

## ***Managing invasive carp (*Cyprinus carpio* L.) for habitat enhancement at Botany Wetlands, Australia***

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### ABSTRACT

1. In Australia, the carp *Cyprinus carpio* L. is regarded as a threat to the native fish and the aquatic environment. In recent years, Botany Wetlands, a significant coastal wetland in the Sydney region, has been invaded by the undesirable cyprinids, carp and goldfish (*Carrasius auratus* L.).

2. In 1996 a cyprinid removal programme commenced at Botany Wetlands with the objective of managing the invasive species, increasing fish diversity, reducing cyanobacterial blooms and hence enhancing the aquatic habitat. Using electrofishing and gill netting, 4073 carp and 261 goldfish, amounting to 10 117 kg of cyprinid biomass were removed between 1996 and 2004. The captured carp ranged from 60 to 835 mm. Males matured before females. Carp between 350 and 680 mm in length grew at the rate of  $1.66 \pm 0.38 \text{ g day}^{-1}$ .

3. The success of the programme was monitored by assessing four indicators related to carp populations and two related to habitat. The former included the pattern of length–frequency distribution, mean weight per size class, condition factor (CF) and the catch per unit effort (CPUE), and the latter the Secchi disc transparency and cyanobacterial counts. After 8 yr of removal, the plots of carp length–frequency distribution flattened, CF decreased from 2.86 to 1.82 and CPUE decreased from  $97 \text{ kg day}^{-1}$  to  $50 \text{ kg day}^{-1}$ . A 10-fold decrease occurred in cyanobacterial counts and the Secchi disc transparency increased by 20%. More than 20 000 fingerlings of native Australian bass *Macquaria novemaculeata* (S.) have been introduced to the wetlands, increasing the potential for juvenile carp predation and biodiversity.

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KEY WORDS: carp; goldfish; CPUE; condition; cyanobacteria; transparency; wetland

### INTRODUCTION

The Australian flora and fauna are unique owing to their evolutionary status, biogeographical isolation and vulnerability to competition from non-Australian species. The carp *Cyprinus carpio* Linnaeus is one such invasive species of oriental origin, distributed to the Palaearctic and introduced to the Australian biogeographical zone. Carp arrived in Australia *circa* 1860 (Shearer and Mulley, 1978) and colonized

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rapidly, now contributing more than 90% of the freshwater fish biomass in many areas of south-east Australia (Harris and Gehrke, 1997). All Australian surface waters appear to be climatically suitable for carp, threatening the relatively depauperate freshwater fish fauna of Australia (Koehn, 2004). Realizing the gravity of the problem, a National Carp Task Force was established, carp management workshops held (Nannestad *et al.*, 1994; Roberts and Tilzey, 1997) and research on the ecology of carp undertaken (King *et al.*, 1997; Robertson *et al.*, 1997).

The Botany Wetlands, the largest coastal freshwater body in the Sydney region, has also been invaded by carp, causing a threat to the resident native fish community. Sydney Water Corporation, as the owner of Botany Wetlands, commenced a rehabilitation programme in 1996–97 to improve the quality of the partially degraded wetlands (GHD, 1993; SWC, 1997). The programme included management of noxious species and control of cyanobacterial blooms. Carp management was undertaken with the dual objectives of controlling cyanobacteria and reducing invasive carp. Concurrently with carp removal, the native Australian bass, *Macquaria novemaculeata* (Steindachner), was reintroduced to prey on carp juveniles. The analysis of data from the carp removal programme provides evidence of aquatic habitat improvement as a result of carp removal from long-term studies, so far not documented in the Southern Hemisphere. The paper also suggests indicators that can be used to measure the effectiveness in carp removal programmes.

### LOCATION AND HABITAT

Botany Wetlands are located on the south-eastern coast of Australia, in the Sydney region (longitude 151°11'–151°14'; latitude 33°55'–33°57'). The wetlands comprise 11 interconnected ponds and adjacent land, covering an area of 58 ha (Figure 1). Botany Wetlands are ecologically important because they harbour an endangered plant community, the Eastern Suburb Banksia Scrub (ESBS), and offer refuge to migratory wading birds. The wetlands and the associated dam and weirs are heritage listed. Although the wetlands provided drinking water to early settlers until 1867 (Aird, 1961), it now serves as a stormwater basin, receives runoff and drainage from a highly urbanized catchment, and flows into Botany Bay.

Inappropriately termed 'ponds', the wetland system consists of diverse aquatic habitats from lentic to lotic, and lacustrine to palustrine ponds. Carp removal was conducted in pond 6 and pond 4/5 only, as carp were most abundant in these ponds. A weir separated pond 6 from pond 4/5, and a dam separated pond 4/5 from pond 3. The wetlands experience a temperate climate, with winter from June to August and summer from December to February.

### METHODS

The two-pronged strategy of the carp removal programme attempted to reduce the spawners and crop recruits.

Carp were removed from pond 4/5 and pond 6 by electrofishing and gill netting. Gill nets of mesh sizes 114 mm, 127 mm and 152 mm (equivalent to 4.5", 5" and 6" respectively) with a total length of 750 m were used. The mesh size was determined after a preliminary investigation using mesh sizes of 100, 106, 114, 139 and 150 mm. Mesh sizes between 114 and 150 mm gave the best catch per unit effort (CPUE). Preliminary investigations also showed that gill-net fishing at night yielded more fish than fishing during the day. The nets were first set after midnight and were drawn every 2 h to ensure that any native species of fish caught were released, in order to avoid predation of netted fish by eels.

