Poster Paper

Carp (Cyprinus carpio L.) impacts and recruitment in Australian wetlands: strategies for management

Patrick Driver[1], Ivor Stuart[2], Gerry Closs[3], Michael Shirley[4] and John Harris[5]

1. Resource Analysis Unit, NSW Department of Infrastructure, Planning and Natural Resources, Australia, PO Box 136, Forbes, NSW, Australia 2871. Email: patrick.driver@dipnr.nsw.gov.au;
2. Arthur Rylah Institute for Environmental Research, PO Box 137, Heidelberg, Australia, 3084. Email: ivor.stuart@dse.vic.gov.au;
3. Department of Zoology, University of Otago, PO Box 56, Dunedin, New Zealand. Email: gerry.closs@stonebow.otago.ac.nz;
4. Sinclair Knight Merz, Environmental Operations South East Australia, PO Box 2500 Malvern 3144, Email: mshirley@skm.com.au;
5. Rifflerun, 568 Bootawa Road, Tinonee, NSW 2430, Australia. Email: john.h.harris@bigpond.com.

Abstract

In Australia, wetlands are often the primary sites for Carp recruitment within a catchment, and are also the habitats where Carp are most likely to detrimentally impact water quality and native fish and invertebrate community composition. The most detrimental Carp impacts are likely to be associated with large biomass populations of adult Carp, but other factors such as inundation regimes and plant community and substratum characteristics influence ecosystem resistance to Carp impacts. Long-term impacts of Carp on wetlands are difficult to accurately predict and quantify with current evidence. However, there is sufficient knowledge for the implementation of sophisticated ecosystem-manipulation that might control or reduce Carp impacts within individual wetlands and for whole Carp metapopulations.

Carp control programs for wetlands within interconnected river systems with naturalised Carp populations (e.g., the Murray-Darling Basin, hereafter MDB) should be prioritised strategically at catchment and larger spatial scales. Such strategies should aim to:

1. control Carp at source habitats (or recruitment hot spots), which are usually in still waters such as wetlands and reservoirs;
2. define and reduce Carp impacts in fresh waters where these impacts (e.g, on native fish) are most undesirable (impact hot spots), noting that impact versus Carp recruitment control management activities would not necessarily occur in the same locations because of size-specific dispersal by Carp;
3. compliment other large-scale river rehabilitation measures for native fish communities and wetlands, such as environmental water releases and land stewardship initiatives;
4. develop basin-scale decision support tools that provide quantitative measures of the success of the control of Carp impacts and recruitment *versus* monetary cost and impacts on native wetland; and
5. support research that helps the development of these decision support tools, including the long-term impact of Carp on native fish communities within wetlands.

Frustratingly, Carp control *versus* native fish community rehabilitation is most critical, but also most problematic in natural wetlands, including large low-relief wetlands (e.g., the Great Cumbung Swamp) and numerous smaller wetlands such as billabongs and swamps. Carp control is likely to be far more achievable for small, artificial and flow-regulated waters.

Introduction

Management of Carp within their current range requires control of ecosystem impacts (Braysher 1993, CCCG 2000a) and recruitment (Stuart *et al*. 2000; Driver *et al*. 2005a), and these objectives might require different activities at different locations. Carp control for wetlands is a case in point and is integral for overall population management. Various approaches for Carp control have been proposed, and although a national Carp management strategy exists, other strategies are required (CCCG 2000a; Clunie *et al*. 2002). Many options for Carp control and exclusion (e.g, physical removal, screens, poisoning and lake draw-down) are methods that can be applied for local populations (e.g., see Roberts and Ebner 1997; Koehn *et al*. 2000). However, none of these have proven particularly effective with the possible exception of some smaller enclosed systems. For example, Rotenone has recently been used to successfully eradicate Carp (and Gambusia) in small ponds (<4.4 ha) in New Zealand (Chadderton *et al*. 2003). Modelling suggests that use of genetically modified Carp could also be effective in reducing populations over large spatial and temporal scales, although some concern is expressed about the ability of modified fish to populate even more than 1% of the naturalised Carp population (Brown *et al*. 2003; Lapidge 2003). With all these approaches, the balance of cost *versus* risk of failure, including the risk of under-funding more effective or informative activities is yet to be properly considered (see Lapidge 2003). In particular, a very large-scale and long-term approach to alien and native fish management is required to avoid 'tinkering at the margins' (*sensu* MDBMC 2003).

