Carp in Australian Rivers

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ABSTRACT

Common carp are one of Australia's most despised introduced freshwater fish and have been implicated in the degradation of inland river systems. Although present in Australia for ~150 years, carp did not become a recognised pest until the appearance of the Boolarra strain in the 1960s. Following colonisation of the Murray River, and aided by widespread flooding in 1974, carp populations rapidly spread throughout the Murray-Darling Basin and established populations in all states except the Northern Territory. Although commercial, anecdotal and some scientific data suggest that carp populations have since declined in many areas, the species continues to spread and invade new waterways. Numerous forums and workshops have been held to develop and progress with potential carp control solutions. However most assessments of potential control alternatives have failed to provide effective means of managing the problem. These have included assessments of over-harvest, trapping, poisoning, exclusion, bio-controls, biotechnologies and habitat manipulation. However within the last few years, at least four initiatives are beginning to show some promise. These include: the Tasmanian Carp Management Program which utilised physical removal activities directed by a 'Judas fish' program, carp drafting devices named 'William's Carp Separation Cages' designed to remove carp as they migrate through fishways, a novel molecular genetic approach, 'Daughterless Carp Gene Technology' designed to integrate an inheritable gene into the population that limits the abundance of the highly fecund females, and the identification of discrete and finite carp breeding hot-spots within river systems, in order to provide targeted control options.

Key words: Common carp, distribution, abundance, control strategies.

Introduction

Common carp *Cyprinus carpio* is one of Australia's most despised introduced freshwater fish. Although an important food source across their native range (Panek 1987; Lin and Peter 1991; Koehn *et al.* 2000) and providing recreational fishing opportunities (Splitler 1987), they are perceived as a significant ecological pest in many of the countries where they have been introduced (Koehn *et al.* 2000), causing ecological damage to freshwater ecosystems. Carp have been implicated in the degradation of Australian river systems, particularly those of the Murray-Darling Basin (Koehn *et al.* 2000). They have been declared a noxious species in most Australian states. Further, the introduction of fish (including carp) to freshwaters within a catchment outside their natural range has been listed as a key threatening process to threatened fish and aquatic ecosystems in NSW, under the *Fisheries Management Act 1994*.

Carp were released into the Australian environment on a number of occasions over the last 150 years and at least four separate genetic stains exist (Davies *et al.* 1999). The first carp introduced were released around Melbourne between 1859 and 1876 (Kuiter 2005). However these introductions did not establish as self sustaining populations. The first established population arose from the release of carp into the isolated Prospect Reservoir (Sydney) in 1907 and 1908, with this population becoming known as the Prospect strain (Shearer and Mulley 1978). A bright orange strain of koi was released into irrigation canals in the Murrumbidgee Irrigation Area in southern-central NSW sometime during the 1940s or 50s. These fish established a second self-sustaining population known as the Yanco strain (Brumley 1996). Despite surviving in the irrigation area, the Yanco strain did not disperse widely (Lake 1967). The most significant strain of carp in Australia, the Boolarra strain, was responsible for the invasion of the majority of the Murray –Darling Basin, and caused the most ecological damage. This strain was imported from Europe and reared in a fish farm at Boolarra, Victoria (Shearer and Mulley 1978). The Victorian authorities tried to prevent their sale and distribution, but were unsuccessful (Butcher 1962). An intensive eradication campaign undertaken by the Victorian government failed to prevent the spread of Boolarra strain carp in that state. By 1968, the Boolarra strain was found in the Murray River at Mildura.

Following the widespread flooding that occurred in 1974, carp populations in the Murray River boomed and spread to encompass the lower reaches of the Darling River, Lachlan River, Murray River, Murrumbidgee River and Victorian tributaries of the Murray. Over the following few years, they continued to spread throughout most of the Murray-Darling Basin, invading the Darling tributaries by the mid 1980s (Reid *et al.* 1997). Boolarra strain carp were also discovered in farm dams in Northern Tasmania in the 1970s and again in 1980, but were successfully eradicated using a fish poison (rotenone). Carp populations (presumably the Boolarra strain) occur in all but five of the 39 river basins in Victoria, with the far south-east (east of the Snowy River) the only major carp-free area of the state (Koehn *et al.* 2000).

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A further strain of koi carp (although with wild-type coloration) also became established in many areas, including isolated coastal catchments in NSW such as the Shoalhaven (post 1986, Gehrke *et al*. 2002), Hawkesbury-Nepean (post 1975, Llewellyn 1983) Hunter (post 1979, Battaglene 1985) and Richmond (post 1975, Llewellyn 1983), Lake Burley Griffin (Canberra) in 1976 (Lintermans 2002), Lakes Crescent and Sorell (Tasmania) in 1995 (Diggle *et al.* 2004), and the Albert –Logan Rivers (south-east Queensland) and waterways around Perth some time in the 1990's (Shearer and Mulley, 1978; Harris 1995; Brumley 1996) (Note: Many of these populations are a mixture of Boolarra and koi strains, Davis *et al.*1999).

Ornamental koi carp continue to appear in coastal river catchments of NSW (Graham *et al.* 2005), however it is not yet known if any of these have established self-sustaining populations.

Carp are now present in all Australian states except the Northern Territory and their range continues to increase (Brumley 1996). Koehn (2004) suggests that carp have the ecological tolerances to establish populations in any Australian river system, and that the further expansion of carp across most of the remainder of Australia should be expected. Carp are able to withstand water temperatures between 4 - 35^{o}C, pH between 5 – 10.5, high turbidity, moderate salinities, high toxicant loads and very low dissolved oxygen levels (Panek, 1987; Mackenzie *et al.* 2000; Smith 2005).

There are a number of factors that have helped facilitate the spread of carp, including; large floods, interbasin water transfer, the use of live carp as bait-fish and deliberate introductions. The establishment of carp populations was facilitated by the already degraded condition of Australian river systems and fish communities, resulting from river regulation and its associated effects as well as over harvest of the major predatory species (Cadwallader 1978; Lake 1980; Gehrke *et al.* 1995; Koehn *et al.* 2000).

