RESEARCH **8**

2017-094

WILL CARP VIRUS BIOCONTROL BE EFFECTIVE?

NATIONAL CARP CONTROL PLAN

Review of carp control via commercial exploitation

This suite of documents contains those listed below.

NCCP TECHNICAL PAPERS

1. Carp biocontrol background
2. Epidemiology and release strategies
3. Carp biocontrol and water quality
4. Carp virus species specificity
5. Potential socio-economic impacts of carp biocontrol
6. NCCP implementation
7. NCCP engagement report
8. NCCP Murray and Murrumbidgee case study
9. NCCP Lachlan case study

NCCP RESEARCH (peer reviewed)

Will carp virus biocontrol be effective?

1. 2016-153: Preparing for Cyprinid herpesvirus 3: A carp biomass estimate for eastern Australia
2. 2018-120: Population dynamics and carp biomass estimates for Australia
3. 2017-148: Exploring genetic biocontrol options that could work synergistically with the carp virus
4. 2016-170: Development of hydrological, ecological and epidemiological modelling
5. 2017-135: Essential studies on Cyprinid herpesvirus 3 (CyHV-3) prior to release of the virus in Australian waters
6. 2020-104: Evaluating the role of direct fish-to-fish contact on horizontal transmission of koi herpesvirus
7. 2019-163 Understanding the genetics and genomics of carp strains and susceptibility to CyHV-3
8. 2017-094: Review of carp control via commercial exploitation

What are the carp virus biocontrol risks and how can they be managed?

9. 2017-055 and 2017-056: Water-quality risk assessment of carp biocontrol for Australian waterways
10. 2016-183: Cyprinid herpesvirus 3 and its relevance to humans
11. 2017-127: Defining best practice for viral susceptibility testing of non-target species to Cyprinid herpesvirus 3
12. 2019-176: Determination of the susceptibility of Silver Perch, Murray Cod and Rainbow Trout to infection with CyHV-3
13. 2016-152 and 2018-189: The socio-economic impact assessment and stakeholder engagement
    Appendix 1: Getting the National Carp Control Plan right: Ensuring the plan addresses community and stakeholder needs, interests and concerns
    Appendix 2: Findings of community attitude surveys
    Appendix 3: Socio-economic impact assessment—commercial carp fishers
    Appendix 4: Socio-economic impact assessment—tourism sector
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    Appendix 9: Engaging with the NCCP: Summary of a stakeholder workshop
14. 2017-237: Risks, costs and water industry response
15. 2017-054: Social, economic and ecological risk assessment for use of Cyprinid herpesvirus 3 (CyHV-3) for carp biocontrol in Australia
    Volume 1: Review of the literature, outbreak scenarios, exposure pathways and case studies
    Volume 2: Assessment of risks to Matters of National Environmental Significance
    Volume 3: Assessment of social risks
16. 2016-158: Development of strategies to optimise release and clean-up strategies
17. 2016-180: Assessment of options for utilisation of virus-infected carp
18. 2017-104: The likely medium- to long-term ecological outcomes of major carp population reductions
19. 2016-132: Expected benefits and costs associated with carp control in the Murray-Darling Basin

NCCP PLANNING INVESTIGATIONS

1. 2018-112: Carp questionnaire survey and community mapping tool
2. 2018-190: Biosecurity strategy for the koi (*Cyprinus carpio*) industry
3. 2017-222: Engineering options for the NCCP
4. NCCP Lachlan case study (in house) (refer to Technical Paper 9)
5. 2018-209: Various NCCP operations case studies for the Murray and Murrumbidgee river systems (refer to Technical Paper 8)

The role of commercial fishing in control of invasive freshwater fish species

Common carp, can we fish them out through overfishing?

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2019

FRDC Project No **[2017-094]**

The role of commercial fishing in control of invasive freshwater fish species: Common carp, can we fish them out through overfishing?

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Executive Summary

Researchers from La Trobe University's Centre for Freshwater Ecosystems, Tasmania's Inland Fisheries Service and the New South Wales Department of Primary Industry-Fisheries collaborated in 2018-2019 to review case studies of invasive fish management using commercial fishing and assess the prospects for overfishing Australian populations of Common carp; identifying factors critical to success.

The objectives of the study were to:

- Review literature on removal of vertebrate pests through commercial exploitation (with emphasis on pest-fish)
- Use CarpSim software to explore the limits of critical factors identified in the literature review, with respect to the control of Carp in Australia through commercial exploitation
- Summarise findings of review (1) and modelling (2) in lay persons terms, in a magazine article, to answer questions such as "Can we just fish them all out with commercial fishing?"
- Prepare and submit a research article based on review (1) and modelling (2) for publication in a peer-reviewed, open-access, scientific journal

Using an existing population model, they simulated commercial fishing methods exploring the limits for successful biomass-reduction or eradication. Common carp are an important invasive pest fish in many countries worldwide. Development of a National Carp Control Plan in Australia means there is a need to evaluate the role commercial harvest can play for control on a continental scale, in an enduring way.

A productivity-susceptibility analysis suggested that Common carp are unlikely to be overfished accidentally or deliberately. Review of published invasive fish control projects using commercial fishing revealed no examples of large-scale, lasting success. Rarely, when in combination with other management methods, commercial fishing has achieved short-term reductions in biomass. Common carp population-simulation models indicated that to achieve eradication, fishing mortality rates (F) were required far exceeding those estimated for existing Australian populations. Temporal refuge or spatial complexity required further increases in F to achieve population eradication. In meta-populations containing an area protected from fishing, eradication was not achieved, and biomass reduction was less effective.

Key aspects of Common carp biological productivity include recruitment- and growth-compensation. Pervasive inhabitation of spatially complex floodplain-wetland and river systems including refuges from fishing reduces the susceptibility of most Australian populations.

Population modelling and the examination of many case studies worldwide does not support the use of commercial fishing as an enduring control at a large scale.

While the researchers conclude that Common carp populations have a strong resistance to eradication, or even to significant long-term biomass reduction, using commercial fishing methods; they point to lessons learned from other invasive-species commercial removal schemes. If management of Common carp proceeds using commercial exploitation, contracts should use significant, staged bonus payment on reaching biologically meaningful harvest-targets and contracted pricing that increases above staged thresholds to achieve harvest-targets. Bonus payments should preferably be on a sliding, reducing scale that encourage increased effort as abundance declines.

Case studies suggest that the use of commercial harvesting to achieve biomass reduction targets is certainly more useful in small, closed populations where juvenile recruitment can also be controlled (e.g. through harvesting) or eliminated. In more open or structurally-complex populations, there are perhaps circumstances where intense harvesting of carp may make sense within an integrated control-plan which also includes biological-control measures; particularly, where there is a high-risk of rapid mortality from biological-control measures causing acute water-quality, or aesthetic air-quality issues. However, the effect of such pre-emptive commercial biomass-reduction on the subsequent transmission rates for virus

vectored biological control should be thoroughly investigated before an integrated control program is considered.

Keywords

Common carp, *Cyprinus carpio*, simulation model, CarpSim, Australia, commercial fishing, invasive, overfishing, population management

Introduction

Common carp (*Cyprinus carpio*) are the third most introduced fish species in the World (GISD 2017) and a widespread and important invasive species in North America, southern Africa and Australasia (Koehn et al. 2000; Winker et al. 2011). The annual economic and environmental impact of Common carp in Australia was quantified in 2004 as $16 Million (McLeod 2004). The benthic feeding behaviour of adults causes declines in water quality, degraded water-plant communities and negatively affected invertebrates and vertebrates including amphibians and waterfowl (Bajer et al. 2009; Vilizzi et al. 2015).

Questions about harvesting invasive fish species as a control-option are not new; they have been asked before about many species (Downey 2017; Hoag 2014; Kuebbing et al. 2013; Nuñez et al. 2012; Petty 2016; Snyder 2017). Worldwide, when faced with problems from invasive fish species the community often suggests commercial fishing as a solution to removing the problem. Modern history is littered with examples of overexploitation leading to the decline of fish stocks (Pauly et al. 2002; Post et al. 2002). Most of these have been 'accidental' over fishing when the actual goal was sustainable fishing. It is understandable why the community should think: "*If we can accidentally overfish valued fish stocks while trying to fish sustainably; it should be easy to deliberately overfish a pest-fish stock*".

Following more than two decades of concerted research and management efforts to control Common carp (Anon 2000; Roberts & Tilzey 1996), in 2016 the Australian Government funded a National Carp Control Plan (NCCP, www.carp.gov.au) to determine how Common carp can be controlled on a continental scale, in a lasting way. An NCCP goal is "…a smart, safe, effective and integrated suite of measures to control carp impacts"; recognizing that eradication is probably impossible given the geographic distribution and population size of carp in Australia. The present review addresses a question identified during the community consultation phase of that plan. "Can we fish them out through overfishing?"

In valued fish populations, overfishing is often due to lack of precautionary management, or poor management decisions based on incorrect assumptions about the size of the stock, the biology of the stock, or the amount of fishing-effort (e.g. how many fishers) (Haddon 2001; Hilborn & Walters 1992). There are three largely accepted forms of overfishing for valued fisheries; growth-overfishing, recruitment-overfishing and ecosystem overfishing (Pauly 1983). Growth-overfishing is when too many individual fish are harvested at a size smaller than the optimum size to provide the overall largest sustainable yield (Silberschneider et al. 2009). Recruitment-overfishing occurs if too many mature adults are harvested to provide enough offspring to subsequently replace the harvest and so recruitment declines proportionally with spawner abundance (Allen et al. 2013). Ecosystem overfishing occurs when intense fishing of large predators causes a trophic cascade leading to altered ecosystem states (Daskalov et al. 2007). Perhaps the first two types of overfishing are more directly relevant to commercial capture of carp. The third type–ecosystem overfishing, may be less relevant for carp in ecosystems with few naturally occurring large-fish predators, such as Australia. Although, the restoration of abundant piscivorous predators is commonly used to assist in suppressing carp populations following bio-manipulation, in USA and at high densities, predators have been shown to exert control over carp recruitment (Bajer & Sorensen 2010; Paukert et al. 2003).