Programs for ecosystem rehabilitation are critical for reducing the large-scale root causes of alien fish proliferation, as well as for rehabilitating native fish communities (Harris 1997; CCCG 2000; MDBMC 2003). Hence, studies of large-scale, long-term ecological processes (population viability, climate change, predation, migration, effects of removing a keystone species etc.) and associated large-scale human effects (flow regulation; erosion etc.) that describe the processes that need to be manipulated or mitigated in rehabilitation are also critical for effective conservation (Soulé and Kohm 1989; CCCG 2000a; Charlie Krebs in Lapidge 2003).

In this paper we provide information on possible Carp impacts on native fish, partly based on research currently being or recently published. We then discuss methods to control these impacts using a metapopulation–scale approach that is complementary to, and, in part, at a larger spatial scale to the sub-catchment and catchment-scale approaches discussed in the National Management Strategy for Carp Control (e.g., see Lapidge 2003; CCCG 2000a). In particular, we provide evidence that show that Carp control methods need to be employed strategically to meet two separate objectives:

1. to control local impacts of Carp; and
2. to limit the large-scale, long-term recruitment of Carp.

Finally, we consider Carp control in different types of wetlands.

Carp impacts on other fish species in wetlands

Impacts of Carp on other fish species are not convincingly documented, even globally. The magnitude and types of impacts of Carp in wetland ecosystems, or exactly what the trajectory of recovery would be if they were removed are not well understood because experimental studies have been of limited spatial and temporal scope. Furthermore, field observations of Carp-ecosystem interactions are usually based on patterns of association where other factors, usually human impacts, could also be influencing fish communities (e.g., Whillans 1995 for wetlands; Driver *et al*. 1997 for rivers). The only way to understand long-term impacts in wetlands is by long-term experimental manipulation, which has not occurred in Australia. Research on long-term (≥ 1 year) Carp impacts on native fish or other wetland biota is not explicitly addressed in strategies for future Carp research (CCCG 2000b), and should be. Nevertheless, short-term, small-scale studies on Carp impacts have been essential for understanding the complexity of Carp impacts, and some reasonable conclusions can be made, as discussed below (also see reviews with different emphases in Roberts and Ebner 1997, Koehn *et al*. 2000 and Koehn 2004).

Carp are benthivorous fish that feed in and on the sediments to a depth of about 12 cm.

Benthivores can be the major effect on water quality within a wetland (Cahn 1929; Braband *et al*. 1990; Meijer *et al*. 1990; e.g., the source of 80% of phosphorus over two months; Braband *et al*. 1990). The most profound influences on native fish by Carp are probably a result of ecosystem alteration, and possibly also disease transmission (e.g., transmission of dropsy in Europe via parasitic copepods; Welcomme 1984). Carp create an unfavourable environment for the net recruitment of other fish species in slow flowing or still waters by altering prey availability for non-benthic predators (Driver 2002). Carp suspend sediments and probably reduce visibility for visual-feeding fish and clog gill-rakers and gill filaments with sediments (Driver 2002; Shirley 2002). Carp also destroy existing and, in particular, soft-bodied and recolonising plants (Roberts *et al*. 1995; Swirepik 2000), which would otherwise provide critical habitat for fish feeding, spawning and nursery habitat. Such large-scale loss of plants after Carp colonisation in wetlands is well recorded in oral histories (e.g., Lake Cargelligo, NSW, Roberts and Sainty 1997) and is suggested by the negative association between Carp and soft-bodied aquatic plants in NSW's rivers (Driver 2002).

Field and laboratory Carp studies all suggest that piscivory by Carp is unlikely to be a major influence on native fish, although the consumption of fish eggs by Carp is perhaps important (Driver 2002; Shirley 2002). Overlap in prey use between Carp and native fish species, particularly small species such as galaxids and Australian smelt, has been shown (Khan *et al*. 2002; Koehn 2004), but there is yet no compelling evidence for competition for similar prey (exploitative competition) that might affect native fish health. Field observations and experiments do indicate that Carp can physically exclude smaller fish species and smaller Carp from their preferred habitat *via* overcrowding and behavioural dominance (i.e., interference competition) and might reduce feeding efficiency in visual predators such as Redfin perch (*Perca fluviatilis*) by increasing turbidity (Driver 2002; Shirley 2002).

Local control of Carp impacts and recruitment

The ecosystem impacts of Carp that should be controlled need to be determined with science and community/stakeholder consultation and ownership of the strategies implemented (CCCG 2000a; Lapidge 2003), but this paper mostly focuses on the science. We discuss some approaches to Carp control below, and their implications for the local control of Carp impacts and recruitment.

