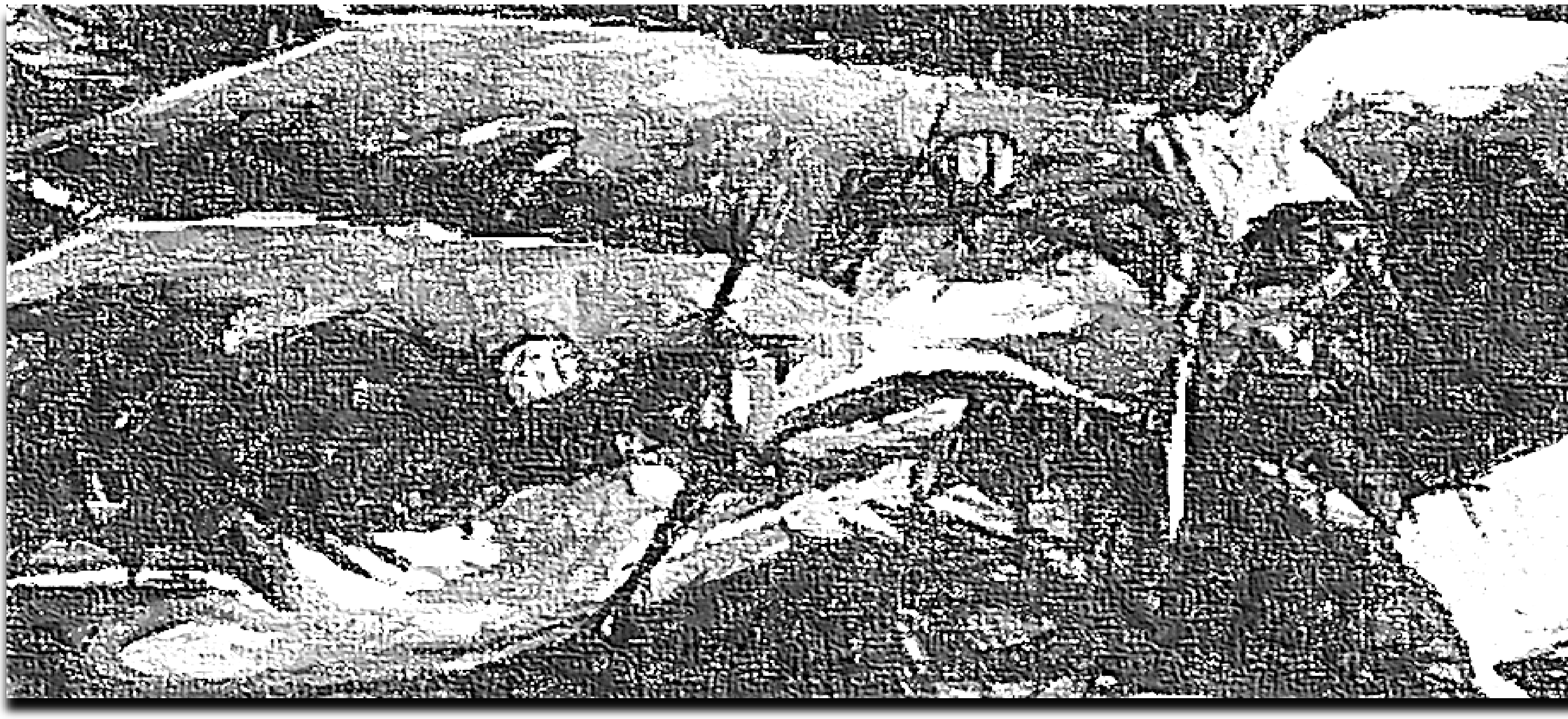
Summary of the impacts and control methods of Brown Bullhead catfish (*Ameiurus nebulosus* Lesueur 1815) in New Zealand and overseas



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Executive summary:

A literature review was undertaken for the Bay of Plenty Regional Council to report the known impacts that Brown Bullhead catfish in New Zealand and to present the methods of control with their level of success of those attempted. Initially the literature was searched for documents reporting impacts and control methods specific to brown bullhead catfish in New Zealand. However, only anecdotal information on their impacts has been reported but none has been scientifically proven. This lack of information is not typical to New Zealand and this review was able to find worldwide only one published attempt to eradicate brown bullhead catfish from some small ponds in Belgium. Therefore, this review focuses on potential impacts and potential methods of control that come from other species having a comparable ecology. Eradication or long-term control of alien species are common management endeavours, however, given the large amount of resources required for long-term control or eradication projects, it is important to identify the severity of the impacts that the species considered. The severity of the impacts will in turn guides strategies and associated costs and outcomes before any particular control/eradication plan is implemented. Early detection and rapid response may increase the probability of successfully eradicating or controlling non-native populations, however, before implementing a management plan, managers should determine whether eradication is a realistic objective. If eradication is not feasible, managers can determine the reduction required to reduce detrimental effects through long-term control. The effectiveness of eradication projects for fishes appears to be limited compared with other taxa and decreases with increasing spatial scale. For example, the few published management successes that exist indicate that non-native fishes have been eradicated only in some small alpine lakes using mechanical removal and in streams and small impoundments using chemical treatments. Some recommendations are made in the last section of this document of what could be the next steps in the control of brown bullhead catfish in the Rotorua lakes.

Introduction

Ameiurus nebulosus is a fish of the Ictaluridae family, commonly known as a brown bullhead (BB). It has been introduced outside of its native range first in New Zealand in 1877 with the release of 100-200 individuals for angling in St. Johns Lake in Auckland (McDowall 1994). The inspiration for this introduction came from Thomas Russell, a New Zealander living in San Francisco (McDowall 1994). These introductions resulted in local viable populations by 1885 (Holcík, 1991). Additional introductions for angling and sport occurred in Hawaii in 1893 (Welcomme, 1988). European introductions occurred concurrently, with individuals from North America introduced to Germany for angling, sport and aquaculture in 1885 (Scott & Crossman, 1973), leading to subsequent intentional and unintentional secondary spread to Poland (1885) (FAO, 1997), the United Kingdom (Bartley, 2006), Hungary (1902) (FAO, 1997), Finland (1922) (FAO, 1997), Belarus (1935) (Reshetnikov et al., 1997) and Bulgaria (1975) (Uzunova & Zlatanova, 2007). Recent introductions (1984) of BB from North America to Hubei province and Beijing, China have also occurred but solely for aquaculture.

Its spread has been undoubtedly facilitated by its ability to survive in high water temperatures (up to 37.5°C), to withstand industrial pollution, and low oxygen concentrations for prolonged periods (Scott & Crossman, 1973). Its establishment, once introduced, is likely assisted by its generalist, omnivore diet with feeding aided, even in turbid waters, by its 8 barbels (Scott and Crossman, 1973). This broad diet results in predation on a wide variety of native invertebrates, small fish and fish eggs. Conversely, its stout shape and strong dorsal and pectoral fin spines protect it from predation by native predators.

These three fin spines become robust when juvenile BB reach about 10 cm in length making juveniles more susceptible to predation by carnivorous fishes. Juvenile BB were found in Brown trout (*Salmo trutta*) stomach in Lake Taupo (DOC Fishery Taupo, unpublished data). Adult BB also take care of their eggs and young and this also reduce mortality in the young (Scott and Crossman, 1973).

The choice of how to control or eradicate an invasive species must reflect the extent of its ecological, economic and social impacts (Meronek et al. 1996, Van Poorten et al. (2109). If these impacts are severe then radical methods can be warranted and justified but if impacts are light or unknown any choice of a strategy will be a difficult decision. A further consideration is when to begin implementing control. It may be difficult to communicate the urgency of recently established invasive populations because adverse effects may be largely undetected and difficult to predict, particularly in a novel ecosystem. It is also hard to forecast the potential magnitude of the problem soon after invasion because the carrying capacity is largely unknown, thereby making the potential abundance difficult to predict (Van Poorten et al. 2019).

One of the reasons that the impacts of invasive species are unknown is due to the myriad ways in which a species may interact with a novel environment (Parker et al. 2013).

Brown bullhead potential impacts:

Generally, impacts of invasive fish in New Zealand water bodies occur through the combined effects of nutrient excretion, bioturbation, predation, loss of macrophytes, food-web modification and interspecific aggression (see Collier & Grainger, 2015 for a detailed review).

