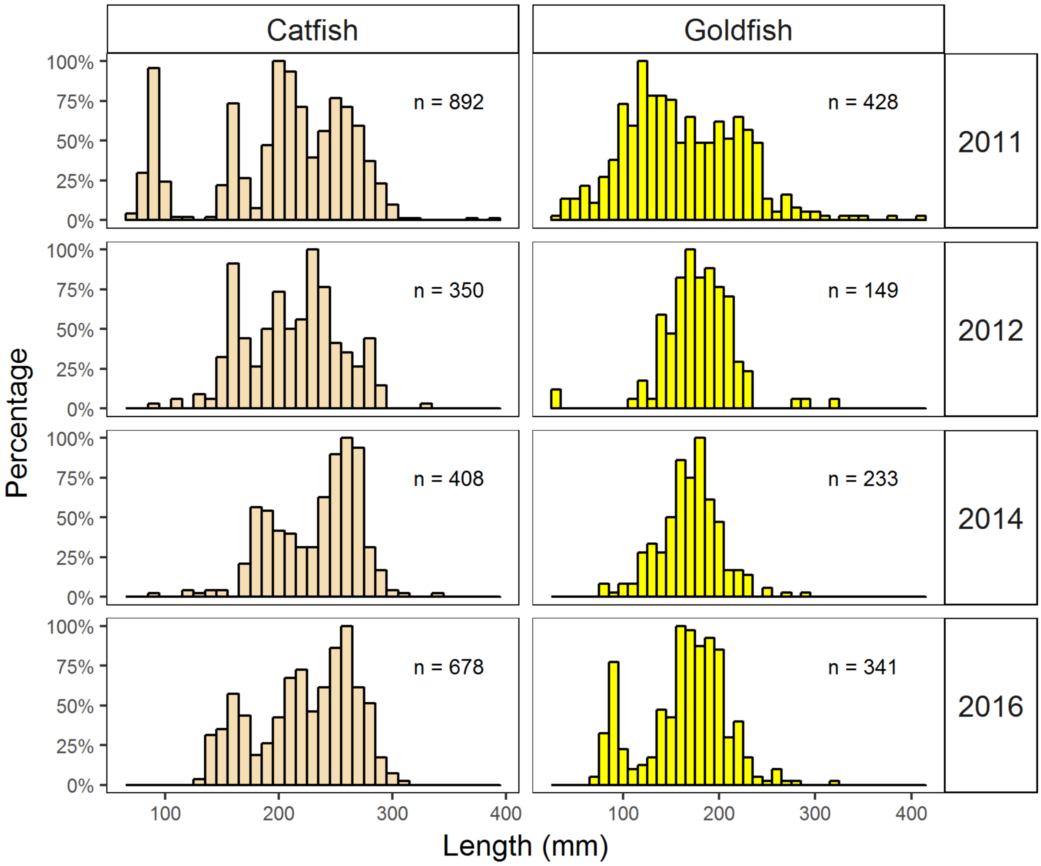
## 3.2 Population size structure

Notable changes in the population structure of koi carp, catfish, goldfish, longfin eel and shortfin eel occurred between 2011 and 2016 (Figure 5). In 2011 and 2012, koi carp, catfish and goldfish populations had greater proportions of smaller fish (i.e., catfish and goldfish <200 mm; koi carp <275 mm) compared to 2016. However, by 2016 the population structure had changed, with larger fish (catfish and goldfish >250 mm; koi carp >325 mm) becoming more prevalent. Changes in the rudd population are also evident between 2011 and 2016 with a shift to a greater proportion of larger (>250 mm) fish in 2016 compared to 2011 (Figure 5). However, these data should be treated cautiously as too few rudd, koi carp-goldfish hybrids and longfin eels were caught in some years to make statistically meaningful comparisons (Appendix 4).

While there is some bias due to sampling techniques, size selectivity effects of the removal methods can be observed in the koi carp population, with a decline in the proportion of fish >275 mm between pre-removal (2011) and the follow up study in 2012 (Figure 5). Some recovery of the population size structure can be seen in the 2014 survey data with a bi-modal distribution apparent. However this has not translated through to the 2016 data which appears comparatively depauperate in smaller juvenile fish.

In 2011, the catfish population exhibited four size classes that were not apparent in later years, which were more bimodal and skewed towards larger fish due to the fishing methods employed. Otherwise, there appears to have been little change in population structure following the fish removal programme and installation of the one-way barrier with two exceptions. The goldfish population structure showed a pulse of recruitment in 2016, with increased relative abundance of fish in the 76–100 mm FL range, indicating a successful spawning in the spring of 2015 (Figure 5A). Shortfin eels similarly showed a pulse in eel recruitment <160 mm TL (Figure 5B). Small increases in the proportion of shortfin eels >400 mm are apparent from the 2014 and 2016 data compared to 2011 and 2012. Changes in the population structure of longfin eels are less well defined due to the smaller number of individuals, but there was an increased proportion of smaller eels in 2012 following carp removal. The abundance of longfin eels 300–500 mm TL increased progressively in 2014 and 2016 as overall numbers of longfin eels increased (Figure 5C).

A. Catfish and goldfish




B. Koi carp and shortfin eels

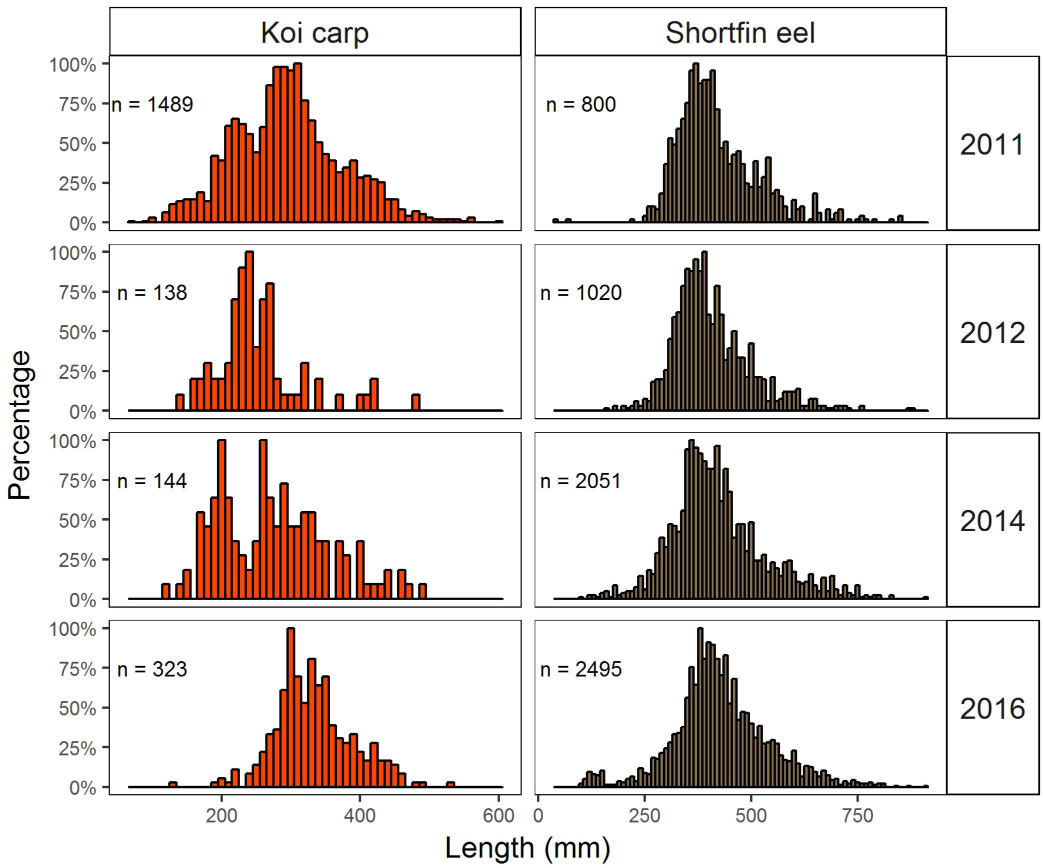



**Figure 5.**Changes in population structure of A. catfish and goldfish and B. koi carp and shortfin eels from Lake Ohinewai from four population surveys conducted from 2011 to 2016. Note: data for rudd and koi carp x goldfish hybrids are not presented due to low sample size.

C. Longfin eels

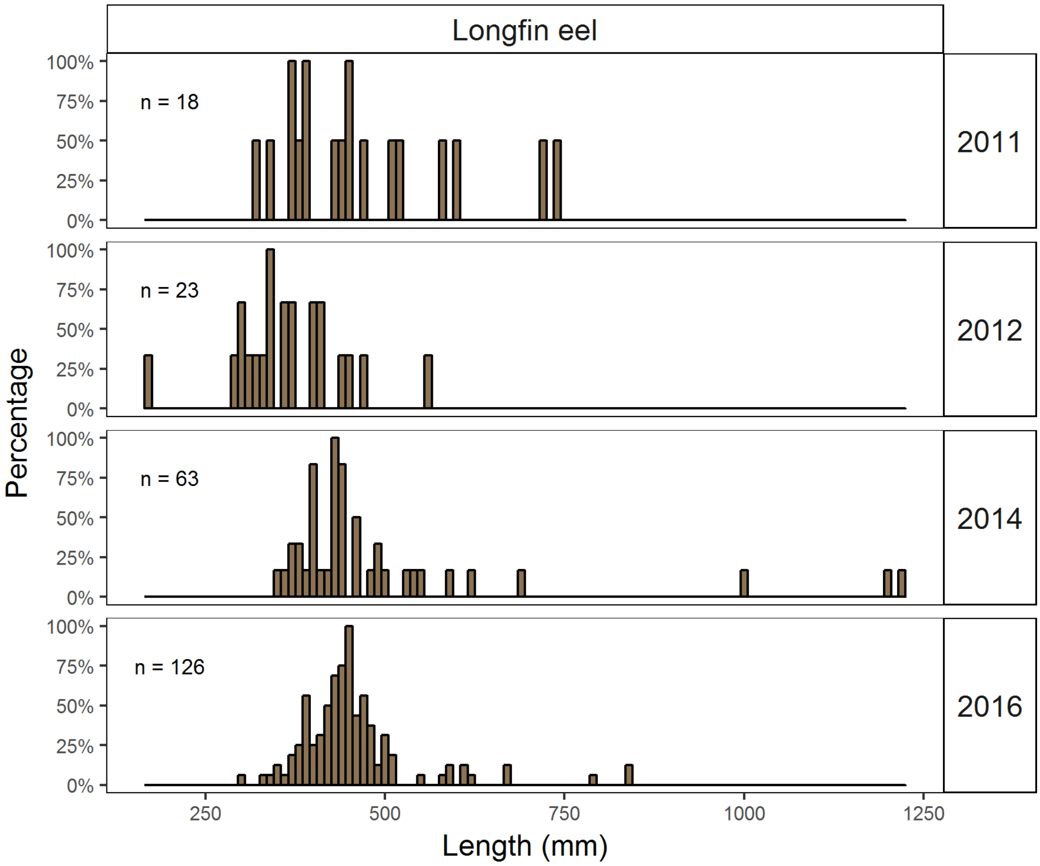



**Figure 5(continued).** Changes in population structure of C. longfin eels from Lake Ohinewai from four population surveys conducted from 2011 to 2016. Note: data for rudd and koi carp x goldfish hybrids are not presented due to low sample size.