Current distribution

Within NSW, carp are distributed across most of the Murray-Darling Basin, occurring in 85% of inland waterways (Graham *et al.* 2005). Only 17 individual sub catchments (of various sizes) are free of carp in inland NSW (Graham *et al.* 2005). Graham *et al.* (2005) reported that ~70% of NSW coastal waterways remain carp-free. These include the Tweed, Brunswick, Lake Illawarra, Macleay, Manning, Clyde, Moruya, Tuross, and East Gippsland catchments. In contrast, the Richmond, Hunter, Lake Macquarie - Tuggerah Lakes, Hawkesbury-Nepean, Port Jackson and Shoalhaven catchments each have well established populations of carp, whilst the Clarence, Bellinger, Hastings, Port Stephens, Bega, Towamba and Snowy catchments each have isolated reports of individual or small numbers (usually ornamental koi) (Graham *et al.* 2005). Subsequent assessment of these isolated reports suggests that recruiting populations have not yet established in these catchments (Gilligan, unpublished data).

Abundance

Commercial fishery data from NSW (Reid *et al.* 1997) suggest that carp populations increased rapidly from 1970 through to 1977 (Figure 1). After reaching their peak, carp harvests have declined steadily and are now at the lowest levels since the peak of invasion (Figure 1). However these data are not standardised by fishing effort, and therefore are not entirely appropriate as a means of assessing the status of carp populations, particularly given that fishing effort is known to have declined since the late 1970s. Further, the commercial fishery for native finfish closed in 2001, with all inland fishing licences now restricted to harvest of carp and yabbies *Cherax destructor*.

Similarly, recreational fishermen have increasingly reported general declines in carp populations over the last few years.

Since 1994, much of the field sampling undertaken by NSW DPI (formerly NSW Fisheries) has followed a consistent standardised sampling procedure, enabling trend analyses of carp populations over the last decade. These trend analyses suggest that across NSW (including coastal and inland catchments), there has been little change in the abundance of carp populations over the last eleven years (r = -0.006, p = 0.962, unpublished data). However, when populations are stratified into those in the lowlands of the Murray-Darling Basin (below 200m elevation), slopes-uplands of the Murray-Darling Basin (above 200m elevation) and coastal catchments, divergent trends are observed. Carp numbers are increasing in the slopes and uplands of the Murray-Darling Basin (r = 0.340, p = 0.07, unpublished data) with the trend approaching statistical significance. In contrast, data from the lowlands of the Murray-Darling Basin (r = -0.207, p = 0.227, unpublished data) and coastal catchments (r = -0.217, p = 0.562, unpublished data) show no significant trends in carp abundance.

Although the commercial fishery data and recreational fisher reports suggest a decline since the 1980s, carp still contribute a substantial proportion of fish biomass, with carp making up 87% of the fish biomass in the Murrumbidgee (Gilligan 2005*a*) and 49% in the Lower Murray-Darling (Gilligan 2005*b*) catchments. Even though carp populations are at a fraction of their abundances in the 1980s, they are still likely to have substantial ecological impacts.

Impacts

The impacts of carp are estimated to cost ~$15.8 million dollars annually (McLeod 2004), $2 million of which is spent on carp management, $2 million for research and $11.8 million on remediation of environmental impacts. Increased incidence of blue-green algae blooms, declining native fish populations, increased turbidity in major rivers, damage to stream banks and loss of aquatic vegetation have all been attributed to carp populations (Lachner *et al.* 1970; Crivelli 1983; Hume *et al.* 1983; Fletcher *et al.*, 1985; Page and Burr 1991; Wilcox and

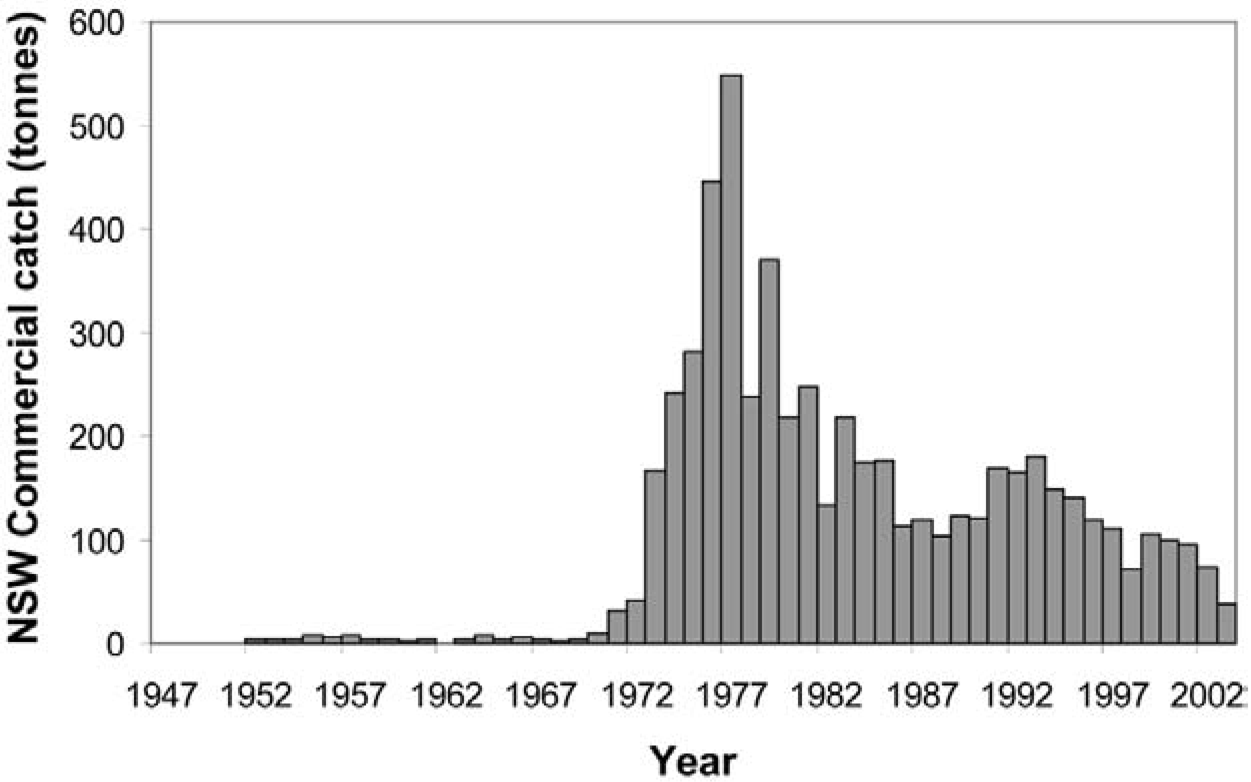

Figure 1. NSW commercial harvest of carp from 1947/48 to 2002/03 (data from Reid ***et al.*** 1997 and the NSW DPI comcatch database).

