Rotenone-based approaches to pest fish control in New Zealand

David K. Rowe

National Institute for Water & Atmospheric Research Ltd, P.O. Box 11–115, Hamilton, New Zealand. d.rowe@niwa.cri.nz

ABSTRACT

In New Zealand, rotenone's main use will be to eradicate rather than to control pest fish. Practical considerations will limit eradication to relatively small, shallow, still-water environments and to small streams. Here, eradication would be justified for: (1) geographically 'strategic' populations of pest fish that could easily spread to other waters within the region; (2) restoring lake environments degraded by pest fish species; and (3) restoring the native fish fauna of sanctuaries within reserves. Bait-based applications of rotenone offer a way of targeting pest fish species and of providing ongoing control where eradication is not possible. However, recent experience in New Zealand indicates that some carp may develop resistance to repeat applications. Bait-based systems provide a delivery method to fish which may be adapted to other piscicides (e.g. antimycin) and which could be customised to other pest species. However, research is needed to determine both the potential uses as well as unwanted side effects of this approach. Although rotenone can be expected to be an important tool in the New Zealand 'toolbox' for pest fish management, other control options (e.g. predator control, habitat manipulation) need to be developed to provide alternative management tools, and to provide the opportunity for integrated control.

Keywords: piscicide, exotic fish, eradication, selective control, Prentox, antimycin, containment, reserve, biomanipulation

1. INTRODUCTION

Rotenone is the main piscicide used for controlling or eliminating pest fish internationally. As a liquid formulation, its lethal concentration, mode of action and effectiveness under differing environmental circumstances has been well established and extensively documented (Lennon et al. 1970; Schnick 1974; Davies & Shelton 1983). However, rotenone is a form of chemical control and, as such, can be expensive to use, is generally limited to lacustrine environments, and may kill many of the fish species present, not just the target species. Therefore its use may be limited. International knowledge, local experience, and New Zealand's unique fish fauna all need to be considered in deciding the potential roles for rotenone in pest fish management here.

Prentox® is a new ‘bait-based’ application for rotenone which is currently being used in the United States to reduce grass carp (*Ctenopharyngodon idella*) numbers in lakes after they have been used to control plant pests. It is also being trialed for this purpose in New Zealand (Rowe 1999) and for removal of common carp (*Cyprinis carpio*) in Australian waters (Gehrke 2001). Prentox® offers a theoretical way of targeting pest fish species, but this technology is in a developmental stage and its advantages and limitations are yet to be fully appreciated.

In this paper, the potential uses and limitations of these two technologies are discussed in the context of New Zealand’s pest fish problems. I ask where their use is likely to be feasible and justified, and whether they could have a role in New Zealand’s ‘toolbox’ of pest fish management techniques.

2. SELECTIVE CONTROL OF PEST FISH SPECIES

In the United States, rotenone was historically used as a sports fishery management tool to reduce unwanted fish and thereby to increase the number of desirable fish for anglers. Such restructuring of fish populations proved possible mainly because of differences in species’ tolerances and habitats which allowed unwanted species to be selectively removed. For example, in trout lakes, warm-water fish such as percids and many cyprinids can be controlled by treating the epilimnion with rotenone (Greenbank 1941; Tompkins & Mullan 1958). This is because the warm-water species are largely confined to the epilimnion whereas the more desirable salmonids inhabit deeper waters. However, re-treatment is needed after several years and the cost of this has resulted in the decline of this practice except in a few intensively fished waters where it can be economically justified.

In New Zealand, Willis & Ling (2000) looked at the feasibility of selective control for mosquitofish (*Gambusia affinis*) in the swampy waters inhabited by the black mudfish (*Neochanna diversus*). Although mudfish are more sensitive to rotenone than mosquitofish, control may nevertheless be possible when water levels drop, as the mudfish then aestivate. Aestivation in the sediments is likely to protect them from exposure to rotenone while the mosquitofish remain vulnerable in the remaining pockets of open water. Although the use of rotenone to reduce mosquitofish in environments inhabited by mudfish populations is theoretically possible, this needs to be field tested and the cost-benefit considered to determine its long-term viability. One potential problem is that long-term use of rotenone can produce resistant strains of mosquitofish (Fabacher & Chambers 1972).