Firstly, we reviewed the research literature on Common carp population biology in invasive populations and looked for case studies of invasive fish management using commercial fishing. We consider to what extent invasive carp populations in Australia match the characteristics of populations likely to be overfished and we identify factors within the case studies critical for success and failure. Lastly, using an existing modelling framework for Carp population and control dynamics, we construct simulations of commercial fishing methods to explore the limits for success (Brown & Gilligan 2014; Brown & Walker 2004).

Objectives

Table 1. Objectives of the project – as agreed in the contract

No.	Detail
1	Review literature on removal of vertebrate pests through commercial exploitation (with emphasis on pest-fish)
2	Use CarpSim software to explore the limits of critical factors identified in the literature review, with respect to the control of Carp in Australia through commercial exploitation
3	Summarise findings of review (1) and modelling (2) in lay persons terms, in a magazine article, to answer questions such as "Can we just fish them all out with commercial fishing?"
4	Prepare and submit a research article based on review (1) and modelling (2) for publication in a peer-reviewed, open-access, scientific journal

Method

Three types of active control target were described as relevant for Common carp by Bomford and Tilzey (1996). Eradication–the complete removal of the population, they suggest has six stringent requirements: Removal rate exceeds population growth at all densities, zero immigration, all individuals must be vulnerable, population monitoring should be possible at all densities, cost benefit analysis favours eradication over control and there should be a supportive socio-political environment.

Strategic control–either one-off, sustained or targeted removal is more common where some of these requirements for eradication may not be met. Here the objective is often to reduce Common carp biomass below a critical habitat-damaging density. Requirements of zero immigration and common vulnerability are often those most-obviously relaxed in many strategic control scenarios. A third type of control, crisis management (Bomford & Tilzey 1996), can perhaps be considered an extension of strategic control, and examples include where 'pulsed commercial fishing' is used to reduce carp biomass below some tolerable limit. These requirements form the initial framework for our success-criteria analysis of the literature.

Literature review and case studies

The scope of case studies for the review includes all incentivised physical harvest (Pasko et al. 2014) of pest-fish. This includes physical removal operations where the operators are agency staff as well as purely 'commercial' contract operators. Some non-fish examples will also be included where the authors consider it beneficial to do so. Many published studies of invasive fish management report the short-term effects (<5 years) and as our NCCP context has long-term goals, where possible we have sought clarification from authors asking whether results were subsequently sustained. Responses are included as personal comments where follow-up publications were not evident (i.e., in most cases).

Search strings constructed by combining subject-terms with action-terms listed in Table 2, were used in two standard search-engines to identify relevant published studies; ISI Web of Science (https://www.webofknowledge.com/), and Google Scholar (https://scholar.google.com.au/).

From the thousands of resulting articles, titles and abstracts were scanned for relevance and further detail was read, if required, to establish whether each publication was within scope and significant. Database searches yielded 85 papers and reports considered significant. Along with useful secondary literature, cited in the initial list, and reverse literature searches from key papers, this list was expanded to 114 sources to review, with 100 references finally being cited in Appendix 3.

In reviewing the literature, we particularly considered pest fish and with emphasis on invasive carp control programs, although not exclusively so. Pasko et al (2014), defined harvest incentives as contract operations, commercial markets, bounty programs or recreational harvest. The distinction being that contractors are paid directly as service providers and commercial operators sell the catch into a market on removing or harvesting the target invasive species. In practice, these distinctions are often blurred by a variety of contractual instruments. Carp management programs contract a commercial operator to provide a certain amount of fishing-effort (e.g. no. of days, or seine-hauls, etc.) and allow sale of harvest. Some programs simply licence an operator to fish the targeted region or waterway and sell the target species on the open market.

Table 2. Literature search criteria used to identify published sources to review the role of commercial or subsidised harvest in control of Common carp.
Subjects and actions were combined in all possible combinations of 'subject' AND 'action'.

Subject	Actions
Common carp, *Cyprinus carpio*, European carp	Fishing, commercial fishing, recreational fishing/angling
Invasive species, pest fish, introduced species	Subsidised, bounty, incentive, reward
Vertebrate pests, invasive crayfish	Trapping, netting, electrofishing, electro-fishing, electric fishing
Specifically (Asian carp, lionfish, arapaima/paiche, tilapia)	Removal, capture, catch, market, cull
	Over harvest, overexploitation

Simulation modelling strategy

The success-criteria identified relating to population dynamics were used to explore sensitivity to successful control using an established carp population model, CarpSim v2.1 (Brown & Gilligan 2014; after Brown & Walker 2004). Sensitivities of model outputs to the identified success-criteria were explored in two carp population modelling scenarios. The base model descriptions are found in Brown & Gilligan (2014) and simulate the Common carp population found in the Lachlan River sub-catchment of the Murray-Darling River system in south eastern Australia. The base model simulates changes in biomass by age-specific density dependant growth and simulates changes in population abundance through recruitment and size-dependant mortality within multiple connected population units. The starting population parameters were estimated for the Lachlan River population and other Australian carp stocks. Natural mortality (M) varies by fish-size throughout the simulations; but for the starting parameters in all simulations M=0.8 for a fish of 200 mm TL.

Simulation of a single, simple, closed population was first used to explore; the required level and duration of harvest, the effect of compensatory recruitment typical of carp populations and the effect of only harvesting adults rather than most age-classes on population viability.

A second simulation of a relatively complex set of connected sub-populations each with different characteristics was used to explore the effect on population viability of spatial complexity and spatial refuge from fishing.

Model 1 is based on the starting parameters for the population simulation in the lower catchment noted as 'zone 4' (Brown & Gilligan 2014), but in this case is modelled as a simple-closed population.

Model 2 is based upon the full simulation of 'zones 1–6' (Brown & Gilligan 2014), a collection of sub-populations connected by fish migration among zones to be a more complex meta-population.

Exploring the required level of harvest

During the simulations, success is defined as eradication, although biomass reduction is also reported, as the percentage of unfished biomass removed, when eradication didn't occur.

Yield (kg/ha) is reported annually and in total for the first five years illustrate the scale of initial commercial harvest achievable at each fishing mortality. In a single zone, treated here as a closed population (no emigration, no immigration), commercial fishing was started 33-years after initial carp introduction, when the population had stabilised. Fishing was simulated at multiple F-values, including the base-level (*F*=0.03), which matches actual efforts and yield reported in (Brown & Gilligan 2014) for Zone-3, a zone where commercial fishing has been practised. Natural mortality for a 200 mm TL fish is 27-times higher than this base level of fishing mortality. Fishing was further simulated at a hypothetical fishing mortality level 10-times higher than base-level; and then at a range of increased hypothetical F-values from the minimum F-value that caused total eradication of carp within the model-run period (167 remaining modelled years). Where simulations result in eradication, the time-to-eradication (population viability) was reported for both 10% (PV0.1) and 100% (PV1.0) of trials. Where simulations resulted in sustained yield but no eradication, we report the approximate biomass reduction.

Exploring the effect of compensatory recruitment

Brown and Gilligan (2014), observed that abundance of carp recruits per spawner and the strength of the density-dependence of that relationship, varied among the zones simulated in the Lachlan catchment. To investigate the sensitivity of population viability to the capacity for recruit-production, to vary according to population density – these fishing simulations were first completed with strong and then with weak-capacity for compensatory recruitment. This was achieved by using parameters for stock-recruitment curves of varying steepness that were fitted to carp abundances observed within zones in the Lachlan catchment (Brown & Gilligan 2014).

Exploring the effect of temporal refuge from fishing

The size at which individual carp become vulnerable to fishing in a simulated population has previously been shown to affect control outcomes (Brown & Walker 2004). Initial simulations (Model 1) were completed using reasonably broad selection where 95% of carp were vulnerable by the end of their first year and all fish potentially can encounter the gear. We explored the sensitivity of population viability to reduced selectivity by repeating a Model 1 scenario under conditions where vulnerability to fishing is delayed until maturity as would be the case where spawning aggregations are targeted.

Exploring the effect of spatial complexity and meta-population structure

First we simulated the six spatially separated sub-population zones as specified in (Brown & Gilligan 2014), with zero-fishing as a base-model. Multiplying the biomass density attained in each zone by the habitat area for that zone provides an estimated total meta-population biomass. Then to each zone we applied the minimum F-value (F=1.2) that resulted in eradication during all Model 1 simulations (above) and the maximum F-value (F=2.0) used in simulations of the simple closed population. The effect of a spatial refuge from fishing was simulated by reducing F to zero in one zone where F=2.0 in all other zones.

Results

Are Common carp in Australia likely to be overfished? A productivity-susceptibility analysis.

Productivity Susceptibility Analysis shows that Common carp score moderate–high on productivity metrics and low–moderate on susceptibility metrics–meaning that they are unlikely or hard to overfish.

Characteristics of fish populations useful to highlight the likelihood of overfishing include the combination of biological productivity and the susceptibility of the population to fishing; i.e., productivity-susceptibility analysis, or PSA (Hobday et al. 2011; Lapointe et al. 2013; Patrick et al. 2010). Fish populations that score low on measures of productivity and high on measures of susceptibility are more at risk of overfishing and therefore may be more vulnerable to deliberate over-exploitation in a pest-fish control context.

Invasive populations of Common carp score moderate–high on productivity metrics (Patrick et al. 2010). They reach a large maximum-size, show rapid growth rates, low natural mortality rates, high fecundity, a frequently successful recruitment pattern, maturity at a young age and occupy a relatively low trophic level (Brown et al. 2005; Khan 2003; Parkos et al. 2003; Phelps et al. 2008; Sivakumaran et al. 2003; Vilizzi & Walker 1999; Winker et al. 2011).

Walker (2005), defined susceptibility of a fish stock to overfishing as the product of availability × encounterability × selectivity. Patrick et al (2010), proposed similar concepts working on U.S. marine fish stocks such that risk of overfishing is heightened by; areal and vertical overlap of the fishery with the fish stock, geographic concentration from seasonal migration or behavioural responses to fishing, and morphological characteristics affecting capture. Additionally, they proposed additional attributes useful to define the susceptibility of fish stocks to overfishing such as; a high value of the fishery, a fishing rate higher than the natural mortality rate and the appropriateness of the management strategy.

