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Fish and Macroinvertebrates in Lowland Drainage Canals With and Without Grass Carp

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ABSTRACT

Diploid grass carp (*Ctenopharyngodon idella* L.) were introduced to a lowland Waikato drainage canal at an initial density of 40-80 kg ha^{-1} (83-167 fish ha^{-1}) to control aquatic macrophytes and improve water flow. A near-by canal was left without grass carp to act as an untreated control. After 7 months, macrophytes occupied 17% of the water column in the treated canal compared to 78% in the untreated canal. Fish and macroinvertebrates in both canals were examined before and after the release of grass carp by sampling with replacement by fyke netting on seven occasions. Brown bullhead catfish (*Ameiurus nebulosus* (Lesueur)) and shortfinned eels (*Anguilla australis* Richardson) comprised most of the resident fish biomass in both canals; however, before grass carp stocking, eels were more abundant than catfish in the treated canal. There was no change in the abundance of resident fish after stocking, but young-of-the-year catfish had greater mortality and grew faster in the treated canal than in the untreated canal. Macroinvertebrates were primarily associated with aquatic macrophytes. Grass carp reduced aquatic macrophyte abundance in the treated canal by about 80%, which by inference reduced the abundance of associated macroinvertebrates, but there was no observed impact of grass carp stocking on the resident fish assemblage. We examined the relationship between head width and fish length, and from this determined that 70% of the grass carp could have escaped through the downstream retention screen. Despite this possibility, grass carp remained in the canal and effectively controlled aquatic macrophytes for 18 months.

Key words: Waikato, New Zealand, aquatic macrophytes, fish, hornwort, coontail, *Ceratophyllum demersum.*

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INTRODUCTION

Grass carp (*Ctenopharyngodon idella* (Valenciennes)) have been used in New Zealand for control of aquatic macrophytes (e.g., Schipper 1983, Rowe and Schipper 1985, Rowe and Hill 1989, Rowe and Champion 1994, Clayton and Wells 1999), and have controlled macrophytes in canals with some success (e.g., Wells et al. 2003). Mechanical macrophyte removal is still common in New Zealand, partly because grass carp cannot survive in all locations in which aquatic macrophyte control is required. Water with low dissolved oxygen is often associated with dense aquatic macrophyte beds and low pH from peat lands, making some locations unsuitable for grass carp (Clayton et al. 1998).

The impact of grass carp on fish populations in New Zealand appears to have been related to the extent of macrophyte removal and stocking densities. No decline in eel numbers occurred in a short-term study in a Waikato drainage canal where partial weed control was obtained for a limited period by grass carp at an initial stocking density of 500 fish ha^{-1} (261 kg ha^{-1}; Schipper 1983, Rowe and Schipper 1985). However, at a higher initial stocking density (1,000 fish ha^{-1} or 460 kg ha^{-1}), where grass carp eliminated all plants, abundance of native eel (*Anguilla* spp.) and exotic goldfish (*Carassius auratus* L.) and mosquitofish (*Gambusia affinis* Baird and Girard)) declined (Schipper 1983, Rowe and Schipper 1985). In Lake Parkinson (1.92 ha in area), which was stocked with grass carp at 44 fish ha^{-1} (132 kg ha^{-1}), increased sizes of native bullies (*Gobiomorphus* spp.), common smelt (*Retropinna retropinna* (Richardson)), and exotic rainbow trout (*Oncorhynchus mykiss* Walbaum) followed complete removal of beds of aquatic macrophytes (Mitchell 1986).

There has not, however, been an integrated study of macroinvertebrates and fish with grass carp in a New Zealand. The primary objective of this study was to investigate the potential of grass carp to control aquatic macrophytes in a lowland canal. Secondly, we sought to evaluate the effects of grass carp on fish and invertebrates in a canal where grass carp were introduced to control aquatic macrophytes by comparison with an untreated canal without grass carp. Thirdly, because containment of grass carp is an issue in New Zealand, we estimated the minimum opening size required in screens to contain the grass carp by determining grass carp growth rate and the relationship of head width to fork length (FL).