Restructuring of fish populations by rotenone is not likely to be feasible for many of the other combinations of desirable and undesirable fish species in New Zealand waters (Table 1). This is because most of the pest species have relatively high tolerances to rotenone (Marking & Bills 1976). Moreover, habitat segregation is unlikely to occur to the extent where the pest species would be more vulnerable than the desirable fish. Exceptions may occur in situations where perch (*Perca fluviatilis*) or brown trout (*Salmo trutta*) are affecting native fish such as eleotrids or galaxiids, and are of little value because they do not

TABLE 1. SOME COMMON COMBINATIONS OF POTENTIAL PEST FISH AND DESIRABLE FISH SPECIES IN NEW ZEALAND LAKES, PONDS, AND OTHER LACUSTRINE WATERS.

WATER TYPE	POTENTIAL PEST FISH	DESIRABLE SPECIES
1. Northland dune lakes	Mosquitofish, rudd	Dwarf inanga
2. Auckland reservoirs	Rudd	Trout, galaxiids
3. Auckland lakes	Koi carp, rudd, tench, perch	Galaxiids
4. Waikato reservoirs	Rudd, catfish	Trout, smelt, bullies
5. Waikato lakes	Koi carp, rudd, catfish, perch	Eels, galaxiids, smelt
6. NI wetlands	Mosquitofish[a]	Mudfish
7. Small SI lakes and ponds	Perch, trout	Galaxiids, bullies

[a] Species which may be vulnerable to selective control using liquid rotenone.

contribute to fisheries. These exotic species have relatively low tolerances to rotenone (Marking & Bills 1976) so may prove to be more susceptible than lacustrine native species. However, the tolerances of common bullies (*Gobiomorphus cotidianus*), koaro (*Galaxias brevipinnis*), smelt (*Retropinna retropinna*), eels (*Anguilla dieffenbachii* and *A. australis*), inanga (*Galaxias maculatus*), and dwarf inanga (*Galaxias gracilis*) to rotenone are unknown. Use of rotenone in New Zealand will therefore require some research to determine the toxic levels for native fish species as well as the important molluscan and crustacean macroinvertebrates of lakes.

The cost of ongoing rotenone treatment is likely to be the overriding factor limiting its long-term use for selective control. However, an exception may occur where fish aggregate for spawning (or can be aggregated at feeding stations) and are therefore highly vulnerable within a restricted area for a short time. For example, spawning grounds for species such as koi carp can be relatively few and localised in some environments such as the Whangamarino River in the Waikato (Hanchet 1990). It may therefore be feasible to enclose large numbers of fish in block nets during spawning and to remove them using rotenone. Rotenone control targeted on spawning aggregations may not only reduce large numbers of adults, but also reduce recruitment. This 'double-whammy' effect could justify its ongoing use, but most fish would need to aggregate in a relatively few spawning areas. Such an approach would therefore require research to locate spawning grounds, identification of the main physical factors that attract fish to these areas, and then habitat manipulation to reduce and localise spawning to areas where rotenone control is feasible. In Australia, radio-tagged 'Judas' fish are routinely used to locate aggregations for trapping (Lintermans & Raadik 2003).

Other factors which aggregate pest fish may also greatly improve the cost-benefit of selective control with rotenone. For example, benthivorous fish may be strongly attracted to baits and in lakes may be conditioned to feed in a shallow area where they can be easily trapped and removed using rotenone.

3. ERADICATION OF PEST FISH SPECIES

Because of the high costs of regular application, rotenone is more likely to be used on a one-off basis to eradicate rather than to control pest fish. However, experience in New Zealand indicates that eradication of coarse fish species, particularly cyprinids, requires a relatively high concentration to be maintained throughout the entire environment being treated for a period of at least 5 hours in warm waters (Rowe & Champion 1994). Longer times are generally required in cooler waters. This is difficult to achieve in many aquatic systems and the use of rotenone for eradication will be limited to where a successful application is possible. For example, it would be precluded in most third order or higher streams and in lakes where in-flowing waters could not be dammed or diverted as this water would continuously dilute the rotenone. Its use would also be precluded in waters where upstream or downstream populations of pest fish could act as a source of re-infestation, and where artificial barriers or screens could not be constructed that allow free passage of native species. Research into such barriers is currently being carried out in Australia (Walker 2001). Because of such practical limitations, the successful application of rotenone for the purposes of eradication would be restricted mainly to closed ponds and lakes. However, rotenone has been successfully used to eradicate trout from small (i.e. first to second order) streams in Australia (Lintermans 2000) so could find a use in similar waters in New Zealand.