# 3.3 Water quality

Secchi depth, chlorophyll *a* concentration, suspended solids and nutrient concentrations were sampled on three occasions between November 2016 and January 2017 (Figure 4). Windy conditions during the days prior to sampling in November and January are likely to have prevented lake stratification that was seen in December and possibly caused wind driven resuspension that resulted increased total suspended solids (TSS) in January. This is reflected in the notably high TSS concentrations and reduced Secchi depth. Also of interest is the comparatively large percentage of organic matter as TSS (mean 87.6%) in relation to inorganic material (12.3%). Surface water (0.5 m) total phosphorus (TP) and total nitrogen (TN) concentrations for 21 January are not available due to sample loss during storage.

Water temperature, dissolved oxygen and conductivity profiles from CTD casts indicate Lake Ohinewai was fully mixed on 21 November, strongly stratified on 7 December and fully mixed again on 20 January (Figure 6). Stratification on 7 December resulted in strongly anoxic conditions forming in the hypolimnion from ca. 2 m depth. Fluorescence profiles indicate uniform vertical distributions in phytoplankton abundance on these dates. Light attenuation ($k_d$) was 6.18 $m^{-1}$ on 21 November and 5.81 $m^{-1}$ on 7 December, mean $k_d$ of the two values was 6.0 $m^{-1}$ ($k_d$ for 20 January was not valid due to low coefficient of determination), euphotic zone depth was 1.37 m.

**Table 4**. Water quality measures taken between November 2016 and January 2017 including Secchi depth, chlorophyll *a* (Chl *a*), total suspended solids (TSS) volatile suspended solids (VSS), inorganic suspended solids (ISS), total phosphorus (TP), dissolved reactive phosphorus (DRP), total nitrogen (TN), nitrate ($NO_3$), nitrite ($NO_2$) and ammonium ($NH_4$). Note: 20 January TP and TN concentrations at 0.5 m depth are not available (N/A) due to sample loss during storage.

| Sampling Date | Sample depth (m) | Chl *a* ($g/m^3$) | Secchi (m) | TSS ($g/m^3$) | VSS ($g/m^3$) | ISS ($g/m^3$) | TP ($g/m^3$) | DRP ($g/m^3$) | TN ($g/m^3$) | $NO_3$ ($g/m^3$) | $NO_2$ ($g/m^3$) | $NH_4$ ($g/m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 21/11/2016 | 0.5 | 0.138 | 0.42 | 25.33 | 20.41 | 4.92 | 0.093 | <0.006 | 1.752 | 0.008 | 0.012 | 0.036 |
| | 3 | 0.154 | | | | | 0.081 | <0.006 | 1.693 | 0.009 | 0.010 | 0.035 |
| 7/12/2016 | 0.5 | 0.043 | 0.49 | 28.00 | 25.81 | 2.19 | 0.107 | <0.006 | 1.809 | 0.007 | 0.013 | 0.041 |
| | 3 | 0.068 | | | | | 0.102 | <0.006 | 1.749 | 0.007 | 0.012 | 0.038 |
| 20/01/2017 | 0.5 | 0.168 | 0.32 | 43.43 | 38.56 | 4.87 | N/A | <0.006 | N/A | 0.011 | 0.011 | 0.048 |
| | 3 | 0.232 | | | | | 0.105 | <0.006 | 1.769 | 0.013 | 0.011 | 0.046 |

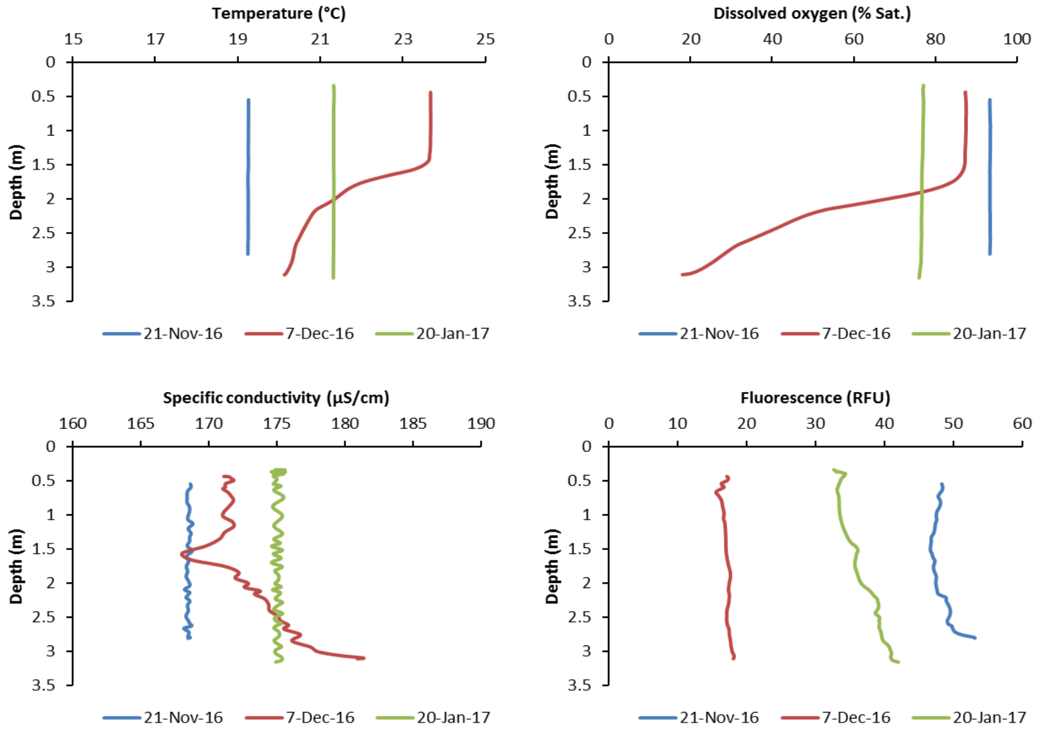



**Figure 6.** Water temperature, dissolved oxygen conductivity and fluorescence profiles of Lake Ohinewai taken on 21 November 2016, 7 December 2016 and 20 January 2017.

Annual means for Lake Ohinewai water quality data collected by the Waikato Regional Council and the University of Waikato showed no substantial improvements following the reduction in invasive fish biomass after 2011 for Secchi depth, total suspended solids, and volatile suspended solids. Total nitrogen concentrations appeared to be declining from 2009 to 2013, before fish removal, but the decline in chlorophyll *a* concentrations from 0.085 to 0.040 $g/m^3$ between 2011 and 2014 was coincident with a reduction in invasive fish biomass from 334 to 28 kg/ha (Figure 7). The subsequent increase of invasive fish biomass, estimated in 2016 as 157 kg/ha, was accompanied by an increase in mean annual chlorophyll *a* concentration to 90 $g/m^3$. Mean TLI3, which excludes Secchi depth (Burns et al. 1999), ranged from 6.1 to 6.6, so the lake remained hypereutrophic with low water clarity likely to inhibit re-establishment of submerged macrophytes.