There was no significant difference in the catch between the day and night electrofishing, so this method of fishing was carried out during the day. Electrofishing was conducted from a boat with a cathode mounted across the bow and anodes mounted on poles. The stunned fish at the anode were caught in

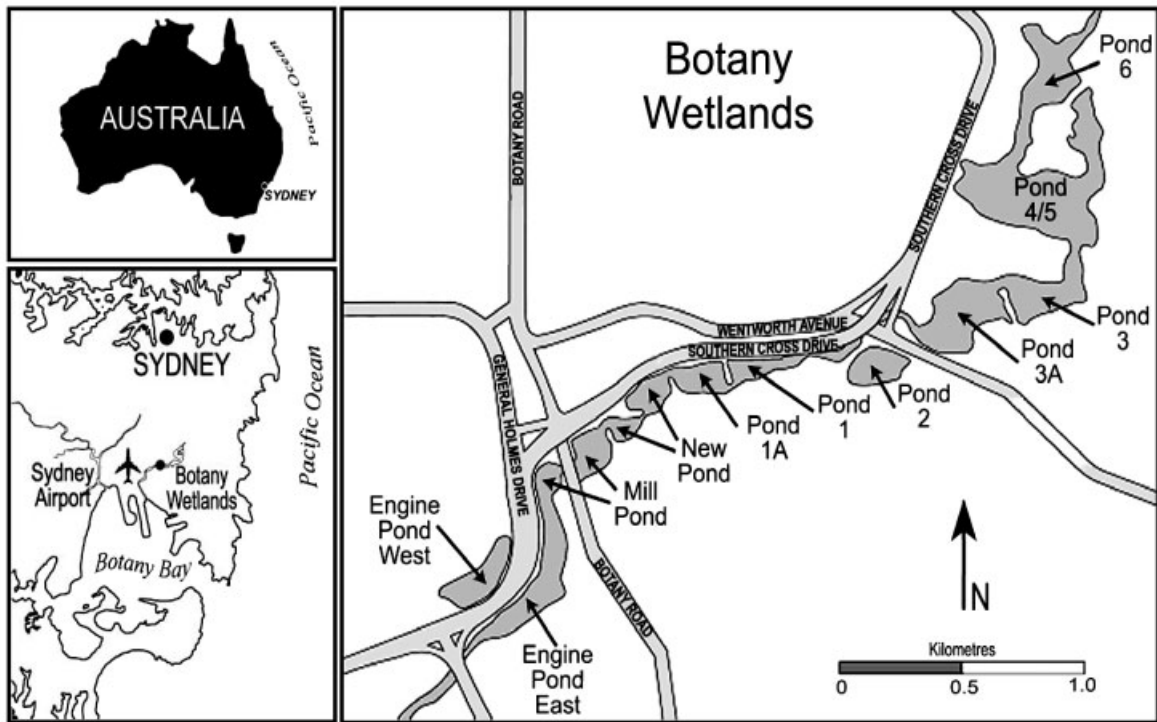


Figure 1. Location of Botany Wetlands and its ponds.

long-handled dip nets. Non-target species were identified in the water and allowed to escape by turning off the current. The fish were disposed of as offal at the Sydney fish market, as required by the NSW fishing licence.

Gill nets caught medium and large fish, whereas electrofishing caught fish of all sizes. Combining gill netting with electrofishing provided the best results. That is, the nets were laid and electrofishing was conducted close to the nets so that the fish receiving sublethal current would often swim into the nets. The native fish caught during fishing were returned to the water alive, but goldfish *Carrasius auratus* (Linnaeus), another noxious species, were disposed of with carp.

Weight, length, sex, abnormalities and gonad condition of carp were recorded in the field. CPUE was determined by dividing the total carp catch by the number of days of fishing. The gonad condition was classified based on the following field observations:

- (RR) running — eggs or milt extrude when pressed
- (R) ripe — bulging belly, eggs or milt do not extrude when pressed
- (S) spent — fish large, gonads shrunk
- (I) immature — fish small, gonads inconspicuous.

The abundance of carp was estimated by Chapman–Petersen estimator ( $N^*$ ) from a tagging experiment, where  $n_1$  is the number of carp originally marked and released,  $n_2$  is the number of carp (marked and unmarked) in the second sample, and  $m_2$  is the number of marked fish in the second sample (Seber, 1982):

$$N^* = \frac{(n_1 + 1)(n_2 + 1)}{m_2 + 1} - 1$$

The success of the carp removal programme was assessed by examining four indicators related to the carp population and two related to habitat. The former were the pattern of the length–frequency distribution, mean weight per size class, condition factor (CF), and CPUE. The latter were Secchi disc transparency and blue–green algal (cyanobacterial) abundance.

CF was determined by the methodology described by Pauly (1980) and Froese and Pauly (2003) based on the following length–weight relationship:

$$W = kL^3$$

(from  $W \propto L^b$ , where  $b \approx 3$ ) or

$$\log W = \log a + 3 \log L$$

When weight is measured in grams and length in centimetres, CF can be given as

$$CF = a \times 100$$

Although different definitions of CF have been used, such as the Ricker CF (Tesch, 1988) and Fulton CF (Anderson *et al.*, 2001), the above definition is the most appropriate when large quantities of length–weight data are available (pers. comm. Daniel Pauly).

Blue–green algal counts were made according to the method described by Hotzel and Croome (1999) and Secchi disc transparency was determined based on standard methods (Wetzel and Linkens, 1991). Rainfall, wind speed and air temperature data for the period 1996 to 2003 were obtained from Sydney Airport located at longitude 151° 17' and latitude 33° 94'.

## RESULTS

### The climate

During the study period the monthly mean air temperature at Sydney Airport in the vicinity of Botany Wetlands increased from 17.9°C in 1996 to 18.8°C in 1998 (Figure 2). The mean air temperature decreased in 1999 and thereafter levelled off. Monthly mean wind speed fluctuated between 19.4 and 18.8 km h<sup>-1</sup> from 1996 to 1999 and reached the lowest value of 18.1 km h<sup>-1</sup> in 1999. From 2000 onwards the mean wind speed increased, reaching 20.3 km h<sup>-1</sup> in 2003. The highest annual rainfall of 1347 mm was recorded in 1998, and the lowest rainfall of 743 mm in 2002.