The costs of using rotenone will generally preclude its use in large lakes. However, other limiting factors are also important in such waters. For example, if the lake is used as a source of potable water, the use of rotenone is unlikely to be approved because periods of several up to 10 days may be required before the rotenone loses its toxicity. More significantly, recent neurological research has suggested that rotenone-like chemicals may be linked to Parkinson's disease. Although there is currently little scientific basis for this (Ross 2000), the possibility of a link would in all likelihood preclude approval of its use in any waters used for drinking purposes. Similarly, if water is abstracted for stock supply or irrigation, difficulties may arise with resource consents, particularly if alternative supplies are unavailable. Water containing rotenone can be detoxified using potassium permanganate (Jackson undated). This provides a way of limiting the duration of toxic conditions but would increase the cost of rotenone use. In addition, large lakes may contain populations of native fish which cannot easily be replaced and this would preclude the use of rotenone for pest fish eradication in these waters.

Deep water may also prevent its effective use in some lakes. Rotenone needs to be well mixed throughout the water column and, although this is feasible in waters down to about 10 m, it becomes more difficult as depth increases. A strong thermocline can increase the difficulty of full mixing, so applications need to be scheduled for times when the lake or pond water is mixed. However, rotenone is more effective on fish in warm than in cold waters so is more likely to be used when lakes are stratified. Deep lakes or lakes with deep holes where mixing would be difficult would be unsuitable because refugia would remain. Similarly, lakes or ponds with dense vegetation or log-jams in the littoral zone would present difficulties because these prevent mixing, and eradication would be impossible while such refugia remained. Rotenone is also difficult to use in turbid waters as high concentrations of organic particles can react with rotenone, reducing its toxicity.

The number of waters where rotenone could be successfully used to eradicate pest fish is therefore likely to be very limited. Careful planning would be required and possibly some pre-management of the environment to ensure the success of an application, both of which will increase costs. The use of rotenone for eradication purposes is therefore likely to be restricted to locations where eradication is a high priority and where costs can be justified. Three types of use fall into this category: (1) eradication of geographically 'strategic' pest fish populations to stop their spread; (2) the restoration of lake environments degraded by pest fish; and (3) the restoration of native fish faunas in reserves.

4. ERADICATION OF STRATEGIC PEST FISH POPULATIONS

Strategic eradication of pest species would be warranted at locations where pest species first occur and eradication could prevent their further spread to other waters. Such a geographically strategic use of rotenone occurred recently in Nelson where it was used to remove koi carp and mosquitofish from local ponds in order to restrict their further spread throughout the South Island (Chadderton et al. 2003). Use of rotenone to eradicate a fish species before it spreads would also be warranted in Auckland where the only known population of orfe (*Leuciscus idus*) in New Zealand occurs (McDowall 1990). The effects of orfe on New Zealand's aquatic fauna are not known and cannot be until it becomes more widespread. However, by this stage any adverse impact will be too late to remedy. The orfe has a wide tolerance of environmental conditions, and has no highly specific breeding or feeding habits (McDowall 1990), so can be expected to be a good invader. In particular, it has a wide salinity tolerance so may colonise the lower reaches of rivers and estuaries that are important gateways for the juvenile migrant stage of many of New Zealand's native fish. Strategic eradication would therefore be warranted and justified on the precautionary principles that it has potential to invade most waters in New Zealand and that New Zealand's fauna has proved vulnerable to invaders. The other known populations of fish that are candidates for eradication because of their geographically strategic location and the need for precautionary containment are listed in Table 2.

The 'location of geographically strategic populations of pest fish' implies two management approaches. First, surveys would be required to determine the current locations of pest fish so that the existing strategically important populations can be identified. Secondly, it requires identification and ongoing monitoring of waters where pest fish are absent but where they are likely to be illegally introduced. This requires knowledge of the main vectors responsible for spreading pest fish.