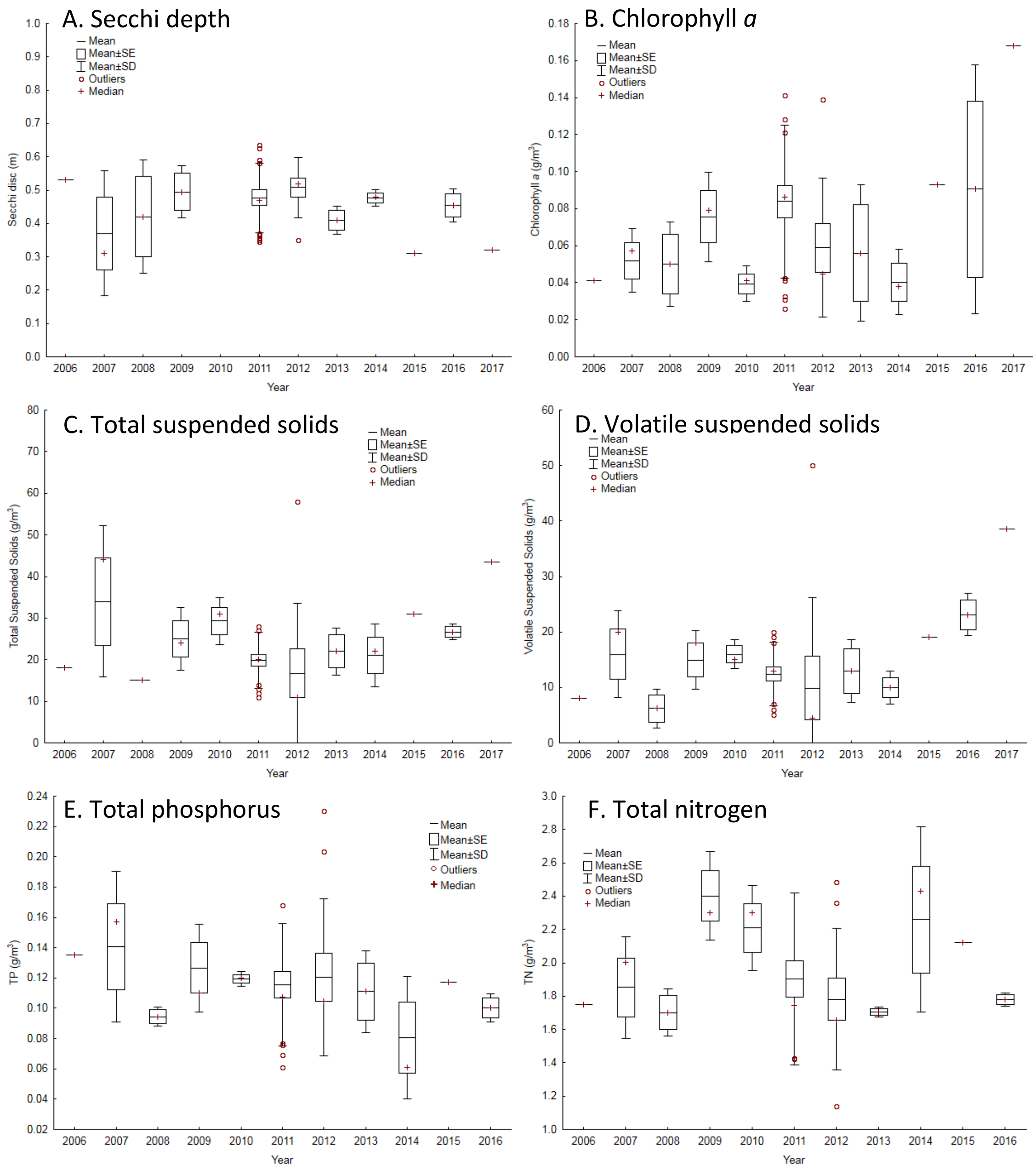



**Figure 7.** Trends in annual data for A. Secchi depth, B. Chlorophyll a, C. Total suspended solids, D. Volatile suspended solids, E. Total phosphorus (TP) and F. Total nitrogen (TN) in Lake Ohinewai from 2006 to January 2017 (no TN and TP data for 2017) collected by Waikato Regional Council and the University of Waikato. Note: Invasive fish removal programme was conducted from January 2011 to December 2016; a one-way barrier was installed on Lake Ohinewai outlet in May 2011.

## 3.4 Plankton communities

The rotifer species *Trichocerca pusilla* and *Filinia novaezealandiae* were the most common species observed across all three sampling dates (Table 5). *Polyarthra dolichoptera* and *Brachionus calyciflorus* were transiently abundant on 7 December but otherwise uncommon. Copepod abundance was generally low until 20 January when the copepod nauplii abundance increased and small increases in *Boekella delicata* and *Mesocyclops* sp. abundance were observed. Cladoceran species were abundant on all three sampling dates. Zooplankton distribution between epilimnion (0.5 m) and hypolimnion (3 m) corresponded with lake stratification, with little difference in abundance between depths on 21 November and 20 January when the lake was mixed in comparison to greater epilimnion abundance when the lake was stratified on 7 December (Table 5).

**Table 5**. Zooplankton abundance in Lake Ohinewai sampled from the epilimnion (0.5 m) and hypolimnion (3 m) on three dates between 21 November 2016 and 20 January 2017.

| | 21 November 2016 | | 7 December 2016 | | 20 January 2017 | |
|---|---|---|---|---|---|---|
| Number of individuals/L | Epilimnion (0.5 m) | Hypolimnion (3 m) | Epilimnion (0.5 m) | Hypolimnion (3 m) | Epilimnion (0.5 m) | Hypolimnion (3 m) |
| **Rotifers** | | | | | | |
| *Asplanchna brightwelli* | 1.0 | 1.0 | 3.0 | 3.0 | 0.0 | 0.0 |
| Bdelloid rotifers | 0.0 | 0.0 | 3.0 | 6.0 | 2.4 | 2.4 |
| *Brachionus calyciflorus* | 1.0 | 1.0 | 40.5 | 6.0 | 0.0 | 0.0 |
| *Collotheca* sp. | 0.0 | 2.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Filinia novaezealandiae* | 14.0 | 19.0 | 19.5 | 26.0 | 22.8 | 12.0 |
| *Hexarthra mira* | 4.0 | 1.0 | 3.0 | 3.0 | 3.6 | 1.2 |
| *Keratella cochlearis* | 0.0 | 1.0 | 1.5 | 16.0 | 3.6 | 6.0 |
| *Keratella tecta* | 0.0 | 0.0 | 0.0 | 0.0 | 2.4 | 1.2 |
| *Keratella tropica* | 1.0 | 0.0 | 0.0 | 115.0 | 2.4 | 3.6 |
| *Polyarthra dolichoptera* | 5.0 | 8.0 | 82.5 | 17.0 | 0.0 | 0.0 |
| *Pompholyx complanata* | 0.0 | 0.0 | 0.0 | 2.0 | 12.0 | 12.0 |
| *Trichocerca pusilla* | 110.0 | 96.0 | 22.5 | 6.0 | 152.4 | 124.8 |
| *Trichocerca similis* | 0.0 | 0.0 | 0.0 | 0.0 | 19.2 | 13.2 |
| Total Rotifers | 136.0 | 129.0 | 175.5 | 200.0 | 220.8 | 176.4 |
| **Copepods** | | | | | | |
| *Boekella delicata* | 4.0 | 3.0 | 3.0 | 9.0 | 9.6 | 16.8 |
| *Elaphoidella bidens* | 0.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Mesocyclops* sp. | 2.0 | 0.0 | 4.5 | 3.0 | 8.4 | 15.6 |
| Copepod nauplii | 4.0 | 7.0 | 4.5 | 39.0 | 66.0 | 56.4 |
| Total copepods | 10.0 | 11.0 | 12.0 | 51.0 | 84.0 | 88.8 |
| **Cladocerans** | | | | | | |
| *Bosmina meridionalis* | 133.0 | 123.0 | 310.5 | 127.0 | 111.6 | 104.4 |
| *Daphnia galeata* | 37.0 | 38.0 | 69.0 | 21.0 | 40.8 | 62.4 |
| Total cladocerans | 170.0 | 161.0 | 379.5 | 148.0 | 152.4 | 166.8 |
| **Total zooplankton** | 316.0 | 301.0 | 567.0 | 399.0 | 457.2 | 432.0 |

Phytoplankton abundance was highest in the epilimnion on 21 November (157,510 cells/mL) and had decreased 2 weeks later on 7 December and was significantly decreased to (20,043 cells/mL) in the epilimnion on 20 January. Phytoplankton community composition was dominated by cyanobacteria (Table 6) with *Microcystis* sp. the numerically dominant species in the epilimnion and *Worinichina* sp. dominant in the hypolimnion. Bacillariophyta (diatoms) were also relatively abundant on each sampling occasion with *Aulacoseira* sp. almost exclusively dominating this group. There was a notable peak in chlorophyte (green algae) and cryptophyte abundance in the epilimnion on 7 December with the chlorophytes *Botryococcus* sp. and *Coelastrum* sp. abundant in the epilimnion and the cryptophyte *Cryptomonas* sp. abundant in the hypolimnion along with the euglenoid *Trachelomonas* sp.

**Table 6.** Phytoplankton abundance in Lake Ohinewai sampled from the epilimnion (0.5 m) and hypolimnion (3 m) on three dates between 21 November 2016 and 20 January 2017.

| | 21 November 2016 | | 7 December 2016 | | 20 January 2017 | |
|---|---|---|---|---|---|---|
| | Epilimnion (0.5 m) | Hypolimnion (3 m) | Epilimnion (0.5 m) | Hypolimnion (3 m) | Epilimnion (0.5 m) | Hypolimnion (3 m) |
| Taxa | Cells/mL | Cells/mL | Cells/mL | Cells/mL | Cells/mL | Cells/mL |
| Chlorophyta | | | | | | |
| *Ankistrodesmus* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Botryococcus* sp. | 196.7 | 0.0 | 9441.2 | 0.0 | 983.5 | 15.0 |
| *Chlamydomonas* sp. | 0.0 | 0.0 | 0.0 | 19.7 | 39.3 | 0.0 |
| *Chlorella* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Closterium* sp. | 19.7 | 0.0 | 393.4 | 59.0 | 0.0 | 59.0 |
| *Coelastrum* sp. | 0.0 | 0.0 | 7867.7 | 629.4 | 216.4 | 0.0 |
| *Cosmarium* sp. | 0.0 | 0.0 | 0.0 | 157.4 | 0.0 | 0.0 |
| *Crucigenia* sp. | 0.0 | 236.0 | 1573.5 | 236.0 | 708.1 | 0.0 |
| *Dictyosphaerium* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Elakotothrix* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Eudorina* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Euglena* sp. | 0.0 | 19.7 | 0.0 | 0.0 | 0.0 | 19.7 |
| *Kirchneriella* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Monoraphidium* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Mougeotia* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Oocystis* sp. | 59.0 | 196.7 | 0.0 | 118.0 | 39.3 | 216.4 |
| *Pandorina* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Pediastrum* sp. | 0.0 | 0.0 | 0.0 | 137.7 | 0.0 | 137.7 |
| *Scenedesmus* sp. | 78.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Sphaerocystis* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Staurastrum* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Treubaria* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Ulothrix* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Euglenophyta | | | | | | |
| *Trachelomonas* sp. | 78.7 | 78.7 | 2557.0 | 59.0 | 236.0 | 609.7 |
| *Phacus* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cryptophyta | | | | | | |
| *Chroomonas* sp. | 0.0 | 59.0 | 0.0 | 196.7 | 0.0 | 59.0 |
| *Cryptomonas* sp. | 19.7 | 59.0 | 3737.1 | 0.0 | 59.0 | 59.0 |
| Chrysophyta | | | | | | |
| *Dinobryon* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Mallomonas* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 19.7 | 0.0 |
| *Synura* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Bacillariophyta | | | | | | |
| *Acanthoceras* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Amphora* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Asterionella* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Aulacoseira* sp. | 5546.7 | 4523.9 | 1966.9 | 236.0 | 3088.1 | 5664.7 |
| *Cyclotella* sp. | 59.0 | 19.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Epithemia* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Fragilaria* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Gomphonema* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 19.7 |
| *Navicula* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Nitzschia* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Melosira* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Synedra* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Tabellaria* sp | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Dinoflagellates | | | | | | |
| *Ceratium* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Peridinium* sp. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cyanobacteria | | | | | | |
| *Worinichina* sp | 0.0 | 511.4 | 63137.9 | 413.1 | 2852.0 | 1888.2 |
| *Chroococcus* sp. | 0.0 | 2065.3 | 4327.2 | 0.0 | 0.0 | 0.0 |
| *Microcystis* sp. | 151452.3 | 0.0 | 20849.3 | 334.4 | 11801.5 | 25530.5 |
| *Oscillatoria sp.* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *Pseudanabaena limnetica* | 0.0 | 0.0 | 1180.1 | 0.0 | 0.0 | 0.0 |

# 4 Discussion

The abundance and biomass of invasive fish and native eels in Lake Ohinewai were determined by mark-recapture in December 2016, >5 years after the installation of a one-way barrier on the lake's outlet. Population estimates were compared to previous mark-recapture estimates carried out prior to a large-scale invasive fish removal operation and installation of a one-way barrier on the lake's outlet (2011), and in the years following barrier installation (2012 and 2014). Also of interest were changes in the composition of the fish community and water quality following the 96% decrease in koi carp biomass between 2011 and 2014. The biomass of shortfin eels responded strongly to the removal of koi carp, but so did catfish (Figure 8). Though longfin eels remained at low abundance they probably also increased in abundance between 2012 and 2014.