Invasive populations of Common carp score low–moderate on susceptibility metrics for existing and historic Australian carp fisheries (Graham et al. 2005; Patrick et al. 2010). Targeted commercial carp fishing largely focusses on a small part of the geographic range of the pest (Forsyth et al. 2013; Graham et al. 2005). This low areal overlap between the distribution of the stock (e.g. most freshwaters in SE Australia,) and the distribution of the main commercial fishery (e.g. Gippsland Lakes, Lake Alexandrina and Lake Albert, (Kailola et al. 1993)) is one reason why the commercial fishery in its present form cannot overfish the population (Patrick et al. 2010). Common carp are also broadly distributed across their range throughout much of each year. Fishing strong aggregations in patches of habitat such as during spawning is another characteristic that could increase the chances of overfishing (Bajer et al. 2011; Johnsen & Hasler 1977; Lechelt & Bajer 2016); but the large populations in south-eastern Australia have many such aggregations that show annual variability; which makes them less reliable as a regional resource (Crook et al. 2013).

Seasonal lateral movements of spawners to and from preferred wetland spawning habitat (Conallin et al. 2012; Jones & Stuart 2009); and flow-related longitudinal movements through fishways (Stuart et al. 2006; Thwaites et al. 2010), may offer opportunities for increasing susceptibility to fishing through heightened availability and/or ‘encounterability’. Selective trap designs are available to sort Common carp from Australian native fish (Stuart & Conallin 2009; Thwaites et al. 2010). Common carp morphology and behaviours also make them highly susceptible to electrofishing (Bajer & Sorensen 2012); gill-nets– because of their barbed dorsal and anal fin-spines (Graham et al. 2005) and seine-nets when schooling in open lakes (Kailola et al. 1993).

The value of invasive Common carp fisheries is relatively low (FRDC 2017). Low-value fisheries have reduced risk of overfishing (Patrick et al. 2010). Catch and value statistics are no-longer published for the few remaining commercial Carp fishers due to client-confidentiality policies (Savage 2015). However, a recent feasibility study for a commercial carp fishery in a sub-catchment of the Murray-Darling River system used price estimates of \$0.70–\$1.20 kg^{-1} for whole fish and 'fertiliser' into the domestic market; and exports of carp and carp roe between \$2.90 and \$7.00. These estimates were provided by commercial fishers, and based on an annual catch of 300 tonnes, in 2011 (GHD 2011). An estimate of the size of the existing Australian domestic market for whole fish is approximately 50–100 tonnes annually at \$1.50–\$3.00 kg^{-1} (Keith Bell, K & C Fisheries Global Pty Ltd. Pers. Com.)

For, invasive carp populations in Australia, as a risk factor for overfishing, fishing mortality (*F*) has not been estimated across most of the geographic range. However, in one area that was subjected to significant commercial harvest, the Barmah-Millewa Forest, Brown et al (2005) estimated using a combination of age-frequency analysis and empirical methods that *F*-values ranged from 0.05 to 0.3 and that in most cases, *F* was unlikely to exceed the natural mortality rate (*M*).

The type of management strategy for the fishery is clearly an important context; what is perhaps less clear is whether PSA can inform the likelihood of *deliberate* overfishing as a preferred outcome for invasive Common carp management. This combination of moderate–high productivity albeit with moderate–high susceptibility certainly suggests that invasive Common carp populations are unlikely to be 'accidentally' overfished. From this we can probably infer that deliberate overfishing may be difficult. While PSA can perhaps guide how susceptibility should be maximised in a Carp management program; no management strategy can affect the underlying productive nature of invasive Common carp populations, which is a root-cause of difficulties in using commercial fishing techniques to effectively control the population.

Case studies

A review of fish control projects in the U.S. in 1996 examined 250 control projects including 70 that used physical removal and reservoir drawdowns to control unwanted fish species. Unwanted species included Common carp along with a list of 30 other 'non-game fish' species and also stunted populations of 15 species of 'panfish.' Meronek et al. (1996), defined success variously and broadly, although reduction in standing stock was the most common determinant. Most projects studied were relatively short-term in nature and the authors concluded that success was achieved if there was evidence of improvement over periods exceeding 1-year. Of these 70, between 33% and 57% achieved success with 'commercial gear' such as seines, nets, traps or electrofishing.

Eleven representative case studies were identified in the literature and summarised in (Table 3) and Table 4). These include five representative management projects utilizing commercial removal methods for Common carp (Table 3); one at a catchment scale and four in closed, large-lake populations. Table 4, also includes some insightful invasive vertebrate removal-management projects, targeting animals other than Common carp. While the theoretical study of these Common carp management practices yields information about the circumstances in which they might be used for population-control (Bajer et al. 2011; Brown & Gilligan 2014; Lechelt & Bajer 2016; Mattingly & Kevern 1979; Simpson et al. 2017; Weber et al. 2011; Weber et al. 2016); in practice we could find no published examples of large-scale, lasting success.

Recent examination of Common carp population trends in 1300 km of the Upper Mississippi River, USA, revealed by a two standardised, long-term (i.e., 30 & 60 years) monitoring programs, concluded that there was no evidence to support the role of management activities aimed at eradication or severe reductions (Gibson-Reinemer et al. 2017). These activities included large commercial fisheries which harvested between 1.5 to 3.1 Million kg of carp per year between 1900 and 1981 (Lubinski et al. 1986). In the Lachlan River catchment, in Australia's Murray–Darling Basin, an ambitious plan to develop an integrated set of removal methods for Common carp control including commercial fishing, did not succeed (Gilligan et al. 2010). The feasibility study developed for the commercial harvest of Common carp in that catchment predicted that the annual commercial harvest rate of 300 tonnes that was the threshold for commercial viability, represents only ~5% of likely carrying capacity (GHD 2011). A simulation study, of all the existing and planned management activities within that catchment concluded that in combination, the proposed removal methods (e.g. commercial fishing and trapping) would only reduce biomass by 48–52% over a 70-year period (Brown & Gilligan 2014).

On a smaller scale, two projects in Iowa, USA, are perhaps representative of a typical lake management practice across the USA (Table 3). In the USA, in contrast to Australia, commercial fisheries for Common Carp (and other freshwater species) are well-established and commonly used to assist the management of more valued fish and wildlife species (Lubinski et al. 1986; Meronek et al. 1996). Commercial fishing at Clear Lake had varied success in achieving the required harvest-targets and the biomass-target was not achieved. At Lost Island Lake, innovative bonus schemes promoted success through incentivising adequate fishing effort and timely action from the commercial fishers (Table 3).

Another innovative bonus incentive was employed in the successful control of Nutria (*Myocastor coypus*), an invasive aquatic mammal in the U.K (Table 4). To overcome the natural reluctance of trappers to work themselves out of a job, contracted trappers were rewarded for increasing their effort as the population declined (Gosling & Baker 1989). Trappers were provided with substantial salary bonuses (of up to three times their annual salary), if eradication was achieved within six-years. After six years the bonus value declined until it was capped at ten-years. Eradication was achieved after nine years.

The varied success reported in the Tasmanian examples (Table 3), reflects the differing ability to control recruitment in two similar lakes. In Lake Crescent, where water levels were able to be managed to limit spawning habitat–the intensive, integrated program of commercial-scale fishing effort has led to eradication of Common carp. Sporadic spawning success in the neighbouring Lake Sorell has left cohorts of recruits that have delayed, and may yet prevent, eradication (Table 3).

Table 3. Case studies: Examples of successes and failures using removal of Common Carp, with key success criteria driving outcomes

Target	Method	Management objective	Removal Outcome	Reference	Population open or closed	Success-criteria
Common carp, Upper Mississippi River, USA	Commercial harvest (various methods)	Initially none, or fishery development – later control	Unsuccessful	(Gibson-Reinemer et al. 2017; Lubinski et al. 1986)	Open	Massive commercial fishery harvesting between 1.5 and 3.1 Million kg annually before 1980s. Recent decline in population but no evidence to support the role of harvesting in that decline. Chemical contamination, market forces and biological factors thought to lead to decline in fishery from 1970s. Recent fishery-independent monitoring data suggests recruitment also became sporadic around the same era and suggest cause is disease related.
Common carp Clear Lake, Iowa, USA	Pulsed Commercial harvest (with harvest targets), minimisation of recruitment (marsh restoration)	Control, to biomass target 100kg ha^{-1}	Unsuccessful	(Colvin et al. 2012)	Closed	The current common carp removals on Clear Lake have not been large enough to make population level changes to the fishery. In most seasons the commercial angler removes between 50,000 lbs - 125,000 lbs which is likely only 10%-20% of the population. No recent population estimates but authors speculate that the carp populations have risen slightly since the original work.(Pers. Comm. M. Hawkins, District Fisheries Biologist IDNR, 2017).
Common carp, Lakes Herman, Madison and	Trap nets and multi-panel mesh nets.	Control (Hypotheses investigated effect of exploitation	Unsuccessful	(Weber et al. 2016)	Closed	Survival rates of common carp were reduced through exploitation rates of up to 43%, however population abundance, recruitment and