Hornbach, 1991; Breukelaret *et al.* 1994; Faragher and Harris 1994; Gehrke and Harris 1994; Hindmarsh 1994; Roberts and Ebner 1997; Koehn *et al.* 2000; Schiller and Harris 2001; Williams *et al.* 2001), although with differing levels of credible scientific evidence. There is still debate as to what extent carp are the cause of major disturbances in freshwater ecosystems and to what extent they are a response to disturbance (Rolls 2005). These issues are hard to resolve as the true effects of carp on freshwater systems are complex, difficult to isolate, and are often inter-related with other impacts and ecosystem changes (Hume *et al.*, 1983).

Management Solutions

Given the scale of the problem, numerous workshops and working groups have been convened in order to develop and progress with potential carp control solutions. These included:

- Forum on European carp (Murrumbidgee Catchment Management Committee, 1994)
- National Carp Summit (Broster 1996).
- Controlling carp – Exploring options in Australia (Roberts and Tilzey 1997)
- Carp Control Reference Group
  - o National Management Strategy for carp control (2000-2005) (Murray-Darling Basin Commission, 2000*a*)
  - o Future directions for research into carp (Murray-Darling Basin Commission, 2000*b*).
  - o Ranking areas for action: A guide for carp management groups (Murray-Darling Basin Commission, 2000*c*).
- Managing invasive freshwater fish in New Zealand (New Zealand Department of Conservation, 2001)
- National Carp Workshop (Lapidge 2003)

A number of control strategies have been proposed, developed, modelled and/or tested.

These control methods fall into four broad categories: biological control, habitat modification, physical control and chemical control (Roberts and Tilzey 1997).

Unsuccessful carp control strategies

Thresher (1997) and Brown and Walker (2004) modelled the feasibility of physical removal as a control strategy and concluded that potential for broad-scale control of carp populations in open river systems in the long-term were limited. Gilligan *et al.* (2005) tested the feasibility of using large fish traps for physical removal of carp populations from isolated waterbodies and reported limited success.

Gehrke (2003) trialed the use of rotenone-laced carp baits as a control technique and found that rejection of the toxic baits (following several days of training with non-toxic trainer baits) and unacceptable bycatch mortality prevented the uptake of this control strategy.

Fish screens have been installed at wetland inlets and outlets in the Lower Murray River in South Australia to prevent the entry of adult carp (Nichols and Gilligan 2004). Assessment of screened and unscreened wetlands suggested that screens were not effective at limiting carp abundance or biomass (Nichols and Gilligan 2004). This is probably due to the rapid growth of juveniles and larvae capable of passing through the mesh screens. Screens may still be suitable for excluding reproducing adults.

Potential for the use of a cyprinid specific pathogen, spring viraemia of carp virus (*Rhabdovirus carpio*) as a bio-control agent was reviewed and found to be unsuitable (Crane and Eaton 1997).

Wetland draw-down has been proposed and tested as a method of disrupting spawning and recruitment success (Shields 1957; Gafny *et al.* 1992; Bonneau *et al.* 1995; CRC FE 1999; Wilson 2000). Rapid reduction in water level during or following a spawning event could be used to desiccate recently spawned eggs. The technique has been used effectively under some conditions (Shields 1957; Bonneau *et al.* 1995). However, one major difficulty in applying this technique under natural conditions is that, as carp spawn during high flow events, the feasibility of being able to reduce the water levels in wetlands during spawning events is limited, particularly those very large marshy wetlands identified as carp spawning 'hot-spots' (see below). The length of the potential spawning season (up to nine months in Victoria (Sivakumaran *et al.* 2003)) also means that it is essential to maintain constant vigilance in order to control all (or most of) the spawning events. However, although probably ineffective in lowland river systems, draw-down of large impoundments during the spawning season may be very successful at eliminating carp populations form upland river systems.

Carp control strategies and techniques that are showing promise

Despite the limited success of the above control options, several recent carp control initiatives are showing some promise. These include the Tasmanian Carp Management Program (Inland Fisheries Service 2004), William's Carp Separation Cages (Stuart *et al.*, 2003), Daughterless Carp Gene Technology (Lapidge 2003) and identification of carp breeding hot-spots in the Murray-Darling Basin (Stuart and Jones 2002; Gilligan and Schiller 2003; Crook 2004; Driver *et al.* 2005; Gilligan, unpublished data).

Tasmanian Carp Management Program

Following the discovery of established carp populations in Lakes Crescent and Sorell in Tasmania in 1995, the Tasmanian Inland Fisheries Service undertook a campaign of containment and eradication (Diggle *et al.* 2004). Screens were installed in the channel linking the two lakes and at the outlet of Lake Crescent (the downstream lake), with mesh small enough to prevent eggs and larvae leaving the lakes. This was successful in preventing the colonisation of the Derwent catchment downstream. Had this occurred, it would have significantly reduced the potential for eradication. Both lakes were closed to recreational angling in order to minimise the risk of further translocations, with the waters of Lake Crescent closed to all forms of access.

Water levels in Lake Crescent were manipulated to exclude carp from spawning areas (shallow marshy areas) during the spawning season. This could not be achieved at Lake Sorell. As an alternative, marsh areas were fenced off with carp-proof mesh to exclude spawning fish. Although these approaches have undoubtedly assisted in limiting recruitment, they have not been entirely successful, with some recruitment detected in 1995/96, 1997/98, 2000 and 2003 (Diggle *et al.* 2004; Inland Fisheries Service 2004).

To physically remove adults, a variety of fishing methods were used, including fyke nets, seine nets, gill nets, traps and electrofishing. Since 1997, fishing effort was enhanced by incorporation of a 'Judas fish' strategy into the control program, where a number of males were radio tagged in order to identify spawning aggregations, and help understand habitat preferences and behaviours (Diggle *et al.* 2004). From 1999, the Carp Management Program routinely tagged (double dart-tagged) and returned all male carp to in order to enable estimation of population size using mark –recapture models.