### Statistics of fish captured

From 1996 to 2004 a total of 4073 carp and 261 goldfish, equivalent to 10 117 kg of fish biomass were removed from Botany Wetlands (Table 1). During the period of the project, an annual cyprinid biomass of 1265 ± 94 kg ( $\bar{X} \pm SE$ ) was removed from Botany Wetlands. This comprised an average of 495 ± 17 kg of carp and 33 ± 9 kg of goldfish ( $\bar{X} \pm SE$ ) per year. The carp captured ranged from 60 to 835 mm in length. Carp was the dominant cyprinid, with goldfish contributing <10% to the catch in all years except in 1997–98, when their percentage catch was 19%.

During fishing operations, 21 eels (*Anguilla australis* Richardson, *Anguilla reinhardtii* Steindachner), 274 catfish *Tandanus tandanus* Mitchell, 84 Australian bass *M. novemaculeata* (Steindachner) and 210 tortoises (long-necked *Chelodina longicollis*, short-necked *Elseya macquarii*) were caught in the nets and were released. Anatomical abnormalities were found in 1–2% of the carp population. The abnormalities noted were the absence of pelvic girdle, deformed mouth, atrophied jaw, crooked vertebral column, atrophied eye, tumorous testis and poorly developed ovary.

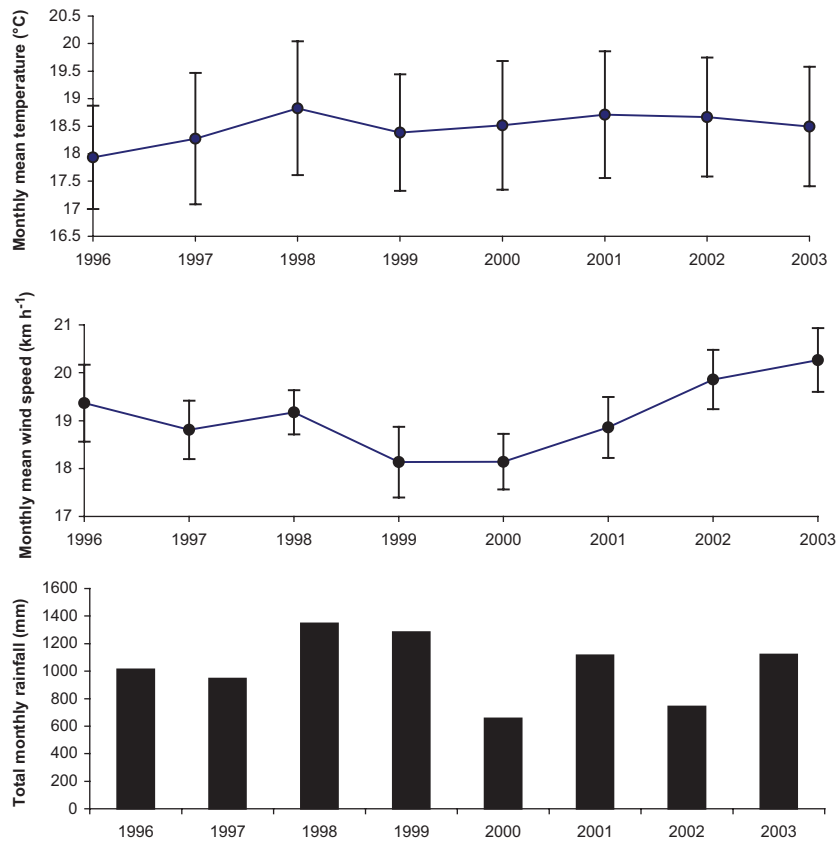


Figure 2. Mean air temperature, wind speed and annual rainfall at Sydney Airport near Botany Wetlands from 1996 to 2003.

Table 1. Biomass and average size of cyprinids captured from Botany Wetlands

Year	Carp	Carp mean length (mm)	Carp maximum length-class (mm)	Goldfish	Total fish biomass (kg)
1996–97	750	531	775	34	1650
1997–98	488	520	725	93	1024
1998–99	675	393	775	19	1327
1999–2000	754	464	800	36	1494
2000–01	446	539	775	29	1472
2001–02	327	493	800	23	1069
2002–03	329	525	800	18	1191
2003–04	304	496	850	9	890
1996–2004	4073	495	850	261	10 117

The length–frequency distribution of carp captured from 1996 to 2003 is given in Figure 3. The data are mainly from gill netting, except in 2002–03 when extensive electrofishing was conducted. Most fish captured during the first 2 years were relatively large. During the third year a large number of small fish were captured and no large fish, suggesting the successful removal of most of the large fish. This proved not to be