Although BB is not considered a quarantined pest, several countries Switzerland (Wittenberg, 2005); Poland (FAO, 1997); Chile (Welcomme, 1988) report adverse effects on native fish communities following its establishment.

In absence of the description of the ecological impacts specific to BB in New Zealand we present some of the impacts reported for three of the most similar species: wels catfish (*Silurus glanis*) in Europe ,carp (*Cyprinus carpio*) in Australia (Koehn 2004, Koehn & Mackenzie 2004),

In an initial invasiveness assessment (Copp et al. 2005 in Copp et al 2009), *S. glanis* attracted an intermediate mean risk score (21.5 of 54 possible points), which places it in the lower part of the 'high risk' score range; 19–54. And the lack of evidence for demonstrated impacts (e.g. low predation on native fishes in Iberia; would appear to corroborate this assessment. This emphasizes that caution may be advised when assumptions of adverse impact are based on anecdotal information sources.

Environmental impacts

There are several types of environmental impacts attributed to exotic fish. The known environmental impacts of alien fish can be classed as biological, ecological, physical and chemical.

Biological impacts

Some alien species also transmit serious exotic disease and parasites to valuable non-native species (Lintermans 1991), some of which may have economic consequences. However, to date no parasite and disease have been associated with the introduction of exotic fish in New Zealand (Champion et al. 2002) and BB in Lake Taupo hasn't appeared to be responsible for any disease outbreak amongst the other fish species present in the catchment. This risk, however, cannot be completely ruled out in Rotorua lakes as the introduction of BB in new waterways may affect the new environment differently.

Ecological impacts

Continuing spread of invasive fish among lakes can lead to biotic homogenization (Champion et al. 2002). Alien fish can overlap with, or prey on, native species with cascading implications for aquatic food webs (Collier et al. 2016). However, this has to be demonstrated in New Zealand.

Predation by alien species on native fish is considered as a major issue in New Zealand (Champion et al. 2002). However, BB are also predating on other introduced species.

Reports of ecological impacts of BB in New Zealand on freshwater fish has not been the subject of any scientific study until 2015, however, in 2012 their impacts were derived from some ecological impact scores (EIS) as outputs from the Fish Risk Assessment Model (FRAM) (Rowe & Wilding 2012). BB scored – 26 and were not assessed as potentially detrimental as common carp (– 32), perch (– 31), and gambusia (– 28) but being more so than rudd (– 22), tench and goldfish (– 17). These scores were derived from the responses of three New Zealand freshwater fish specialists to 35 questions on reported species-specific characteristics and impacts in New Zealand and other countries. FRAM considered feeding and competition impacts, reproductive rate, dispersal mechanisms, invasive relatives, special quarantine requirements, and undesirable traits.

In 2015, Kusabs & Taiaroa explored the impacts of BB on freshwater crayfish by comparing the abundance of freshwater crayfish in deep lakes where catfish were present (Lake Taupo) and where (at the time) they hadn't been detected (Rotoiti, Rotomā and Tarawera). The abundance of freshwater crayfish measured by CPUE showed no significant differences between lakes Rotoiti, Rotomā and Taupō. However, Taupō kōura were significantly smaller ($p < 0.05$) than those in Rotomā but not Rotoiti.

Predation on kōura is likely to be a major impact on the kōura population in Rotorua lakes. This predation could be substantial in shallow lakes like Rotorua where kōura will not find refuge in deeper water as they do in lakes Taupo or Rotoiti (Dedual 2002, Kusabs & Taiaroa 2015). Although, participants to the annual catfish spearfishing competition reported BB swimming in deep water (without mentioning the exact depth) Dedual (2002) showed that in Lake Taupo BB fitted with acoustic transmitter equipped with depth sensor were not detected in water deeper than 17 m. However, Lake Rotorua maximum depth of 14 m suggests that BB in this lake will be able to use the entire water column and consequently have potentially a far greater impact on the kōura population than in Taupo or Rotoiti.

Kōura and non-native species (goldfish *Carassius auratus*) have been found in the stomachs of BB caught in Lake Taupo (Taupo Fishery, unpublished data). However, in Taupo catfish need to be at least 270mm long before they can prey on adult kōura (DOC Fishery Taupo, unpublished results). It is likely that catfish will also prey on juvenile kōura where they share similar habitat but the extent to this potential predation is unknown.

It is worth noting that BB can also have some beneficial impacts on other species. For example in Taupo it is not uncommon to find juvenile BB (<10cm) in brown trout stomach (Taupo Fishery, unpublished data). The size of the prey is an important factor regulating fish growth rate. A brown trout feeding on small items will grow much slower than a conspecific feeding on larger prey.

Physico-chemical impacts

Physical and chemical impacts attributed to alien fish include: alteration or degradation of habitat, erosion of stream banks, and increased turbidity (eg from the resuspension of fine sediment due to carp foraging behaviour (Collier et al. 2016). BB may increase physical disturbance within freshwaters due to their benthivorous feeding habits. Although their barbels may aid in prey capture, foraging aggressively within substrates may be necessary to dislodge certain benthic prey items, which in-turn can increase turbidity and lead to altered productivity and nutrient cycling. However, estimates regarding habitat impacts following exotic fish introductions in New Zealand have not been quantified. Alien fish can also reduce water quality by disturbing sediment that releases nitrogen and phosphorous and can lead to algal blooms (Koehn et al 2004).

In summary, in New Zealand virtually all aspects of the environmental impacts of introduced BB require study, with some initial information available on distribution (Barnes 1996, Dedual 2002, Doc Fishery Taupo), movement behaviour (Dedual 2002), diet (Barnes 1996, DOC Fishery Taupo unpublished data). The lack of research in New Zealand may also have been caused by a lack of obvious ecological impact.

Economic impacts

In certain cases of establishment, exotic species introductions have the potential to hinder local commercial and sport fisheries through competition with target species. However, to date, economic impacts resulting from BB introductions in New Zealand have not been quantified, but that doesn't mean that the presence of BB is totally free of economic repercussions.

There is no doubt that, the establishment of BB populations in the Rotorua lakes may hinder local trout fisheries (Dedual 2002), freshwater crayfish (Barnes 1996) and eels (Rowe & Graynoth, 2002) fisheries and generating some substantial economic impacts on the local economy that relies heavily on tourism and on the world renowned recreational trout fisheries.

The economic impact could also be reversed from negative to positive. For example, BB has good eating quality if properly prepared and with astute marketing could be turned into a sport and/or commercial species that may provide new or valued angling opportunities. Eradication or control of BB in the Rotorua lakes could also have some economic benefits as employment opportunities for the region and even a potential export market as catfish are sought after by the local or international Asian community.

Social and cultural impacts

There are a number of ways that alien fish may impact on social values, however many of these impacts are poorly understood in comparison to other forms of impact. Most of the social impacts of alien fish are indirect and are often not easily identified.

Alien fish can damage the aesthetic integrity of the waterways, that in turn can impact on tourism and community recreation as previously mentioned. The impacts of alien fish species on other fish species may cause the decline of fish species sought after by traditional activities.

Similarly, the control of alien fish can reduce recreational fishing opportunities and tourism. For example, recreational angling was closed for several years during control/eradicaton operation as it happened in Lake Sorell and Lake Crescent in Tasmania (Diggle et al. 2004). Depending on the nature of the chosen strategy if deemed necessary such disruption could also occur in Rotorua lakes.

The adverse impacts of alien fish may also be cultural if alien species are implicated in the decline of traditional food. For instance, in Rotorua kōura are highly regarded by Maori as a traditional food source and if BB are shown to decimate the kōura population then it will certainly negatively affect Māori way of life.

The decline of native populations or aquatic communities, temporarily or permanently, also has implications for future generational use and is directly opposed to the principles of ecologically sustainable development.

See Table 1 in annex for a summary of the identified impacts of BB and those that have been shown in New Zealand

ERADICATION AND CONTROL METHODS

No eradication program of catfish in New Zealand has ever been attempted. Most of the material in this section relevant to BB control/eradication in the Rotorua lakes is drawn from the work on monitoring, eradication and control methods of alien freshwater fish species made in Australia and in Hawaii by West et al. (2007) and Tavares (2009) respectively. Additional potential control methods were identified from sampling methods presented during the 2000 international ictalurid symposium organised by the American Fisheries Society held at Davenport.