Physical Carp removal is an essential management tool, but will only provide short term benefits unless supported by ongoing programs and maintenance. For example, Carp have been manually removed from fishways along the Murray River for the past 15 years and this process has recently been streamlined with automated Williams traps (Stuart *et al*. 2001; Stuart *et al*. 2003). Extending the use of these cages to control the invasion of Carp at the exits and, most importantly for individual wetlands, the entrances, is likely to be a fundamentally important tool and a high priority for control of Carp impacts and recruitment. This approach may be combined with physical removal within the wetland. For example, at Moira Lake, NSW there is annual removal of up to 76 tonnes of adult Carp (Keith Bell, KandC Fisheries, pers. com.).

For control of recruitment it would be important to capture and destroy sexually mature Carp (mostly >300 mm) before they enter wetlands. Nevertheless, the capacity for such techniques to control recruitment needs to be quantitatively determined for each location and method, because the high fecundity of Carp and density-dependent responses might ensure that remaining adult Carp produce essentially the same amount of eggs as an unfished population (see Koehn *et al*. 2000; Sivakumaran *et al*. 2003). Physical removal of a high biomass of medium to large Carp (e.g., with non-commercial or commercial electrofishing or the Williams' trap) is desirable for control of Carp impacts because large Carp at higher densities have a greater effect (per unit weight) on invertebrates likely to be utilised by native fish, sediment suspension, mobilisation of sediment-bound phosphorus and aquatic plants (Crivelli 1983; Driver 2002; Driver *et al*. 2005b). In contrast, other approaches such as genetic techniques and drawdown would have a greater impact on smaller fish and, hence in the short-term, would have a greater effect on the mobilisation of phosphorus by excretion and on reducing phytoplanktivores such as *Daphnia* spp. that could be important for algal control (see Driver *et al*. 2005b).

Ecosystem rehabilitation is likely to be important for the control of Carp impacts. Ecosystem resistance and resilience to Carp impacts are not well understood, but are likely to be higher in the absence of fine sediments, in naturally variable flow or inundation regimes characterised by episodic high energy flows, when plant biomass is high and comprised of harder-bodied plants, or where human impacts are low and where (often as a consequence) native fish species diversity is high (sensu Roberts and Ebner 1997; Driver 2002).

Other factors such as depth, wind, local run-off, flow and sediment type also affect Carp impacts, and potentially are useful to consider in ecosystem manipulation for the control of Carp impacts (e.g., King and Robertson 1997; Driver *et al*. 2005b).

Introduction of predatory native fish has also been suggested as a control mechanism but, even globally, there is little evidence for other fish species controlling Carp abundance (Driver 2002), but there is evidence that native predatory fish are more common in the presence of Carp within Australian rivers (Rolls 2005).

Ecosystem rehabilitation for the reduction of alien fish would include both land and water management, and in the current political environment, Catchment Management Authorities and the like are probably the best vehicle for facilitating a combination of local land and water stewardship, which includes combining wetland rehabilitation with larger scale natural resource management, such as the allocation of environmental flows.

Water level manipulation in wetlands is an obvious way forward for invasive and native fish management. American lake management experiments (Shields 1958) suggest that it is practical to apply water level draw-down to preferentially desiccate Carp eggs after observed Carp spawning events. Carp screens on a billabong flow regulator and implementation of wet-dry cycles were also used to short-term advantages for the local restoration of native fish populations, notably gudgeons and Bony bream, but also Gambusia (*Gambusia holbrooki*, Recknagel *et al*. 1998). Various field studies similarly indicate that high flows followed by quick drops of water depth on the floodplain can be used to desiccate Carp eggs and leave young of the year (YOY) or adult Carp stranded in isolated floodplain waters, whereas Australian native fish often have behavioural responses that lead to lower mortality, but often also less reliance on wetland environments (Koehn *et al*. 2000; King *et al*. 2003; Budd 2005; Driver *et al*. 2005a). The main challenge is that Carp typically spawn over spring and summer (e.g., King *et al*. 2003; Sivakumaran *et al*. 2003), and any attempts to restrict Carp spawning and use of nursery habitat could negatively affect native fish attempting the same behaviours and positively affect other alien fish (e.g., gambusia, which can be prolific in shallow water). Accordingly, the Ovens billabong study by King *et al*. (2003, Figure 7, Table 3) showed overlap between Carp and native fish YOY recruitment with Murray cod, Golden perch and Carp gudgeons (November-December) and Macquarie perch (October-December). However, the timing of fish recruitment described by King *et al*. (2003) for Ovens billabongs also indicates that, for example, targeted drawdown after Carp spawning events during September to early December, followed by wetland inundation during January to March should favour Carp gudgeons.