Brant South Dakota, USA		on growth, recruitment, survival and abundance)				growth remained stable due to compensatory processes.
Common carp Lost Island Lake, Iowa, USA	Contract operation using commercial fisher + stocking predators + habitat management	Control, to biomass target 112 kg Ha^{-1}	Successful	Mike Hawkins, Iowa DNR, pers. Comm.	Closed	Commercial fishing-effort and harvest targets with cash bonuses for achieving targets on time have succeeded in reaching a target biomass-threshold for habitat damage (112 kg/Ha) (Mike Hawkins, Iowa DNR, pers. Comm.) The contract for a commercial fisher in 2010 stipulated a minimum of 15 seine hauls or a harvest target of 90 tonnes and a price of USD$0.33/kg for each kilogram harvested over 90 tonnes. In addition, USD$8000 and USD$12,000 bonuses were offered for reaching 136 tonnes and 181 tonnes, respectively. Consequently, a harvest of 196 tonnes of carp was achieved in 2010. Stock-enhancement of predatory game fish and habitat management has minimised subsequent recruitment and to 2016, annual surveys of Carp population abundance confirmed the maintained trend for low carp density.
Common carp, Lachlan River catchment, Australia	Contract operation + commercial fishing	Control to biomass target 75-90% reduction	Unsuccessful	(Brown & Gilligan 2014; GHD 2011; Gilligan et al. 2010)	Open (closed on a catchment –scale)	Removal rate less than rate of population growth Target to reduce population biomass by 75–90% (i.e., below ecologically damaging biomass thresholds) unlikely to be achieved using removal methods such as trapping and commercial fishing (Brown & Gilligan 2014; Gilligan et al. 2010). Predicted annual commercial harvest rate of 300 tonnes represents only ~5% of likely carrying capacity (GHD 2011). Commercial fishing/trapping has been

						sporadic since 2010 (M. Asmus, NSW DPI, Pers. Comm.)
Common carp, Lake Crescent, Tasmania, Australia	Contract operation (multiple methods) and trapping	Eradication	Successful	(Diggle et al. 2004; Donkers et al. 2012; Wisniewski 2009)	Closed	Contained by fine-mesh screens upstream and downstream– a closed system. Managed water-levels maintain spawning prevention. Optimising fishing with a range of integrated techniques (e.g., Judas carp, gear selectivity known etc,) Population estimation through mark-recapture. Cost efficiency (vs Cost of failure) high. Maintaining socio/political support.
Common carp, Lake Sorell, Tasmania, Australia	Contract operation (multiple methods) and trapping	Eradication	Unsuccessful to date, but ongoing	(Inland Fisheries Service 2016)	Closed	Factors similar to those for Lake Crescent except for incomplete spawning-prevention, recruitment events have occurred sporadically (last major one in 2009) and offer significant. setbacks

Table 4. Case studies: Examples of successes and failures using removal of other invasive vertebrate pests, with key success criteria driving outcomes

Target	Method	Management objective	Removal Outcome	Reference	Population open or closed	Success criteria
Nutria, (aquatic mammal), UK	Contract operation	Eradication	Successful	(Pasko et al. 2014)	Open	Limited geographic spread. Good understanding of population ecology Population and control simulations estimated effort and duration required. Bonus scheme rewards increasing effort as population declines (bounty + salary bonus for timely eradication
Feral cat, *Felis catus,* (mammal), Macquarie Island.	Contracted trapping/shooting	Eradication	Successful	(Bergstrom et al. 2009; Parks and Wildlife Service 2014)	Closed	Island population. Removal rate exceeded reproduction rate Small population (~2000 cats killed in 15 years).
Asiatic topmouth gudgeon, *Pseudorasbora parva*, (freshwater fish) UK	Contract operation + follow-up piscicide treatments	Control	Successful	(Britton et al. 2010)	Closed	Method effective against all life-stages and deployed at vulnerable stages in life-cycle. Biomanipulation using mass removal with seine nets. Regular cropping of adults prior to spawning) and juveniles (young-of-year). Small ponds only. Reduced population density by >99% over 2-years. Follow-up treatment with piscicide later eradicated this population following revaluation of objectives. (Dr Rob Britton, Bournemouth University, Pers. Comm.)

Peacock hind (Roi), *Cephalopholis argus*, (marine fish), Hawaii, USA	Contract operation & Recreational fishing, Community-event fish downs	Control	Scale-dependant success: successful population control at patch-reef scale.	(Giddens et al. 2014; The Nature Conservancy 2016)	Open	Feasibility of active removal of >90% population by spearfishers (freedivers followed by SCUBA) is proven on open populations on patch reefs (1-2 Ha). Slow recruitment and re-colonisation rates enable low densities to be maintained by ongoing removal efforts Costs estimated at USD $400–$1400 per hectare
Indo-pacific Lionfish (*Pterois volitans/miles* complex), (Marine fish) Carribean and Atlantic coast USA	Community-event fish downs, Contract operations	Control	Success variable: Scale-dependant. Successful population control at patch-reef scale.	(Green et al. 2014; Hare & Whitfield 2003; Hoag 2014)	Open	Culling by divers on patch reefs was effective in reducing population densities below ecologically damaging thresholds over 18-months Suppression of population density achieved until a stochastic weather event (Hurricane Irene)
	Experimental removal (simulating Contract operations)		Unsuccessful at patch reef scale following hurricane Irene.	(Smith et al. 2017)	Open	Following hurricane, densities greater on culled-reefs than controls

Rainbow smelt, *Osmerus mordax*, (Freshwater Fish), Wisconsin, USA	Contract operation	Control	Unsuccessful population control	(Gaeta et al. 2015)	Closed	Fished adult spawners for 9-years attempting recruitment-overfishing. Also increased predation of target species by stock-enhancement and restricted harvest of large predators, attempting biocontrol. Strong compensatory recruitment dynamics occurred at low spawning stock densities. Unpredictable spawning behaviour made success of recruitment-overfishing variable

Based on results of Success Criteria Analysis from case studies in the literature it appears that the following criteria are important in driving success:

1. Achieving a high enough exploitation rate through appropriate levels and duration of effort (Productivity)
2. Commercial viability or the budget available for subsidy and its use in managing declining cost-benefit near completion (Susceptibility)
3. Accessibility/vulnerability of the whole population and absence of temporal and spatial refuge from fishing (Susceptibility)
4. Spatial complexity/connectivity and temporal variability in abundance (Susceptibility)
5. Population traits (e.g. recruitment compensation)(Productivity)

Four out of five success criteria are examined further below using simulation modelling. The commercial viability and subsidy-budget question is beyond the scope of this simulation analysis. Although, it is seems clear from some of the case studies, that innovative commercial contracts can help incentivise commercial fishers to increase fishing effort as abundance declines. Financial bonuses on reaching clear harvest targets; or on a sliding scale that decrease over-time have clearly helped some invasive animal control programs achieve success (Mike Hawkins, Iowa DNR, pers. Comm.; Pasko et al. 2014).

Model simulation results

Model 1: Simple closed population. The required fishing mortality for eradication and sensitivity to recruitment compensation.

A closed carp-population was parameterised with relatively strong compensatory recruitment. A ten-fold increase in the existing estimate of fishing mortality produced a 5-year yield of 337 tonnes and was able to reduce the population biomass by 49% yet did not result in eradication (

Figure 1). At increasing F-values at least 40-fold higher than estimated existing levels of fishing mortality (F=1.2), reducing yields indicate signs of overfishing starting to occur which did result in eradication during the model run period (200 years). However, eradication would take approximately 20-years at sustained hypothetical F-values over 66-fold higher than estimated existing levels of fishing-mortality.

If the same closed carp-population is parametrised with relatively weak compensatory recruitment, the effects of commercial harvest are stronger (

Figure 2). A ten-fold increase from base level fishing mortality now produced a lower 5-year yield of 217 tonnes and an 82% reduction in population biomass. Eradication was possible within the modelled period with a lower F-value (F=0.5) and within approximately 20 years using an F-value equivalent to 40-fold higher than the base value, and approximately 10 years with an F-value 60-fold higher than base levels.

Temporal refuge from fishing

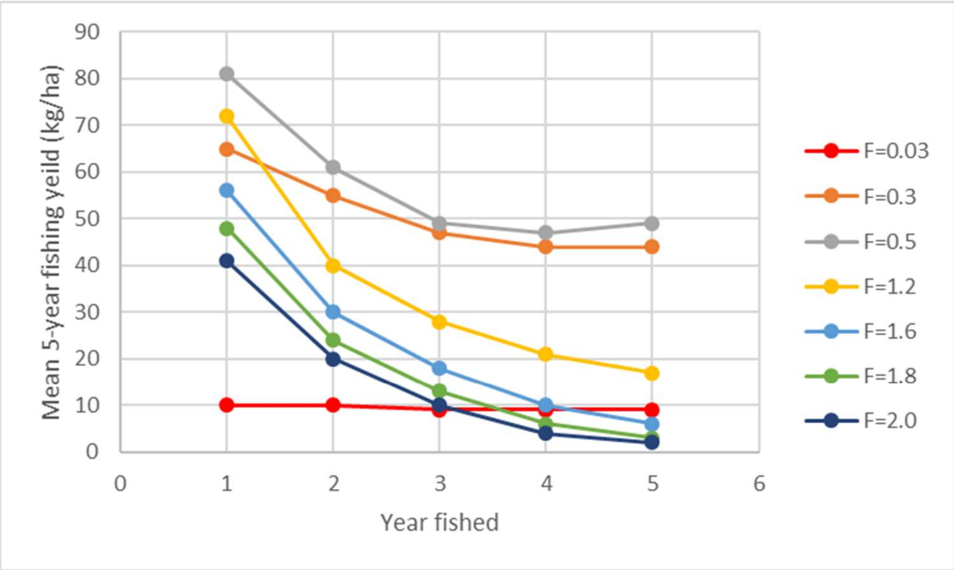
Delaying vulnerability to fishing until size-at-maturity, even for the carp population with weak compensatory recruitment, substantially reduced the useful-impact of fishing. The stock could no longer be eradicated with F-values greater than 40-fold higher than estimated existing levels of fishing mortality (F=1.2) although the biomass was reduced by 92%.

Model 2: Complex connected metapopulation.