The control and eradication of BB will pose a real challenge to environmental managers. In general, eradication of an established aquatic invader is very difficult at best, and more often impossible (Bax et al. 2001; Clearwater et al. 2008; Mack et al. 2000; Wittemberg & Cock 2005). Here, the terms eradication, control, and management refer to distinct concepts. “Eradication” refers to all efforts aimed at completely eliminating BB from Lake Rotorua; “control” refers to all efforts aimed at maintaining BB population at a level where the identified negative impacts no longer exist.

Fisheries managers rely on a variety of tools to control and eradicate undesirable fish populations, including chemical, physical and mechanical methods. These methods can be used alone or in combination in order to increase efficiency.

To be valuable any method to control any alien fish must have several qualities. First, they need to be as selective as possible to avoid inflicting unacceptable level of collateral damage to other species. Ideally, they want to be affordable, easy to apply or implement, be effective over a broad range of environmental condition but not persist in the environment. They also need to be legal e.g. registered for use in the aquatic environment. Finally, and maybe more importantly they need to be acceptable to the public and other stakeholders. See Table 2 in annexe.

Thus, when choosing, managers must consider the pros and cons of each control methods according to the particular characteristics of the project.

Dewatering

The drainage of water bodies as a strategy to kill undesirable fish populations is a advantageous practice because it creates low risks to human health and usually inflicts limited long-term effects on the ecosystem. Also, it entails relative uncomplicated permitting process and neutral to positive public perception. On the other hand, dewatering is a nonselective practice, frequently expensive and difficult to implement in large waterways.

The method consists of partial or total removal of water through the construction of drainage ditches or use of pumps. These techniques can be very costly and present various difficulties depending on the characteristics of the site and of the target species. In the case of eradicating or controlling brown bullhead in lakes Rotorua and Rotoiti, complete dewatering is clearly not a viable option. However, if brown bullhead may concentrate in area for spawning or overwintering, partial dewatering of these areas if possible could be considered.

Water levels may be manipulated to exclude pest fish from spawning areas, and fish screens can be constructed to create an exclusion zone preventing entry of any adult fish to breeding areas (Gilligan & Rayner 2007). Destructive methods, such as draining/drying of wetlands can also be used (Koehn et al. 2000), however, the public support for the drying of wetland would be badly received by the public and the environmental agencies.

Netting and trapping

Nets and traps have been employed with various levels of success and in a variety of different settings to control and eradicate non-native fish (Meronek et al. 1996, Neilson et al. 2004). Benefits of these physical removal methods include low impact on human health and general neutral to positive public acceptance. Also, the use of nets and traps usually do not impose long-term effects on the ecosystem. However, these approaches tend to be ineffective and cost-prohibitive in larger water bodies especially in the capture of the full range of sizes in a population. For instance, a mesh size appropriate for capturing adults may allow juveniles to escape, while using a smaller mesh size may be inefficient to capture larger individualsor yet clog the nets (gill nets) in a way that it becomes very difficult to haul them in and very time consuming to untangle the fish. Selectivity of nets and traps will vary with fish size and behaviour (Mcinerny & Cross 2004), but these methods are usually indiscriminate in nature and can also result in damage to valued species of fish. These negative impacts can be minimized by returning valued fish to the water, but this mitigation practice adds extra cost to an already expensive method.

Reports of the efficiency of various types of nets used to capture catfish are not consistent an even contradictory. Robinson (1999) reports that the use of multiple-mesh size gill nets was far more effective than baited “pot” trap and baited hoop nets (fyke net without a wing) whereas Sullivan and Gale (1999) and Gale et al. (1999) found the opposite for capturing channel catfish. However, Santucci et al. (1999) mention that hoop nets perform poorly in lakes. Robinson (1999) also reports that gill nets required more worker hours to set and run than the other gears, but they caught more fish per worker hours. However, gill nets would have to be used with caution in areas used by other species. Valuable species caught would not be able to be released alive. This could be problematic in the Rotorua lakes that used extensively by trout. However, if gill nets are used in areas used only by BB then they would be an effective method of control. Furthermore, the trajectory of the catch-per-unit effort and of the length-class distribution of the BB caught would provide a useful data on the state of the population and on the efficiency of the control method.

Santucci et al. (1999) evaluated and compared the efficiency of electrofishing, experimental gill nets, baited traps, trot lines and a creel census (angler catch) to collect channel catfish in Ridge Lake (5.6 –ha, mean depth 2.8m) in Illinois. The authors recommend gill netting as they found that this was the only gear that reflected annual changes in relative abundance of channel catfish. However, gill netting CPUE was not high meaning that if the purpose is to severely control fish abundance then considerable effort would be needed to capture adequate number of fish. Unfortunately, the exact efficiency of gill netting at capturing BB is unknown but has been reported as low in California (Helfrich et al, 1999). However, gill netting may not be a good option as catfish will be difficult to untangle with their locked fin rays. Bodine et al. (2013) also recommend double hoop netting as the most effective method for catching channel catfish both as CPUE and manpower required (Table 3 in Annexe).

Louette & Leclerc (2006) provide the only published result on the efficiency of fyke nets as a sampling and control method of BB in small ponds. The mark-recapture study took place in northern Belgium in an area containing 34 small, shallow (mean depth: 1.5 m) and interconnected ponds. Capture was done with double fyke nets consisting of two conically shaped fyke nets of which the mouth openings were connected with a vertically hanging net (length, 11 m; height, 0.9 m). Each fyke had a total length of 7.7 m and a mesh-size of 8 mm (dimensions of mouth opening: width at the bottom, 1.2 m; height, 0.8 m).

The mark-recapture procedure consisted of three steps. When sampling an entire pond population, 12 to 16 fyke nets were set up at randomly chosen locations in the pond (step 1). After 1 to 2 days (step 2), the fyke nets were harvested and all captured fishes of different species were measured (LS), weighed (g), counted and subcutaneously marked with ink on the base of the caudal fin. All marked fishes were pooled and restocked at a minimum of 10 randomly chosen locations in the pond and the fyke nets were re-established. The number of marked individuals that were restocked in entire ponds ranged between 233 and 991. After 1 or 2 days (step 3), the fyke nets were harvested and the captured fishes were identified, checked for the presence of a mark, counted and measured. For each of the sampled bullhead populations, fyke net catch efficiency, density and biomass were calculated for seven different size classes separately (smallest size class, 8–10 cm LS; largest size class, 20–22 cm LS).

Fyke net efficiency was found to be very high for BB >8 cm in small ponds and in enclosed areas. In ponds with a surface area ranging between 0.25 and 1.5 ha, a set of 12 to 16 double fyke nets was capable of recapturing on average 66% of marked individuals during a time interval of 1 or 2 days. Recapture success in pond 12, a relatively large pond of c. 3 ha, was found to be considerably lower (14%). In enclosed areas of 625 m2, average recapture success of a set of eight fyke nets amounted to 72%. When applied to entire pond populations, fyke nets were found to be size selective. Recapture efficiency of fyke nets significantly increased with LS. BB between 8 and 10 cm LS were recaptured with a mean efficiency of 45%. The mean recapture efficiency for individuals between 18 and 20 cm amounted to >80%. As a result, significant differences were found between the mean LS of the individuals that were marked and restocked and the marked individuals that were recaptured afterwards. In contrast, no size selectivity was found for fyke nets in enclosed areas. The density and biomass estimates for the BB populations varied significantly between the ponds and ranged between 393 and 2022 individuals per hectare.

The authors conclude that double fyke nets are potentially a very effective tool for the removal of BB populations from small to medium-sized shallow water bodies. Double fyke nets are easy to handle and cause relatively little damage to other fish species. The results showed that the catch efficiency of fyke nets for brown bullhead is relatively high compared to that for other fish species and that large proportions (up to 80%) of the larger size classes (>8 cm) can be removed from small ponds in a time span of 2 days with a minimum of effort. When repeatedly applied to a brown bullhead population, double fyke nets should enable managers to accomplish a substantial reduction of the number of reproductive individuals in 1 year. When efforts are consequently continued during a number of subsequent years, the method may prevent smaller size classes from reaching sexual maturity and may eventually lead to a substantial reduction or even extinction of the brown bullhead populations on a longer term.