Study Site Description

Two canals, Churchill East (37°23.87'S, 176°3.98'E) and Rangiriri (37°25.44'S, 175°6.52'E), were selected in the lower Waikato River catchment about 24 km northwest of Huntly, North Island, New Zealand. These canals were once free-flowing streams, but they have been deepened by excavation to improve drainage from surrounding farmland, and both are now separated from the Waikato River by flood-control levees. Float-level controlled pumps empty water from the canals into the lower Waikato River. Both canals have a history of problem growth of aquatic macrophytes. Grass carp were released into the treated canal within the Churchill East drainage system. The treated canal has a catchment area of 1,371 ha, consisting of 720 ha of pastoral hills and 651 ha of developed pastoral flat land. Its pumps have a capacity of 4,800 L s^{-1}. Shallow water depths restricted the grass carp to a 2.5-km section of the main canal between two pump stations (~3 ha in surface area; Wells et al. 2003). The treated canal was large (up to 13 m wide and often greater than 1 m deep in the lower section) and had a metal screen and a pumped outlet to contain the released grass carp and reduce the chance of their escape into the Waikato River.

Rangiriri canal (untreated) is 6 km south-east of the treated canal and also discharges into the Waikato River via a pump station. The untreated canal was up to 9 m wide and mostly about 0.8 m deep, with 1 km of open channels and a drainage area of 259 ha. The pump station had a capacity of 900 L s^{-1}. The catchment of the untreated canal had similar soils to the treated canal, comprising 94 ha of wetland and 165 ha of pasture.

MATERIALS AND METHODS

Water Quality

Spot measurements dissolved oxygen, water temperature, specific conductivity, and pH were measured 20 cm below the water surface at three permanently marked, equally spaced locations within 500 m of the lower pump station on six occasions on the same days as the fishing. The recordings for each canal were made between 1400 and 1600 h on the same day except in June, when water quality in the treated canal was measured in 17 June 1999, before measurements were made in the untreated canal (24 June 1999).

Macrophytes

Five permanently marked 1-m wide belt transects were selected in each canal to represent the three-dimensional range of vegetation types present. In the untreated canal, transects were about 50 m apart, and in the treated canal they were about 200 m apart. Each belt transect was sampled using a 1 m^2-quadrat placed at 1-m intervals. Water depth, plant species, heights, and cover were recorded within each quadrat. The vertical distribution of plants was also recorded because much of the vegetation formed surface mats, growing into the channel from the margins with open water beneath. The transects were monitored in mid-June 1999 after mechanical removal of the aquatic macrophytes for flood control, but before grass carp were released, and in January 2000, seven months after grass carp release.

The mean cover of each plant species was calculated for five transects per canal. Differences between the canals were compared using ANOVA between canals with a Dunn-Sidak multiple-test correction to control for the family-wise error rate (Sokal and Rohlf 1995). Floating species data were not included in this analysis because they were not adequately sampled by 1-m wide transects due to their irregular distribution.

Grass Carp

On 24 June 1999, 250 diploid grass carp were released into the treated canal. Prior to release, the FL of all carp was measured, and a subsample of 123 fish was weighed. Weights of the remaining unweighed carp were calculated from a regression model (Wells et al. 2003). The head widths of 60 grass carp were measured on release, and these were combined with 40 previous measurements to calculate the regression relationship with length (S. Pullan, New Zealand Ministry of Fisheries, unpubl. data).

The metal screen upstream of the pump station in the treated canal comprised a series of rectangular vertical bars. This screen was originally installed to trap macrophytes that might otherwise block the pumps. The width of the three widest openings in the screen, and 17 openings chosen at random, was measured to the nearest mm prior to release of the grass carp.

To assess growth and survival, the grass carp population was sampled using a combination of netting and electrofishing on 22 March 2000, nine months after their original stocking. A trammel net was set across the treated canal, and a 600-m section was electrofished upstream towards the net using a boat-mounted 300-W generator-powered electrofisher. The side canals were netted off to prevent carp escaping. The captured grass carp were weighed and measured before being returned to the canal.

Resident Fish

Both canals were fished overnight on seven occasions between 18 June 1999 and 6 December 2000. We used six 6-mm mesh fyke nets and six 12-mm mesh fyke nets with 4-m long leaders for the fish sampling. The 12 nets were baited with commercial trout food pellets and set perpendicular to the bank in one canal at a time within 500 m of the lower pump station. Coarse and fine meshed nets were set alternately from the true left bank. Length of all captured fish was measured to the nearest mm after anaesthetisation with 2-phenoxy ethanol; total length (TL) was measured for eels, and FL was measured for other species. Fresh weight of 70 randomly selected fish of each species was measured to the nearest 0.1 g, and weight-length regressions were used to estimate the weights of remaining fish. Regressions were calculated with SYSTAT 10.0 from natural-log transformed data. All fish were released at the point of capture after processing.