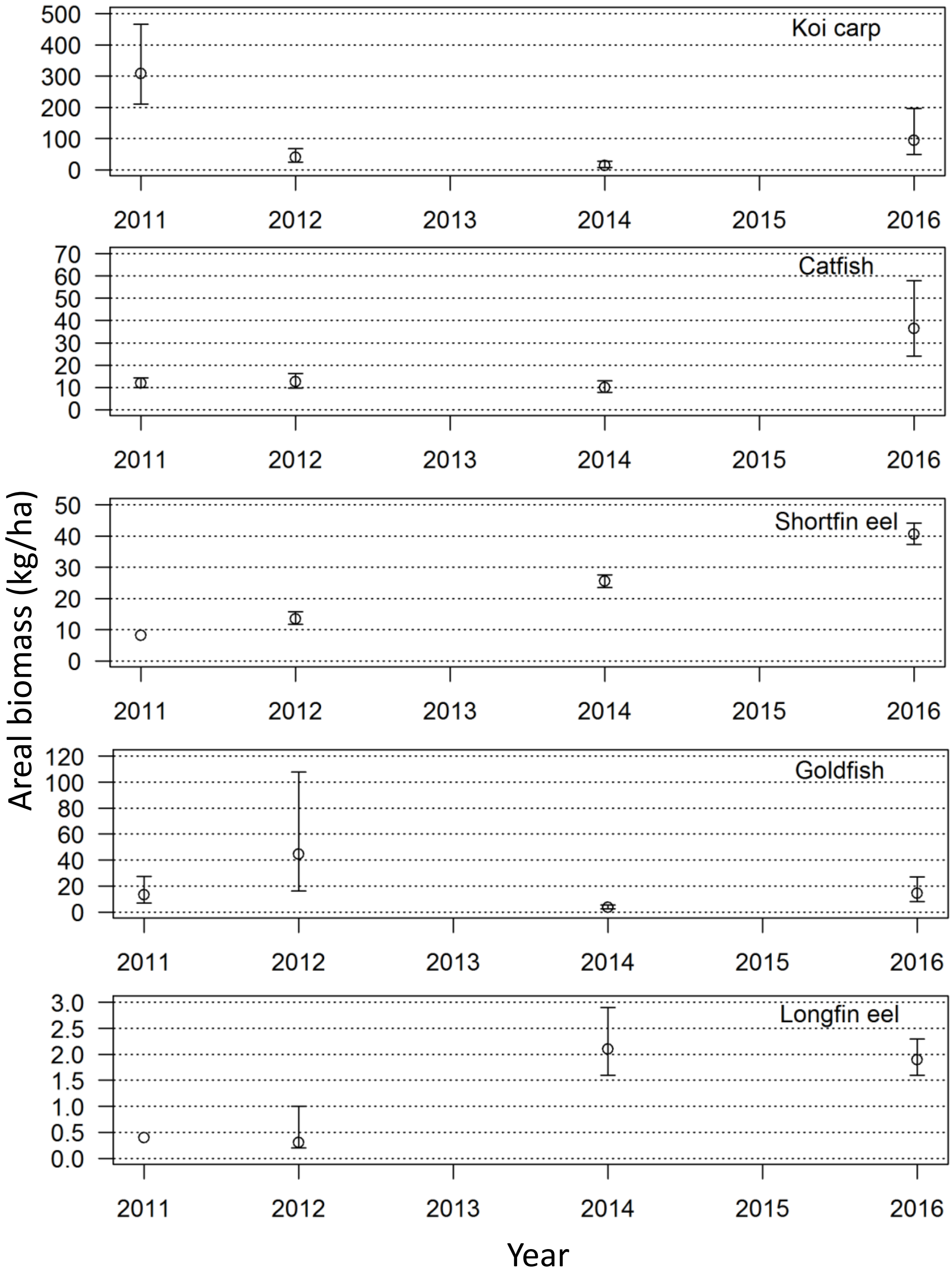



**Figure 8.** Estimated areal biomasses of koi carp, catfish, shortfin eels, goldfish, and longfin eels in Lake Ohinewai between 2011 and 2016. Vertical bars are 95% confidence intervals. Eel biomasses in 2011 are actual catches as no recaptures were made.

## 4.1 Fish population dynamics

Estimates of koi carp abundance indicate a decline from 8548 fish (5863–12937, 95% CL) in January 2011 to 454 fish (251–889, 95% CL) in 2014. Smaller but notable declines in abundance were also observed in the catfish and goldfish populations over the same period (Figure 4). Active fishing accounted for ca. 75% of the biomass reduction in the first year (2011-12) and 43% of the biomass decline from 2012–14. However, the most recent assessment of the population has seen an increase in population size and biomass from 14 kg/ha (8–27, 95% CL) in 2014 to 94 kg/ha (49–197, 95% CL) in 2016 (Figure 8). The current koi carp population size and biomass remains below the pre-removal estimate of 308 kg/ha (211–466, 95% CL), although the large 95% confidence limits indicate the relative imprecision of the population estimates. Low recapture rates of marked koi carp (2-9%; Appendix 3) caused these imprecise estimates. Recapture rates were also low for rudd, goldfish and koi carp-goldfish hybrids, but were generally higher for catfish (6-27%), and shortfin eels (28-34%). While it was not possible to test the five principal assumptions of mark-recapture we assume that the most important, that the populations were closed, was fulfilled for the duration of each mark-recapture estimate. This was because of the short duration between marking and recapture, the seasonal timing when adult fish migration is minimal, and the single outlet for the lake. Several estimates failed because no marked fish were recaptured. In the case of eels in 2011, high water temperatures (>22°C) would have caused eel mortalities so eels were not recaptured. Another important criterion for satisfactory population estimates from the Lincoln–Petersen model is that the product of $M$ and $C$ should exceed four times the estimated population abundance, i.e., $MC > 4\widehat{N}$. Our estimates for koi carp, catfish, goldfish and shortfin eels usually met this criterion, but estimates for rudd and koi carp-goldfish hybrids generally did not because of low recapture rates (Appendix 3). Goldfish failed to meet this criterion in 2012 when only 2 fish were recaptured out of 122 fish originally marked. Nevertheless, these are the best estimates that we have for these species.

Changes in koi carp size frequency suggest that the one-way barrier may have prevented re-invasion of adult koi carp into the lake, accounting for about 30% of the biomass decline from 2011 to 2014. Analysis of koi carp size frequency data indicates that the 2011 removal programme was highly effective in reducing the number of adult fish (>250 mm), resulting in populations in 2012 and 2014 that were skewed to juveniles and young adults (i.e., <3 years old) (Figure 5). Up to 75% of adult koi carp leave lakes adjacent to the Waikato River at some point in their life history (Daniel et al. 2011). The drivers for this migratory behaviour were speculated to be for breeding or feeding activity (Daniel et al. 2011), but this has not yet been conclusively determined. Large migrations of koi carp have been observed just prior to spawning in the Waikato region (Garrett-Walker 2015). Similarly in Australia, carp moved longitudinally in the Murray River to the Barmah-Millewa floodplain to spawn (Jones and Stuart 2009). The preferred spawning habitat of koi carp is shallow or flooded areas with grass or submerged vegetation and little to no flow (Balon 1995, Stuart and Jones 2006), characteristics congruent with many of the lakes in the Waikato region, including Lake Ohinewai. Assuming that koi carp resident in Lake Ohinewai are not obligated to migrate for breeding and the observed changes in the population structure, it is plausible that a successful spawning event occurred in Lake Ohinewai in the spring of 2013, which has since translated through to increased recruitment to the adult population in 2016. A spawning event in 2013, and potentially subsequent spawning events, were not previously detected due to the size selectivity bias of the sampling methods (i.e., fyke nets and boat electrofishing) and insufficient sampling frequency.

In addition to the spawning and recruitment of koi carp in Lake Ohinewai, it is possible that upstream migration by young-of-the-year from Lake Rotokawau and/or Lake Waikare may have supplemented the Lake Ohinewai population. In Australia's Murray River, large numbers of young-of-the-year common carp (typically 80–100 mm FL) have been observed migrating upstream, approximately 100 km from where they were likely spawned (Stuart and Jones 2006). This suggests that young-of-the-year carp are capable of significant dispersal movements and that Lake Ohinewai could be acting as a sink for dispersing juvenile koi carp, as demonstrated for Lake Waikare (Boubée et al. 2004). The bar spacing of the one-way gate would not prevent juveniles from entering Lake Ohinewai. There has been some suggestion that common carp return to preferred areas to spawn (Jones and Stuart 2007), whether this behaviour might prompt mature koi carp that have migrated into Lake Ohinewai to leave the lake would require further investigation. The single outlet and one-way barrier to Lake Ohinewai does provide an opportunity to conduct radio-tag or pit-tag monitoring of potential migratory movements. Monitoring equipment could be mounted at either end of the culvert which would also act as a choke point improving chances of detection. Conducted during the spawning season (August–December) directional movements of adult koi carp tagged in Lake Ohinewai could then be determined from the time interval between the two detection points.