In November 2003, the carp population in Lake Crescent was estimated to consist of just 32 individual fish (Diggle *et al.* 2004). The number of tagged male fish returned is now being limited to the minimum number required to assist in the collection of the remaining females. Lake Crescent was re-opened to recreational fishing in August 2004 (Inland Fisheries Service, 2004).

In Lake Sorell, continued improvements in fishing efficiency are required in order to achieve eradication (Diggle *et al.* 2004) as the small population in this Lake (originally less than 200 fish) is hard to target (Inland Fisheries Service 2004). As of 2004, only 16 adult females had been removed from the Sorell population (Inland Fisheries Service 2004). Modelling of the recruitment event in 2000 suggested that a maximum of 3,000 juveniles were recruited, of which 2,070 have been so far been removed. This suggests that around 930 carp remain in Lake Sorell (Inland Fisheries Service 2004).

William's Carp Separation Cages

Carp are highly mobile and regularly pass through fishways designed to enable the migration of native fish. As migrating fish must pass through fishway structures in order to move within regulated waterways, fishways create a migration bottleneck, with all fish passing through the ~25cm fishway 'slots'. These bottlenecks have potential as locations for the removal of migrating carp.

Within the Murray-Darling Basin, there are many observations of carp jumping, whilst native fish rarely jump. Further, carp are known to escape easily from fish traps not fitted with a secure roof (Stuart *et al.*, 2003). Mr Alan Williams, a lock master (Goulburn-Murray Water) at Torrumbarry Weir (Murray River) conceived a carp drafting device that capitalised on the jumping behaviour of carp and the fact that they regularly pass through fishway bottlenecks.

The "William's Carp Separation Cage' (Stuart *et al.*, 2003) is a low cost trap/drafting device suitable for installation in vertical slot fishways (see Stuart *et al.* 2003 for a diagram). A prototype trap was constructed and trialled at the Torrumbarry fishway. Of the 16 carp entering the fishway during the trial, 100% jumped into the containment area. No native fish jumped the baffle when it was set at 20cm above the water surface. A further trail was undertaken were 66 carp were placed in the trap, in which case 82% jumped into the containment area. Carp are held in the containment area until the trap is emptied. A means of releasing the native fish is currently being developed.

The 'William's Carp Separation Cage' provides a cost-effective and efficient means to remove carp from river systems. The only requirements for the device are the existence of a functional fishway and a means of harvesting the contained carp on a regular basis. Carp separation cages have now been installed at Torrumbarry and Euston fishways, and designs are being prepared for Lock 1 and Lock 7 (all on the Murray River) (Lieschke 2005).

Daughterless Carp Gene Technology

Ron Thresher and his team from CSIRO Marine Laboratories (Hobart) have been considering the applicability of molecular control techniques for carp for almost a decade (see Grewe 1997). In 2003 CSIRO obtained funding from the Murray-Darling Basin Commission to commence development of 'Daughterless Carp Gene Technology'.

The daughterless concept arose from the widespread use of chemical aromatase inhibitors to create single-sex lines of fish for aquaculture. Aromatase is the enzyme responsible for female development. If aromatase is inhibited, all embryos develop as fully functional phenotypic males irrespective of their genotypic sex (XX or XY) (Piferrer *et al.* 1994). The 'daughterless' gene proposed by Thresher (Lapidge 2003) is an inheritable modified sequence of carp DNA that inhibits the expression of the aromatase gene (Thresher and Bax 2003). Thresher and Bax (2003) proposed that the release of a sufficient density of artificially-reared daughterless gene carriers, each carrying a sufficient number of copies of the daughterless gene, and with stocking continued for a sufficient number of years, the sex ratio of the wild carp population will be skewed to the extent that the viability of the population will decline.

Apart from potential fitness affects arising from the gene insertion process, the proposed 'daughterless' gene is not predicted to have negative affects on the fecundity or fitness of the neo-males (XX daughterless gene carriers), and consequently the gene could potentially escape natural selection (Thresher and Bax 2003). Further, despite the fact that each copy of the daughterless gene has a 50% chance of being lost during meiosis in every generation (hence the requirement for numerous copies in each individual fish released), the number of 'daughterless' carriers in the population is predicted to "snowball" each generation (Thresher and Bax 2003). These hypotheses have been tested in population models (Thresher and Bax, 2003) which predict that carp populations could decline significantly within 20 years and reach pseudo-extinction within 30 years.

CSIRO are in the process of developing daughterless gene constructs and integrating them into the genomes of a model organism (medaka: Japanese rice fish) in order to demonstrate proof-of-concept. Once achieved, laboratory based population studies of medaka will be used to test population responses. From there, carp specific daughterless constructs will be created and field trials are proposed. Funding for further development of the technology is being provided by the Murray-Darling Basin Commission and the Invasive Animals CRC for the next three years.

Numerous concerns regarding the field application of daughterless technology exist. The principal concerns are: i) It is not known whether the reproductive fitness of hatchery-produced neo-males will be equivalent to true males, ii) the infrastructure to produce sufficient numbers of daughterless fish in hatcheries does not exist, and iii) that declines in carp abundance could take much longer than modelled, with carp populations potentially remaining at carrying capacity for many decades. Despite these concerns, if the technology is proven feasible, daughterless technology may provide a generic means of controlling pest fish (and perhaps other phyla) across the world. Consequently, development and testing of this high-risk/great benefit solution to pest fish control warrants current levels of financial support for further development and testing of the technology.

Identification of carp breeding hot-spots

Recent studies of carp reproduction in the Murray River indicate that carp spawning and recruitment success are highly dependent on seasonal flow peaks which inundate floodplain habitats, and that carp recruitment does not occur uniformly throughout river systems (Stuart and Jones 2002; Gilligan and Schiller 2003, Crook 2004, Driver *et al.* 2005; Brown *et al.* 2005). Two independent teams of researchers, Stuart and Jones (2002) and Gilligan and Schiller (2003), sampling in the Murray Riverina between 1997 and 2001, observed that the Barmah-Millewa forest was the point-source of carp recruitment in that region. This was later verified by Crook (2004) using advanced biochemical techniques. The implications of these findings were that a majority of recruits were originating from a finite number of carp breeding 'hot-spots'.