We compared mean catch rates of fish between canals for each date with multiple analyses of variance. To control for the family-wise error rates inherent in this procedure, we used a Dunn-Sidak multiple-test correction (Sokal and Rohlf 1995).

Macroinvertebrates

Macroinvertebrates were sampled in association with five vegetation transects in each canal (Wells et al. 2003). A systematic, qualitative sampling approach was used to identify species composition and relative abundance in the major habitat types. Macroinvertebrates on each plant species present in patches >1 m^2 were sampled by vigorous sweeps across the submerged plant tips in area of about 1 m^2 to a depth of about 0.2 m with a 0.5-mm mesh net. The top 0.2 m of the soft sediments that comprised the bottom substrate in both canals was sampled by sweeping the same net through the sediment for 1 m. The samples were sorted in the laboratory and all macroinvertebrates were identified and counted. The mean number of each species per sample was calculated and compared between sampling periods for each canal. We compared mean number of macroinvertebrates in each sample between canals for each date with multiple analyses of variance. To control for the family-wise error rates inherent in this procedure, we used a Dunn-Sidak multiple-test correction (Sokal and Rohlf 1995).

RESULTS

Water Quality

Dissolved oxygen concentrations were greater in the treated canal (mean 69%) than in the untreated canal (mean 40%; ANOVA $p = 0.018$). Specific conductivity was also greater in the treated canal (mean 246 µSeimens cm^{-1}) than in the untreated canal (mean 196 µSeimens cm^{-1}; ANOVA $p < 0.001$), as was water temperature (mean 18.4°C in the treated canal, and 16.5°C in the untreated canal; ANOVA $p = 0.013$). pH was not different between the canals (range 5.1-7.6, ANOVA $p = 0.445$).

Macrophytes

Coontail, or hornwort (*Ceratophyllum demersum* L.), was the dominant macrophyte species. In addition, the treated canal had extensive marginal vegetation of reed sweet grass (*Glyceria maxima* (Hartm.) Holmberg), but this species was not present in the untreated canal. Both canals had water primrose (*Ludwigia peploides* (Kunth) Raven), parrot's feather (*Myriophyllum aquaticum* Cambess), and knotgrass (*Paspalum distichum* L.). The treated canal also had the native submerged pondweed (*Potamogeton ochreatus* Raoul) (Wells et al. 2003). Aquatic macrophytes were mechanically removed from both canals in June 1999 prior to the release of the grass carp into the treated canal so that winter rain did not cause flooding.

Mechanical removal in June 1999 reduced aquatic macrophytes to 28-32% of the water column before grass carp were released (Table 1). At this point, there was no difference in macrophyte abundance between the canals for any taxon. By late January, 7 months after grass carp release, macrophytes occupied much less of the treated canal than the untreated canal, and the treated and untreated canals had become quite different in their vegetative composition. *Ceratophyllum demersum* had all but disappeared from the treated canal, but was still the dominant submerged species in the untreated canal (Table 1). The treated canal had virtually no submerged vegetation in January 2000, and sprawling emergent *Glyceria maxima* comprised most of the macrophytes. In the years before the study, macrophytes often covered 80% of the surface area of the treated drain before mechanical clearing (NIWA Hamilton, unpubl. data).

Resident Fish Diversity, Abundance, and Growth

A total of 11,438 fish comprising seven species was caught at both sites. The treated canal had populations of brown bullhead catfish (*Ameiurus nebulosus* (Lesueur)), shortfinned

TABLE 1. MEAN PERCENTAGE COVER OF AQUATIC MACROPHYTES THROUGHOUT THE WATER COLUMN IN FIVE 1-M WIDE TRANSECTS IN THE TREATED CHURCHILL EAST CANAL (WITH GRASS CARP) AND THE UNTREATED RANGIRIRI CANAL (WITHOUT GRASS CARP). PROBABILITY OF DIFFERENCES BETWEEN TREATED AND UNTREATED CANALS FOR EACH DATE WAS DETERMINED BY ANOVA WITH A DUNN-SIDAK MULTIPLE-TEST CORRECTION. *N* = 5 FOR EACH CANAL AND DATE.