Large low-relief wetlands, including swamps (*Phragmites*, *Carex* etc; back swamps in Green 1997) and periodically inundated grasslands (e.g., *Paspalidium jubiflorum*) provide a great challenge for invasive and native fish management. These wetlands are highly significant locations for spawning and nursery habitat of both native and exotic fish because they fill at relatively low river discharge onto extensive floodplain depressions. For example, the Carp infested Great Cumbung Swamp (88% of the fish catch immediately upstream) receives less water overall under the current regulated flow regime, but because of flow regulation now receives far more water in the centre of the swamp, where there is extensive fish nursery habitat (McBryde 1995; Sims 1996; Driver *et al*. 2002). Similarly, the extensive floodplain habitats of the Barmah-Millewa Forest system constitute a major source of young-of-the-year Carp (and weatherloach) which then recruit into broader riverine populations because unseasonally-high summer irrigation flows provide greater access to spawning habitats (Stuart and Jones 2002; Chong and Ladson 2003). However, although the flow modifications in these large wetlands create some of the most important Carp recruitment hot spots, it would be very difficult to capture (e.g., with a Williams trap) and remove Carp effectively along their main dispersal routes, because such wetlands flood over very large and low relief areas often with no discernible connection to flow channels.

The abundance of billabongs and other small wetlands (e.g. small back swamps) in the Murray-Darling Basin ensures that local intensive management of all these water bodies is financially prohibitive. Nevertheless, effort is required because billabongs collectively might provide the greatest diversity of native wetland fish in Murray-Darling Basin floodplains because of their high physical and chemical variation (McNeil 2004; Closs *et al*. 2005). Carp are common in permanent small wetlands over a wide range of physical and chemical conditions (e.g., Shirley 2002 for the Murray River; King *et al*. 2003 and McNeil 2004 for the Ovens River; unpublished DIPNR data for the Lachlan River). Carp utilise temporarily inundated billabongs for YOY recruitment more than most Australian native fish, although they can also become stranded when floods recede and as billabongs dry up (King *et al*. 2003; Budd 2005). Gilligan (2005) endorsed the use of wet-dry cycling and screens with the addition of artificially bred fish stock, which would counter the isolating effect of the regulator on native fish outside the wetland. However, this is a labour intensive management approach requiring ongoing maintenance because of the ability of small Carp to pass through grills and screens (Recknagel *et al*. 1998).

Off-river storages, dam reservoirs, weir pools and probably also irrigation channels can be highly Carp dominated systems that act as source Carp habitats (Meredith *et al*. 1995; Lintermans 1996; Reid *et al*. 1997; Driver *et al*. 1997, 2005a; Kerezsy 2005). Such water bodies also tend to be highly flow regulated and, in particular, off-river storages have clearly defined inflow and outflow channels. These controlled wetland environments provide an opportunity for exploring management of native fish populations and the control of Carp recruitment in large wetlands (as with Lake Cargelligo in NSW, Kerezsy 2005).

Carp control at the catchment and basin scale

Carp in interconnected river systems (e.g., the Murray-Darling Basin) should be managed as a large interconnected population (metapopulation, Gotelli and Kelley 1993), where control in source habitats is a high priority. Source Carp populations are mostly within regulated lowland (≤ 300 m altitude) river catchments, and include wetlands, weirs and river backwaters. These waters enhance ‘sink’ populations in upstream riverine reaches or other less regulated parts of the Murray-Darling Basin (Driver *et al*. 1997; Driver 2002; Stuart and Jones 2002; Driver *et al*. 2005a). Migration of Carp to and from source habitats provides an opportunity to selectively remove adult fish from fishways or regulators at wetland entrances (Stuart *et al*. 2003). Hence, the most active source or recruitment ‘hot spot’ wetlands need to be identified and prioritised in terms of which wetland populations are likely to have the most affect on the viability of the basin-wide Carp metapopulation. These wetlands should then be subject to intensive Carp control.

There is probably still too large a gap between what we would like in a Basin-wide Carp control model and the data it would require, but strategic management of Carp populations at a Basin scale can only be done properly using modelling approaches and associated management decision tools. Hence, models of Carp control and population viability (e.g., Gotelli and Kelley 1993; Brown *et al*. 2003) should be further developed to determine the influence of Carp size-dependent, as well as Carp biomass-dependent impacts on ecosystems. Such models should, if possible, estimate the spatial and temporal complexity of Carp impacts and recruitment. In particular, size-specific and even sex-specific dispersal patterns by Carp indicates that locations of high Carp impact could be in locations that are poor habitat for Carp recruitment and growth, and this would vary with time of year (see Stuart *et al*. 2001; Driver *et al*. 2005a). Once the dynamics of Carp dispersal, recruitment and impact are suitably modelled, then management options should be subject to cost-benefit and/or risk analysis in the broader contexts of native fish and wetland biodiversity management. Such decision support systems are already being developed, such as the cost-benefit analysis for the local Carp control works in a wetland in Choquenot *et al.* (2004), and a broader risk assessment approach for pest species in Clunie *et al.* (2002).