Prevention of new introductions is just as important as containment and eradication, and requires good public relations and education. Collaboration with fish and game councils and with coarse-fish angling groups would be

TABLE 2. SOME POPULATIONS OF 'GEOGRAPHICALLY STRATEGIC' POTENTIAL PEST FISH SPECIES IN PONDS OR LAKES WHERE ERADICATION MAY BE FEASIBLE.

POTENTIAL PEST SPECIES	LOCATION WHERE PRESENT	REGION TO WHOSE LAKES/ RIVERS IT MAY SPREAD
Orfe	Auckland pond	New Zealand
Mosquitofish	Nelson ponds (17)	South Island
Koi carp	Nelson ponds (2)	South Island
Koi carp and rudd	Lake Parawanui	Northland
Koi carp	Mangorei Stream pond	Taranaki
Koi carp	Te Awanga lagoon	Hawkes Bay
Perch	Lake Pohue	Hawkes Bay
Perch	Lake Tuanui	Northland
Rudd	Lake Rotomanu	Taranaki
Rudd	Lake Wairarapa	Wellington

required to develop agreed strategies for the provision of coarse-fish angling. Education programmes would need to be developed to focus on coarse-fish 'over-enthusiasts'. Similarly, commercial eel fishers may have a role in spreading certain pest species and aquarists may harbour potential pest species (e.g. Asian eel, weather loach, white cloud mountain minnow) so would also require targeted public education programmes.

5. LAKE AND FISHERY REHABILITATION

Eradication of pest fish is likely to be justified in some small lakes where the environment or fishery has been compromised by the introduction of pest fish species. This occurred in Lake Parkinson (Pukekohe), a 2 ha eutrophic lake in which large numbers of stunted rudd (*Scardinius erythrophthalamus*) comp-romised trout angling (Rowe & Champion 1994). Both rudd and tench (*Tinca tinca*) were eradicated from this lake with rotenone. It was then restocked with trout and common bullies by the local fish and game council to successfully restore the trout fishery.

The eradication of rudd and tench in this lake would not have been possible without the prior removal of all macrophytes (including exotic pest species) as these would have prevented mixing of the rotenone and created small pockets of untreated water providing refugia for rudd and tench (Rowe & Champion 1994). The prior removal of macrophytes was carried out using grass carp (*Ctenopharyngodon idella*). After they were removed, the native plant fauna regenerated providing better habitat for trout. These biomanipulations of and by fish restored both the lake environment and the fishery. Ironically, an exotic species (the grass carp) played a pivotal role in the eradication of both the exotic macrophyte and other pest fish species present. Such integrated management of plants and fish using biomanipulation and rotenone treatment is likely to be needed to restore other small New Zealand lakes (Rowe & Champion 1994).

Such integrated restoration measures are drastic, comprehensive, and therefore can be costly. It is unlikely that they would be contemplated by fish and game councils for other small lakes/ponds, as the fishery values of such waters are not generally high. However, such measures can be expected to be increasingly contemplated by regional councils to restore lake environments. There is a growing international body of evidence that certain exotic fish species are responsible for the degradation of small lakes. For example, large populations of planktivores may reduce water clarity in lakes by reducing zooplankton and thereby increasing phytoplankton densities (Carpenter et al. 1987; Jeppersen et al. 1990; McQueen 1990). Some cyprininds (e.g. common carp and the goldfish *Carassius auratus*) may reduce macrophytes and thereby increase turbidity in shallow lakes (Hanchet 1990; Richardson et al. 1995). Both herbivorous and benthivorous fish species may increase eutrophication through bio-perturbation of sediments and by increasing the rates of nutrient cycling (Lammens 1988). Requests have already been received from regional councils contemplating the use of rotenone to eradicate such problem fish in order to restore lake environments. However, research is needed to identify whether and where such problems occur in New Zealand lakes and whether eradication is justified. For example, not all waters containing common carp experience water quality problems (Northcote 1988; Hanchet 1990), and impacts of koi carp, goldfish, rudd, and tench in New Zealand lakes may result as much from bio-perturbation and nutrient cycling (viz. Prejs 1984; Lammens 1988) as from macrophyte browsing. Furthermore, impacts may arise only through the synergistic effects of several species, or when nutrient levels are already high. Research is therefore needed to determine which fish species are pests and in which environments and circumstances; otherwise expensive investment in control options may not achieve the desired outcome.