Even though Lake Rotorua is much larger than the ponds in the study above, fyke netting could still be an effective method to control BB, particularly if they concentrate in shallow habitat during their annual life cycle. However, it will be necessary to wait on the results of the acoustic tracking of catfish in lakes Rotoiti and Rotorua to see if BB in this system concentrate in shallow and more restricted habitats where they become vulnerable to fyke netting.

Vokoun & Rabeni (2000) mention cans, drums and noodling boxes that are gear providing cavities to seek refuge or to spawn in. These gears are lifted quickly to the boat where fish are removed. These gears have been shown to be seasonally efficient. The habitat used by BB to spawn in lakes Rotoiti and Rotorua is not known but if they can be identified then such traps could be useful.

Trammel nets combined with electric fishing herding the fish was successfully used to capture channel catfish larger than 230mm.

Beach seine has also been used to capture BB in lakes in Quebec (Pierce et al. 1990).

When the areas of high BB concentrations are known midwater trawl nets could be used to target catfish (Vokoun & Rabeni 1999). For examples catfish in Lake Taupo have been observed and filmed forming large shoals in midwater along the drop-off (Taupo Fishery, unpublished data) where they could be targeted by trawls. However, it is not known if BB show the same behaviour in Rotorua lakes.

Dedual (2002) suggests that commercial harvesting of brown bullhead using fyke nets in Lake Taupo, New Zealand could be an option to control bullhead if they are found to impact upon trout. Some of the migrations that BB make in Lake Taupo are known (Dedual 2002) and targeting catfish at certain times of the year and in strategic locations would be effective.

Electrofishing

Electrofishing consists of using electric fields in water to stun fish and, by doing so, to facilitate their capture. This method is commonly applied to sample fish populations and determine abundance, density, and species composition but I am not aware of any example when it was used to eradicate or control an alien species.

The only option of using electric-fishing to monitor or control catfish in the Rotorua lakes would be from a boat. University of Waikato is using such a boat to monitor fish populations in the Rotorua lakes and in the Ohau Channel that connects Lake Rotorua to Lake Rotoiti. However, electric fishing is not a viable option on its own to control and even less to eradicate BB in the Rotorua lakes, unless the fish concentrate in shallow water (<3m).

Electricity has been used in other unconventional ways. Vokoun & Rabeni (2000) indicate that: telephone and tractor magneto derivatives have been used. However, these devices called “monkey rigs” were capable of capturing only certain species of catfish but their efficiency for capturing BB is unknown. Pacemakers powered from deep cycle marine batteries and draped from a boat has been successful at capturing flathead catfish but no indication exists for BB.

In another rather dramatic experiment Larimore (1961 *in* Vokoun & Rabeni 1999) used a 9m electric seine, followed with a rotenone treatment, and finally pumped the stream to reduce discharge to collect the remaining fish. This mammoth effort resulted was not particularly rewarding as not a single channel catfish was captured with the electric seine probably because its efficiency is linked to shallow depths (<1m).

Overall the efficiency of day and/or night electrofishing for sampling BB is low. In Minnesota lakes electrofishing has been shown to be low and much less effective than trap netting (Mcinemy & Cross 2004). However, Helfman (1998, in Mcinemy & Cross 2004) also wrote that brown bullhead flee when illuminated with artificial light, which could reduce effectiveness of night electrofishing. In Mcinemy & Cross study (2004) neither trap nets nor electirofishing was effective at capturing age-0 BB because the mesh size of trap nets is too large, and odds are low that they would be encountered during day or night electrofishing because BB swarm into dense, but widely scattered schools after leaving nests (in Mcinemy & Cross 2004)

Blasting/ Explosives

While worldwide most applications of explosives in fisheries have been carried out for sampling purposes, explosives have been used in New Zealand for eradication. McDowall (1990) reported that in 1983 explosives were used to eliminate koi carp from farm ponds in Taranaki. The sizes and environments of these ponds is unknown but Pullan (1984) reports that after several attempts to eradicate these fish with the use of poisons and explosives, only two fish remained. Grainger (2015) also reports the use of explosives to control pest fish in the northern South Island. Unfortunately, there is no information on the efficiency of the program.

The degree of damage is related to type of explosive, size and pattern of the charge(s), method of detonation, distance from the point of detonation, water depth, and species, size and life stage of fish. Explosive shock waves affect both fish eggs and larvae. Larval fish would be expected to be less sensitive than those in which the swim bladder has developed, but a number of studies have found increasing sensitivity to blasting with decreasing fish size (Govoni et al. 2008). In addition, vibrations from the detonation of explosives may cause damage to incubating eggs.

Two studies (Metzger & Shafland (1986), Bayley & Austen (1988) compared the efficiency of explosives to sampling fish to that of rotenone in canals, lake areas, and ponds. Their results differed greatly: while Metzger & Shafland found that detonating cord was a preferred alternative to toxicant sampling with rotenone, Bayley &Austen concluded that efficiency of this method varied with site characteristics, and that under their experimental conditions, retrieval efficiency was always greater for rotenone samples than for Primacord samples. The later authors recognized specific advantages of detonating cord over rotenone (i.e. cost-effectiveness under certain conditions, no chemical residues, absence of chemical escapement from target area) but recommended Primacord as a tool for estimating fish abundance only in deep-water areas (> 1.8 m) free of obstructions, or when excessive wind would cause rotenone to escape before it could be detoxified, leading to nontarget fish kills.

Primacord® is usually measured in grams of PETN per meter of detonating cord, or in number of grains of explosive per foot. One grain of explosive contains approximately 0.06 grams of PETN (Dyno Nobel Inc. 2009). Metzger & Shafland (1986) set parallel strands of detonation cord with a load of 50 grains PETN per ft. at mid-water or deeper at intervals of 29.4 ft. or less depending on specific site conditions (e.g., depth and vegetation) in areas blocked with netting. At two lake detonation sites, 60% (94 of 157) of tagged fish released into the blocked area were recovered. They found that five species of fish stationed within 21.6 feet of a single strand of detonation cord were killed instantly upon detonation and 88% were killed at the maximum tested distance of 27.8 feet. This study was designed to evaluate the use of detonation cord for sampling fish. It doesn't provide information on the magnitude of mortality beyond 27.8 ft from the detonation cord explosion. However, it does indicate that all five species tested were killed at 21.6 feet. In another experiment to control pike in Lake Davis, the Californian Department of Fish and Game laid approximately 900 feet of Primacord® (50 grain per ft for estimated 10.8 g PETN m-1) in a rectangle of 400 feet by 40 feet across the mouth of Mosquito Slough, an area of soft and silty substrate. Submerged “cars” containing pike were placed at various distances from the detonation to determine the radius of effect of the explosive. All fish enclosed in the suspended cages at distances less than 28 feet were killed, but in the end, the CDFG found detonation cord not to be a successful means for eradication during the pike project.

The use of explosives to kill BB in Rotorua lakes could be considered depending on which life stage(s) of BB is targeted. Spawning is thought to occur in late spring and summer in New Zealand (Barnes 1996; DOC Taupo Fishery, unpublished data). During spawning, one or both sexes clear a shallow nest in mud or sand, usually near aquatic vegetation or other available cover (rocks, stumps). Water depth may be between 15 cm and several meters. Spawning sites are usually contained within protected waters (coves, bays, etc.), with spawning occurring during the day. Male and female circle the nest, caressing with their barbels.

As it was mentioned above, the relative efficiency of Primacord decreases in shallow waters (<1.8m), thus knowing the ecology of the life cycle of BB in Rotorua lakes would help deciding if explosives are a viable method.

Public acceptance is expected to be neutral to good, depending on public involvement and education regarding the method.

Biocontrol

Biocontrol, or biological control, refers to the introduction or enhancement of a population of organisms that are predators, competitors, parasites or pathogens of a target species, such as unwanted invasive fish. The use of living organisms to control pests is an ancient practice which can in certain instances be beneficial but in others detrimental.

In general, biocontrol practices present low risks to human health, can be inexpensive and tend to be well accepted by the general public. However, examples of biocontrol programs that have backfired causing long-term negative environmental impacts abound in New Zealand.

There are three general approaches to biocontrol: 1) the introduction of a non-native biocontrol agent; 2) the improvement of existing natural enemies through mass production and periodic release of natural predators, competitors, parasites or pathogens of the pest; and 3) ecosystem enhancement, which involves manipulating factors that may limit the effectiveness of natural controlling agents, such as nutrients or third species.