Water depths within source habitats could be managed by local controls on flows (e.g., via regulators) as discussed, but also using coarser large-scale tools such as environmental flow releases to enhance native fish *versus* Carp recruitment. Further flow manipulation, such as the use of off-river storages by water users, should also be used to allow more natural drying regimes within rivers and wetlands. Sophisticated catchment-scale approaches are required because depending on the location and season, high flows (by limiting Carp recruitment; Driver *et al.* 2005a) or low flows (e.g., through stranding Carp as discussed) provide the natural 'filter' that removes non-natives such as Carp (sensu Gido *et al.* 1997). Government-initiated programs for the recovery of natural flows into wetlands are already underway (e.g., for Lachlan River billabongs and swamps; Driver *et al.* 2005c). Such inundation regime manipulation should occur with reference to the framework of integrated pest management as outlined in National Management Strategy for Carp Control (CCCG 2000a) and the Native Fish Strategy for the Murray-Darling Basin (MDBMC 2003). Unfortunately (to our knowledge), in south-eastern Australia the current large-scale strategies for environmental flow releases (e.g., the recently planned 500 GL release in the Murray River) do not even attempt to find a trade-off between native fish and alien fish recruitment. In contrast, in San Juan River, Colorado, USA, river managers are deliberately mimicking natural spring flow regimes to maximise the reproductive success of native fish, thereby avoiding some of the inherent benefits for non-native fish (including Carp) during summer flows (Propst and Gido 2004).

A strategy for managing source Carp habitats *versus* source native fish habitats using local and large-scale flow manipulation needs to be adopted at the MDB scale so that the connections between source and sink Carp habitats can be modelled. That is, overarching co-ordination at the level of State, Territory and Commonwealth Governments and the Murray-Darling Basin Commission (CCCG 2000; MDBMC 2003; Koehn and Mackenzie 2004). To reduce the risk of recent predictions that Carp will inhabit most Australian rivers within the next 50 years (Koehn 2004), and mitigate current Carp impacts on ecosystems, strategic control strategies are needed and targeting wetland-spawning sites will be a key management option.

Catchment and MDB-wide initiatives that address large-scale, long-term root causes of alien fish proliferation and associated ecosystem impacts (environmental flow allocations, fishways, improved riparian buffers, thermal pollution mitigation and regulation of fishing etc.) are also critical tools for the restoration of native fish communities and Carp control (Harris 1997).

Although this article is focussed on the more newsworthy Carp issue, we must emphasise that simply focussing on Carp ignores the risk that other wetland specialist alien species, such as Oriental weatherloach (*Misgurnus anguillicaudatus*) and goldfish (*Carassius auratus*), as well as generalist invaders such as European perch (*Perca fluviatilis*) and Tilapia (*Oreochromis* spp.) could similarly dominate lowland fresh waters (see Clunie *et al.* 2002). Furthermore, there are ecological analogues of Carp (some ictalurids, catastomids and cyprinids, Driver 2002) that, if released into Australia, could emulate the Carp population expansion observed in the 1970s. For these species there are no existing risk assessments of potential impacts or control options, a failure which can only enhance their potential spread, as demonstrated presently by Northern snakeheads (*Channa argus*) in several eastern American states. The removal of Carp could also have less obvious effects, such as allowing *Gambusia holbrooki* to proliferate when aquatic vegetation recovers (*cf.* Recknagel 1998; Rolls 2005).

Conclusions and recommendations

At present Carp control within wetlands is somewhat *ad hoc*. We are suggesting a framework that is a more resource-efficient approach to Carp control. We are not arguing against the control of non-source Carp populations (or source Carp populations that have a small effect on the metapopulation) in wetlands, but we suggest that there must be reasons such as high conservation or community values that justify efforts that will have little effect on Carp control at catchment or Murray-Darling Basin scales. In order to control Carp impacts and invasion beyond their current range we suggest that:

1. resources are required to continue to develop and refine Carp population, recruitment and migration models. In particular, research is required to identify the source habitats that have the greatest impact on the MDB Carp metapopulation;
2. small-scale adaptive management *via* use of regulators, Williams traps etc. and other physical forms of Carp removal should be implemented immediately at wetlands currently suspected to be contain large source Carp populations; and
3. large-scale adaptive management of native fish versus alien fish recruitment should be integrated into environmental flow management as part of the National Water Initiative.