6. RECONSTRUCTING NATIVE FISH FAUNAS IN RESERVES

The use of rotenone to eradicate exotic fish species may also have a useful role in conservation biology and in the re-establishment of native fish faunas in New Zealand lakes, particularly those within DOC reserves. Eradication of mammalian pest species from islands and restocking with native birds and reptiles has proved to be a useful approach for the conservation of native terrestrial faunas in New Zealand. Land-locked lakes are the aquatic equivalent of islands and could provide sanctuaries for native fish. However, eradication of exotic or pest fish and restocking with native species is needed to re-establish the native fish faunas in such lakes. Several small North Island lakes known to have once contained native fish faunas but which are now degraded or threatened by exotic fish species are listed in Table 3. In addition, some small South Island lakes are also likely to contain exotic fish species (e.g. perch or salmonids) which on removal would allow them to become native fish sanctuaries.

Rotenone would be a useful tool for the eradication of the exotic fish in such lakes as the native species can be restocked from genetically similar stocks in adjacent waters. Recently, a population of brown trout was removed (by electrofishing) from a small stream above a barrier, to create a sanctuary for a

TABLE 3 SMALL LAKES WHERE THE ERADICATION OF PEST FISH SPECIES AND RESTOCKING WITH NATIVES WOULD BE JUSTIFIED ON CONSERVATION AND BIODIVERSITY GROUNDS.

LAKE	PEST FISH OR UNWANTED SPECIES	NATIVE SPECIES AFFECTED	OTHER SPECIES PRESENT
1. Rotopounamu	Smelt	Koaro	Common bully
2. Kai iwi	Mosquitofish	Dwarf inanga	Common bully
3. Waikare-iti	Rainbow trout	Koaro	Common bully
4. Christabel	Brown trout	Koaro	None

rare inland galaxiid (Chadderton 2003). Faunistic reserves may therefore include small headwater streams as well as lakes.

However, such use of rotenone implies a strategy to identify those New Zealand lakes and streams that would provide suitable sanctuaries within reserves, including those where the eradication of exotic fish is feasible. The creation of such sanctuaries for native fish species in reserves is likely to be as important to maintaining native biodiversity as the control of unwanted exotics in other waters.

7. PELLET-BASED APPLICATIONS OF ROTENONE

Prentox® is a patented system for removing grass carp from lakes and ponds using floating food-pellets containing rotenone. The carp first need to be trained to feed on non-toxic pellets and this is achieved by flavouring them (e.g. with alfalfa for grass carp) and supplying them at a set time and place by an automatic feeder over an appropriate number of days (at least 10). Once large numbers of fish are conditioned to feed on these non-toxic pellets, the pellets are replaced with pellets containing rotenone and fed to the fish as usual. In general, the rotenone concentration per pellet is enough to provide the oral LD50 for a 1 kg fish and enough pellets are fed out to provide each fish estimated to be present with a lethal dose.

An initial trial with grass carp in New Zealand established that large numbers of 5–11 kg carp could be quickly conditioned over several days to feed on non-toxic, 'trainer' pellets (Rowe 1999). Later, when fed toxic pellets at a rate needed to introduce a toxic dose of rotenone, a relatively high mortality (c. 40%) occurred (Rowe 1999). This was achieved despite initial teething problems which would have limited the conditioning process and hence the number of fish feeding. The system therefore works. However, more recent experience indicates that repeat treatments do not work nearly as well, either because the grass carp learn to discriminate between the toxic and non-toxic pellets, or develop enzyme systems needed to break down the rotenone. The toxic pellets are readily ingested by the grass carp, but it is impossible to tell whether they are subsequently ejected because of some learned taste difference. Therefore, the future reduction of grass carp by the rotenone-based Prentox® system will require careful planning to ensure a successful, one-off application. Problems with the efficacy of repeat applications of rotenone in pellets designed for grass carp may lead to trials with antimycin, as this is apparently more toxic and, being tasteless, may allow effective repeat treatments.