Reduction of koi carp biomass in Lake Ohinewai may have facilitated changes to the fish community composition. Catfish abundance increased from 1558 (1299–1879, 95% CL) individuals in 2011 to 4010 (2641–6373, 95% CL) in 2016, potentially increasing the catfish contribution to total fish biomass from 3.5% in 2011 to 18.6% in 2016. Goldfish and koi carp hybrids have also increased in abundance between 2011 and 2016. Changes in fish community composition following targeted removal or fishing-down have been widely documented over a range of ecosystems (Stevens et al. 2000, Closs et al. 2003, Evangelista et al. 2015). Removals of invasive fish have resulted in altered size structure (Evangelista et al. 2015), recruitment (Closs et al. 2003), growth rates and population abundance (Klemetsen et al. 2002) of interspecifics. In Lake Ohinewai, the 2011 removal programme appears to have increased catfish and goldfish abundance by facilitating increased juvenile recruitment. Koi carp, catfish and goldfish have significant dietary overlap, particularly among juveniles, which feed predominantly on zooplankton, insect larvae and small crustaceans (Collier and Grainger 2015). Both catfish and goldfish appear capable of successful spawning in a wide variety of habitat types given appropriate spawning substrate and do not undertake long distance migrations to breed (Blumer 1985, Kunimune et al. 2011). Therefore, it is likely that these species have successfully spawned in Lake Ohinewai and the large-scale removal of koi carp biomass has allowed greater recruitment of goldfish and catfish to the lake population due to the decreased competition for resources with koi carp and large adult goldfish and catfish. Natural changes climatically-driven recruitment events may also have a part to play; for instance, the large number of small catfish observed in 2011 (Figure 5) was not seen in subsequent years. However, we cannot rule out upstream dispersal of juvenile catfish and goldfish into the lake, again as demonstrated for Lake Waikare (Boubée et al. 2004). Likewise, a distinct size class of small shortfin eels was seen in 2016, indicating a recruitment event.

The reduction in koi carp population may also be responsible for the observed increase in abundance of koi carp hybrids. Interspecific hybridisation is known to increase as conspecific mate availability decreases (Fleming et al. 2015). In fish, hybridisation is further increased in species that reproduce by broadcast spawning such as goldfish and koi carp (Kirczuk and Domagala 2010). Koi carp x goldfish hybrids have generally constituted 1–2% of the koi carp population as was observed in the 2012 Lake Ohinewai population, by 2016 hybrids accounted for 12% of the koi carp population. This may be the result of increased incidental hybridisation as koi carp were triggered to spawn by goldfish spawning activity and the release of associated spawning aggregation hormones such as cyprinol sulphate, which are known to effect a wide range of cyprinid species (Olsen et al. 2006, Stacey et al. 2012). In Australia, most hybrids were inferred to be $F_1$-generation, but some $F_2$-generation and back-crossed individuals were detected, indicating that gene flow occurs between carp and goldfish. Gene flow was biased in favour of male carp mating with female goldfish, so control programmes for koi carp should consider controlling goldfish to prevent the risks posed by introgression with this related species (Haynes et al. 2012; Hicks and Ling 2015). Research in this area is fairly limited in New Zealand but could be an interesting avenue for future investigations.

Increases in abundance, size and biomass of native eel species were indicators of improvement in the Lake Ohinewai fish community. It is reasonable to assume that the decreases in invasive fish biomass would result in increased resource availability for competing native species. Smaller eels (<300 mm) of both species consume mainly amphipods, oligochaetes and insect larvae before transitioning to a more piscivorous diet upon attaining 400 mm in length (Jellyman 1989). Larger eels (>500 mm) may also benefit by increased prey availability of common bully, which in-turn, also benefit from increased food availability following a reduction in invasive fish biomass. These assumptions have not been validated in Lake Ohinewai, but stable isotopes provide evidence of very similar trophic positions for shortfin eels and large koi carp in both the Waikato River and Lake Waikare (Figure 9), which suggests extensive dietary overlap (Hicks 2010).

## 4.2 Water quality

Water quality indicators such as nutrient concentrations, Secchi depth and total suspended solids showed no improvement in the five years following the reduction in invasive fish biomass, except for chlorophyll *a* concentration, which declined with decreasing biomass of invasive fish from 2011 to 2014, and returned to previous concentrations as invasive fish biomass increased by 2016. It is not entirely clear that this was caused by changes in the fish biomass as total nitrogen declined from 2009 to 2013. Total phosphorus remained similar throughout the study period. In addition, phytoplankton species and abundance appear consistent with other hypereutrophic lakes in the Waikato region. Because the lake is hypertrophic, chemically-driven internal nutrient cycling is likely to maintain poor the water quality. Measurements of water quality in Lake Ohinewai from 2006 to 16 have been sporadic; in some years the lake was only sampled once. This has limited the extent of data analysis and made potential changes in water quality difficult to ascertain. Mean annual concentrations of total suspended solids were predicted from remote sensing to be relatively stable from 2000 to 2009 (33-77 mg/L; Hicks et al. 2013). It is possible that the combination of internal loads from sources other than fish and external loads from the catchment were more important drivers of water quality than fish alone. Allan (2016) suggested that koi carp at their highest biomass could contribute about 10% of the total annual TN load and 21% of the annual TP load. Lake water clarity remains below the level need for submerged macrophytes to establish across the main basin of the lake. This lack of sediment stabilising vegetation is likely contributing to the high levels of TSS as wind driven sediment resuspension is facilitated by the predominantly westerly winds and the east-west orientation of the lake maximising wind fetch (Kristensen et al. 1992). Sediment and associated phosphorus loading have also been identified as significant contributing factors to eutrophication of many lakes in the Waikato region (Collier et al. 2010). This has resulted in the prominent cyanobacterial blooms (e.g. *Microcystis* sp.) observed in Lake Ohinewai (Table 6,). These blooms are likely propagated by the polymictic nature of Lake Ohinewai (Figure 6), which rapidly deoxygenates in the bottom waters following stratification and then distributes nutrients into the surface waters following mixing (Søndergaard et al. 2003).

A water quality restoration study including modelling scenarios of koi carp removal down to 10 kg/ha suggested that such a management action would result in modest increases in water quality (i.e., Trophic Lake Index (TLI) was reduced from 6.45 to 6.29 and Secchi depth increased from 0.37 m to 0.51 m (Allan 2016). However, this improvement would not be sufficient to permit significant macrophyte reestablishment. Another modelled scenario was the reduction of koi carp biomass to 10 kg/ha and a 50% reduction in internal and external nutrient loads achieved by integrated catchment management. This could result in a TLI decrease from 6.45 to 5.68 and an improvement in Secchi depth from 0.37 m to 0.73 m, which would be a sufficient to allow reestablishment of submerged macrophytes (Allan 2016). Koi carp biomass estimates for Lake Ohinewai indicate that an areal biomass level of 10 kg/ha has not been sustainably achieved and there have been no discernible improvements in water quality, although the initial targeted level of decreasing koi carp biomass to <100 kg/ha has been accomplished.

When coupled with the modelling work of Allan (2016) these results highlight the need to determine the primary causes of lake eutrophication before attempting lake restoration. Catchment and internal loading play a significant role in the eutrophication of Lake Ohinewai. While invasive fish such as koi carp may facilitate the degradation of freshwater systems from clear-water macrophyte dominated states to turbid phytoplankton states, their removal alone is unlikely to initiate a return to the initial trophic state. However, effective control of invasive fish species should be considered an integral part of lake rehabilitation if restoration targets such re-establishment of native macrophytes and reduction in trophic state are to be achieved (Collier and Grainger 2015). Similar conclusions regarding the need for holistic lake restoration management can be found elsewhere, including study results following the exclusion of common carp from Cootes Paradise Marsh in the United States (Lougheed et al. 1998).

## 4.3 Comparison to previous reports

This study provides an updated assessment of the invasive fish control programme carried out on Lake Ohinewai. Calculations of weight and abundance have been revised and standardised, along with the automated selection of the most appropriate distribution for calculating confidence intervals (Ogle 2015, 2016). Standardisation of the regression equations used to calculate weight and limiting the extent of the recapture period in the 2011 pre-removal study to align it with subsequent studies has resulted in the initial koi carp biomass estimate being reduced from 374 kg/ha reported by Tempero et al. (2015) to between 211 and 466 kg/ha with 95% CL. This change is primarily due to revision of the mean weight used in calculating koi carp biomass rather than changes in abundance. Calculation of koi carp biomass using length-weight regression was performed on data collected during the 2011 mark-recapture programme, subsequent studies collected actual length-weight measurements.

## 4.4 Recommendations

Reductions in koi carp abundance and biomass were temporarily achieved in Lake Ohinewai with some confidence. This can be attributed to the intensive fish removal programme and the installation of the one-way barrier on the outlet of the lake. However, there appears to have been a least one successful koi carp spawning event or upstream migration of juveniles in the lake following the biomass reduction resulting in partial recovery of the population. In addition, reduced interspecific competition has likely contributed to increased recruitment of the catfish and goldfish populations. Therefore, while the Lake Ohinewai one-way barrier appears effective in preventing immigration of adult koi carp into an area, it should not be considered as a mechanism to exclude both adult and juvenile koi carp nor as a sole measure of control. Long-term (>10 years) monitoring of the Lake Ohinewai koi carp population at two-yearly intervals will provide insight as to whether the one-way barrier supports suppression of koi carp biomass below pre-removal levels or if population recruitment exceeds emigration. Development of a simple logistic-type growth model would aid in determining the optimal time period between koi carp removal events to prevent recovery of the population. Increasing the frequency of water quality monitoring of Lake Ohinewai will allow more robust determinations of trends in water quality and will provide improved parameterisation and calibration of ecological models such as PCLake. Such models, properly parametrised, can be a valuable resource for lake managers exploring restoration scenarios. However, these models will need to be able to integrate fish community dynamics across multiple trophic levels, in order to fully assess the effects of control programmes.

### 4.4.1 Opportunities to further enhance our knowledge of carp control and its consequences

We see a number of potential opportunities learn from the fish removal experience in lake Ohinewai.

1. As the water quality monitoring was not particularly robust a remote sensing study of water quality over the study period would be useful.
2. Investigate the response of growth rates of shortfin eels to carp removal through examination of otoliths.
3. Determine the extent of upstream recruitment of koi carp, catfish and goldfish through the one-way gate.
4. Determine the utility of cyprinol sulphate to create aggregations of koi carp and goldfish for selective harvest.
5. Use radio-tagged male koi carp to identify aggregations of koi carp for selective harvest.
6. Use stable isotopes and dietary analysis to investigate the extent of dietary overlap of eels and koi carp in Lake Ohinewai.