With funding from the Murray-Darling Basin Commission and the Pest Animal Control CRC, NSW Department of Primary Industries has been sampling carp larvae in order to locate other carp hot-spots throughout the NSW portion of the Murray-Darling Basin. A network of 239 sampling sites (Figure 2), distributed roughly every 50 km along each of the major rivers of inland NSW, was sampled during the carp breeding seasons in 2003/04 and 2004/05. Sampling activity was coordinated to coincide with the second high flow event in each river between October and March. Timing of sampling was important as adult carp spawn during the first high flow during the breeding season. Larval carp then remain in the spawning areas until dispersing on the second high flow event. The larvae disperse in a downstream direction as they have little ability to swim against the flow. Therefore, a high density of carp larvae sampled at any one site, with few or no larvae sampled at sites upstream, indicates a carp breeding hot-spot in the 50 km reach upstream of the sampling site.

During the 2003/04 and 04/05 breeding seasons, 12 of the 22 catchment areas were sampled (Table 1). The remaining 10 could not be sampled due to a lack of flows during the prevailing drought. Within the 12 systems sampled, four new hotspots were identified: the

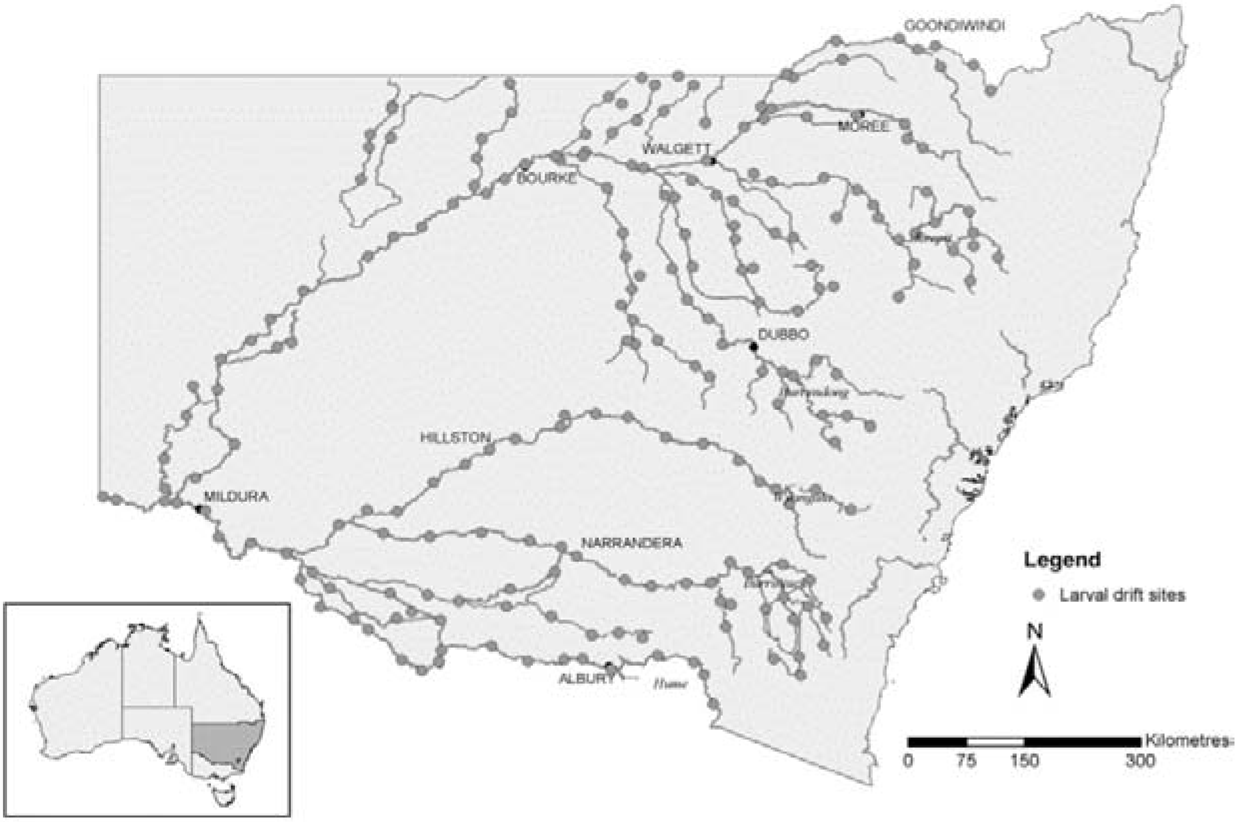

Figure 2. Distribution of sites sampled in inland NSW in order to locate carp breeding hot-spots.

Lower Mehi River (Gwydir wetlands), Lower Namoi River (Namoi wetlands), Lower Boomi River and Lower Warrego River. The lack of carp larvae in the upper Murray and upper Lachlan Rivers led to the inference that the point source of recruitment in these upper reaches must be the large irrigation storages, as no carp larvae in the riverine reaches suggests that either no carp breeding occurred in the upper reaches (which is known to be false), or more likely that they originated below the most downstream riverine site (ie. in the impoundments). Lastly, the Barmah-Millewa Forest in the Murray Riverina, which had formerly been identified as a hot-spot, provided mixed results from sampling over both seasons. In the 1998 study by Gilligan and Schiller (2003), a density of 1,700 ML^{-1} was recorded during the second flow peak, however sampling for this project in 2004 and 2005 seasons recorded densities of only ~12 ML^{-1} (18 ML^{-1} from the upper forest and 6 ML^{-1} from Barmah and Moira Lakes) and 0 ML^{-1} respectively (Table 1). This indicates substantial annual variability in the carp breeding activity within any one hot-spot and suggests that replicated sampling will be required in each river system in order to minimise false negative results. That is, once a hotspot has been identified, it can be considered a true positive result, however a negative finding may be a result of annual variability.