The difficulties associated with developing an efficient biocontrol program are many and usually derive from the still limited understanding of species adaptation, niche plasticity and functional variability in biological communities. Frequent problems of biocontrol programs are related to long-term impacts of biocontrol agents on non-target species and/ or on natural resources such as food and space. For instance, it is common that a species introduced to compete with or prey on a pest will find an alternative niche and manage to coexist with the pest. Instead, they may displace the target pest but also other beneficial species and by doing so become a pest as well. Post-introduction changes in behaviour and even in the physiology of biocontrol agents can defeat the purpose of the biocontrol effort all together. These adverse outcomes can occur not only when a non-native species is introduced as biocontrol agent, but also when a species native to the treatment region is introduced to a treatment site where it was absent or when the augmentation of a native species is attempted. Thus, careful consideration of potential adverse effects is necessary; managers should try to model post-introduction population dynamics in order to prevent unexpected outcomes.

Mass stocking of a predator species may reduce populations of invasive fish but is unlikely to result in complete eradication. Highly piscivorous flathead catfish (*Pylodictis olivaris*) have been introduced in a 31 ha Virginia impoundment to control a stunted and undesirable population of BB (Odenkirk et al. 1999). The programme was successful as anglers survey revealed that the harvest of BB dropped from 2285 in 1992 to 25 in 1998. However, the average size of the remaining BB increased over the same period from 150 to 761g.

Biological control of adult BB in New Zealand by predation is unlikely given the paucity of natural predators, although juveniles BB are known to be predated by brown trout, shag, and sea gull in New Zealand and by Esox spp. (pikes) within their native range. The justification for introducing of a new predator in New Zealand waters would certainly be very contentious and not be granted with a lot of support from environmental agencies.

Virus

In May 2008 a mass mortality event of BB has been reported in a Hungarian reservoir near Szeged. Sequence analysis revealed that a ranavirus infection most similar to the European sheatfish and catfish viruses was responsible for the massive mortality. In the study the authors describe the first detection of ranavirus in connection with the haemorrhagic syndrome of BB causing high mortality (Juhasz et al. 2013).

However, the introduction of a new strain of virus in the environment is a risky business as the fate of the virus in the environment will never be known for sure and will not be able to be controlled should it create a new problem. The ethology of virus is poorly known and furthermore, the support from the public would certainly be very low as it has been with the introduction of the calicivirus to control rabbits.

Piscicides

In a small lake that doesn't have many tributaries where targeted species could find refugee it is possible to eradicate alien species by using piscicides. Even though most experts involved in fish control/eradication agree that chemical methods are often the most cost-effective, and sometimes the only actually available for managers to achieve the expected control goals it is not an option for eradicating BB from lakes Rotorua or Rotoiti due to their size. It is also important to keep in mind that in every instance in which pesticides are used as a management tool, the ecology of the treated system will be inevitably disrupted. In addition, certain pesticides have the potential to persist in the environment for extend periods of time and may cause the contamination of adjacent soil, groundwater, superficial water, and air leading to indirect harm to non-target species.

Other indirect negative effects of pesticides include the bioaccumulation of the active ingredient in the food chain, or the intoxication of non-target species by the solvents used in end-product. Organic compounds with piscicidal properties like rotenone tend to rapidly break down in the environment and are easily metabolized by animals receiving sub-lethal doses (Ling 2003). Nevertheless, it is important to be attentive to potential side effects from piscicidal uses of natural products as well.

In general, public perception towards the application of any pesticide to the environment, especially to water bodies, is negative. People usually fear for human intoxication and negative impacts on local fauna and flora, which are common side-effects of chemical products that have been used as pesticides. Public opposition to projects that intend to use piscicides to control invasive species is a recurrent problem and requires special attention during the pre-treatment phase in order to avoid repercussion that may escalade into legal action. It is very important that the public is properly educated about the importance of the invasive species control plan and about the piscicide, its biological origin, metabolisms and risks before the project is implemented.

There are two EPA-registered piscicide in New Zealand, rotenone and Fintrol® that contains antimycin is and it may have advantages over rotenone in some situations.

Rotenone

Rotenone is a substance that is extracted from the various tropical and subtropical plant species, the most common sources being the roots of the plant genus Derris spp., Lonchocarpus spp., and Tephrosia spp. Rotenone has been used for centuries by indigenous people of various parts of the world as narcotics to capture fish for eating purposes. In the US, rotenone has been used to manage fish populations since the 1930's (Finlayson et al. 2000).

The use of rotenone using both whole lake dosing and poisoned-bait treatments have been undertaken in New Zealand (Ling 2003; Clearwater et al. 2008, Grainger 2015). In 1981, Lake Parkinson (Waiuku) was treated to eradicate all fishes, including grass carp (*Ctenopharyngodon idella*) following their introduction to remove nuisance water plants (Ling 2003). A review of the toxicity and use of rotenone for fisheries management in New Zealand has been previously undertaken (Ling 2003). Grainger (2015) also mentions that 58 sites in New Zealand have been treated with rotenone.

Mode of action and selectivity

Rotenone interrupts cellular respiration at mitochondria in gill-breathing animals (Fajt & Grizzle 1998; Ling 2003). In high concentration (~100-200 ppb), rotenone acts as a broad-spectrum pesticide affecting all aquatic fauna, including amphibians and invertebrates. In lower concentration, rotenone effects seem to be somewhat selective, killing some fish such as rainbow trout (*Oncorhynchus mykiss*), but not others like black bullhead (*Ameiurus melas*) (Finlayson et al. 2000).

This suggests that if rotenone is considered to kill BB it would have to be at high concentration, and it would kill all the other species present. Furthermore, unless all parts of the water body are treated simultaneously, fish may avoid death by migrating back into treated waters in which the concentration of the active ingredient are already too low to be efficient (Ling 2003). The efficiency of rotenone is also dependant on the depth of the lake. Rotenone needs to be diluted throughout the water column and deeper than 10 m it is difficult to achieve. Furthermore, rotenone is expensive to apply preventing it to be an obvious choice for the Rotorua lakes.

A more promising approach for using rotenone in much larger lakes/waterways is to use fish baits impregnated with rotenone (Prentox). This has been used in lakes to remove large numbers of grass carp (Rowe 1999). However, Champion et al. (2002) report that trials in New Zealand have shown that fish quickly learn to detect toxic baits and avoid them. Furthermore, to be useful these baits not only need to be specific to attract BB but they also need to be treated to mask any cues that make BB avoiding them. Rowe (undated) mentions that trials using pellets impregnated with antimycin (Fintrol™), that is more toxic than rotenone and, being tasteless, may allow effective repeat treatments. However, the research on and development of such methods are in their infancies and their reliability hasn't been demonstrated yet.

Other piscicids

CFT Legumine™, is a liquid 5% rotenone formulation. The country of Norway uses CFT Legumine™ to treat large rivers for eradicating the ecoparasite *Gyrodactylus salaries* on Atlantic salmon (*Salmo salar*) smolts. In comparison to conventional rotenone formulations on the market today, CFT Legumine has several advantages, including a special emulsifier and solvent package that reduces the presence of highly toxic petroleum hydrocarbon solvents (benzene, toluene, naphthalene) present in liquid form of rotenone that affect the public's acceptance of rotenone.

Below are the links to two successful applications of CFT Legumine™
http://www.dfg.ca.gov/lakedavis/enviro-docs/).
http://www.dfg.ca.gov/lakedavis/det_cord.html

Lime
Champion et al. (2002) report that lime was used to increase the pH and eliminate a population of koi carp in an ornamental pond in Tauranga. The same authors report that although being relatively cheap lime is potentially more dangerous than rotenone because the strongly alkaline water can burn birds or mammals using the waterways.

Antimycin A

Antimycin is a naturally occurring substance extracted from cultures of actinobacteria of the genus Streptomyces. Antimycin is a cellular respiration inhibitor and is used in cellular physiology studies for its specific action as an electron transport inhibitor, specifically for mitochondrial. Juvenile life stages are more susceptible than adult fishes to antimycin (Finlayson et al. 2002).