Finally, although this paper is largely about Carp, these approaches are applicable to the management of introduced fish in general. Carp numbers might drop because of natural boom-bust cycling and/or because of Carp control measures, and could be replaced by fish species that are similarly undesirable. For this reason, we suggest that the national Carp management strategy should be expanded to include other alien fishes.

Acknowledgements

Thanks to the following people for communications that, we believe, through informal conversations on these issues and/or provision of relevant publications have improved the quality of this paper: Bill Phillips (MainStream Environmental Consulting), Chris Budd, Adam Kerezsy, Robert Rolls and Robyn Watts (Charles Sturt University, Wagga Wagga, NSW), John Koehn (Arthur Rylah Institute, Heidelberg, Victoria), Dale McNeil and Jane Young (Lachlan Catchment Management Authority, Forbes, NSW) and Sam Davis (Department of Primary Industries, Wellington, NSW).

Disclaimer

References

Braband, A., Faafeng, B. A., and Nilsson, J. P. (1990). Relative importance of phosphorus supply to phytoplankton production: fish excretion versus external loading. *Canadian Journal of Fisheries and Aquatic Science* 47, 363–372.

Braysher, M. (1993). Managing vertebrate pests: principles and strategies. Canberra, Bureau of Resource Sciences, Australian Government Publishing Service.

Brown, P., Sivakumaran, K.P., Stoeseel, D., Giles, A., Green, C. and Walker, T. (2003). Carp population biology in Victoria. *Marine and Freshwater Resources Institute Report*, No. 56.

Budd, C. (2005). The distribution and abundance of fishes in middle Murrumbidgee River billabongs, New South Wales. A dissertation submitted for the degree of Bachelor of Applied Science (Environmental Science) Honours , Charles Sturt University, June 2005.

Cahn, A. R. (1929). The effect of Carp on a small lake: the Carp as a dominant. *Ecology* 10, 271–274.

CCCG (2000a). National Management Strategy for Carp Control. Carp Control Coordinating Group. Murray-Darling Basin Commission.

CCCG (2000b). Future directions for research into Carp. Carp Control Coordinating Group. Murray-Darling Basin Commission.

Chadderton, L., Kelleher, S., Brow, A., Shaw, T., Studholme, B. and Barrier, R. (2003). Testing the efficacy of rotenone as a piscicide for New Zealand pest fish species. In: Managing Invasive Freshwater Fish in New Zealand. Proceedings of a Workshop Hosted by Department of Conservation, 10-12 May 2001, Hamilton. Department of Conservation, Wellington, New Zealand.

Choquenot, D., Nicol, S.J. and Koehn, J. D. (2004). Bioeconomic modelling in the development of invasive fish policy. *New Zealand Journal of Marine and Freshwater Research* 38, 419–428.

Chong, J. and Ladson, A. R. (2003). Analysis and management of unseasonal flooding in the Barmah-Millewa Forest, Australia. *River Research and Applications* 19, 161–180.

Clunie, P. and 10 co-authors (2002). A risk assessment of the impacts of pest species in the riverine environment in the Murray-Darling Basin. Project R2006 report to the Murray-Darling Basin Commission. Arthur Rylah Institute.

Crivelli, A. J. (1983). The destruction of aquatic vegetation by Carp. Comparison between Southern France and the United States. *Hydrobiologia* 106, 37–41.

Driver, P. D., Harris J. H., Norris, R. H. and Closs, G. P. (1997). The role of the natural environment and human impacts in determining biomass densities of common Carp in New South Wales' rivers. In: 'Fish and Rivers in Stress. The NSW Rivers Survey'. (Eds P. C. Gehrke and J. H. Harris) pp. 225–250. (NSW Fisheries Office of Conservation and the Cooperative Research Centre for Freshwater Ecology, Cronulla.).

Driver, P. D. (2002). The role of Carp (*Cyprinus Carpio*) size in the degradation of freshwater ecosystems. PhD thesis. Cooperative Research Centre for Freshwater Ecology and the Division of Science and Design, University of Canberra, ACT.

Driver, P., Higgins, C., Lloyd-Jones, P., Mackenzie-McHarg, A., Raisin, G., Unthank, S. and Wettin, P. (2002). Lachlan Floodplain Wetlands: Adaptive Water Management Framework. Final Report. NSW Department of Land and Water Conservation, Natural Heritage Trust and the Lachlan River Management Committee.