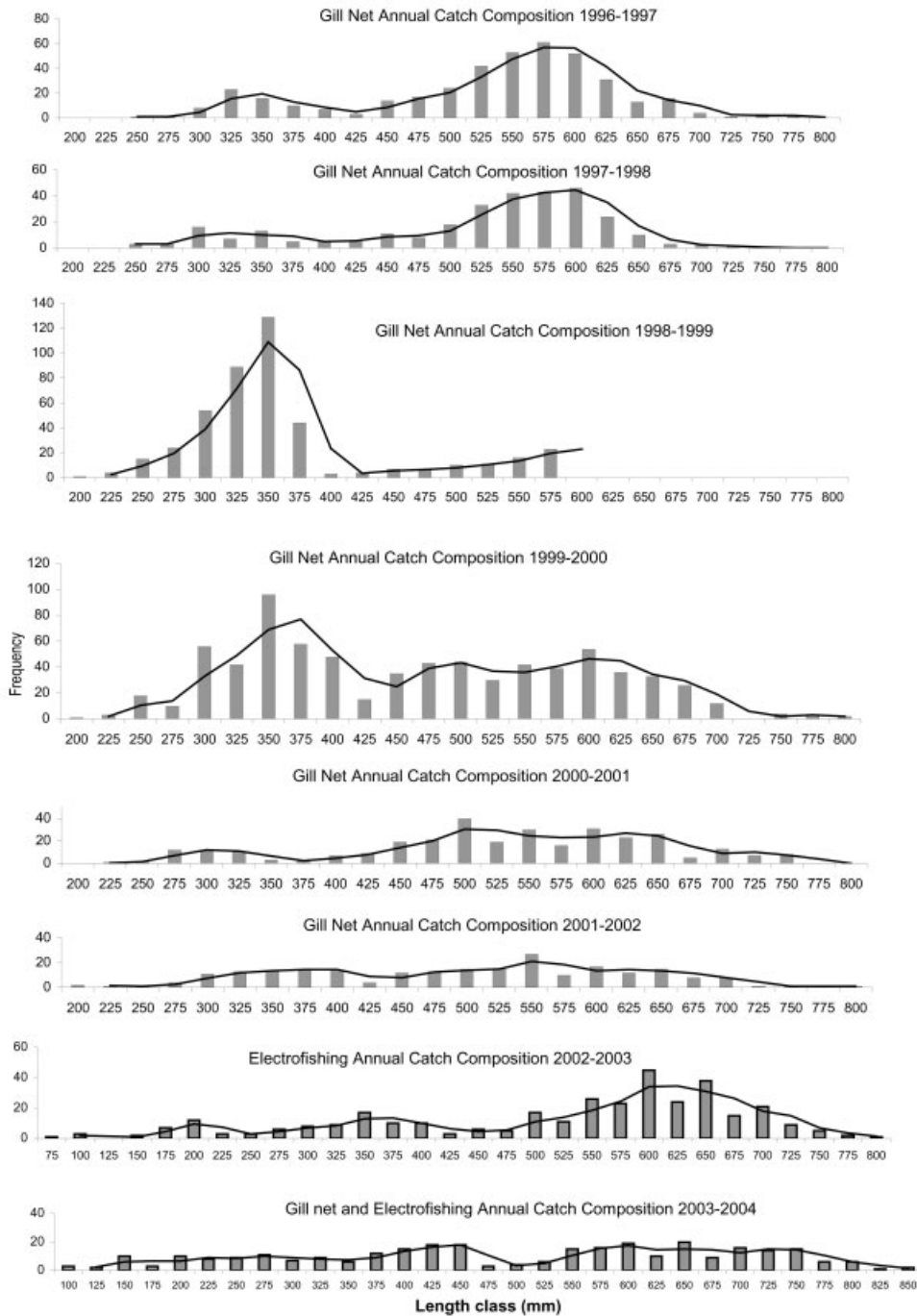


Figure 3. Length–frequency distribution of carp captured from Botany Wetlands from 1996 to 2004.

the case, as large fish were captured in subsequent years, probably indicating that large fish had taken refuge where electrofishing could not be conducted. From 2000 to 2003, the number of carp captured was lower than in previous years, and the modes in the frequency distribution were not prominent. Unlike in early years, when the captured fish had relatively narrow size range classes, the fish captured in 2002–03 had a wide size range from 75 to 800 mm, and in 2003–04 from 100 to 850 mm. The largest ( $L_{\max}$ ) carp captured was 835 mm, and the asymptotic length  $L_{\infty}$  of carp in Botany Wetlands, calculated from the relationship  $L_{\max}/0.95 \approx L_{\infty}$  (Pauly, 1980), was 879 mm.

Attempts were made to estimate the total population of carp by tagging, measuring, weighing and releasing 45 carp on 25 July 2003. Plastic-tipped dart tags with serial numbers were inserted behind the dorsal fin. During fishing in 2003 and 2004, 16 tagged fish were caught out of the 633 carp captured. These figures suggest a total population of about 1700 carp in pond 4/5, or 300 kg ha<sup>-1</sup> (considering the area of pond 4/5 to be 17 ha and the average weight of fish at Botany Wetlands to be 3 kg). The tagging experiment also showed that the growth rate of tagged carp of 350 to 680 mm at Botany Wetlands was  $1.66 \pm 0.38$  g day<sup>-1</sup> or  $0.25 \pm 0.06$  mm day<sup>-1</sup>, although growth and survival may be affected by tagging.

### Spawning biology

The gonad condition of carp at Botany Wetlands indicates that the major peaks in spawning are in spring from September to November, and in summer and autumn from February to May. Spawning activity is intense after a drizzle and there is splashing of water as they swim towards the surface and roll over. Hence, carp removal was scheduled for August, January and April before the onset of the main spawning periods. The smallest ripe male captured was 250 mm, and the smallest ripe female was 390 mm. As with many cyprinid species, male carp seem to mature sexually before the females.

### Reintroduction of native fish

The native fish community of Botany Wetlands comprises Australian smelt *Retropinna semoni* Weber, freshwater catfish *T. tandanus* Mitchell, short-finned eel *A. australis* Richardson, long-finned eel *A. reinhardtii* Steindachner, firetail gudgeon *Hypseleotris galii*, striped gudgeon *Gobiomorphus australis*, and common jollytail *Galaxias maculatus* (Jenyns) (Mallen-Cooper and Harris, 1990).

In 1998, about 10 000 fingerlings of the Australian bass (*M. novemaculeata*) were reintroduced to ponds 4/5 and 6. Between 2000 and 2002, a further 10 000 slightly larger sized bass were released in the same ponds. While fishing for carp, 92 Australian bass were caught in 2001–02, 8 in 2000–01 and 62 in 1999–2000. The Australian bass netted in 2001–02 ranged in size from 150 to 350 mm, compared with 200 to 250 mm in 2000–01. On some fishing days, the bass caught in gill nets outnumbered carp, suggesting the successful establishment of the bass population.