However, Antimycin A is not an option at least for now as it is not registered for use in New Zealand (Clearwater et al. 2008). Furthermore, Antimycin is particularly toxic to scaled fishes, but much less toxic to channel catfish (*Ictalurus punctatus*) (Finlayson et al. 2002). In the USA Antimycin is most frequently used is in recreational fishing and aquaculture industries to remove scaled fish from catfish fingerling ponds.

Antimycin A causes death by oxygen deprivation at the mitochondria, in a process similar to the one provoked by rotenone. However, the effects of antimycin A in fish are irreversible and once fish are exposed to effective doses, they will not recover if placed in clean water (Chapman et al. 2003). The piscicide has generally been found to be less toxic to bottom-dwelling invertebrates than to fishes (Finlayson et al. 2002).

Genetic methods *(Thresher et al. 2014)*

Genetic options for the control of invasive fishes were recently reviewed and synthesized at a 2010 international symposium, held in Minneapolis, USA. The only option currently available ''off-the-shelf'' is triploidy, which can be used to produce sterile males for a release program analogous to those widely and successfully used for biological control of insect pests. However, the Trojan Y and several recombinant options that heritably distort pest population sex ratios are technologically feasible, are at or are close to proof-of-concept stage and are potentially much more effective than sterile male release programs. All genetic options at this stage require prolonged stocking programs to be effective, though gene drive systems are a potential for recombinant approaches. They are also likely to differ in their current degree of social acceptability, with chromosomal approaches (triploidy and Trojan Y) likely to be the most readily acceptable to the public and least likely to require changes in legislative or policy settings to be implemented. Modelling also suggests that the efficacy of any of these genetic techniques is enhanced by, and in turn non-additively enhance, conventional methods of pest fish control.

Table 1. Recombinant methods considered to date. See Thresher et al. 2014 for the references.

Method	Description	Reference(s)
Lethal construct	Construct induces embryonic death of offspring. When homozygous results in sterility and is equivalent to a sterile male/female release	Thomas et al. (2000), Horn and Wimmer (2003), Phuc et al. (2007), Thresher et al. (2009), Harris et al. (2012)
Sex-specific lethality	As above, but male or female-specific; transmitted through male or female line	Heinrich and Scott (2000), Schliekelman and Gould (2000a), Fu et al. (2007, 2010), Ant et al. (2012)
Sex-specific sterility	Construct causes offspring of one sex to be sterile; transmitted through male or female line	Schliekelman et al. (2005), Thresher (2008)
Gender distortion (''daughterless'' or ''sonless'')	Construct causes offspring to develop as specified sex irrespective of sexual genotype	Hamilton (1967), Schliekelman et al. (2005), Thresher et al. (2005)
Inducible mortality	Construct causes death when externally triggered by, e.g., extreme environmental variability or artificial trigger; construct maintained in population by further stocking	Grewe (1997), Schliekelman and Gould (2000b)
''Trojan gene''	Construct pleiotropically has positive effect on one or more fitness components, and negative effects on others, e.g., increases mating advantage while decreasing viability of genetically modified offspring	Muir and Howard (2004)
Mutual incompatibility	Construct is lethal when present in 2 or more copies (unless genes are identical)	
Engineered under-dominance	Construct is lethal when only 1 copy present (or more than one copy but genes are identical)	Davis et al. (2001), Magori and Gould (2006)

''Sterile feral'' technology

Sterile feral technology is the recombinant analogue of triploidy. As currently configured in fish, sterile feral constructs consist of a stage-specific promoter, a blocker for a critical developmental gene and a repressible element. The inheritable gene construct renders both males and females sterile (unless repressed for hatchery breeding purposes) by triggering the lethal blocker in their eggs or fry, including those produced by any wild type fish with which a homozygous carrier breeds. A number of different combinations of promotors, target genes and repressible elements are currently being trialled.

The prototype sterile feral technology has been tested successfully in transient assays in channel catfish and in integrated channel catfish lines.

Sterile feral technology is being developed for the aquaculture industry, as a means of preventing the establishment of feral populations should exotic or genetically modified fish escape containment. However, as the sterility is similar to that produced by triploidy, it can potentially be used for many of the same applications and can also be used in a preventative mode. An area that is about to be invaded can be stocked with a small number of sterile feral males and females, as to soak up the reproductive inoculum of invading individuals and thereby prevent establishment. The use of the sterile feral technology for long-term pest control can potentially be enhanced by delaying expression of the construct and allowing it to spread (via inheritance) throughout a population prior to expression. Technical options for delaying across generations the onset of gene expression, however, are complex and expensive to develop and are currently limited to few species.

"Trojan genes"

The Trojan Y Chromosome (TYC) approach uses female fish with two Y chromosomes (YY) to shift the sex-ratio of a target population towards males. Carried to its limit, this could result in extinction of the pest population. In fish with an XY sex-determination system, the presence of a Y chromosome normally results in a male phenotype. For some species, YY ''super males'' can be generated by a combination of selective breeding techniques and the use of hormones to sex-reverse juveniles. These super males nominally have the same mating characteristics as an XY male, but produce only male progeny. In the TYC strategy, YY fish are induced, via hormone treatment in the laboratory, to develop into phenotypic females, which are then introduced into the pest population. These females cause increased production of males in two ways. First, all of their progeny are males: XY males and YY males. Second, these YY progeny in turn generate only male offspring: XY males if mating occurs with a normal XX female, but YY males if mating occurs with the stocked Trojan YY female.

However, the TYC strategy remains untested at this time, and is in need of further research. Furthermore, it is also not yet clear whether all species can tolerate a YY genotype. YY female channel catfish (*Ictalurus punctatus*), for example, ''do not reproduce or have severe reproductive problems''. This could also be the case in BB and if it does then the TYC approach, despite its elegance, would not be a viable strategy for the Rotorua lakes.

Pheromones

Most species of fish rely on pheromones which are chemical signals released by conspecifics to mediate social behaviour. Pheromones can be produced as anti-predator cues, social cues, and reproductive cues (Sorensen & Stacey 2004). Pheromones are remarkably potent and can be used to exploit weaknesses in species' life histories.

Generally pheromones are used to supplement and increase the efficiency of control strategies. For example pheromones can be used as an attractant to direct fish towards traps. A handful of fish pheromones have been chemically identified but I am not aware of any specific to BB. However, if specific pheromones to BB could be identified and if the factors related to the life history of BB are well understood, then the use of pheromone would definitively be a prime candidate. Pheromones are not only effective but also environmentally safe (Sorensen & Stacey 2004).

Commercial and recreational fishing

Commercial fishing could be an effective method of controlling BB if a reliable market for it can be established. If no market then the transformation of BB into fertilisers can be considered. This is a very attractive approach that will have the public's support as it "transforms something bad into something good". Subsidised commercial harvest has also the potential to rapidly reduce BB populations; however it can be very costly if planned on a long term.

Recreational fishers/anglers can also play a significant role in the removal of pest fish species. Fishing competitions can be organised to catch and remove pest fish using a hook-and-line approach. This technique is biased towards larger specimens, as smaller fish are unlikely to be caught on a line.

BB spearfishing competitions in Lake Taupo occur annually and are becoming increasingly popular. However, the potential to affect the overall population exists but only on a much localised scale.

Unexplored methods

Catfish around the world use their complicated pectoral joint featuring a spine that can be used as a defensive weapon and as a sound producing organ. Rigley & Muir (1979) described the agonistic sound production in BB. Obviously the function of these sounds and their importance in the social context such as courtship and agonistic behaviour requires further investigations.

Nevertheless, the understanding of the purpose of these sounds could be used as a very specific and elegant method to catch BB by "calling" them. This would be particularly effective it the sound production is related to the mating behaviour as spawners could be targeted. Deciphering some of the significance of the sounds produced by BB would also certainly be a fascinating subject of research for a student.

Japanese investigators observed that the behaviour of BB changed several hours before the onset of earthquakes, presumably as a response to the electrical disturbances caused by changes in the earth's magnetic field generated by seismic disturbances (New 1999). Many species of catfish use their electro sensory system to locate prey at a distance of 5 to 10 cm giving them a decided advantage when feeding at night. The potential use of this ability of detecting electrical field has not been as a method for attracting or directing BB to catch them has not been investigated yet but could be in its own or combined with sound another way to target BB.

Integrated Approaches

Regardless of the strategy chosen, the best outcome of any control/eradication program will be achieved within an adaptive management context. The strategy needs to evolve as the program unfolds, and focussed on exploiting the biological vulnerabilities of BB as they are discovered.