Similar problems with other types of pellets containing rotenone may also arise with other species. However, this technology is new and may be successfully adapted to different piscicides and/or to other species. For example, pellets more palatable to common carp have already been manufactured and tested, and smaller or different-tasting pellets could conceivably be made for smaller fish and for other pest fish species. Sinking pellets may be of some use in controlling benthivorous fish. This is an area where future research may result in the development of cost-effective control technologies that can be targeted at problem species.

Environmental effects of Prentox® have been evaluated in Australia (Gehrke 2003). Tank studies indicated that fish mortalities can occur through leaching. This may not be an issue in the field where dilution would be greater and where fish movement is not constrained. However, mortality of some Australian fish species in ponds raises concerns and the need for comprehensive field testing. In New Zealand, mortalities of non-target species such as common bullies and dwarf inanga did not occur in any of the three New Zealand trials. These two species showed no interest in the pellets and were not observed to be affected by them. In field tests, four to six floating pellets were enclosed in each of three wire-mesh cages containing common bullies and in each of another three cages containing several dwarf inanga. These fish were exposed to the pellets for up to 5 hours in the shallows of the lake. Although the pellets started to break down and would have leached rotenone into the surrounding water, none were eaten and no fish mortalities occurred in any of the cages. Uneaten pellets from the grass carp control trials drifted downwind and concentrated around the lake margin on the windward shore. Before-and-after foot surveys of the entire lake margin, especially on the windward shore, revealed that there was no attempt by either bullies or dwarf inanga to eat these pellets and that there was no increase in the mortality of either species (i.e. no increase in the occurrence of dead fish around the lake edge). However, other fish species not present in this lake may be susceptible, or acquire a taste for the pellets during the conditioning phase. This would preclude the use of toxic pellets in waters where such non-target species occurred. Other unforseen environmental side effects may emerge in other lakes with other species, so trials would be needed to test both the effectiveness of these methodologies and to detect any unwanted environmental effects.

8. CONCLUSIONS

Rotenone is a chemical treatment and, despite the many reports indicating that it can be safely used, experience with chemicals used to control plant, insect, and rodent pests in terrestrial environments indicates that it too needs to be treated with caution. Other piscicides have not been used as extensively as rotenone, or used in New Zealand waters, so little can be said about their comparative value. However, Fintrol® that contains antimycin is the only other EPA-registered piscicide and it may have advantages over rotenone in some situations (Davies & Shelton 1983). It is apparently tasteless to fish (Burress &

Luhning 1969) so may be more effective than agents that taint the water, in environments from which fish can escape to refugia; or in pellet-based applications for targeted control (Rach et al. 1994). It can also be used in a wider range of waters than rotenone (Burress & Luhning 1969). As it kills fish eggs as well as adults (Berger et al. 1969) it may be more useful than rotenone for targeting spawning aggregations of pest fish. Field trials in the United States have demonstrated its potential uses as a piscicide (Gilderhus et al. 1969) but it appears to be less popular than rotenone, perhaps because its effects are generally irreversible (Davies & Shelton 1983).

It is clear that rotenone is likely to have a restricted but still important role in the management of some pest fish species in New Zealand. The cost of its use is likely to militate against its role as an agent for the ongoing control of pest fish. However, as a tool for eradication, its use would be justified to restore a valued lake environment or a lake fishery that has been seriously compromised, to remove a strategic pest fish population likely to spread unless it is eradicated, or to remove unwanted fish in reserve lakes where the native fish fauna is to be restored and a sanctuary for native species created. Control options are likely to be limited to pellet-type applications which target pest fish species. These may find a use in specific pest fish control programmes once their reliability can be demonstrated. At present, the research on and development of such methods is in its infancy, but can be expected to grow internationally as problems with pest fish species increase.

Overall, rotenone is a useful tool and likely to find a place in the New Zealand management ‘toolbox’ for pest fish species. However, it is apparent that piscicide use will be restricted by cost and practical limitations and that other forms of control will need to be researched and developed for use in other waters in New Zealand. In particular, biological controls and/or habitat manipulation are likely to offer the best low-tech alternatives to complement the potential of high-tech approaches using new, genetic technologies now being developed internationally.