Driver, P. D., Harris, J. H., Closs, G. P. and Koen, T. (2005a). Effects of flow regulation on Carp (*Cyprinus Carpio* L.) recruitment in the Murray-Darling Basin, Australia. *River Research and Applications* 21, 327–335.

Driver, P. D., Closs, G. P. and Koen, T. (2005b). The effects of size and density of Carp (*Cyprinus Carpio*) on water quality in an experimental pond. *Archiv für Hydrobiologie* 163, 117–131.

Driver, P., Chowdhury, S., Wettin, P. and Jones, H. (2005c). Models to predict the effects of environmental flow releases on wetland inundation and the success of colonial bird breeding in the Lachlan River, NSW. In: 'Proceedings of the 4th Annual Stream Management Conference: linking rivers to landscapes. 19-22 October 2004, Country Club Casino, Launceston, Tasmania.' (Eds. Rutherfurd, I. D., Wiszniewski, I., Askey-Doran, M. J. and Glazik, R.), pp. 192–198.

Gilligan, D. (2005). Fish communities of the Murrumbidgee catchment: status and trends. NSW Department of Primary Industries. Fisheries Final Report Series: Cronulla, NSW.

Gido, K. B., Propst, D.L. and Molles, M.C. Jr. (1997). Spatial and temporal variation of fish communities in secondary channels of the San Juan River, New Mexico and Utah. *Environmental Biology of Fishes* 49, 417–434, 1997.

Gotelli N.J. and Kelley W.G. (1993). A general model of metapopulation dynamics. *Oikos* 68, 36–44.

Green, D. (1997). Wetland Classification. In: NSW Wetland Management Policy. Management Guidelines (Ed., DLWC (Anon.)), NSW Department of Land and Water Conservation, Parramatta, NSW.

Harris, J. H. (1997). Environmental rehabilitation and Carp control. In: 'Carp Control Workshop'. (Eds J. Roberts and R. Tilzey.). (Murray-Darling Basin Commission and CSIRO, 1996.).

Kerezsy, A. (2005). The distribution and abundance of fish in the Lake Cargelligo system, New South Wales. Honours thesis, Charles Sturt University.

Khan, T. A., Wilson, M. E., and Bhise, M. P. (2002). Dietary studies on Carp and other fish species in western Victorian lakes. *Internationale Vereinigung für Theoretische und Angewandte Limnologie* 28, 1191–1198.

King, A .J., Robertson, A. I., and Healey, M. R. (1997). Experimental manipulations of the biomass of introduced Carp (Cyprinus Carpio) in billabongs. I. Impacts on water column properties. *Marine and Freshwater Research* 48, 435–43.

King, A., Humphries, P. and Lake, P. (2003). Fish recruitment on floodplains: the roles of patterns of flooding and life history characteristics. *Canadian Journal of Fisheries and Aquatic Sciences* 60, 773–786.

Koehn, J.D., Brumley, A., and Gehrke, P. (2000). 'Managing the Impacts of Carp'. (Bureau of Rural Sciences: Canberra.).

Koehn, J.D. (2004). Common Carp (*Cyprinus common Carpio*) as a powerful invader in Australian waterways. *Freshwater Biology* 49, 882-894.

Koehn, J.D. and Mackenzie, R.F. (2004). Priority management actions for alien freshwater fish species in Australia. *New Zealand Journal of Marine and Freshwater Research* 38, 457–472.

Lapidge, K.L. (Ed). (2003). Proceedings of the National Carp Control Workshop, March 2003, Canberra. Cooperative Research Centre for Pest Animal Control. Canberra. June 2003.

Lintermans, M. (1996). 'The Lake Burley Griffin Fishery – 1996 Sampling Report. A Report to the National Capital Planning Authority. August 1996'. (Wildlife Research Unit, ACT Parks and Conservation Service.).

McBryde, D. (1995). A population study of European Carp (*Cyprinus Carpio* L.) in the lower Lachlan River, New South Wales. Dissertation submitted as part of the assessment requirement for the Bachelor of Applied Science (Environmental Science) Honours degree.

McNeil, D. (200). Physiological constraints to fish distributions on the Ovens river floodplain. PhD Thesis. Cooperative Research Centre for Freshwater Ecology and La Trobe University, Wodonga.

Meredith, S., Roberts, J., Walker, K. and Fairweather, P. (1995). The role of common Carp (*Cyprinus Carpio* L.) in phosphorus export from irrigation drains. Proceedings of the conference 'Nutrient Management in Irrigated Agriculture – Research and Implementation', 19–20 June.