### Indicators related to carp population

#### *Length–frequency distribution*

The number of carp caught annually at Botany Wetlands decreased from 1996–97 to 2001–02 (Figure 3). The modes that were prominent during the early period of the project have also diminished, indicating that more of the dominant year classes have been removed.

#### *Mean weight per size class*

The mean weight of carp captured in 1998–99 and 2002–03 of four size classes was determined. Only unripe carp, i.e. excluding R and RR, were used in this analysis. These size classes were selected because a

Table 2. Comparison of mean weight of unripe carp of different classes captured in 1998–99 and 2002–03

Size class (mm)	Mean weight (kg)		Df	<i>t</i>
	1998–99	2002–03		
400–450	2.29	1.43	12	6.89***
450–500	3.11	2.26	23	4.07***
500–550	4.36	3.04	36	8.22***
600–650	6.27	4.93	42	5.37***

\*\*\* Significant  $P < 0.001$ .

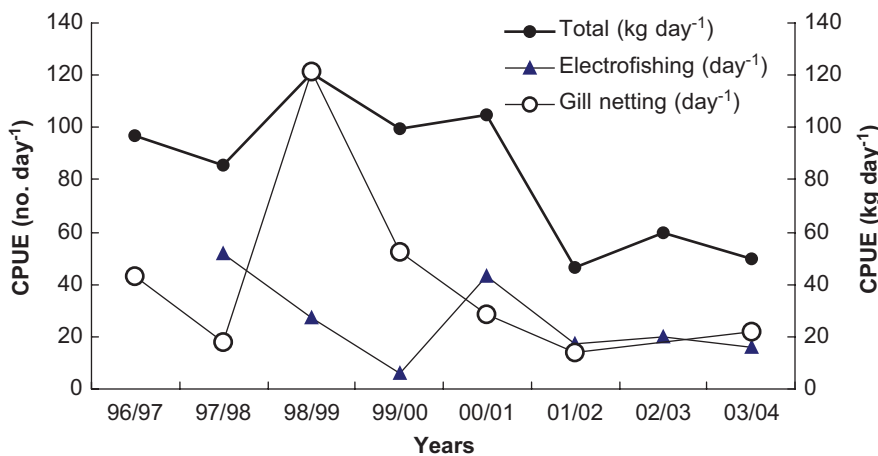


Figure 4. Catch per unit effort from gill net fishing and electrofishing.

comparatively large number of fish were available in the catch. There was a significant decrease ( $P < 0.001$ ) through time in the weight of each size class considered (Table 2).

### CPUE

This indicator was used to assess the impact of fishing on the resident carp population. Figure 4 shows the change in CPUE of carp captured at Botany Wetlands by gill netting and electrofishing between 1996 and 2004. The number of fish captured per day (i.e. night catch for gill netting and day catch for electrofishing) was used as the unit of effort.

Figure 4 shows the CPUE as numbers per day from each method, and the total catch in kilograms per day. The total CPUE in weight was  $97 \text{ kg day}^{-1}$  in 1996–97, increasing to  $121 \text{ kg day}^{-1}$  in 1998–99, and decreasing to  $50 \text{ kg day}^{-1}$  in 2003–04. The CPUE as numbers from gill netting in 1996–97 was  $43 \text{ day}^{-1}$ , and it decreased to  $18 \text{ day}^{-1}$  in 1997–98. The highest CPUE from gill netting was in 1998–99, reaching  $121 \text{ day}^{-1}$ , and thereafter decreasing to  $22 \text{ day}^{-1}$  in 2003–04. Electrofishing commenced in 1997–98 with a CPUE of  $52 \text{ day}^{-1}$  and decreased to  $6 \text{ day}^{-1}$  in 1999–2000. Then, it increased to  $43 \text{ day}^{-1}$  in 2000–01, but decreased to  $16 \text{ day}^{-1}$  in 2003–04. The overall pattern of the CPUE from 1996 to 2004 was a general decrease in the total weight and number of carp captured by gill netting and electrofishing.

### Condition factor

The examination of large gravid carp at Botany Wetlands and nearby Centennial Park showed that gonads contributed up to about 25% of the total biomass of the fish. The results of a one-tailed *t*-test comparing

the weight of ripe and unripe carp of similar length classes are given in Table 3. Though not statistically significant ( $P < 0.05$ ) for most size classes, ripe carp were generally heavier than unripe carp of similar size. The results in Tables 2 and 3 indicate that the CF of carp at Botany Wetlands is influenced by the development of gonads.

Figure 5 shows the relationship between weight and length of carp from Botany Wetlands expressed in log values, with the gradient forced through 3.0 for the data of 1998–99 and 2003–04. Table 4 indicates that the CF has decreased from 2.85 in 1998–99 to 1.82 in 2003–04. This means that fewer fish with ripe gonads were caught in recent years than in 1998–99.

Table 3. Comparison of the mean weight of ripe and unripe carp of similar size classes

Size class (mm)	Mean weight (kg)		Df	<i>t</i>
	Unripe	Ripe		
<b>2000–01</b>				
400–450	1.58	1.69	15	0.68 ns
450–500	2.41	2.32	11	0.38 ns
500–550	3.40	3.40	16	$2.37 \times 10^{-15}$ ns
600–650	4.86	5.39	14	1.40 ns
<b>2002–03</b>				
400–450	1.43	1.90	2	2.18 ns
450–500	2.26	2.50	12	0.85 ns
500–550	3.04	3.40	22	1.91*
600–650	4.72	4.73	19	0.03 ns

ns. not significant; \*significant  $P < 0.05$ .