Biological control usually comprises species-specific, self-reproducing parasites, diseases, or predators and this could apply to pest fish in New Zealand. However, species-specific parasites and diseases for fish are rare, and in time may adapt and cross generic boundaries, so are unlikely to be introduced. Similarly, new fish species, particularly predators that can reproduce in New Zealand waters, are unlikely to be introduced. However, some control over fish such as rudd has been achieved by piscivorous fish in European lakes (Pihu & Maemets 1982; Garcia-Berthou & Moreno-Amich 2000) and the use of non-breeding, littoral zone piscivores already present in New Zealand may be possible. Research would be needed to explore such ‘low-tech’ biological control options to see whether they too may have a role in the management ‘toolbox’ for pest fish control in New Zealand. They would provide a useful adjunct to rotenone-based controls and allow a more integrated approach to pest fish management. Integrated control, using several management techniques, each complementing the others, is more likely to be successful than control based on a single method. In the long term, there will be no ‘silver bullet’ for pest fish control.

9. REFERENCES

Berger, B.L.; Lennon, R.E.; Hogan, J.W. 1969: Laboratory studies on antimycin *a* as a fish toxicant. *Investigations in Fish Control No. 26*. Bureau of Sports Fisheries and Wildlife. United States Department of the Interior. 19 p.

Burress, R.M.; Luhning, C.W. 1969: Use of antimycin for selective thinning of sunfish populations in ponds. *Investigations in Fish Control No. 28*. Bureau of Sports Fisheries and Wildlife. United States Department of the Interior. 10 p.

Carpenter, S.R.; Kitchell, J.F.; Hodgson, J.R.; Cochran, P.A.; Elser, J.J.; Elser, M.M.; Lodge, D.M.; Kretchmer, D.; He, X. 1987: Regulation of lake primary productivity by food web structure. *Ecology 68*: 1863–1876.

Chadderton, L. 2003: Management of invasive fish for conservation purposes: striking the right balance? Pp. 71–83 in Managing Invasive Freshwater Fish in New Zealand. DOC workshop, May 2001, Hamilton. (This volume.)

Chadderton, W.L.; Kelleher, S.; Brow, A.; Shaw, T.; Studholme, B.; Barrier, R. 2003: Testing the efficacy of rotenone as a piscicide for New Zealand pest fish species. Pp. 113–130 in Managing Invasive Freshwater Fish in New Zealand. DOC workshop, May 2001, Hamilton. (This volume.)

Davies, W.D.; Shelton, W.L. 1983: Sampling with toxicants. Pp. 199–214 in Nielsen, L.A.; Johnson, D.L. (eds) Fisheries Techniques. American Fisheries Society, Bethesda.

Fabacher, D.L.; Chambers, H. 1972: Rotenone tolerance in mosquitofish. *Environmental Pollution 3*: 139–141.

Garcia-Berthou, E.; Moreno-Amich, R. 2000: Introduction of exotic fish into a Mediterranean lake over a 90 year period. *Archives für Hydrobiologie 149*: 271–284.

Gehrke, P. 2003: Preliminary assessment of oral rotenone baits for carp control in New South Wales. Pp. 143–154 in Managing Invasive Freshwater Fish in New Zealand. DOC Workshop, May 2001, Hamilton. (This volume.)

Gilderhus, P.A.; Berger, B.L.; Lennon, R.E. 1969: Investigations in Fish Control No. 27. Bureau of Sports Fisheries and Wildlife. United States Department of the Interior. 21 p.

Greenbank, J. 1941: Selective poisoning of fish. *Transactions of the American Fisheries Society 70*: 80–86.

Hanchet, S. 1990: The effects of koi carp on New Zealand's aquatic ecosystems. *New Zealand Freshwater Fisheries Report No. 117*. 41 p.

Jackson, C.F. undated: Detoxification of rotenone-treated water. *Technical Circular No. 14*. Management and Research Division, New Hampshire Fish and Game Department and the University of New Hampshire Engineering Experiment Station, New Hampshire, United States.