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# Appendices

## Appendix 1. R statistical code (Ogle 2016) for Lincoln-Petersen fish population estimates for Lake Ohinewai (see Appendix 3)

```
# Refer to Ogle 2015 p173 section 9.2 Closed Population, Single Recapture, 9.2.1 Single Group
#Ogle uses n = C and m = R compared to Ricker 1975 and Pine et al. 2012
install.packages("FSA")
library(FSA)

# 2011 population estimates

sl22 <- mrClosed(222,670,95,method="Chapman") #Catfish 2011. This function requires M, C or n, and R or m as the first three arguments
summary(sl22,incl.SE=TRUE) #Gives N, population estimate and standard error
confint(sl22,verbose=TRUE) #Gives lower and upper 95% confidence limits

sl23 <- mrClosed(16,412,7,method="Chapman") #Goldfish 2011
summary(sl23,incl.SE=TRUE)
confint(sl23,verbose=TRUE)

sl24 <- mrClosed(1,5,0,method="Chapman") #Koi carp-goldfish hybrid 2011.
summary(sl24,incl.SE=TRUE)
confint(sl24,verbose=TRUE)

sl25 <- mrClosed(167,1322,25,method="Chapman") #Koi carp 2011.
summary(sl25,incl.SE=TRUE)
confint(sl25,verbose=TRUE)

sl26 <- mrClosed(18,0,0,method="Chapman") #Longfin eel 2011.
summary(sl26,incl.SE=TRUE)
confint(sl26,verbose=TRUE)

sl27 <- mrClosed(5,33,1,method="Chapman") #Rudd 2011.
summary(sl27,incl.SE=TRUE)
confint(sl27,verbose=TRUE)

sl28 <- mrClosed(800,0,0,method="Chapman") #Shortfin eel 2011.
summary(sl28,incl.SE=TRUE)
confint(sl28,verbose=TRUE)

# 2012 population estimates

sl15 <- mrClosed(268,231,44,method="Chapman") #Catfish 2012.
summary(sl15,incl.SE=TRUE)
confint(sl15,verbose=TRUE)

sl16 <- mrClosed(122,126,2,method="Chapman") #Goldfish 2012.
summary(sl16,incl.SE=TRUE)
confint(sl16,verbose=TRUE)

sl17 <- mrClosed(15,5,0,method="Chapman") #Koi carp-goldfish hybrid 2012.
summary(sl17,incl.SE=TRUE)
confint(sl17,verbose=TRUE)

sl18 <- mrClosed(76,292,15,method="Chapman") #Koi carp 2012.
summary(sl18,incl.SE=TRUE)
confint(sl18,verbose=TRUE)

sl19 <- mrClosed(20,3,0,method="Chapman") #Longfin eel 2012.
summary(sl19,incl.SE=TRUE)
confint(sl19,verbose=TRUE)
```

```
sl20 <- mrClosed(0,6,0,method="Chapman") #Rudd 2012.
summary(sl20,incl.SE=TRUE)
confint(sl20,verbose=TRUE)

sl21 <- mrClosed(477,407,120,method="Chapman") #Shortfin eel 2012.
summary(sl21,incl.SE=TRUE)
confint(sl21,verbose=TRUE)

# 2014 population estimates

sl8 <- mrClosed(251,157,42,method="Chapman") #Catfish 2014.
summary(sl8,incl.SE=TRUE)
confint(sl8,verbose=TRUE)

sl9 <- mrClosed(57,176,19,method="Chapman") #Goldfish 2014.
summary(sl9,incl.SE=TRUE)
confint(sl9,verbose=TRUE)

sl10 <- mrClosed(6,18,2,method="Chapman") #Koi carp-goldfish hybrid 2014.
summary(sl10,incl.SE=TRUE)
confint(sl10,verbose=TRUE)

sl11 <- mrClosed(45,98,9,method="Chapman") #Koi carp 2014.
summary(sl11,incl.SE=TRUE)
confint(sl11,verbose=TRUE)

sl12 <- mrClosed(24,37,20,method="Chapman") #Longfin eel 2014.
summary(sl12,incl.SE=TRUE)
confint(sl12,verbose=TRUE)

sl13 <- mrClosed(1,1,0,method="Chapman") #Rudd 2014.
summary(sl13,incl.SE=TRUE)
confint(sl13,verbose=TRUE)

sl14 <- mrClosed(795,1184,408,method="Chapman") #Shortfin eel 2014.
summary(sl14,incl.SE=TRUE)
confint(sl14,verbose=TRUE)

# 2016 population estimates

sl1 <- mrClosed(269,311,20,method="Chapman") #Catfish 2016.
summary(sl1,incl.SE=TRUE)
confint(sl1,verbose=TRUE)

sl2 <- mrClosed(201,104,10,method="Chapman") #Goldfish 2016.
summary(sl2,incl.SE=TRUE)
confint(sl2,verbose=TRUE)

sl3 <- mrClosed(38,25,3,method="Chapman") #Koi carp-goldfish hybrid 2016.
summary(sl3,incl.SE=TRUE)
confint(sl3,verbose=TRUE)

sl4 <- mrClosed(128,127,7,method="Chapman") #Koi carp 2016.
summary(sl4,incl.SE=TRUE)
confint(sl4,verbose=TRUE)

sl5 <- mrClosed(62,60,37,method="Chapman") #Longfin eel 2016.
summary(sl5,incl.SE=TRUE)
confint(sl5,verbose=TRUE)

sl6 <- mrClosed(7,8,1,method="Chapman") #Rudd 2016.
summary(sl6,incl.SE=TRUE)
confint(sl6,verbose=TRUE)

sl7 <- mrClosed(975,1423,401,method="Chapman") #Shortfin eel 2016.
summary(sl7,incl.SE=TRUE)
confint(sl7,verbose=TRUE)
```

# Appendix 2. Summary of fishing effort for the four mark recapture studies conducted from 2011-2016.

| Mark-recapture study | | Marking | Recapture | Total |
|---|---|---|---|---|
| 17-28 Jan 2011 | Fyke net nights | 80 | 160 | 240 |
| | Boat electrofishing (minutes) | 220 | 400 | 620 |
| 17 Nov 2011-20 Jan 2012 | Fyke net nights | 240 | 122 | 362 |
| | Boat electrofishing (minutes) | 220 | 220 | 440 |
| 18 Nov-4 Dec 2014 | Fyke net nights | 56 | 59 | 115 |
| | Boat electrofishing (minutes) | 360 | 360 | 720 |
| 22 Nov-8 Dec 2016 | Fyke net nights | 60 | 60 | 120 |
| | Boat electrofishing (minutes) | 360 | 360 | 720 |

# Appendix 3. Population estimates of fish in Lake Ohinewai from 2011 to 2016.

Note: Eels not enumerated in recapture. Acceptable population estimates meet the criterion of $MC > 4\hat{N}$. No recaptures ($R$ = 0) results in a failure of the population estimation (= fail), for which actual fish catches were substituted.