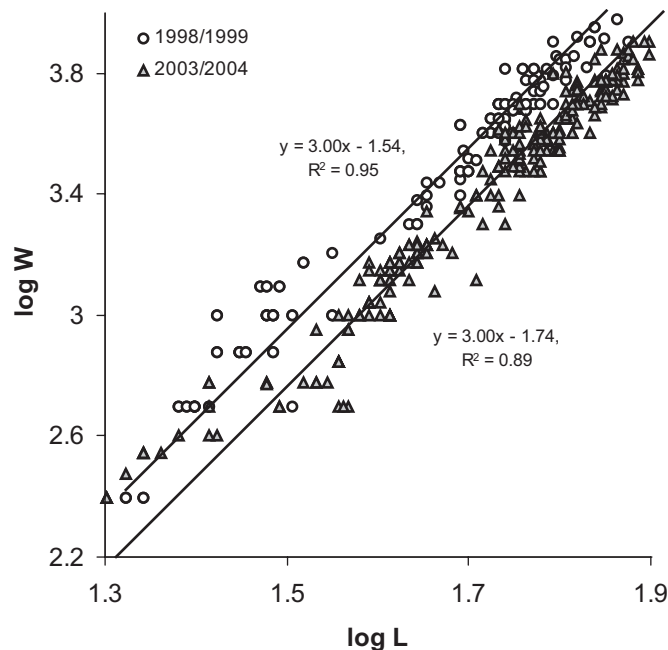


Figure 5. Change in the intercept of the plot of  $\log W$  vs  $\log L$  with gradient 3.0 for the data of 1998–99 and 2003–04.

Table 4. Length–weight relationship and condition factor (CF) of carp captured from 1998–99 to 2003–04

Year	Length–weight relationship	$R^2$	CF
1998–99	$\log W = 3 \log L - 1.54$	0.95	2.851
2000–01	$\log W = 3 \log L - 1.68$	0.85	2.089
2002–03	$\log W = 3 \log L - 1.70$	0.75	1.995
2003–04	$\log W = 3 \log L - 1.74$	0.74	1.820

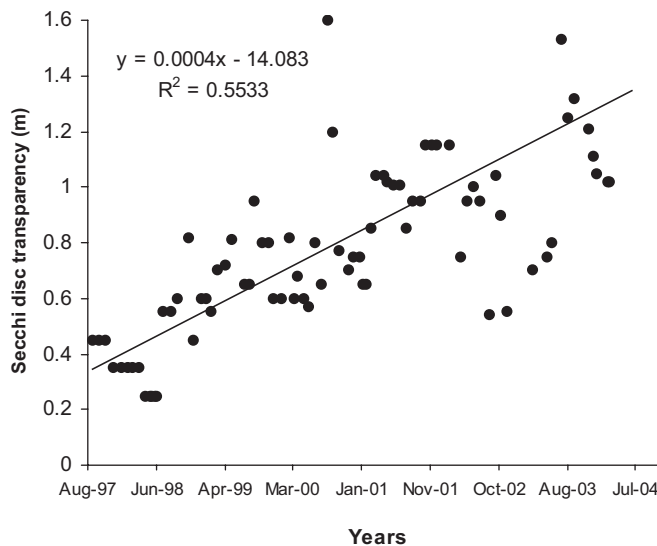


Figure 6. The increase in the Secchi disc transparency from 1996 to 2004.

### Indicators related to habitat

Since one of the objectives of carp removal was to enhance aquatic habitat at Botany Wetlands, cyanobacterial counts were made and Secchi disc transparency measured monthly at Botany Wetlands. Figure 6 shows the Secchi disc transparency values obtained at monthly intervals from 1996 to 2004. The regression line indicates a 20% improvement in the transparency of water.

Figure 7 shows the monthly counts of *Microcystis aeruginosa* and *Anabena circinalis* in pond 4/5 and the decreasing trend in the occurrence of blooms since the commencement of the carp removal programme. Blue–green algal counts in 2000–01 were comparatively low, and that trend has continued in 2002. Although no visible scum was observed in 2002–03, there was an increase in the abundance of blue–green algae.

Figure 7 also shows the ANZECC (2000) guideline for cyanobacteria expressed as a log value. In the figure, the 15 000–20 000 cells mL<sup>-1</sup> guideline value has been transformed to the log value of 4.2–4.3. The duration and intensity of blue–green algal blooms have decreased, and the trend of the decrease has been 10-fold from 1996 to 2004.

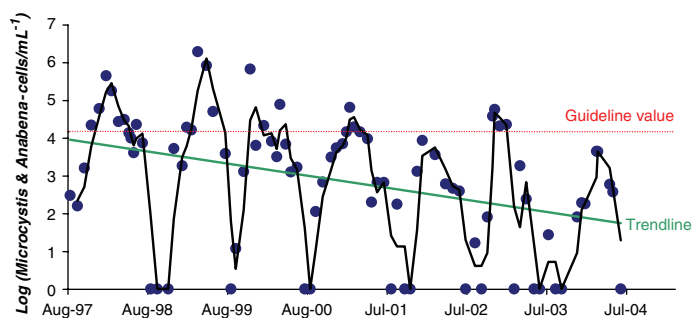


Figure 7. Decrease in the blue–green algal density since the commencement of the carp removal programme.

## DISCUSSION

Although carp (*C. carpio*) is an aquaculture species in many countries, it is regarded as a noxious species in Australia because of its adverse impacts on the environment and the native biota. The adverse effects they cause are the increase of turbidity resulting from their mode of feeding, nutrient enrichment from sediment disturbance, bloom formation by nutrient enrichment, reduction of macrophytes, destabilization of banks, competition with native fish and engorgement of their eggs and larvae (Harris, 1995).

### Carp population and the fish community

The carp at Botany Wetlands ranged from 60 to 835 mm in length, the upper limit being slightly higher than that of carp in the Murray and Darling rivers, where they reached 750 mm (Gehrke, 1997; Vilizzi and Walker, 1999). Although carp can grow up to 1200 mm in length and 60 kg (Allen, 1989), in Australia they commonly reach 3 kg (Brumley, 1996). At Botany Wetlands, the average weight of carp was about 3 kg, with the largest fish reaching 9.9 kg. The ponds in Centennial Park, which are connected to pond 6 of Botany Wetlands, harboured carp as big as 900 mm in length and weighing 24 kg (AWT, E&I, 2002).