Sensitivity to spatial complexity and refuge from fishing

The base-model of six, connected sub-populations with zero fishing effort in any zone simulated a meta-population that plateaued at a biomass of approximately 7500 tonnes of carp across a total habitat area of 26,666 Ha. However, in 100 trials of Model 2, applying fish effort across the whole meta-population at an F-value which was sufficient to eradicate a simple-closed population (F=1.2), no-longer resulted in eradication (

Figure 3). The more complex stock-structure is much less sensitive to fishing. After 167 years of fishing in every zone, at the rate that resulted in eradication in our previous simple, closed-population, the remaining biomass in the final model-year (year 200) was between 3 x 10^{-8} kg ha^{-1} and 0.66 kg ha^{-1} across zones 1–6 and represented a final average removal of 99% of the biomass. The uniform application of the maximum F-value (F=2.0) to all zones, did result in eradication in at least 10% of trials (PV0.1) after 27 and 100% of trials (PV1.0) after 28 years. However, when a partial spatial refuge from fishing was introduced (in this example, in zone 6) eradication was no longer achieved and biomass-reduction declined to 72%.



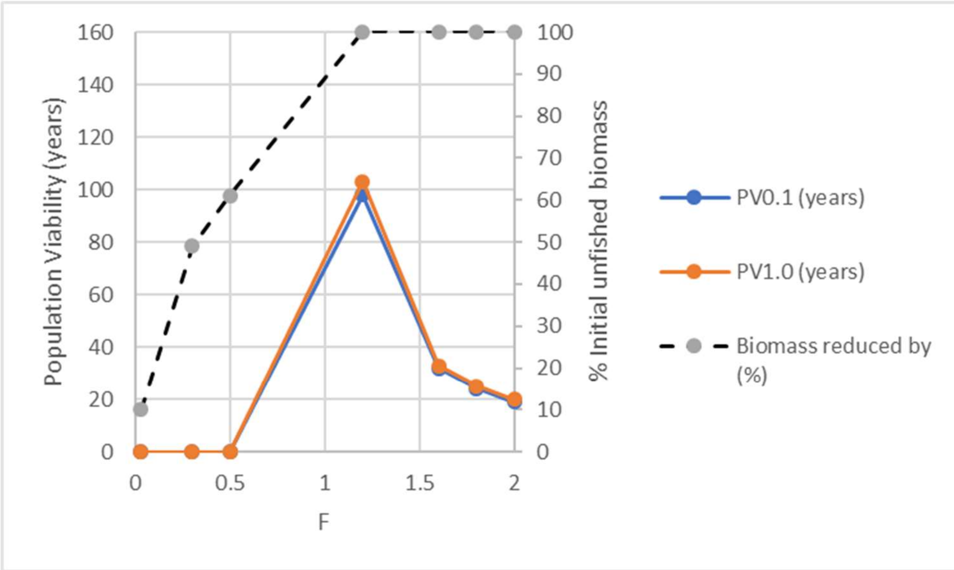
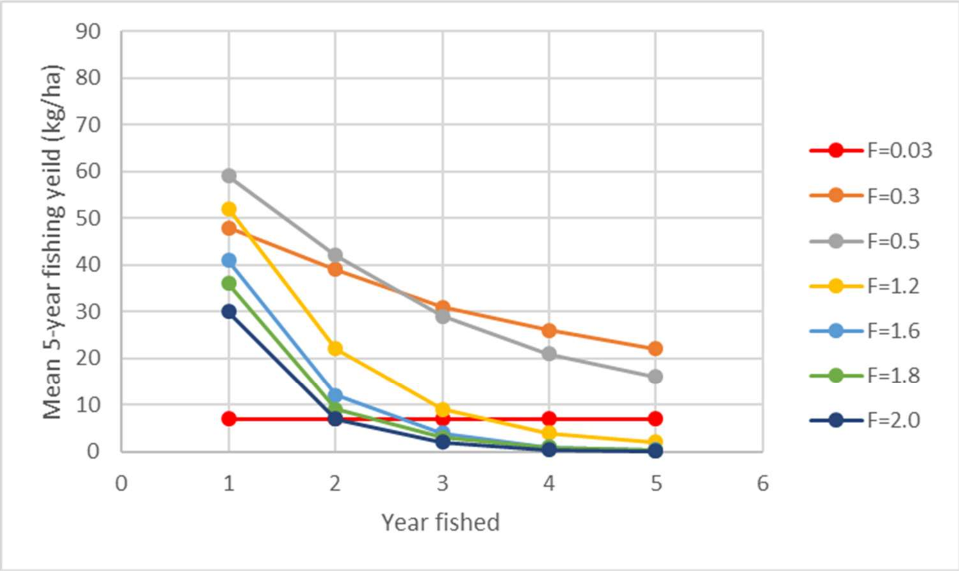


Figure 1 Fishing yield (left), population viability and biomass reduction (right) in a simple, closed carp population parameterised as in Brown & Gilligan (2014) where the Zone 3 population shows strong compensatory recruitment (α=34.7, β=0.0191).
Outputs from Model 1 of a 1331 ha habitat in the Lachlan River catchment (n= 100 trials). Population viability (right) is reported as years of fishing until eradication for at least 10% (PV0.1) and 100% (PV1.0) of trials. Biomass reduction is the % of unfished biomass removed. Simulated mean fishing yield for the first five fished years (left). Results for a range of F values including F=0.03 representing estimated historic management efforts, F=0.3 a ten-fold increase in fishing mortality and example values of F≥1.2 that led to eradication within the simulation. (See appendix 2. Table 5 for data table).



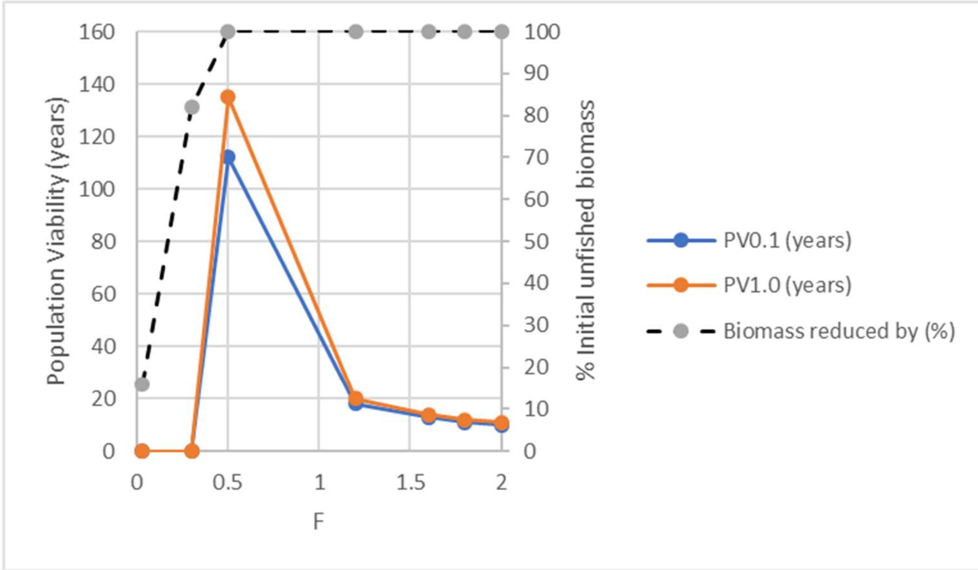


Figure 2. Fishing yield (left), population viability and biomass reduction (right) in a simple, closed carp population parameterised as in Brown & Gilligan (2014) where the Zone 3 population shows weaker compensatory recruitment (α=4.1, β=0.0162).
Outputs from Model 1 of a 1331 ha habitat in the Lachlan River catchment (n= 100 trials). Population viability (right) is reported as years of fishing until eradication for at least 10% (PV0.1) and 100% (PV1.0) of trials. Biomass reduction is the % of unfished biomass removed. Simulated mean fishing yield (left) is for the first five fished years. Results for a range of F values including F=0.03 representing estimated historic management efforts, F=0.3 a ten-fold increase in fishing mortality and F≥0.5 that led to eradication within the simulation. (See appendix 2. Table 6 for data table).