A clear example of a positive result is a hotspot identified upstream of Collarenebri on the Barwon River (Figure 3). Virtually no carp larvae were sampled in the ~400 km of river upstream. However at Collarenebri, the density of carp larvae suddenly rose to 33,547 larvae ML^{-1}. The next site upstream in the Barwon, Mogil Mogil, had only 1 ML^{-1}, suggesting that the hotspot was located somewhere between these two sites. However the Gwydir/Mehi River junction enters the Barwon in this reach. The most downstream site in the Mehi River (the Gwydir Highway Bridge) had a density of 29,737 larvae ML^{-1}, a figure consistent with that sampled at Collarenebri. Given that no carp larvae were sampled from the site immediately upstream in the Mehi River (Bullarah), this pin-points the carp breeding hot-pot to the ~50 km reach of the lower Mehi River upstream of the Gwydir Highway Bridge, in the vicinity of the Gwydir wetlands. Upon entering the Barwon River , the density of dispersing carp larvae then decreased at each subsequent sampling site downstream in the Barwon/ Darling Rivers (with a slight increase at Collywahoy).

The identification of carp breeding hot-spots is a major step forward for carp control. Rather than implementing control activities over tens of thousands of kilometres of river systems, control activities can now be targeted at a finite number of 50 km reaches, and potentially have a much greater impact on carp populations. The knowledge that carp populations have a source and sink population structure adds further possibilities for control.

Potential control activities could include targeted harvest of adults as they migrate towards breeding hotspots, and limiting or preventing dispersal of carp from source populations to sink populations using appropriately placed William's Carp Separation Cages. Potential control activities could also include the targeted harvest and removal of adults and juveniles as they disperse from recruitment areas, the construction

Table 1. Catchment areas sampled during the 2003/04 and 2004/05 carp spawning seasons, the location of carp breeding hot-spots identified and the density of carp larvae originating from each. * represent catchment areas not yet assessed.

Catchment area	Hot-spot identified	Density of carp larvae (per Megalitre)
Border Rivers	Lower Boomi River	7,500
Gwydir River	Lower Mehi River (Gwydir wetlands)	29,737
Barwon River	None	
Upper Namoi	*	
Namoi River	Namoi wetlands	7,700
Castlereagh River	*	
Upper Macquarie	*	
Macquarie River	*	
Bogan River	*	
Culgoa River	*	
Warrego River	Lower Warrego River	4,400
Paroo River	*	
Middle Darling River	None	
Lower Darling River	*	
Lachlan River	*	
Upper Lachlan River	Wyangala Dam	Inferred due to lack of larvae in river samples
Murrumbidgee River	None	
Upper Murrumbidgee River	*	
Upper Murray River	Hume Dam	Inferred due to lack of larvae in river samples
Middle Murray River	Barmah-Millewa Forest	1,700 in 1998 12 in 2004 (but with 38 at the next site downstream 'Echuca') 0 in 2005 (but no larvae anywhere in the Murray)
Edwards River	None	
Lower Murray River	None	

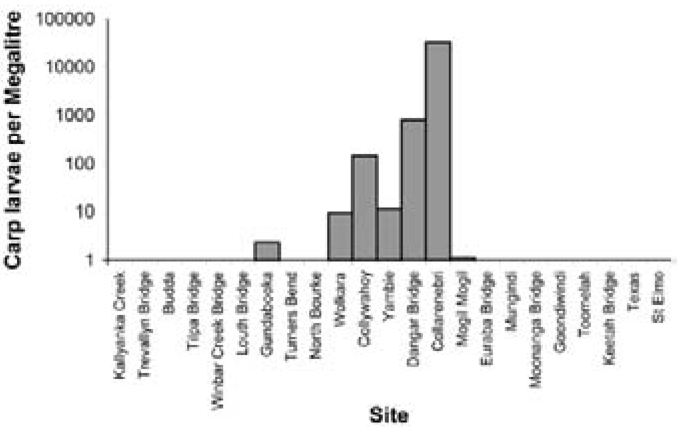

Figure 3. The density of carp larvae sampled at sites distributed at ~50 km intervals throughout a ~1,150km length of the Border-Barwon-Darling River system in north-west NSW. 'St Elmo' on Dumaresq River was the most upstream site and 'Kallyanka Creek' on the Darling River was the most downstream. A carp breeding hot-spot was identified in a tributary stream (the Mehi River) upstream of Collarenebri. Little carp breeding activity was detected in the ~400km upstream of Collarenebri. Note: The Y axis is expressed on a logarithmic scale.

of regulation structures on wetland inlets and outlets to prevent access of carp to spawning areas, the use of the regulators to prevent juvenile carp dispersing into the river and potentially eliminating them by allowing evaporation of wetlands, and the coordination and management of environmental flows to deliberately trigger carp aggregation at time when well-planned removal exercises can be undertaken. Lastly, the knowledge of carp recruitment areas may inform future releases of daughterless carp if that technology eventually proves feasible.

Further sampling is required in order to complete the exercise of locating hot-spots of carp recruitment. To date, ten catchment areas in NSW remain to be sampled, sampling has been restricted to NSW and did not extend into other waters within the Murray-Darling Basin (Queensland, Victoria, South Australia and the ACT) and, in most cases, only a single replicate sample has been collected from each system. As a result, the Murray-Darling Basin Commission and the Invasive Animals CRC have provided funding for the next three years in order to rectify these short-falls in the sampling program.

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References

Battaglene, S.C. 1985. Preliminary study of the fish resources of the Hunter Valley. Division of Fisheries - New South Wales Department of Agriculture.

Bonneau, J., Scarnecchia, D.L. and Berard, E. 1995. Better fishing means less carping at Bowman-Haley Reservoir. *North Dakota Outdoors Magazine, June.* http://www.und.edu/org/ndwild/carp.html accessed 21/02/2006.

Broster, L. (ed.) 1996. Proceedings of the National Carp Summit, Renmark, South Australia, October 6-7, 1995. (Murray-Darling Basin Association, Adelaide)

Brown, P. and Walker, T. 2004. CARPSIM: stochastic simulation modelling of wild carp (*Cyprinus carpio* L.) population dynamics, with applications to pest control. *Ecological Modelling* **176:** 83-97.

Brown, P., Sivakumaran, K.P., Stoessel, D. and Giles, A. 2005. Population biology of carp (*Cyprinus carpio* L.) in the mid-Murray River and Barmah Forest Wetlands, Australia. *Marine and Freshwater Research* **56:** 1151–1164..