A good example of such an integrated approach is the eradication program of koi carp in lakes Sorell and Crescent in Tasmanian (Wisniewski et al 2015). The physical removal of an invasive fish species from a lake system as large as lakes Sorell and Crescent (5,310 ha and 2,305 ha respectively) had not previously been recorded, either in Australia or elsewhere in the world. Physical removal was deemed the most feasible option, and was underway from the outset as part of evaluating carp distribution, biology and population structure in Tasmanian waters. It became apparent within the first 12 months that physical removal was having a significant impact on the carp population, raising the possibility of eradication.

However, as the population size declined, the ability to locate aggregations of fish was reduced dramatically. At this point there was no, or very little, knowledge on biology, habitat preference or movement of carp under the local conditions. To fill this knowledge gap and to increase the efficiencies of fishing, an integrated strategy incorporating emerging concepts and refining of ongoing monitoring practices was sought and adopted.

A key emerging strategy was to deploy radio-tagged carp to serve as 'Judas fish'. These are carp with surgically implanted radio-transmitters that provide a means to reliably locate carp aggregations. Only male Judas carp were deployed as a strategy to minimise recruitment risk. The Judas fish became a valuable tool not only to target carp aggregations but also to understand carp behaviour, movement and habitat choice. The radio telemetry revealed carp movement and habitat choice in response to changes in lake water level and water temperature allowing to target carp more effectively.

As the strategy evolved from control to eradication, the prevention of recruitment became a high priority. This was accomplished by deploying purpose-built polyethylene barrier nets to exclude mature carp from their preferred spawning habitats with high macrophyte cover. Deployment of traps and purpose-built super fyke nets set along the barriers at key wetland/spawning access points enabled the capture of mature carp attempting to push into the wetlands.

This program was very successful, as the last wild carp was removed from Lake Crescent in December 2007. Eradication of carp from Lake Sorell has not yet been achieved, although the population was reduced to <50 in 2009. Lack of eradication can be attributed to its relatively larger size and diversity of habitat compared to Lake Crescent, further compounded by resource limitations brought on by split effort between the two lakes. Despite being close to complete eradication, repeated recruitment events have occurred in Lake Sorell.

Wisniewski et al (2015) explain that with sustained effort, it is possible to achieve the six key criteria required for eradication of a pest species. These criteria are:

• Rate of removal exceeds the rate of increase at all population densities.
• Immigration rate is zero.
• All animals must be at risk.
• Populations can be monitored at all densities.
• Discounted cost-benefit analysis favours eradication over control.
• Suitable socio-political environment prevails.

Conclusions/recommendations

For the vast majority of invasive fish, even those causing major ecological or economic damage, logistical considerations and costs prevent large-scale control. Careful communication in a structured decision-making workshop has been shown to be the most effective means of reaching consensus and avoiding short- and long-term conflict (Koehn & Mackenzie 2004, Estevez et al. 2014). Furthermore, by raising community awareness of the issue there is less potential for humans to spread BB further and the public can assist with reporting infestations (Koehn and Mackenzie 2004).

The decision on how to address the establishment of BB in the Rotorua lakes will involve many criteria such as the net environmental and economic benefits, regulatory hurdles associated with some treatment methods, and stakeholders input. As such, measuring the impact of different decisions on these various criteria will be based on other disciplines.

The process of building a common understanding of the necessary objectives across all stakeholders and agencies is arguably the most important elements of successful invasive species management (Estevez et al. 2014). The abundance, cost of control and probability of eradication are some of the objectives to consider in this context, but ecological, social and ecosystem-level objectives will be (at least partially) based on these elements.

There are certainly situations where values change over time and it becomes politically or socially preferable to consider control of a well-established population over eradication. Alternatively, there may be populations that have undergone control measures for years and decision makers would like to consider other control options.

However, one big question remains: what are the real impacts of BB in the Rotorua lakes? At this stage it appears that predation on kōura is the main one. This ecological impact on kōura has potentially also some social and economic ramifications. Kōura is a traditional and cultural food for Maori and predation on kōura can also affect the quality of angling by BB competing for kōura with trout. Lake Rotorua is likely to be more affected than Lake Rotoiti because a Lake Rotorua is very shallow and cannot provide depth refuge to kōura against BB predation.

Although our understanding of the impacts of BB is poor, this brief review shows there is a range of information available that could form the basis of strategies to improve management of BB in the Rotorua lakes.

The first decision needs to be about what to do and when to start? Doing nothing, some control or embarking on more ambitious eradication?

In this context population viability analyses (PVA) may be useful in evaluating the relative strength of support for various management actions. PVA may have utility as a mechanistic driver for decision support tools around strategies for controlling invasive species. Specifically, PVA models may be useful in determining which management actions or level of removal effort will improve probability of eradication (Van Poorten et al. 2019).

While population viability analysis may be used to show how to quickly evaluate and compare various management responses to non-native species with little biological knowledge, the recommended action will only be as good as the parameters provided. As controls and monitoring are initiated, knowledge regarding the invasive population and its response to control will accumulate (Van Poorten et al. 2019) and be used to update parameters and controls to verify the most appropriate course of action.

One limitation of population viability analysis is that it simulates a closed population, which may not be true in the Rotorua lakes. For example, BB can migrate between Lake Rotorua and Rotoiti through the Ohau Channel. Separation of local recruitment and immigration will obviously influence success of control options. However, this could be accommodated by either considering the entire invaded area or completely preventing passage from one lake to the other at the weir or by modifying the model to simulate continuous immigration into the habitat.

Integrated control, using several management techniques, each complementing the others, is more likely to be successful than control based on a single method. Meronek et al. (1996) reviewed 250 control projects from 131 papers where chemical, physical, biological, and combinations of chemical and physical methods found that in general the combination of chemical and physical method was the most successful and that introduction of a predator was the least successful. In the long term, there will be no 'silver bullet' for BB control neither in the Rotorua lakes nor in the other areas of New Zealand affected. Therefore, aside of the "do nothing" approach, any program will have to be developed as a long-term control and hence will be limited by a finite money availability. With that in mind, a strategy that ideally pays for itself by selling or transforming BB into something valuable would be the most defendable.

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IMPACT TYPE	DESCRIPTION	EFFECT	DESCRIBED			
			OVERSEAS	NEW ZEALAND	ROTOITI	ROTORUA
Eological	Nutrient excretion	Negative		No	No	No
	Bioturbation	Negative		No	No	No
	Predation	Negative		Yes, kōura , goldfish (Taupo)	Yes	No
	Predated upon	Positive		Yes, Brown trout (Taupo)	No	No
	Loss of native macrophytes	Negative		No	No	No
	Loss of exotic macrophytes	Negative-Positive		No	No	No
	Food-web modification	Negative		No	No	No
	Interspecific aggression	Negative-Positive	Yes	Yes, goldfish (Taupo)	No	No
Biological	Disease introduction	Negative	No	No	No	No
Physico-chemical	Alteration or degradation of habitat	Negative	No	No	No	No
	Erosion of stream banks	Negative	No	No	No	No

	Increased turbidity due to foraging behaviour	Negative	No	No	No	No
	Reduced water quality by disturbing sediment	Negative	No	No	No	No
Economic	Hinder local commercial and sport fisheries through competition with target species.	Negative	No	No	No	No
	Hinder local economy (tourism)	Negative	No	No	No	No
	Eating quality	Positive	No	No	No	No
	Transformation (compost)	Positive	No	Yes, carp in Waikato	No	No
	New angling opportunities	Positive	No	No	No	No
	Employment through control/eradication	Positive	No	No	No	No
	Export market	Positive	No	No	No	No
Cultural/social	Decline of fish species sought after by traditional activities.	Negative	No	No	No	No
	Decline of aesthetics	Negative	No	No	No	No

Table 1: Reported impacts of brown bullhead catfish (BB) and geographical knowledge