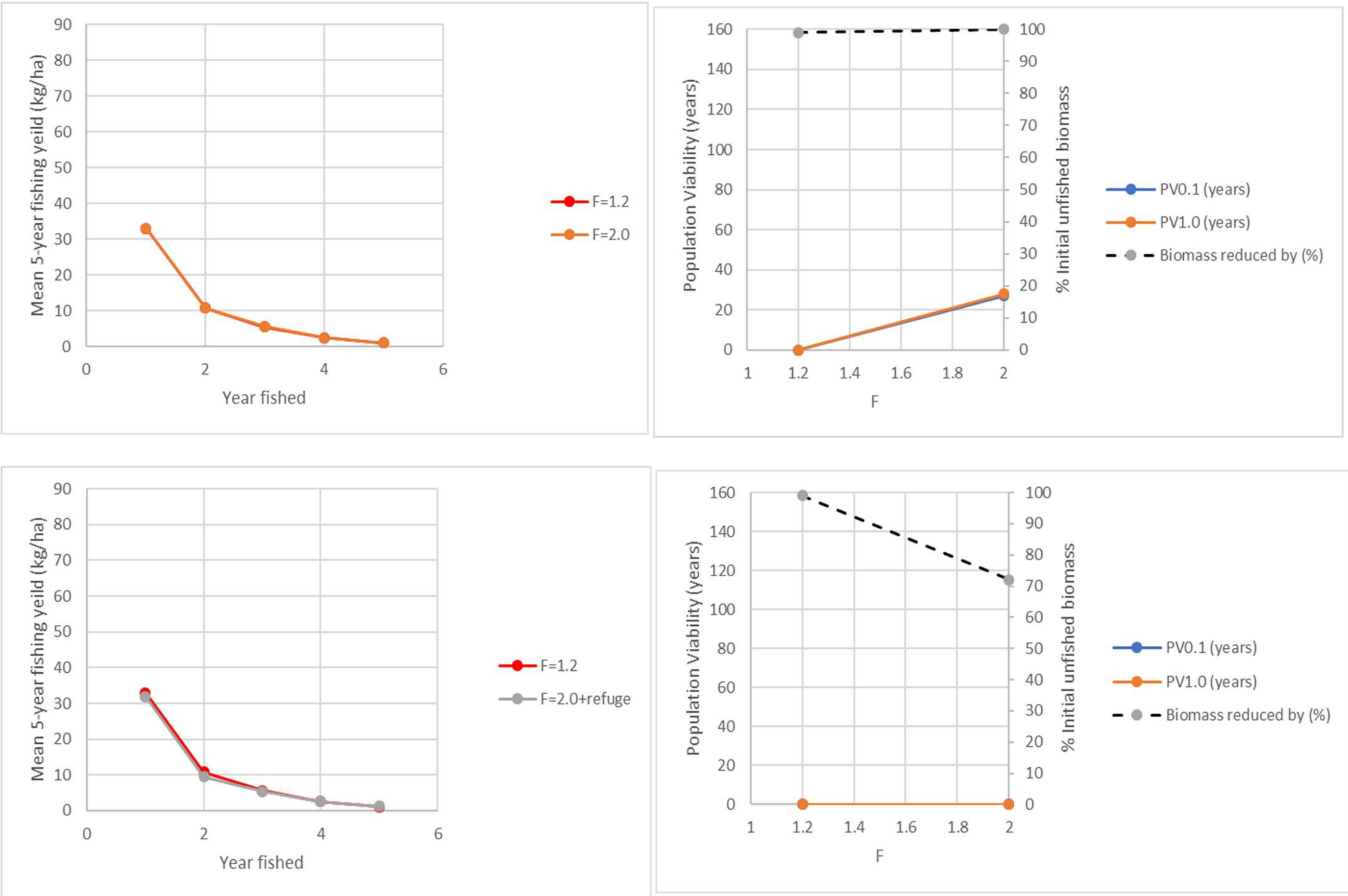


Figure 3. Fishing yield (left), population viability and biomass reduction (right) in a spatially complex metapopulation of six zones, with the carp population parameterised as in Brown & Gilligan (2014) with uniform fishing mortality (F) applied to each zone and showing the effect of refuge.
Outputs from Model 2 of a total of 26,666 ha of habitat in the Lachlan River catchment (n= 100 trials). Population viability is reported as years of fishing until eradication for at least 10% (PV0.1) and 100% (PV1.0) of trials. Biomass reduction is the % of unfished biomass removed. Simulated mean fishing yield (kg ha-1) for the first five fished years. Results in upper panels for F values, F=1.2 and F=2.0 representing minimum and maximum value trialled at which eradication achieved for model 1 (

Figure 1 and

Figure 2) and in lower panels F=2.0+refuge with a single zone (e.g. zone 6), where F=0. (See appendix 2. Table 7 for data table).

Discussion

The biology of susceptibility

Productivity-susceptibility analysis shows that Common carp score moderate–high on productivity metrics and low–moderate on susceptibility metrics–meaning that they are unlikely or hard to overfish. Bomford and Tilzey's (1996) first criteria for judging if eradication of a vertebrate pest is possible, is that the *removal rate should exceed the rate of population growth at all population densities*. This can also be extended to be useful criteria to judge whether strategic control measures are likely to succeed. Patrick et al. (2010), suggested that a risk-factor for susceptibility to overfishing is when fishing mortality (*F*) exceeds natural mortality (*M*). Colvin et al (2012) use the ecotrophic coefficient (EC), defined as the ratio of biomass harvested to biomass produced over an annual period, as a metric to develop harvest targets for pest fish. Their simulation analysis of a 70-year data set of commercial carp data from Clear Lake (1500 Ha) in Iowa, suggests that an EC > 0.76 is required to result in declining biomass; that is an average harvest each year of >76% of the biomass produced that year through growth and recruitment. Recent discussions with the authors suggest that despite the harvest-targets, subsequent commercial carp harvests have been insufficient to make population level changes. "In most seasons the commercial fisher removes 22–57 tonnes which is likely to be only 10-20% of the population, equating to an EC of 0.4–0.95. Additional management options have since also included biomanipulation (carp removal in 2000, 2012 and planned again in 2017) and restoration of wetting and drying regimes and promotion of watering regimes that are conducive to winter-kill in a large adjacent marsh (Ventura Marsh – 160 Ha), thought to be the primary source for carp recruitment. The Clear Lake carp population appears to have remained relatively stable during this period and the current carp removals on Clear Lake have not been large enough to make population level changes to the fishery" (Mike Hawkins, Scott Grummer & Mike Colvin, Iowa DNR, Pers. Comm.). At the nearby Lost Island Lake, management has been more successful with low densities of Common carp achieved during 2010–2016. Again, commercial fishing was used to initially reduce the Common carp biomass; but here, the use of an innovative contract arrangement with cash-bonuses for achieving harvest-targets by set-dates, provided the incentive for continued removal of biomass in a declining population. Following initial biomass reduction the stock-enhancement of predatory game fish and habitat management has commenced and so-far, subsequent recruitment is minimal (Mike Hawkins, Iowa DNR, Pers. Comm. 2018)

Factors in pest populations that make these removal-rate criteria hard to satisfy are that removal rates typically decline at low population densities (Thresher 1997; Weber et al. 2011); and density dependant growth, fecundity, and juvenile survival rates all often increase as the population density declines (Lorenzen 1996; Sehgal & Toor 1995; Weber & Brown 2013). Commercial fishing, or removing pest-fish by any method from well-established populations, is likely to bring the population density below its 'carrying capacity' for the available habitat. For another invasive fish species, Pumpkinseed (*Lepomis gibbosus*) in France; where fishing removed large individuals, medium-sized individuals proliferated through improved survival, so that total population abundance didn't change as fishing pressure increased (Evangelista et al. 2015). Similarly, the experimental removal of smallmouth bass (*Micropterus dolomieu*), from a Canadian lake over seven years reduced the overall biomass of bass, but changed the demographics of the bass population by increasing the abundance of juveniles (Weidel et al. 2007; Zipkin et al. 2008). The authors concluded that continuing deliberate overexploitation of adult smallmouth bass was required to prevent the population exceeding the pre-removal density.

This overcompensation is more likely in fish populations with high fecundity and early maturation (Zipkin et al. 2009) and both factors are applicable to most Australian Common carp (Sivakumaran et al. 2003). Carp have shown compensatory or density-dependant characteristics in India and the USA (Sehgal & Toor 1995; Weber & Brown 2013; Weber et al. 2016). Under fishing pressure the populations respond through individuals growing faster due to less competition for food (Weber &

Brown 2013). Juvenile survival rates increase through outgrowing their predators quicker and staying in peak physiological condition (Lorenzen 1996). Populations with abundant, fast growing carp will mature and reproduce at a younger mean age and so population reproductive-rate can increase (Sehgal & Toor 1995). Large mature females in peak physical condition produce more eggs per kilogram of female with bigger eggs (Sivakumaran et al. 2003), that hatch bigger larvae, which in-turn promotes survival (Weber & Brown 2012).

Most, mainland invasive populations of Carp in Australia have been established long enough to be considered in equilibrium with the carrying capacity of their habitat. Such populations are likely to respond to harvest by growth- and recruitment-compensation resulting in relative abundance of juveniles higher than pre-removal densities. Populations less likely to do so, or to show weaker growth- and recruitment compensation may be those where fecundity and/or recruitment is low, where maturation is delayed or where densities are well below carrying capacity for the habitat, e.g., new populations. In the cooler climate of Tasmania's highland lakes growth is slower (Donkers 2004; Vilizzi & Walker 1998), maturation later and fecundity lower (Donkers 2004), than most Australian mainland stocks (Brown et al. 2005; Sivakumaran et al. 2003); making density-dependant growth-and recruitment-compensation less likely. In the Tasmanian case (Diggle et al. 2004; Wisniewski 2009), all of the criteria identified as essential for eradication success are present or highly likely to be present (Bomford & Tilzey 1996). For example, the benefits of eradicating carp from Lakes Sorell and Crescent are likely to outweigh the cost of likely colonisation of the rest of Tasmania's freshwater systems if the target was one of population control. Further north, on mainland Australia, growth- and recruitment-compensation is much more likely due to higher growth rates (Brown et al. 2005; Vilizzi 1998), earlier maturation and higher fecundity (Brown et al. 2005; Sivakumaran et al. 2003) in warmer climate zones. As our model scenarios show, this potential for growth- and recruitment-compensation makes Australian carp stocks resistant to control through deliberate overfishing.

Simulations in a simple closed population show that commercial fishing can only achieve eradication if fishing mortality is increased to 40–70 times the F-values that are likely to represent actual recent fishing-efforts and approximately 1.5–2.5 times the natural mortality value (for a 200 mm TL fish). The recruitment-compensation levels representative of Australian mainland carp stocks and spatial-complexity typical of the population, increases resistance to eradication prolonging the duration of effort required to eradicate a population. Offering a size-refuge by targeting only larger individuals or a spatial-refuge by not fishing in all areas made eradication impossible and reduced the overall biomass-reduction that could be achieved.

In spatially complex populations, the movement of individuals between zones acts as a buffer against the effects of exploitation. As any given stock nears eradication, some of the individuals can 'escape' through random movement to neighbouring zones. Due to differences in habitat areas modelled exploitation-pressure is different among zones at our modelled uniform-F. In spatially complex populations, it should be possible to have a range of extremely high F-values, differing across zones, which would result in eventual eradication; however, this model scenario illustrates that these are likely to be even higher on average than that required to eradicate a simple, closed population.

Incentivising community driven solutions

Indo-pacific Lionfish (*Pterois volitans/miles* complex), were first observed to have invaded the western Atlantic in 1995. In 2003, the initial integrated assessment of the introduction of Lionfish (*Pterois volitans/miles* complex) to the Western Atlantic seaboard of the USA stated that "Removing lionfish from the southeast United States continental shelf ecosystem would be expensive and likely impossible" (Hare & Whitfield 2003). After considering a bounty system to encourage the removal of fish unviable, the authors considered Lionfish populations as too well established over too wide a distribution and were essentially advocating a "do-nothing" policy in terms of population control. More recently, researchers and local communities have compiled evidence that Lionfish population control is achievable at a local scale (Hoag 2014), with regular targeted culling from spearfishing competitions reducing densities to below thresholds causing ecological damage, and leading to recovery in reef fish communities (Green et al. 2014). Strategic, ongoing control of Lionfish may offer hope for management of reefs in high conservation-value, marine protected areas. An updated integrated assessment (Morris Jr & Whitfield 2009), also supports the development of harvest pressure through promoting human consumption of lionfish. For many, “success” to date has been the removal of lots of lionfish and development of awareness in the community (Chapman et al. 2016), but as with many emerging invasive fish control programs, a long-term solution for true, population-scale control, has yet to be realised.