Breukelaret, A.W., Lammens, E.H. and Breteler, K. 1994. Effects of benthivorous bream (*Aramis brama*) and carp (*Cyprinus carpio*) on sediment re-suspension and concentrations of nutrients and chlorophyll a. *Freshwater Biology* **32**: 113-121.

Brumley, A.R. 1996. Family Cyprinidae: Carps, minnows, etc.. Pp 99 - 106 in *Freshwater Fishes of South-Eastern Australia*, edited by R. McDowall, Reed Books, Sydney.

Butcher, D. 1962. The implications of the introduction of carp into Victorian waters. Fisheries and Wildlife Department, Victoria.

Cadwallader, P.L. 1978. Some causes of the decline in range and abundance of native fish in the Murray-Darling River system. *Proceedings of the Royal Society of Victoria* **90:** 211-224.

Crane, M.S. and Eaton, B.T. 1997. Spring viraemia of carp virus (*Rhabdovirus carpio*): a biological control agent? Pp 87 -105 in *Controlling Carp: Exploring the Options for Australia*, edited by J. Roberts and R. Tilzey, CSIRO Land and Water, Griffith.

Cooperative Research Centre for Freshwater Ecology 1999. Technology Transfer Strategy: Hydrologic manipulation as a potential carp control strategy. Cooperative Research Centre for Freshwater Ecology, Canberra.

Crook, D. 2004. Contribution of the Barmah-Millewa floodplain lakes to carp populations in the mid River Murray. Final Report to the Barmah-Millewa Forum, Department of Sustainability and the Environment, Arthur Rylah Institute, Melbourne.

Crivelli, A.J. 1983. The destruction of aquatic vegetation by carp, a comparison between Southern France and the United States. *Hydrobiologia* **106**: 37-41

Davis, K.M., Dixon, P.I. and Harris, J.H. 1999. Allozyme and mitochondrial DNA analysis of carp, *Cyprinus carpio* L. from south-eastern Australia. *Australian Journal of Marine and Freshwater Research* **50**: 253-261

Diggle, J., Day, J. and Bax, N. 2004. Eradicating European carp from Tasmania and implications for national European carp eradication. Inland Fisheries Service, Hobart, Tasmania.

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

Faragher, R.A. and Harris, J.H. 1994. The historical and current status of freshwater fish in New South Wales. *Australian Zoologist* **29:** 166-176.

Fletcher, R.F., Morison, A.K., and Hume, D.J. 1985. Effects of Carp *Cyprinus carpio* L. on Communities of Aquatic Vegetation and Turbidity of waterbodies in the Lower Goulbourn River Basin. *Australian Journal of Marine and Freshwater Research* **36**: 311-27.

Gafny, S., Gasith, A. and Goren, M. 1992. Effect of water level fluctuation on shore spawning of *Mirogrex terraesanctae* (Steintz), (Cyprinidae) in Lake Kinneret, Israel. *Journal of Fish Biology* **41**: 863-871

Gehrke, P.C. 2003. Preliminary assessment of oral rotenone baits for carp control in New South Wales. Pp 143-154 in *Managing invasive freshwater fish in New Zealand,* proceedings of a workshop hosted by Department of Conservation, 10-12 May 2001, Hamilton. Produced by the New Zealand Department of Conservation.

Gehrke, P.C., Brown, P., Schiller. C.B. and Bruce, A.M. 1995. River regulation and fish communities in the Murray River system, Australia. *Regulated Rivers: Research and Management* **11**: 363 – 375

Gehrke, P.C., Gilligan, D.M. and Barwick, M. 2002. Changes in fish communities of the Shoalhaven River 20 years after construction of Tallowa Dam, Australia. *River Research and Applications* **18:** 265-286.

Gehrke, P.C. and Harris, J.H. 1994. The role of Fish in Cyanobacterial Blooms in Australia. *Australian Journal of Marine and Freshwater Research* **45**: 905-15

Gilligan, D.M. 2005*a*. Fish communities of the Murrumbidgee catchment: Status and trends. New South Wales Department of Primary Industries, Fisheries Final Report Series No. 75.

Gilligan, D.M. 2005b. Fish communities of the Lower Murray-Darling catchment: Status and trends. New South Wales Department of Primary Industries, Fisheries Final Report Series No. 83.

Gilligan, D., Gehrke, P. and Schiller, C. 2005. Testing methods and ecological consequences of large-scale removal of common carp. New South Wales Department of Primary Industries, Fisheries Final Report Series No. 77.

Gilligan, D. and Schiller, C. 2003. Downstream transport of larval and juvenile fish in the Murray River. New South Wales Fisheries, Fisheries Final Report Series No. 50.

Graham, K.J., Lowry, M.B. and Walford, T.R. 2005. Carp in NSW: assessment of distribution, fishery and fishing methods. NSW Department of Primary Industries, Cronulla, Fisheries Final Report Series No. 72.

Grewe, P. 1997. Potential of molecular approaches for the environmentally benign management of carp. Pp 119-127 in *Controlling Carp: Exploring the Options for Australia*, edited by J. Roberts and R. Tilzey, CSIRO Land and Water, Griffith.

Harris, J.H. 1995. Effects of Introduced fish in Australia. In *Unwanted Aliens? Australia's introduced animals,* edited by B. Diekman B., Proceedings of Nature Conservation Council of NSW Seminar, 23-24 September 1994, Sydney.

Hindmarsh, M. 1994. "Carp: a noxious fish or a resource". In the proceedings of the forum on European carp, Wagga Wagga. Murrumbidgee Catchment Management Committee.

Hume, D.H., Fletcher, A.R. and Morison, A.K. 1983. Final report. Carp program report No. 10. Fisheries and Wildlife Division, Victorian Ministry for Conservation.

Inland Fisheries Service 2004. Carp Management Program Report: Lakes Crescent and Sorell 1995 – June 2004. Inland Fisheries Service, Hobart, Tasmania.

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

Koehn, J., Brumley, A. and Gehrke, P.C. 2000. *Managing the impacts of carp.* Bureau of Resource Sciences, Canberra.

Kuiter, R.H. 2005. Common carp; Its origin. *Fishes of Sahul* **19:** 164-166.

Lachner, E.A., Robins, C.R. and Courtenay, Jr. 1970. Exotic fishes and other aquatic organisms introduced into North America. *Smithsonian Contributions to Zoology* **59**. 29pp.