Jeppesen, E.; Sondergaard, M.; Mortensen, E.; Kristenson, P.; Reiman, B.; Jensen, H.J.; Moller, J.P.; Sortkjaer, O.; Jensen, J.P.; Christoffersen, K.; Bosselman, S.; Dall, E. 1990: Fish manipulation as a lake restoration tool in shallow, eutrophic, temperate lakes. 1. Cross-analysis of three Danish case-studies. *Hydrobiologia 200/201*: 205–218.

Lammens, E.H.R.R. 1988: Trophic interactions in the hypertrophic Lake Tjeukemeer: top down and bottom up effects in relation to hydrobiology, predation and bioturbation during the period 1974–1985. *Limnologica (Berlin) 19*: 81–85.

Lennon, R.E.; Hunn, J.B.; Schnick, R.A.; Burress, R.M. 1970: Reclamation of ponds, lakes, and streams with fish toxicants: a review. *FAO Fisheries Technical Paper 100*. Food and Agricultural Organisation of the United Nations, Rome.

Lintermans, M. 2000: Recolonization by the mountain galaxias *Galaxias olidus* of a montane stream after the eradication of rainbow trout *Oncorhynchus mykiss*. *Marine and Freshwater Research 51*: 799–804.

Lintermans, M.; Raadik, T. 2003: Local eradication of trout from streams using rotenone: the Australian experience. Pp. 95–111 in Managing Invasive Freshwater Fish in New Zealand. DOC Workshop, May 2001, Hamilton. (This volume.)

McDowall, R.M. 1990: New Zealand freshwater fishes: a natural history and guide. Heinemann Reed, Auckland. 553 p.

McQueen, D.J. 1990: Manipulating lake community structure: where do we go from here? *Freshwater Biology 23*: 613–620.

Marking, L.L.; Bills, T.D. 1976: Toxicity of rotenone to fish in standardised laboratory tests. *US Fish and Wildlife Service Investigations in Fish Control Bulletin 72*: 1–11.

Northcote, T.G. 1988: Fish in the structure and function of freshwater ecosystems: a 'top-down' view. *Canadian Journal of Fisheries and Aquatic Sciences 45*: 361–379.

Pihu, E.; Maemets, A. 1982: The management of fisheries in Lake Vortsjarv. *Hydrobiologia 86*: 207–210.

Prejs, A.1984: Herbivory by temperate freshwater fishes and its consequences. *Environmental Biology of Fishes 10*: 281–296.

Rach, J.J.; Luoma, J.A.; Marking, L.L. 1994: Development of an antimycin-impregnated bait for controlling common carp. *North American Journal of Fisheries Management 14*: 442–446.

Richardson, M.J.; Whoriskey, F.G.; Roy, L.H. 1995: Turbidity generation and biological impacts of an exotic fish *Carassius auratus*, introduced into shallow seasonally anoxic ponds. *Journal of Fish Biology 47*: 576–585.

Ross, G. 2000: Pesticides and Parkinson's disease in rats: a valuable study, over-interpreted. American Council on Science and Health editorial. ACSH webpage http://www.acsh.org.

Rowe, D.K. 1999: Prentox®: a method for removing grass carp from lakes. *Water & Atmosphere 7*: 15–17.

Rowe, D.K.; Champion, P.D. 1994: Biomanipulation of plants and fish to restore Lake Parkinson: a case study and its implications. Pp. 53–65 in Collier, K.J. (ed) Restoration of aquatic habitats. Selected papers from the second day of the New Zealand Limnological Society 1993 Annual Conference, Department of Conservation, Wellington.

Schnick, R.A. 1974: A review of literature on the use of rotenone in fisheries. United States Department of the Interior, Fish and Wildlife Service, Wisconsin.

Tompkins, W.A.; Mullan, J.W. 1958: Selective poisoning as a management tool in stratified trout ponds in Massachusetts. *The Progressive Fish Culturist 20*: 117–123.

Walker, K. 2001: Outsmarting carp. Watershed April 2001. Cooperative Research Centre for Freshwater Ecology, Canberra, Australia.

Willis, K.; Ling, N. 2000: Sensitivities of mosquitofish and black mudfish to a piscicide: could rotenone be used to control mosquitofish in New Zealand wetlands? *New Zealand Journal of Zoology 27*: 85–91.