The Peacock hind (Roi), *Cephalopholis argus*, is a marine reef fish introduced to Hawaii in 1956 from Mo’orea and now regarded as an undesirable invasive species due to its predation on small endemic reef fish species and the tendency for it to become toxic due to the build-up of Ciguatoxin in its tissues (Randall 1987). Recently, active control by removal methods has again been driven by community groups, often with little incentive other than good-will. The feasibility of active removal of >90% population by spearfishers is proven on open populations on patch reefs (1-2 Ha) (Giddens et al. 2014). For Roi, slow recruitment and re-colonisation rates has enable low densities to be maintained by ongoing removal efforts at a patch-reef scale. Costs estimates range from USD $400–$1400 per hectare (The Nature Conservancy 2016).

For invasive Common carp populations, vulnerability to community based fishing solutions seems limited. Large numbers of Common carp are often removed in fishing competitions (Atchison et al. 2017) as such events are purposely targeted at areas with high carp abundance. Evaluation against population size has shown this not to be effective in reducing population size significantly (<2%) (Norris et al. 2013) despite the incentives of prizes offered. In two years, recreational anglers fishing on the 1500 km of the Murray River and its Victorian tributaries were estimated to have caught and removed almost 60 tonnes of Common carp, mainly as by-catch when targeting native species (Brown 2010). This figure is probably indicative of ‘background’ fishing mortality across the more accessible reaches of the Murray–Darling Basin and as such has been ineffective at reducing Common carp populations.

Incentivising for success

Consideration of market forces can be important in attempts to manage pest fish populations through overexploitation. Pasko et al (2014), reviewed the role of harvest incentives and tabulated “favourable” and “unfavourable” characteristics to establish an effective harvest incentive program for an invasive species. Invasive carp populations arguably satisfy 3 out of 13 of characteristics favourable for effective harvest incentive programs; they are easily identified; a low risk to human health or safety in the handling, use or consumption of Carp; and, at least in Australia, there is strong public support for control of Carp. However, Carp also satisfy 7 (also out of 13) characteristics unfavourable for effective harvest incentive programs; they disperse long distances and have a wide geographical range; they are cryptic (or, “hidden from view”); they live in isolated, remote environments (e.g.,across almost the entire Murray-Darling Basin in Australia); changes in their population density cannot be (*sic*, easily) estimated; it is likely that support for the program would diminishes as Carp density and impacts decrease; it is hard to prevent wilful introduction or re-introduction as Carp are robust and easily transported; and demand for the target species is low or limited.

Pasko et al. (2014) also recommended that successful incentivised harvest management plans for invasive fish should understand and consider the capital costs of setting up trapping and harvesting infrastructure and the hidden cost of administering a commercial or recreational harvest. Such plans should develop an understanding of what proportion of the biomass must be removed annually to achieve the control objectives (Brown & Gilligan 2014; Weber et al. 2011); and of the consequences of under-harvesting this annual quota (Gaeta et al. 2015). The harvest program should be monitored for counter-productive behaviours and unintended outcomes, such as commercial breeding the pest-fish in captivity, intentionally introducing the fish into new areas or deliberate under-harvest to protect the resource sustainability. This also includes preventing deliberate or accidental reintroductions into the management area that will thwart exploitation-based control efforts. They also recommend using harvest-incentive schemes as part of an integrated program. Incentivised harvest may be efficient initially when populations densities are high; and strong incentives could again be useful in circumstances where the last few individuals need to be removed (e.g. Lost Island Lake, Table 3).

Conclusion

The biology, ecology, geographical distribution and habitat preferences of invasive Common carp populations suggest that the species has a strong resistance to eradication, or even to significant long-term biomass reduction, using commercial fishing methods. Critical aspects of their biological productivity that affect the likelihood of commercial fishing as control include; recruitment-compensation and growth-compensation; their moderate susceptibility in open populations due to pervasive habitation of spatially complex floodplain-wetland and river systems that generally include refuges from fishing.

Implications

By definition, pest-fish are often super-abundant leading to low prices in a natural marketplace by the law of supply-and-demand. Low prices mean that markets must process high volumes to be cost-effective, requiring a high product-demand for volume to be sustainable. Our simulations of the level of harvest required in a single area to achieve successful control reveal harvest quantities that would ‘swamp’ the existing Australian domestic and export markets. In Australia, exports of Common carp products between 1998 and 2003 are estimated to have been over 500 tonnes (Keith Bell, Commercial fisher. Pers. Comm) however, this fell due to drought and European import restrictions between 2004 and 2016, to approximately 50 tonnes of Carp products with a value of $206,000 and worth on average $4 kg^{-1}. Import data shows that during 2012–2016, approximately 6000 tonnes of Carp products worth $28 Million were imported into Australia (FRDC 2017), perhaps indicating the potential existence of a larger domestic market for specialised, value-added product than has been exploited to date. Realising this tantalising potential may be a key to generating the required product-demand.

Recommendations

While we conclude that Common carp populations have a strong resistance to eradication, or even to significant long-term biomass reduction, using commercial fishing methods; there are lessons to be learned from other invasive-species commercial removal schemes. Under a fixed-price or open market-price scenario the incentive for commercial operators declines as efficiency declines in low density populations. In a management program, as invasive species densities become low the cost-of-removal per unit increases. Examples of successful, innovative incentive schemes worth mimicking, if management of Common carp proceeds using commercial exploitation, include contracts using significant, staged bonus payment on reaching biologically meaningful harvest-targets and contracted pricing that increases above staged thresholds to achieve harvest-targets. Bonus payments would preferably be on a sliding, reducing-scale of that encourage increased effort as abundance declines (Barnes et al. 2014; Gherardi & Angiolini 2009; Pasko et al. 2014).

Case studies suggest that the use of commercial harvesting to achieve biomass reduction targets is certainly more useful in small, closed populations where juvenile recruitment can also be controlled (e.g. through harvesting) (Carl, Weber & Brown, 2016), or eliminated (e.g. through screening, or water management) (Diggle et al. 2004). In more open or structurally-complex populations, there are perhaps circumstances where intense harvesting of carp may make sense within an integrated control-plan which includes biological-control measures (Brown & Gilligan 2014); particularly, where there is a high-risk of rapid mortality from biological-control measures causing acute water-quality, or aesthetic air-quality issues (Lighten & van Oosterhout 2017). Before this is considered, the effect of such pre-emptive commercial biomass-reduction on the subsequent transmission rates for virus vectored biological control should be thoroughly investigated (McColl et al. 2017).

Extension and Adoption

A research article based on the review and modelling was submitted to the journal *Biological Invasions* (submitted 19-Sep 2018; rejected 15-Dec 2018) (Note: The Principal Investigator ceased employment with La Trobe University 21-Dec 2018).

A magazine style article was also drafted based on the projects key findings and approved by NCCP management for submission to "The Weekly Times" once the final report was approved and sufficient Industry consultation has ensued (see below).

Project coverage

Proposed article for The Weekly Times:

"Opinion: Carp control in Australia. Can't we just catch them and eat them all?

Associate Professor Paul Brown, School of Life Sciences, La Trobe University, Mildura

Chris Wisniewski, Inland Fisheries Service, Tasmania

Dr Dean Gilligan, NSW Department of Primary Industries, Fisheries, Batemans Bay

The Common Carp is a pest fish that has invaded southern Australia's waterways. Often present in high numbers, carp reduce water quality and have an impact on water plants, insects, frogs and birds. They are one reason our rivers and lakes are not as healthy as they should be, and it's estimated they cost our economy millions of dollars each year.

So, why can't we just fish them out? This is a question commonly asked around the world about invasive fish species and has been asked frequently since the Australian Government announced the National Carp Control Plan, spending $15 million to date. The Plan, its funding and its controversial solution of introducing a carp-killing virus to our waterways have the community talking about the role of the commercial fishing industry.

In response to this question, I've been working with my colleagues from New South Wales Department of Primary Industries and Tasmania's Inland Fisheries Service to study the effectiveness of using commercial harvesting to control invasive animals. We wanted to know if it was possible to overfish carp deliberately. To do this we compared what we know about carp biology with the biology of fish where stocks are known to be at risk of overfishing. We focussed on studies and reviewed cases where invasive fish species are managed by commercial fishing around the world. We identified what features were important for the success or failure in each case.

We then used the latest computer models of carp populations to explore these features. The computer simulated carp and commercial fishing activity typical of a known river catchment. We tested the limits for successful control under increasing levels of commercial fishing.

The modelling showed that unless commercial fishing removed many carp of all sizes (even young ones) it struggled to even reduce the population effectively. The amount of carp that had to be fished from one Murray–Darling River sub-catchment (more than 1400 tonnes over the first 5-years of fishing), would overwhelm the existing domestic and export markets. In addition, if some carp were unavailable for commercial fishing–say in inaccessible areas, they acted as a reserve to repopulate the fished areas. Under these conditions, population eradication became impossible and population reduction was ineffective.

Important characteristics of carp include their ability to breed prolifically, survive in a broad range of habitats, have a wide distribution and adaptable biology. These features mean that Australia would need a permanent and much larger commercial carp industry to maintain population control in a lasting way. The existing, commercial carp fishery would need massive, ongoing investment to scale-up to remove enough carp. This 'army' of commercial fishers would need to fish hard in all areas– forever, to control carp in Australia. A commercial fishing industry this size would create a range of other environmental challenges through bycatch of native fish species and other animals. If a role exists for commercial harvesting within the National Carp Control Plan it is likely to be limited to isolated waterways, where survival of young carp is low or controllable and immigration preventable. Population modelling and the examination of many case studies worldwide does not support the use of commercial fishing as an enduring control at a large scale.