| Species and date | Number of fish originally marked (M) | Number of fish caught during recapture (C) | Number of marked recaptures (R) | Recaptured fish as a proportion of marked fish (R/C) | Chapman population estimate (N=(M+1)(C+1) /(R+1)) -1 | Errors for population estimate (N) | | Error distribution | Population estimate acceptable ($MC > 4N$) | Mean fish weight (g) | Total biomass (kg) | Areal biomass (kg/ha) | Errors for areal biomass estimate (kg/ha) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Lower 95% CL | Upper 95% CL | | | | | | Lower 95% CL | Upper 95% CL |
| **Koi carp** | | | | | | | | | | | | | | |
| 17-28 Jan 2011 | 167 | 1322 | 25 | 0.02 | 8548 | 5863 | 12937 | Poisson | yes | 605 | 5170 | 307.7 | 211.1 | 465.7 |
| 17 Nov 2011-20 Jan 2012 | 76 | 292 | 15 | 0.05 | 1409 | 875 | 2400 | Poisson | yes | 468 | 659 | 39.3 | 24.4 | 66.9 |
| 18 Nov-4 Dec 2014 | 45 | 98 | 9 | 0.09 | 454 | 251 | 889 | Poisson | yes | 505 | 229 | 13.7 | 7.5 | 26.7 |
| 22 Nov-8 Dec 2016 | 128 | 127 | 7 | 0.06 | 2063 | 1070 | 4328 | Poisson | yes | 763 | 1574 | 93.7 | 48.6 | 196.6 |
| **Catfish** | | | | | | | | | | | | | | |
| 17-28 Jan 2011 | 222 | 670 | 95 | 0.14 | 1558 | 1299 | 1879 | Binomial | yes | 128 | 200 | 11.9 | 9.9 | 14.3 |
| 17 Nov 2011-20 Jan 2012 | 268 | 231 | 44 | 0.19 | 1386 | 1076 | 1814 | Binomial | yes | 151 | 210 | 12.5 | 9.7 | 16.3 |
| 18 Nov-4 Dec 2014 | 251 | 157 | 42 | 0.27 | 925 | 727 | 1206 | Binomial | yes | 181 | 168 | 10.0 | 7.8 | 13.0 |
| 22 Nov-8 Dec 2016 | 269 | 311 | 20 | 0.06 | 4010 | 2641 | 6373 | Poisson | yes | 153 | 613 | 36.5 | 24.0 | 58.0 |
| **Goldfish** | | | | | | | | | | | | | | |
| 17-28 Jan 2011 | 16 | 412 | 7 | 0.02 | 877 | 454 | 1840 | Poisson | yes | 250 | 219 | 13.1 | 6.8 | 27.4 |
| 17 Nov 2011-20 Jan 2012* | 122 | 126 | 2 | 0.02 | 5206 | 1898 | 12574 | Poisson | no | 144 | 751 | 44.7 | 16.3 | 107.9 |
| 18 Nov-4 Dec 2014 | 57 | 176 | 19 | 0.11 | 512 | 344 | 779 | Binomial | yes | 121 | 62 | 3.7 | 2.5 | 5.6 |
| 22 Nov-8 Dec 2016 | 201 | 104 | 10 | 0.10 | 1927 | 1093 | 3659 | Poisson | yes | 125 | 240 | 14.3 | 8.1 | 27.2 |
| **Koi carp-goldfish hybrid** | | | | | | | | | | | | | | |
| 17-28 Jan 2011* | 1 | 5 | 0 | 0.00 | >5 | 2 | 11 | Poisson | fail | 623 | 3 | 0.2 | 0.1 | 0.4 |
| 17 Nov 2011-20 Jan 2012* | 15 | 5 | 0 | 0.00 | >15 | 19 | 95 | Poisson | fail | 739 | 11 | 0.7 | 0.8 | 4.2 |
| 18 Nov-4 Dec 2014* | 6 | 18 | 2 | 0.11 | 43 | 18 | 126 | Binomial | no | 571 | 25 | 1.5 | 0.6 | 4.3 |
| 22 Nov-8 Dec 2016* | 38 | 25 | 3 | 0.12 | 252 | 115 | 633 | Binomial | no | 743 | 188 | 11.2 | 5.1 | 28.0 |
| **Longfin eel** | | | | | | | | | | | | | | |
| 17-28 Jan 2011* | 18 | – | – | – | >18 | – | – | – | fail | 362 | 7 | 0.4 | - | - |
| 17 Nov 2011-20 Jan 2012* | 20 | 3 | 0 | 0.00 | >20 | 17 | 83 | Poisson | fail | 211 | 4 | 0.3 | 0.2 | 1.0 |
| 18 Nov-4 Dec 2014 | 24 | 37 | 20 | 0.54 | 44 | 35 | 62 | Binomial | yes | 781 | 35 | 2.1 | 1.6 | 2.9 |
| 22 Nov-8 Dec 2016 | 62 | 60 | 37 | 0.62 | 100 | 85 | 126 | Binomial | yes | 312 | 32 | 1.9 | 1.6 | 2.3 |
| **Rudd** | | | | | | | | | | | | | | |
| 17-28 Jan 2011* | 5 | 33 | 1 | 0.03 | 101 | 30 | 198 | Poisson | no | 200 | 20 | 1.2 | 0.4 | 2.4 |
| 17 Nov 2011-20 Jan 2012* | 0 | 6 | 0 | 0.00 | >6 | 0 | 6 | Poisson | fail | 244 | 1 | 0.1 | 0.0 | 0.1 |
| 18 Nov-4 Dec 2014* | 1 | 1 | 0 | 0.00 | >1 | 0 | 3 | Poisson | fail | 116 | 0.1 | 0.0 | 0.0 | 0.0 |
| 22 Nov-8 Dec 2016 | 7 | 8 | 1 | 0.13 | 35 | 14 | 126 | Binomial | yes | 207 | 7 | 0.4 | 0.2 | 1.6 |
| **Shortfin eel** | | | | | | | | | | | | | | |
| 17-28 Jan 2011* | 800 | – | – | – | >800 | – | – | – | fail | 172 | 138 | 8.2 | - | - |
| 17 Nov 2011-20 Jan 2012 | 477 | 407 | 120 | 0.29 | 1611 | 1394 | 1879 | Binomial | yes | 141 | 227 | 13.5 | 11.7 | 15.8 |
| 18 Nov-4 Dec 2014 | 795 | 1184 | 408 | 0.34 | 2305 | 2135 | 2497 | Binomial | yes | 186 | 429 | 25.5 | 23.6 | 27.6 |
| 22 Nov-8 Dec 2016 | 975 | 1423 | 401 | 0.28 | 3456 | 3186 | 3760 | binomial | yes | 197 | 682 | 40.6 | 37.4 | 44.1 |

# Appendix 4. Summary of mean weights calculated from recaptured fish for four two-sample mark-recapture population estimates.

Note: Means with the same group letter are not different (ANOVA $P < 0.05$).

| Sampling period | *n* | Weight (g) | | | | Mean |
|---|---|---|---|---|---|---|
| | | Mean | SE | Upper 95% CL | Lower 95% CL | group |
| **Koi carp** | | | | | | |
| 17-28 Jan 2011 | 1464 | 604.8 | 11.6 | 582.0 | 627.5 | b |
| 17 Nov 2011-20 Jan 2012 | 86 | 468.0 | 47.9 | 374.1 | 561.9 | a |
| 18 Nov-4 Dec 2014 | 134 | 504.8 | 38.4 | 429.6 | 580.0 | ab |
| 22 Nov-8 Dec 2016 | 316 | 763.0 | 25.0 | 714.1 | 812.0 | c |
| **Catfish** | | | | | | |
| 17-28 Jan 2011 | 797 | 128.3 | 3.1 | 122.3 | 134.3 | a |
| 17 Nov 2011-20 Jan 2012 | 288 | 151.2 | 5.1 | 141.1 | 161.2 | b |
| 18 Nov-4 Dec 2014 | 333 | 181.3 | 4.8 | 172.0 | 190.6 | c |
| 22 Nov-8 Dec 2016 | 646 | 152.9 | 3.4 | 146.2 | 159.6 | b |
| **Goldfish** | | | | | | |
| 17-28 Jan 2011 | 421 | 250.1 | 9.6 | 231.3 | 268.9 | b |
| 17 Nov 2011-20 Jan 2012 | 132 | 144.2 | 17.1 | 110.6 | 177.9 | a |
| 18 Nov-4 Dec 2014 | 214 | 121.0 | 13.5 | 94.6 | 147.4 | a |
| 22 Nov-8 Dec 2016 | 327 | 124.7 | 10.9 | 103.4 | 146.1 | a |
| **Koi carp-goldfish hybrid** | | | | | | |
| 17-28 Jan 2011 | 6 | 622.5 | 156.1 | 313.2 | 931.8 | a |
| 17 Nov 2011-20 Jan 2012 | 20 | 739.1 | 85.5 | 569.7 | 908.5 | a |
| 18 Nov-4 Dec 2014 | 22 | 570.5 | 81.5 | 409.0 | 732.1 | a |
| 22 Nov-8 Dec 2016 | 70 | 743.2 | 45.7 | 652.7 | 833.7 | a |
| **Rudd** | | | | | | |
| 17-28 Jan 2011 | 37 | 199.6 | 20.5 | 158.5 | 240.6 | a |
| 17 Nov 2011-20 Jan 2012 | 6 | 243.8 | 51.0 | 141.9 | 345.8 | a |
| 18 Nov-4 Dec 2014 | 2 | 115.5 | 88.3 | -61.1 | 292.1 | a |
| 22 Nov-8 Dec 2016 | 20 | 207.1 | 27.9 | 151.2 | 262.9 | a |
| **Longfin eels** | | | | | | |
| 17-28 Jan 2011 | 18 | 362.0 | 238.5 | -108.9 | 833.0 | a |
| 17 Nov 2011-20 Jan 2012 | 23 | 211.4 | 211.0 | -205.3 | 628.0 | a |
| 18 Nov-4 Dec 2014 | 41 | 780.7 | 158.0 | 468.6 | 1092.7 | a |
| 22 Nov-8 Dec 2016 | 85 | 311.6 | 109.8 | 94.8 | 528.3 | a |
| **Shortfin eels** | | | | | | |
| 17-28 Jan 2011 | 800 | 172.2 | 6.1 | 160.2 | 184.2 | b |
| 17 Nov 2011-20 Jan 2012 | 1013 | 141.1 | 5.4 | 130.4 | 151.7 | a |
| 18 Nov-4 Dec 2014 | 1571 | 185.9 | 4.4 | 177.3 | 194.4 | bc |
| 22 Nov-8 Dec 2016 | 2006 | 197.2 | 3.9 | 189.6 | 204.8 | c |

# Appendix 5. WRC peer review comments and responses by the authors for Technical Report 2017/10.

| Comment No. | Page | Paragraph | Comment | Response |
|---|---|---|---|---|
| 1 | Page iii-iv | 1 | What is the current consensus on koi carp actually being koi carp and should we still be referring to them as such? | Genetic work regarding this question on-going at the University of Waikato by Nick Ling and Steve Bird. Currently, there are no published results to indicate that we should be changing the scientific name of koi carp in New Zealand. |
| 2 | Page iii-iv | 1-8 | Probably worth reporting the confidence limits throughout the exec summary also. | Included 95% CL for most values apart from the non-koi species population changes from 2014 to 2016 as it was felt this would be unnecessary detail that would be confusing for the reader |
| 3 | Page iii | 2 | And zooplankton and phytoplankton samples were taken | Changed plankton to zooplankton and phytoplankton |
| 4 | Page iii | 4 | Do we have any evidence that adult fish did actually also leave the lake? | No, but we have general information for carp movements to and from Waikato lakes from Daniel et al. (2011). |
| 5 | Page iii | 5 | In our experience it is very difficult to capture juvenile eels in lakes with netting until they are >250mm (and presumably off the 'menu' so to speak (even with fykes that have exclusion chambers)… and we know that eels are underestimated by boat fishing so I think interpretation of what's happing with juv recruitment of eels to lakes is best left alone as I'm not sure we have decent methods to sample them properly in lakes yet.. | Statement about juvenile recruitment removed. |
| 6 | Page iv | 2 | It is possible that a longer sustained period of low biomass was required for changes in water quality to manifest?? | It is possible, but given the lack of monitoring data it is difficult to make any firm conclusions about water quality changes in the lake and speculation would not be appropriate. |
| 7 | Page 1 | 1 | Kaemingk, M.A., Jolly, J.C., Paukert, C.P., Willis, D.W., Henderson, K. Holland, R.S., Wanner, G.A., Lindvall, M.L (2016). Common carp disrupt ecosystem structure and function through middle-out effects. Marine and Freshwater Research DOI: 10.1071/MF15068 – very relevant to background effects of carp present in otherwise least impaired systems | Reference included |