METHOD	CONTROL	ERADICATION	PROVEN EFECTIVENESS	COST	EASY TO IMPLEMENT	SELECTIVE	PUBLIC ACCEPTANCE	PERSIST IN THE ENVIRONMENT	FEASIBLE IN ROTORUA
Dewatering	Yes	Yes	Yes	?	?	No	Yes	No	More info needed
Fyke nets	Yes	No	Yes	$$$	Yes	Yes *	Yes	No	Yes
Gill nets	Yes	No	Yes	$$$$	Yes	No	Yes	No	Yes
Traps	Yes	No	Yes	$$	Yes	Yes *	Yes	No	Yes
Beach seine	Yes	No	Yes	$$	Yes	Yes*	Yes	No	Yes
Trawl nets	Yes	No	Maybe	$$$	No	No	Yes	No	More info needed
Electrofishing	Maybe	No	No	$$	No	Yes	Yes	No	More info needed
Explosives	Yes	No	Yes	$$$	No	No	?	No	More info needed
Biocontrol	Yes	Maybe	No	$$$$	No	Maybe	No	Yes	No
Virus	Yes	Yes	Maybe	$$$	No	Maybe	No	?	No
Piscicides	Yes	Yes	Yes	$$$	No	No	?	No	No
Genetic methods	Yes	Yes	Not yet	$$$$	No	Yes	?	No	Not yet
Pheromones	Yes	Yes	Not yet	$$$	Yes	Yes	Yes	No	Not yet
Commercial fishing	Yes	No	Yes	$	Yes	Yes	?	No	Yes

Recreational fishing	Yes	No	No	$	Yes	Yes	Yes	No	Yes
Sound attraction	No	No	Not yet	$$	No	Yes	Yes	No	Maybe
Integrated approaches	Yes	Maybe	Not yet	?**	Maybe	Yes	? ***	No	Yes

Table 2: Reported methods of control or eradication of BB from the Rotorua lakes. * = yes as the fish can be released alive, ** = the cost will depend on the combination selected, *** = the acceptance will depend on the combination selected. More info needed = better knowledge of the behaviour of BB in Rotorua lakes.

Rank	Gear	Median	Percentiles (25th–75th)	Comments	Literature
Efficiency—catch/gear effort					
1	Tandem hoop nets	20.7	11.0–24.0	Gear effort = fish/net/tandem set (48–72 h)	Michaeltz (2001); Sullivan and Gale (1999); Richeters and Pope (2011); McCain et al. (2011); Flammang and Schultz (2007); Flammang et al. (2011); Michaeltz (2009); Michaeltz and Sullivan (2002); Neely and Dumont (2011); Stewart and Long (2012); Wallace et al. (2012); Schultz and Dodd (2008)
2	High-frequency electrofishing	7.0	2.8–9.2	Gear effort = fish/h	Vokoun and Rabeni (2001); Columbo et al. (2008); Michaels and Williamson (1982); Barada and Pegg (2011); Pegg et al. (2006); Santucci et al. (1999); McCain et al. (2011)
2	Low-frequency electrofishing	4.9	2.0–12.8	Gear effort = fish/h	Nelson and Little (1986); Barada and Pegg (2011); Arterburn (2001); Cailteux and Strickland (2009); Jolley and Irwin (2011)
3	Gill nets	4.3	1.0–5.7	Gear effort = fish/net-night	Gale et al. (1999); Nelson and Little (1986); Michaels and Williamson (1982); Yeh (1977); M. S. Robinson (1999); Michaletz (2001); Sullivan and Gale (1999); Richters and Pope (2011); Crandall et al. (1976); Argent and Kimmel (2005); Odenkirk (2002); Mitzner (1999); Jackson (1995); Elrod (1974); Homer and Jennings (2011); Pegg et al. (2006); Santucci et al. (1999)
3	Slat traps	2.1	0.4–3.8	Gear effort = fish/trap-night	M. S. Robinson (1999); Santucci et al. (1999); Perry and Williams (1987)
3	Single baited hoop nets	1.8	0.8–4.1	Gear effort = fish/net-night	Gale et al. (1999); Nelson and Little (1986); Kirby (2001); Vokoun and Rabeni (2001); Columbo et al. (2008); Michaels and Williamson (1982); Barada and Pegg (2011); Arterburn (2001); Pierce et al. (1981); J. W. Robinson (1994); Mayhew (1973); Tillman et al. (1997); Gerhardt and Hubert (1989); Jackson and Jack-

					son (1997); Quist and Guy (1998); Holland and Peters (1992); Kubney (1992); Keller (2011); Cunningham and Cofer (2000); Jordan et al. (2004); Yeh (1977); M. S. Robinson (1999); Michaletz (2001)
3	Angler creel	1.5	0.3–3.0	Gear effort = fish/h	Santucci et al. (1999); Schultz and Dodd (2008); Parrett et al. (1999)
4	Single unbaited hoop nets	0.5	0.3–1.0	Gear effort = fish/net-night	Arterburn (2001); Pierce et al. (1981); J. W. Robinson (1994); Mayhew (1973); Tillman et al. (1997); Gerhardt and Hubert (1989); Jackson and Jackson (1997); Fratto et al. (2008); Funk (1958); Hesse (1980); Hesse et al. (1982); Hubert and Patton (1994); Parrett et al. (1999)
5	Hook and line	0.3	0.02–0.20	Gear effort = fish/hook-set	Gale et al. (1999); Nelson and Little (1986); Kirby (2001); Vokoun and Rabeni (2001); Arterburn (2001); Santucci et al. (1999); Arterburn and Berry (2002); Barabe and Jackson (2011); Jackson and Jackson (1999); Miranda and Killgore (2011)
Efficiency—catch/person-h					
1	Tandem hoop nets	40.0	20.0–60.0		Michaletz (2001); Sullivan and Gale (1999)
2	Slat traps	6.1	2.9–9.3		M. S. Robinson (1999); Santucci et al. (1999)
2	Single baited hoop net	5.6	1.6–11.6		Vokoun and Rabeni (2001); M. s. Robinson (1999); Michaletz (2001); Pugh and Schramm (1998)
2	Gill nets	3.7	1.6–5.5		M. S. Robinson (1999); Michaletz (2001); Sullivan and Gale (1999); Santucci et al. (1999)

3	Low-frequency electrofishing	1.2	1.2		Pugh and Schramm (1998)
3	High-frequency electrofishing	0.9	0.3–1.1		Vokoun and Rabeni (2001); Santucci et al. (1999); Pugh and Schramm (1998)
3	Hook and line	0.8	0.4–1.1		Vokoun and Rabeni (2001); Santucci et al. (1999)
3	Angler creel	0.5	0.5		Santucci et al. (1999)
Accuracy for abundance					
1	Tandem hoop nets			Consistent catchability	Flammang et al. (2011); Michaletz and Sullivan (2002)
1	Angler creel			Consistent catchability	Santucci et al. (1999)
1	Gill nets			Consistent catchability	Santucci et al. (1999)
2	Slat traps			Inconsistent catchabilty; may not accurately measure abundance	Vokoun and Rabeni (2001); Santucci et al. (1999)
2	High-frequency electrofishing			Inconsistent catchability; may not accurately measure abundance	Vokoun and Rabeni (2001); Santucci et al. (1999)
2	Hook and line			Inconsistent catchability; may not accurately measure abundance	Vokoun and Rabeni (2001); Santucci et al. (1999)

Size related metrics			
1	Tandem hoop nets	No bias for fish > 250 mm	Michaletz and Sullivan (2002); Buckmeier and Schlechte (2009)
2	Angler creel	Occasionally overrepresents fish < 300 mm	Santucci et al. (1999)
3	High-frequency electrofishing	Overrepresents fish < 300 mm	Vokoun and Rabeni (2001); Santucci et al. (1999)
3	Gill nets	Overrepresents fish > 460 mm; underrepresents fish < 250 mm	Michaletz (2001); Santucci et al. (1999); Buckmeier and Schlechte (2009)
4	Slat traps	Can overrepresent small or large fish	M. S. Robinson (1999); Santucci et al. (1999); Perry and Williams (1987)
4	Hook and line	Overrepresents large fish	Gale et al. (1999); Nelson and Little (1986); Vokoun and Rabeni (2001); Arterburn (2001); Kubney (1992); Santucci et al. (1999); Arterburn and berry (2002)

Table 3. Relative ranking of Channel Catfish sampling gears based on sampling efficiency (catch/gear-effort and catch/person-h) and accuracy of abundance and size-related metrics. Sampling efficiency is ranked by the median value observed in the literature. Percentile values are the interpolated 25th and 75th percentiles of published means. From Bodine et al. 2013