Sadly, the answer is no. We can't just catch them all.

Acknowledgement: The authors would like to thank The Fisheries Research and Development Corporation for funding the review and modelling research informing this article."

Appendix 1: List of researchers and affiliations

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Co-investigator - Chris Wisniewski – Inland Fisheries Service, 17 Back River Road, New Norfolk, Tasmania 7140

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Appendix 2: Data tables for Figures 1-3

Table 5. Population viability, biomass reduction and fishing yield in a simple, closed carp population parameterised as in Brown & Gilligan (2014) where the Zone 3 population shows strong compensatory recruitment (α=34.7, β=0.0191).
Outputs from Model 1 of a 1331 ha habitat in the Lachlan River catchment (n= 100 trials). Population viability is reported as years of fishing until eradication for at least 10% (PV0.1) and 100% (PV1.0) of trials. Biomass reduction is the % of unfished biomass removed. Simulated mean fishing yield for the first five fished years. Results for a range of F values including F=0.03 representing estimated historic management efforts, F=0.3 a ten-fold increase in fishing mortality and F≥1.2 that led to eradication within the simulation.

Population viability at varying Fishing levels	F=0.03	F=0.3	F=0.5	F=1.2	F=1.6	F=1.8	F=2.0
PV0.1 (years)	-	-	-	98	32	24	19
PV1.0 (years)	-	-	-	103	33	25	20
Biomass reduced by (% unfished biomass)	10%	49%	61%	100%	100%	100%	100%
Mean fishing yield (kg/ha)							
First year fished	10	65	81	72	56	48	41
Second year fished	10	55	61	40	30	24	20
Third year fished	9	47	49	28	18	13	10
Fourth year fished	9	44	47	21	10	6	4
Fifth year fished	9	44	49	17	6	3	2
Total harvest during first 5-years (tonnes)	62	337	376	234	159	125	101

Table 6. Population viability, biomass reduction and fishing yield in a simple, closed carp population parameterised as in Brown & Gilligan (2014) where the Zone 3 population shows weaker compensatory recruitment (α=4.1, β=0.0162).
Outputs from Model 1 of a 1331 ha habitat in the Lachlan River catchment (n= 100 trials). Population viability is reported as years of fishing until eradication for at least 10% (PV0.1) and 100% (PV1.0) of trials. Biomass reduction is the % of unfished biomass removed. Simulated mean fishing yield for the first five fished years. Results for a range of F values including F=0.03 representing estimated historic management efforts, F=0.3 a ten-fold increase in fishing mortality and F≥0.5 that led to eradication within the simulation.

Population viability at varying Fishing levels	F=0.03	F=0.3	F=0.5	F=1.2	F=1.6	F=1.8	F=2.0
PV0.1 (years)	-	-	112	18	13	11	10
PV1.0 (years)	-	-	135	20	14	12	11
Biomass reduced by (% unfished biomass)	16%	82%	100%	100%	100%	100%	100%
Mean fishing yield (kg/ha)							
First year fished	7	48	59	52	41	36	30
Second year fished	7	39	42	22	12	9	7
Third year fished	7	31	29	9	4	3	2
Fourth year fished	7	26	21	4	1	1	0.4
Fifth year fished	7	22	16	2	0.4	0.2	0.1
Total harvest during first 5-years (tonnes)	45	217	218	117	76	64	52

Table 7. Population viability, biomass reduction and fishing yield in a spatially complex metapopulation of six zones, with the carp population parameterised as in Brown & Gilligan (2014) with uniform fishing mortality (F) applied to each zone plus effect of refuge from fishing. Outputs from Model 2 of a total of 26,666 ha of habitat in the Lachlan River catchment (n= 100 trials). Population viability is reported as years of fishing until eradication for at least 10% (PV0.1) and 100% (PV1.0) of trials. Biomass reduction is the % of unfished biomass removed. Simulated mean fishing yield (kg ha-1) for the first five fished years. Results for F values, F=1.2 and F=2.0 representing minimum and maximum value trialled at which eradication achieved for model 1 (Error! Reference source not found. **&**

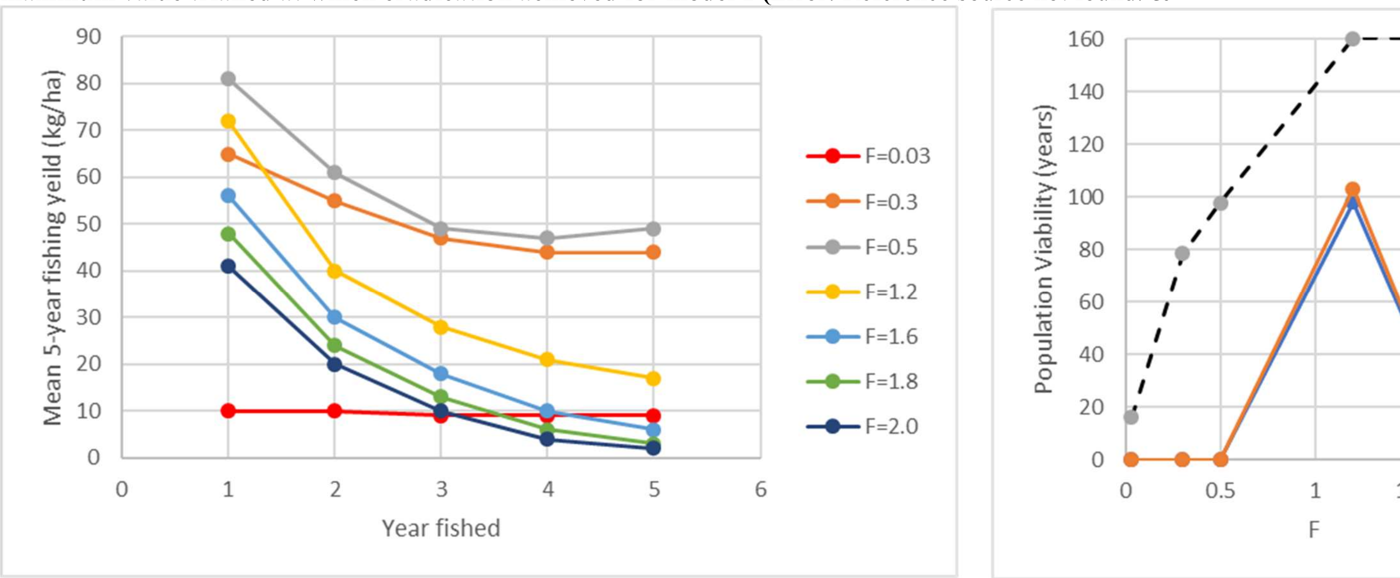

Figure 1 Fishing yield (left), population viability and biomass reduction (right) in a simple, closed carp population parameterised as in Brown & Gilligan (2014) where the Zone 3 population shows strong compensatory recruitment (α=34.7, β=0.0191). Outputs from Model 1 of a 1331 ha habitat in the Lachlan River catchment (n= 100 trials). Population viability (right) is reported as years of fishing until eradication for at least 10% (PV0.1) and 100% (PV1.0) of trials. Biomass reduction is the % of unfished biomass removed. Simulated mean fishing yield for the first five fished years (left). Results for a range of F values including F=0.03 representing estimated historic management efforts, F=0.3 a ten-fold increase in fishing mortality and example values of F≥1.2 that led to eradication within the simulation. (See appendix 2. Table 5 for data table).

) and F=2.0+refuge with a single zone (e.g. zone 6), where F=0.

Population viability at varying Fishing levels	F=1.2	F=2.0	F=2.0+refuge
PV0.1 (years)	-	27	-
PV1.0 (years)	-	28	-
Biomass reduced by (% unfished biomass)	99%	100%	72%
Mean fishing yield (kg/ha)			
First year fished	33.0	33.1	31.9
Second year fished	10.8	10.8	9.4
Third year fished	5.6	5.7	5.3
Fourth year fished	2.5	2.5	2.6
Fifth year fished	1.1	1.1	1.2
Total harvest during first 5-years (tonnes)	1413	1420	1026

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FRDC FINAL REPORT CHECKLIST

Project Title:	Review of Carp control via commercial exploitation		
Principal Investigators:	Paul Brown, Chris Wisniewski and Dean Gilligan		
Project Number:	2017/094		
Description:	Brief one/two paragraph overview of what the project did and achieved.		
Published Date:	03/07/2019	**Year:**	2019
ISBN:	n/a	**ISSN:**	n/a
Key Words:	**Common carp, *Cyprinus carpio*, simulation model, CarpSim, Australia, commercial fishing, invasive, overfishing, population management**		

Please use this checklist to self-assess your report before submitting to FRDC. Checklist should accompany the report.

	Is it included (Y/N)	**Comments**
Foreword (optional)	N	Could be supplied by NCCP?
Acknowledgments	Y	
Abbreviations	N	Explained in text where used
Executive Summary		
− **What the report is about**	Y	
− **Background – why project was undertaken**	Y	
− **Aims/objectives – what you wanted to achieve at the beginning**	Y	
− **Methodology – outline how you did the project**	Y	
− **Results/key findings – this should outline what you found or key results**	Y	
− **Implications for relevant stakeholders**	Y	
− **Recommendations**	Y	
Introduction	Y	
Objectives	Y	
Methodology	Y	
Results	Y	
Discussion	Y	
Conclusion	Y	
Implications	Y	Extracted from original discussion
Recommendations	Y	Extracted from original discussion
Further development	N	Dependant upon direction of NCCP
Extension and Adoption	Y	
Project coverage	Y	
Glossary	N	Terms explained within text

Project materials developed	N	None other than that detailed in Extension and Adoption section
Appendices	Y	External reviewer recommended turning Tables into Figures for increased clarity – whilst this has been adopted the original data tables are now included as an appendix to enable the detailed model outputs to be fully understood bu those interested to do so. Also listed researchers and full attributions Also listed references cited.

NATIONAL CARP CONTROL PLAN

The National Carp Control Plan is managed by the
Fisheries Research and Development Corporation

Tel: 02 6285 0400
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www.carp.gov.au