Lake J.S. 1967. Freshwater fish of the Murray-Darling River System. State Fisheries Research Bulletin Number 7. NSW Fisheries

Lake, P.S. 1980. Conservation. Pp 163-173 in *An Ecological basis for water management*, edited by W.D. Williams, Australian National University Press, Canberra.

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

Lieschke, J. 2005. Victorian update. Pp 50 - 62 in the *Australian Society for Fish Biology Newsletter* **35(2),** December 2005.

Lin, H.R. and Peter, R.E. 1991. Aquaculture. Pp 590 –617. In *Cyprinid fishes: Systematics, Biology and Exploitation*, edited by I.J. Winfield and J.S. Nelson, Chapman Hall, London.

Lintermans, M. 2002. Fish in the Murrumbidgee catchment: A review of current knowledge. Environment ACT, Canberra.

Llewellyn, L.C. 1983. The distribution of fish in New South Wales. Australian Society for Limnology, Special Publication No. 7.

Mackenzie, R., Jackson, P. and Cotterall, E. 2000. Control of exotic pest fishes – an operational strategy for Queenslands freshwaters. Department of Primary Industries, Queensland.

McLeod, R. 2004. Counting the cost: Impact of invasive animals in Australia, 2004. Cooperative Research Centre for Pest Animal Control, Canberra.

Murrumbidgee Catchment Management Committee 1994. Proceedings of the forum on European carp. Wagga Wagga, NSW 20/06/1994. Murrumbidgee Catchment Management Committee, Wagga Wagga.

Murray-Darling Basin Commission 2000*a*. National Management Strategy for carp control (2000-2005). Murray-Darling Basin Commission, Canberra.

Murray-Darling Basin Commission 2000*b*. Future directions for research into carp. Murray-Darling Basin Commission, Canberra.

Murray-Darling Basin Commission 2000c. Ranking areas for action: A guide for carp management groups. Murray-Darling Basin Commission, Canberra.

New Zealand Department of Conservation 2001. Managing invasive freshwater fish in New Zealand. Proceedings of a workshop hosted by Department of Conservation, 10-12 May 2001, Hamilton.

Nichols, S. and Gilligan, D. 2004. What about the fish?: Improving fish passage through wetland flow control structures in the lower River Murray. Australian Landscape Trust, Renmark, South Australia.

Panek, F.M. 1987. Biology and Ecology of carp. Pp 1 - 16 in *Carp in North America*, edited by E.L. Cooper, American Fisheries Society. Maryland, USA.

Page, L.M. and Burr, B.M. 1991. *A field guide to freshwater fishes North America North of Mexico*. Peterson Field Guide Series. Houghton Miffin Company. Boston. 432pp.

Piferrer, F., Zanuv, S., Carrillo, M., Solar, I.L., Devlin, R.I.L. and Donaldson, E.M. 1994. Brief treatment with a Aromatase inhibitor during sex differentiation causes chromosomally female salmon to develop as normal, functional males. *The Journal of Experimental Zoology* **270:** 255-262.

Reid, D.D., Harris, J.H. and Chapman, D.J. 1997. NSW Inland Commercial Fishery data analysis. FRDC Project No. 94/027, NSW Fisheries, Cronulla.

Roberts, J. and Ebner, B. 1997. An overview of carp *Cyprinus carpio* L. in Australia. Part 1. CSIRO, Land and Water. Griffith.

Roberts J. and Tilzey R. (eds) 1997. *Controlling Carp: Exploring the Options for Australia*. CSIRO Land and Water, Griffith.

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. Unpublished honours thesis, Charles Sturt University, Wagga Wagga.

Schiller, C. and Harris, J.H. 2001. Native and Alien fish. Pp 229 - 258 in *Rivers as Ecological Systems: the Murray Darling Basin*, edited by W.J.Young, Murray Darling Basin Commission. Canberra.

Shearer, K.D. and Mulley, J.C. 1978. The introduction and Distribution of Carp, *Cyprinus carpio* Linnaeus, in Australia. *Australian Journal of Marine and Freshwater Research* **29**: 551-63.

Shields, J.T. 1957. Experimental control of carp reproduction through water drawdowns in For randall reservoir, South Dakota. *Transactions of the American Fisheries Society* **87**: 23-32.

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.

Smith, B. 2005. The state of the art: a synopsis of information on common carp (*Cyprinus carpio*) in Australia. Final Technical Report, SARDI Aquatic Sciences Publication No. RDO4/0064-2; SARDI Research Report Series No. 77, Adelaide.

Splitler, R.J. 1987. Sport fishing for carp. Pp 31 - 48 in *Carp in North America*, edited by E.L. Cooper, American Fisheries Society. Maryland, USA.

Stuart, I. and Jones, M. 2002. Ecology and management of common carp in the Barmah-Millewa forest. Arthur Rylah Institute for Environmental Research, Heidelberg, Victoria.

Stuart, I., Mckenzie, J., Williams, A. and Holt, T. 2003. Separation cages for the removal of carp from Murray-Darling Basin fishways. Final report on preliminary trials of the William's Carp Separation Cage. Murray Darling Basin Commission. Project R2104.

Thresher, R.E. 1997. Physical removal as an option for the control of feral carp populations. Pp 58 - 73 in *Controlling Carp: Exploring the Options for Australia*, edited by J. Roberts and R. Tilzey, CSIRO Land and Water, Griffith.

Thresher, R. and Bax, N. 2003. The science of producing daughterless technology; Possibilities for population control using daughterless technology; maximising the impact of carp control. Pp 19 – 24 in the Proceedings of the National Carp Control Workshop, March 2003, Canberra, edited by K.L. Lapidge, Cooperative Research Centre for Pest Animal Control, Canberra.

Williams, A. E., Moss, W. and Eaton, J. 2001. Fish induced macrophyte loss in shallow lakes: top-down and bottom-up processes in mesocosm experiments. *Freshwater Biology*. **47:** 2216-2232.

Wilcox, T.P. and Hornbach, D.J. 1991. Macrobenthic Community Response to Carp (*Cyprinus carpio* L.) Foraging. *Journal of Freshwater Ecology* **6**: 170-183.

Wilson, G. 2000. Carp spawning biology reveals control clues. *Watershed* **May 2000:** 10-11.