The large number of small fish and scarcity of large fish in the catch of 1998–99 was remarkable, but not strange, as similar observations were reported by Koehn *et al.* (2000) at Paroo, Darling, Murrumbidgee and Murray rivers in a survey conducted from 1992 to 1995. Although they concluded that high mortality of large fish was the cause of change in the pattern of the length–frequency distribution, large carp at Botany Wetlands were caught in the following year, so the mortality proposition was rejected. The large fish probably moved away into shallow habitats inaccessible for fishing, buried in sediments or moved sluggishly not to be gill-netted. The estimated growth rate of tagged carp of 350–680 mm at Botany Wetlands was  $1.66 \text{ g day}^{-1}$ , which was within the range for carp in eastern European rivers ( $1.28\text{--}2.42 \text{ g day}^{-1}$ ; Kuznetsov *et al.*, unpublished results) and comparable to the  $1.67 \text{ g day}^{-1}$  in experimental tanks (Raghavan and Ramadhas, 2001). The estimated growth rate at Botany Wetlands is probably an underestimate, as the growth of untagged fish would be higher. High growth rate of carp at Botany Wetlands, a partially degraded habitat, is expected, since invasive species such as carp thrive in stressful abiotic environments (Bruton, 1986).

As in other localities, male carp matured before females at Botany Wetlands, but, whereas spawning at other localities was in late spring and early summer, at Botany Wetlands they spawned throughout the year with peaks in spring, summer and autumn. The presence of the smallest females with developing gonads indicated that female carp at Botany Wetlands reached sexual maturity slightly earlier than recorded in other localities (Koehn *et al.*, 2000). Morphological features, such as the occurrence of barbels, the length:

width ratio, and lateral line scales of carp, goldfish and hybrids, indicated that there is no sexual barrier for reproduction between carp and goldfish. Shearer and Mulley (1978) were able to separate the 'Yanco', 'Boolara' and 'Prospect' populations of carp in Australia based on protein alleles. They recognized hybridization between goldfish and the 'Yanco' strain only. The carp at Botany Wetlands was frequently of the 'Prospect' strain, but occasionally the orange-coloured 'Yanco' strain were also captured. At Botany Wetlands the hybridization was between goldfish and the 'Prospect' strain. Although the 'Yanco' strain was restricted to Murrumbidgee Irrigation Area in 1977 (Shearer and Mulley, 1978) they are now common in Sydney East (e.g. Botany Wetlands) and Sydney West (e.g. Smalls Creek, pers. obs.).

The occurrence of carp in densities  $> 450 \text{ kg ha}^{-1}$  is considered to have a significant impact on aquatic macrophytes (King and Hunt, 1967). Tagging results, as well as the annual catch, indicate that carp density at Botany Wetlands is approximately  $300 \text{ kg ha}^{-1}$ . The highest density of carp reported in a New South Wales river survey was  $3144 \text{ kg ha}^{-1}$  at Lachlan River in the Murray region (Driver *et al.*, 1997). Densities recorded also depend on the capture as Mullen-Cooper *et al.* (1995) found that carp catches in the middle reaches of the Murray River were greatest under stable flow conditions.

As well as the introduced carp (*C. carpio*), goldfish (*Carassius auratus*) mosquito fish (*Gambusia affinis*) and seven native species have been collected from Botany Wetlands (SWC, 2002). About 20 000 fingerlings of Australian bass (*M. novemaculeata*) have been released to the Botany Wetlands with the agreement of NSW Fisheries. The release of the native fish fingerlings and the removal of invasive species would have increased the diversity of the fish community at Botany Wetlands.

### Performance indicators of carp removal programme

Assessment of the carp removal programme was based on two main monitoring areas, namely (1) monitoring the reduction in carp numbers and (2) monitoring the improvement of the aquatic habitat. Although measuring damage caused by carp has been considered to be more important than measuring carp control efforts (Bomford and Tilzey, 1997), population-based indicators were also assessed in this programme, as the reproductive success in carp is to some extent density dependent (Thresher, 1997). In density-dependent populations, the stock-recruitment model shows that, at low densities, small increases in the number of spawning females may result in a large increase in recruitment, but at high densities an increase in the number of spawning fish may result in a decrease in recruitment. That is, at higher densities, the removal of spawning carp is expected to increase recruitment.

Length–frequency distribution, mean weight per size class, CPUE and CF can be used to assess the efficiency of carp removal. With progress in the carp removal programme, the peaks in length–frequency distribution flattened. This is because the abundant size classes have a higher probability of being removed. The flattened length–frequency graphs in recent years indicate that substantial pressure has been exerted on the carp population at Botany Wetlands. Since the commencement of the programme the mean weight per size class of unripe fish has decreased, indicating that carp removal has not helped the remnant population to grow rapidly, as in a totally density-dependent population.

CPUE is a direct indicator of fish density, and provides a better estimate of performance than length–frequency and mean weight per size class. The change in CPUE with time for the total biomass and the number of carp indicate that CPUE has decreased from 1996–97 to 2003–04. The measurement of CPUE at Botany Wetlands is subject to variability, as the numbers of fishing hours per day are approximations, the weather conditions on fishing days are not always uniform, and different fishermen have slightly different fishing techniques. In spite of these variations, CPUE is used extensively in commercial fishery stock assessment to assess fishing mortality and fish abundance (Gulland, 1983), and the parameter can be used to assess the efficiency of carp removal programmes.