Mieijer, M-L, de Haan, M. W, Breukelaar, A. W., and Buiteveld, H. (1990). Is reduction of the benthivorous fish an important cause of high transparency following biomanipulation in shallow lakes? *Hydrobiologia* 200/201, 303–315.

MDBMC (2003). Native Fish Strategy for the Murray-Darling Basin 2003–2013. Murray-Darling Basin Ministerial Council. May 2003.

Propst, D.L. and Gido, K.B. (2004). Responses of native and non-native fishes to natural flow regime mimicry in the San Juan River. T*ransactions of the American Fisheries Society* 133, 922–931.

Recknagel, F., Marsh, F., Matthews, S. and Schiller, N. (1998). Common Carp in natural wetlands: impacts and management. In: 'Wetlands in a dry land: understanding for management'. (Ed. W. Williams). Pp. 259–266. (Environment Australia: Canberra).

Reid, D. D., Harris, J. H. and Chapman, D. J. (1997). NSW Inland Commercial Fishery. Data Analysis. FRDC Project No. 94/027. Fisheries Research and Development Corporation, NSW Fisheries Research Institute (NSW Fisheries Office of Conservation) and the Cooperative Research Centre for Freshwater Ecology.

Roberts, J., Chick, A., Oswald, L., and Thompson, P. (1995). Effect of Carp, *Cyprinus Carpio* L., an exotic benthivorous fish, on aquatic plants and water quality in experimental ponds. *Marine and Freshwater Research* 46, 1171–80.

Roberts, J., and Ebner, B. (1997). 'An overview of Carp Cyprinus Carpio L. in Australia'. (CSIRO Land and Water: Griffith).

Roberts, J., and Sainty, G. (1997). 'Listening to the Lachlan'. (Sainty and Associates, Murray-Darling Basin Commission).

Rolls, R. J. (2005). Patterns in fish communities in the presence and absence of Carp (*Cyprinus Carpio*) in slope and upland regions of the Murray-Darling basin. a thesis submitted to the School of Science and Technology, Charles Sturt University (Wagga Wagga) in partial fulfilment of the requirements for the Degree of Bachelor of Applied Science (Environmental Science) (Honours). June 2005.

Shirley, M. J. (2002). The ecology of billabong fish communities of the River Murray, with a focus on the interactions of European Perch (*Perca fluviatilis*). PhD Thesis. Monash University, Melbourne.

Sims, N. C. (1996). The impact of land and water development on the hydrology of the Great Cumbung Swamp. Thesis for a Bachelor of Science, Honours. University of Canberra.

Sivakumaran, K. P., Brown, P., Stoessel, D. and Giles, A. (2003). Maturation and reproductive biology of female wild Carp, Cyprinus Carpio, in Victoria, Australia. *Environmental Biology of Fishes* 68, 321–332.

Soulé, M. E. and Kohm, K. A. (1989). Research priorities for conservation biology. Critical Issues Series. Island Press, Washington, D.C.

Stuart, I. and Jones, M. (2002). Ecology and Management of common Carp in the Barmah-Millewa Forest. Final Report to the Point Source Management of Carp Project to Agriculture, Fisheries and Forestry, Australia. The State of Victoria, Arthur Rylah Institute.

Stuart, I., Jones, M., and Koehn, J. (2001). Targeting spawning habitats to control Carp populations. In: '12th Australasian Vertebrate Pest Conference, 21–25 May 2001'. pp. 178-182. (Department of Natural Resources and Environment: East Melbourne, Victoria.).

Stuart, I., McKenzie, J., Williams, A. and Holt, T. (2003). Separation cages for removal of Carp from Murray-Darling Basin fishways. Final report to the Murray-Darling Basin Commission. 18 pp.

Swirepik, J. L. (2000). Physical disturbance of *Potamogeton tricarinatus* and sediment by Carp (*Cyprinus Carpio*) in experimental ponds. *Australian Biologist*. 13, 20.

Welcomme, R. L. (1984). International transfers of inland fish species. In: 'Distribution, Biology and Management of Exotic Fishes'. (Eds W. R. Courtenay Jr. and J. R. Stauffer Jr.) pp. 22–40. (John Hopkins University Press: Baltimore).

Whillans, T. H. (1996). Historic and comparative perspectives on rehabilitation of marshes as habitat for fish in the in the lower Great Lakes basin. *Canadian Journal of Fisheries and Aquatic Sciences* 53 (Suppl. 1), 58–66.