| | | | | |
|---|---|---|---|---|
| 8 | Page 2 | Figure 1 | If this was a council pic it would create qns around H&S …may want to check uni policy on these matters?. eg this is typically high vis vests and hard hat material | Image changed. |
| 9 | Page 3 | 1 | Dry summers have much to do with this do you think??? ie potentially lower recolonisation potential?? | Possibly due to reduced habitat availability in dry summers but low density may also compensate?? |
| 10 | Page 3 | 2 | This reads a bit awkward…so what exactly is the objective? | Objective rephrased for improved clarity |
| 11 | Page 3 | 4 | How long is the culvert? | Length provided |
| 12 | Page 4 | 2 | Representing what proportion? | Proportion included |
| 13 | Page 5 | 1 | It is probably worth including an ethics statement here: e.g. you have endeavour to adhere to the stated methodologies, following Standard Operating Procedure that have been have been approved by the University of Waikato Animal Ethics Committee for the capture, handling and captive maintenance of fish and for the marking and tagging of fish. | Statement on ethics provided. |
| 14 | Page 6 | 2 | This would be equation no 1. All subsequent equations need to be re-numbered. | Equation numbering corrected. |
| 15 | Page 7 | 2 | Did you want to comment on which of these assumptions were likely/unlikely to be met? | Provided a short statement on assumptions. "The most important of these assumptions is that the population is closed…" |
| 16 | Page 7 | 2 | Additionally, what are the likely implications of violating assumptions for the population estimates? | Added the comment "The consequence of any of these assumptions being unmet is that the population estimate will be unreliable." |
| 17 | Page 8 | 2 | Just to clarify, this number was measured in the current study? | Rephrased statement to make it clear that the population increased between 2014-16 |
| 18 | Page 8 | 2 | Presumably, we don't really know if and how the gate was operated. Is it possible that debris got stuck in there? | Added a paragraph in the methods section stating that the barrier was checked monthly and that there were no observed instances of debris allowing upstream passage of adult fish pg: 3 |
| 19 | Page 8 | 2 | Perhaps indicate frequency of cleaning/management regime by uni and DOC? | As above |
| 20 | Page 8 | 2 | What were those numbers? | Number of shortfin and longfin eels in 2014 and 2016 now included |
| 21 | Page 8 | Table 1 | Which raises the questions of whether nor not the mean weight is directly comparable? | Mean weights are calculated from the best available evidence and for recaptured fish only, except for eels in 2011 when no recaptures were possible. |
| 22 | Page 8 | 4 | But table 2 does not really show that currently. You could add columns for | Table 2 revised to show the relative contribution changes |

| | | | | |
|---|---|---|---|---|
| | | | each species to the table with the relative contribution of each species to the total biomass. Alternatively, you could delete this table and add some more detail to table 3. | in community biomass by invasive species and native eels. |
| 23 | Page 9 | Figure 4 | Presumably these are the hybrids? | Text has been amended to confirm that the notation refers to hybrids |
| 24 | Page 10 | Table 3 | I am not entirely sure how to deal with this. I assume that the results are largely unreliable in these cases? | This means exactly what it says – we have made population estimates but suggest caution in comparing with other results. The wide confidence limits show the limits of reliability of these estimates. We could omit these results entirely, but they are informative about the limits of the technique in a mixed species fish community where not all species are equally abundant or equally caught by the range of capture techniques used. We have added this point to the text. |
| 25 | Page 12 | Figure 5 | I think there are some interesting things going on in this size freq fig but I think it could be presented better to capture that temporal size structure shift better….for koi in particular ..density plots in gg plot in stacked fashion (by year) would show that temporal shift in popn size better I think | Good suggestion – ggplots added. |
| 26 | Page 13 | 2 | It's probably noteworthy that the hypolimnion was almost anoxic during a presumed relatively short stratification period. | Statement noting anoxia in the hypolimnion included in text |
| 27 | Page 14 | 1 | You could finish this paragraph with a statement along these lines: The lake remains highly eutrophic and turbid with low overall clarity. | Requested concluding statement provided. |
| 28 | Page 15 | 2 | I suggest using the detailed genus list in the main body of the text as Table 6. | Changed phytoplankton Table 6 to detailed species list. |
| 29 | Page 16 | 2 | At this point in the discussion, the reader is not really convinced that this really happened. All you can say for sure at this point is that the invasive fish biomass has changed (not even reduced for some species). The following paragraphs in the discussion should establish that a likely cause for a reduction (if it occurred) could be the removal programme and installation of the one-way barrier. | Point taken. Text has been amended to provide justification for ascribing declines to removals and one-way barrier. |
| 30 | Page 16 | 2 | It will now be crucial to give more serious regard to the confidence estimates of the biomass in the | Added new figure (Figure 9) that clearly shows where the overlaps occur. This makes |

| | | | | |
|---|---|---|---|---|
| | | | discussion. The size and the overlap of confidence estimates between mark-recapture event matter for the way you use qualifying adjectives. | interpretation of the biomasses easier. |
| 31 | Page 16 | 2 | But the confidence limit is close to 200 kg/ha, twice as much as the target. The better way of reporting the result would be: the estimated biomass was between 49 and 197 kg/ha, with 95% confidence.<br>The confidence limits will enable a more precise discussion on the effectiveness of the barrier; i.e. given the confidence limits of pre- and post-removal biomass estimates, there is some possibility that the barrier may have prevented adult koi re-invasion into the lake; albeit the inference is fairly weak. That is ok though, the results are what they are. | Fig 9 helps here, plus a revised Fig 5 showing changes in the size structure more clearly. The effectiveness of the barrier is now discussed. |
| 32 | Page 16 | 2 | Quite large confidence limits though..so this statement and the next appear more conclusive than what confidence limits indicate….suggest temper or acknowledge uncertainty | Now addressed in comment in Section 4.1 about recapture rates of marked fish. |
| 33 | Page 16 | 3 | Is this an assumption??? | Amended to explicitly state this is an assumption |
| 34 | Page 16 | 3 | Why not just reinvasion of juves through the barrier or a combo of the 2? otolith microchem could answer this qn | This is addressed in the following paragraph. Otolith microchemistry is unlikely to provide a definitive answer given the limited catchment size. |
| 35 | Page 16 | 4 | Maybe you could give us a suggestion about how you could investigate this? | Suggestion provided |
| 36 | Page 16 | 5 | But this is an overstatement given the width of the confidence limits. | Text has been amended to be less specific |
| 37 | Page 16 | 6 | Could this be an assumption??? via what causative mechanism(s)….why not for instance just more water and higher levels resulting in more littoral food and more successful breeding compared to dry previous years??? I suggest without a control site you'd need to be more cautious in attributing and community effects to carp | Changed text to be more circumspect. |
| 38 | Page 17 | 1 | I think there is a fair amount of speculation here with no discussion about how different the different years were climatically or without any rea knowledge as to what the degree of juvenile mobility into and out of the system may be for the diff species. In the case of goldfish and catfish we often get large runs at specific times into the carp cage (last week in the space of 2 days over | Added comment " Natural changes climatically-driven recruitment events may also have a part to play; for instance, the large number of small catfish observed in 2011 (Figure 5) was not seen in subsequent years. However, we cannot rule out upstream dispersal of juvenile catfish and goldfish |

| | | | | |
|---|---|---|---|---|
| | | | 1000 catfish were pulled out of the fish trap (whereas the week before there were none)…and many of these smaller fish could easily get through those bars (as they do at our trap when we have the screen down) | into the lake, again as demonstrated for Lake Waikare (Boubée et al. 2004). Likewise, a distinct size class of small shortfin eels was seen in 2016, indicating a recruitment event.” |
| 39 | Page 17 | 1 | Given the above comment and giving regard to the confidence limit, a more balance discussion would include considerations for natural fluctuations of fish community composition rather than a reduction of koi carp biomass. | See changes above. |
| 40 | Page 17 | 2 | This is a bit of a long shot. Maybe you could finish this discussion point by saying that research towards this end is still fairly limited in New Zealand but could be an interesting avenue for future investigations. | Good point. Added some substance here, plus the suggested text. |
| 41 | Page 17 | 3 | But did they really? The confidence limits of eel would suggest otherwise. | Recapture rates for shortfin eels were high (28-34%) and confidence limts were correspondingly low, so these conlcusions are robust. Shortfin eels were the winners. Fig 9 added to provide isotopic evidence. |
| 42 | Page 18 | 4 | Could you also indicate how you would fill some of the knowledge gaps that have arisen during this study; eg. Can we gain more understanding by trying to establish the origin of fish in Lake Ohinewai. | Have included a final section on “Opportunities to further enhance our knowledge of carp control and its consequences:” |
| 43 | Page 18 | 4 | There are a couple of points that can be picked up in a stronger conclusions section:<br>1. There is no strong evidence that would suggest that koi carp biomass was reduced significantly over prolonged periods of time. We have some confidence, however, that koi carp biomass was somewhat reduced after the removal events, which was of rather short-lived nature. It can thus be argued that we would not expect to see a substantial improvement of water quality in the lake because koi biomass was not reduced substantially; an assertion that is supported by both, the biomass estimates of koi (including confidence limits) and the water quality data.<br>2. This leads to a discussion point about the target population 100 kg/ha. It can even be argued that the 100 kg/ha “threshold” for degradation is inappropriate for Lake Ohinewai. Also, such a threshold | 1. Comment added to Section 4.2 on water quality about the limitation of capr removal. “It is possible that the combination of internal loads from sources other than fish and external loads from the catchment were more important drivers of water quality than fish alone. Allan (2016) suggested that koi carp at their highest biomass could contribute about 10% of the total annual TN load and 21% of the annual TP load.”<br>2. Threshold unlikely to be the problem – more the catchment and internal loads. The monitoring was not robust – would be interesting to see what a thorough remote sensing of water quality reveals. Added point about the relative importance of carp |

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| | | | (albeit some literature has been provided) is unlikely to be universally applicable. But let's say, for the sake of argument, a 100kg/ha threshold that leads to degradation is valid for the lake. Then, we would not expect to see a recovery of water quality at the same threshold (rather at a much much lower value) due to other positive feedback mechanisms that keep the lake from "clearing up" (wind-driven resuspension, high nutrient loading, etc… as is discussed in the report). Overall, I am not surprised to see a lack of water quality improvement in the lake. | contribution the TN and TP loads: "Allan (2016) suggested that koi carp at their highest biomass could contribute about 10% of the total annual TN load and 21% of the annual TP load." |
| 44 | Page 18 | 4 | without direct evidence I'd say that re-invasion is as valid an assumption as internal spawning (or both) | Comment added "or upstream migration of juveniles" |
| 45 | Page 18 | 4 | At what frequency over this time period? | Added "at two-yearly intervals" |
| 46 | Page 30 | Appendix 3 | Probably need to explain the group column in the table caption. | Added comment to caption "Means with the same group letter are not different (ANOVA P < 0.05)." |