CF is a measure of fatness of fish determined from the length–weight relationship. Spatial and temporal differences in the CF of a species have been used to interpret several biological events, such as fat reserves,

adaptations to the environment and gonad development (Le Cren, 1951). In a population that is density-dependent, an increase in the CF is expected after the removal of carp. However, this was not found to be the case with carp at Botany Wetlands, because their CF was influenced more by gonad development than by food abundance. The CF of carp at Botany Wetlands decreased from 2.85 to 1.82 as the carp removal programme progressed. This is an indication that more carp were removed before their gonads developed in recent years than at the commencement of the programme. The timing of fishing has led to a remarkable reduction in spawners in recent years.

The CF of *C. carpio* in the lotic habitat of Murrumbidgee River ranged from 1.32 to 1.36, and in lentic habitats of Lake Wyangan and Barren Box Swamp from 1.13 to 1.25 (Adámek, 2002). Botany Wetlands carp appear to be heavier than Murrumbidgee carp, but they are somewhat similar to carp in lakes of Southern California, as the CFs of *C. carpio* in Lake Mathews and Copper Basin Reservoir were 1.99 and 2.02 respectively (Anderson *et al.*, 2001).

There has been a remarkable improvement in the aquatic habitat of Botany Wetlands since the commencement of the carp removal project. Water transparency has increased and the frequency and duration of the cyanobacterial blooms has decreased. The increase in the mean wind speed in the area from 1996 to 2003 (Figure 2) would suggest a decrease in water transparency, contrary to what was recorded. Therefore, there is evidence to support the hypothesis that carp removal has contributed to the increase of water transparency since the beginning of the programme. Earlier studies on the effect of carp on Australian fresh water indicated that turbidity was more a function of hydrology and flooding than carp biomass (Hume *et al.*, 1983). Recent work in irrigation drains (Bowmer *et al.*, 1994), in artificial ponds (Roberts *et al.*, 1995), and in natural billabongs (King *et al.*, 1997) has confirmed the relative effect of carp and other factors on turbidity. In a set of controlled experiments, Breukelaar *et al.* (1994) recorded a significant positive correlation between carp biomass and the concentration of suspended solids.

The removal of carp is considered to reduce bloom formation by reducing the nutrient release from sediments, as well as by increasing algal grazing by cladocerans. As juvenile carp prey on cladocerans, the removal of carp should enrich the cladoceran population, increasing algal grazing. Although it is not yet known whether carp influence the rate of nutrient release from sediments to the water column in Australian waters (King *et al.*, 1997), nutrient release from sediments at Botany Wetlands probably plays a more important role than cladoceran grazing, since a thick layer of organic mud acts as a nutrient sink. Botany Wetlands also receive abundant nutrients and organic pollutants as leachate from a disused tip site at Astrolabe Park (Jankowski and Knight, 1991; AWT, ES&T, 1998). Similar to the observations of Breukelaar *et al.* (1994), where chlorophyll *a*, total phosphorus, silicates and Kjeldahl nitrogen decreased with decrease in fish biomass, it is very likely that the release of nutrients to the water column was reduced by carp removal at Botany Wetlands. King *et al.* (1997) recorded a significantly higher total phosphorus concentration in the presence of high carp biomass, but there was no consistent pattern for dissolved phosphorus. Loughheed *et al.* (1998) also noted that nutrient levels in Lake Ontario wetlands increased predictably with the increasing biomass of carp. They attributed the increase in phosphate and ammonia levels to resuspension of sediments, and to an increase in excretion rate related to carp abundance.

Transparency in water is determined by organic and inorganic particulate matter, dissolved coloured compounds, and microorganisms such as algae and zooplankton. At Botany Wetlands, transparency was strongly influenced by light and by suspended solids that include a significant proportion of algae. The algal blooms are also influenced by seasonal temperature, hence the wider scatter of points in Figure 7. It is very likely that the reduction of carp reduced resuspension of sediments, increased water transparency and decreased the occurrence of algae in the water column. The reduction in cyanobacterial blooms could also be attributed to the reduction in the carp density in the ponds. In ponds with higher fish biomass, Tatrai *et al.* (1997) observed a negative correlation between chlorophyll *a* and Secchi transparency that was significant and with a higher slope compared with ponds containing low fish biomass. On the floodplains of Murrumbidgee River, Robertson *et al.* (1997) found a negative impact of carp on autotrophic biofilms

growing on artificial substrates, and no influence on benthic algae, probably due to the feeding habits of carp.

Carp affect macrophytes in two main ways. On the one hand, the feeding method of carp can uproot macrophytes and reduce leaf biomass; on the other hand, carp activity can increase turbidity, thus reducing photosynthesis of the submerged macrophytes. As the carp removal progressed at Botany Wetlands, the pondweed *Potamogeton javanicus* began to spread rapidly, indicating that carp controlled its expansion. At Goulburn River, Fletcher *et al.* (1985) found that the food of carp mainly consisted of macroinvertebrates with some soft macrophytes, including *Potamogeton* spp. Roberts (1995) noted that the sucking and blowing ('mumblin') method of feeding by carp removed *Vallisneria* and *Chara*, but *Juncus ingens*, *Schoenoplectus validus* and *Myriophyllum papillosum* were fairly resistant. In the wetlands of Lake Ontario, where carp contributed significantly to turbidity, Lougheed *et al.* (1998) noted that, above a turbidity threshold of 20 NTU, there were fewer than five species of submerged macrophytes, and only *Potamogeton pectinatus* could thrive in highly turbid wetlands. Carp removal is only one aspect of wetland rehabilitation at Botany Wetlands, and it needs to be integrated into a comprehensive management scheme for the entire wetland that takes into account the macrophyte community, noxious weeds, water and sediment quality.

Wetland management can aim to achieve one of two stable states: (1) clear water dominated by macrophytes and (2) turbid water dominated by phytoplankton. Restoration of either state requires the identification and removal of the stresses that initiated the switch (Lougheed *et al.*, 1998). Human impact and sedimentation were the main causes of degradation of Botany Wetlands. Before this, they were a source of drinking water. It is suggested that an environment with clear water dominated by macrophytes should be the target for Botany Wetlands.

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