	Mean percentage cover					
	June 1999			January 2000		
Taxa of aquatic macrophytes	Treated*	Untreated	*P*	Treated	Untreated	*P*
Rooted submerged						
Ceratophyllum demersum	12.50	14.00	1.000	0.57	62.00	0.015
Potamogeton ochreatus	4.42	0.48	0.738	0.00	1.42	0.334
Rooted emergents						
Glyceria maxima	6.86	0.00	0.554	15.90	0.00	0.167
Glyceria fluitans	0.00	0.01	0.881	0.00	0.00	1.000
Ludwigia peploides	1.89	4.70	0.943	0.28	6.27	0.823
Myriophyllum aquaticum	2.03	9.73	0.933	0.19	2.17	0.898
Paspalum distichum	0.13	2.17	0.594	0.08	5.61	0.457
Polygonum salicifolum	0.05	0.66	0.651	0.02	0.39	0.900
All rooted macrophytes	27.90	31.80	1.000	17.10	77.90	0.001

*The June survey was made on 11 June 1999, one week after mechanical removal of aquatic macrophytes, but before the release of grass carp on 24 June 1999.

eels (*Anguilla australis* Richardson), goldfish, rudd (*Scardinius erythrophthalmus* L.), common smelt, and mosquitofish. The untreated canal had a population of brown bullhead catfish with some shortfinned eels and goldfish. Brown bullhead catfish were the most abundant fish species in both canals ($N = 10{,}012$), comprising 72% of the fish by number in the treated canal and 97% untreated canal (Table 2). Shortfinned eels comprised 26% of the fish number in the treated canal and 3% in the untreated canal. Goldfish, mosquitofish, two rudd, and two common smelt were caught in the treated canal. Goldfish and mosquitofish were the only fish species other than catfish caught in the untreated canal.

In February 2000, young-of-the-year (YOY) catfish <75 mm FL were a much larger proportion of the total population in the treated canal (75%) than in the untreated canal (6%; Figure 1). Growth of YOY catfish estimated from mean cohort FL was faster in the treated canal (0.10-0.64 mm day^{-1}) than in the untreated canal in all seasons (0.09-0.24 mm day^{-1}; Figure 2). By December 1999, YOY catfish were 40 mm longer in the treated canal than in the untreated canal.

Large numbers of catfish were captured on most sampling dates. In the untreated canal, there were generally five to ten times as many catfish than in the treated canal (Table 3A). Despite the greater abundance of catfish in the treated canal before the introduction of grass carp, there were more catfish in the untreated canal in September 1999 and December 2000; on other sampling occasions catch rates were not different (Table 3A). In February 2000, 1,424 captured catfish died overnight in the untreated canal in fyke nets. Dissolved oxygen concentrations in the untreated canal fell to 0.2 mg l^{-1} as a result of macrophyte decay following chemical control. The subsequent catch rate in the untreated canal in April 2000 did not change, indicating that the number of catfish remained similar (Table 3A). In the treated canal, catch rates were relatively constant until April 2000 when an influx of YOY increased the mean catch rate to 152 catfish net^{-1} night^{-1} (Table 3A; Figure 1).

Shortfinned eels were smaller in the treated canal (mean 342 g, $N = 1{,}004$) than in the untreated canal (mean 696 g, $N = 180$; ANOVA $P < 0.001$). Catch rates indicated that there were about six times more shortfinned eels in the treated canal than in the untreated canal (Table 3A). In the treated canal, catch rates were 5-10 eels net^{-1} night^{-1} except for December 1999, when the mean catch rate rose to 29 eels

TABLE 2. NUMBERS OF FISH CAUGHT IN TWO WAIKATO CANALS WITH (TREATED) AND WITHOUT (UNTREATED) GRASS CARP.

	Treated canal		Untreated canal		
Fish species	Number	Percentage	Number	Percentage	Total
Brown bullhead catfish	3029	71.5	6983	97.0	10012
Shortfinned eels	1112	26.2	180	2.5	1292
Goldfish	57	1.3	28	0.4	85
Mosquitofish	32	0.8	10	0.1	42
Grass carp	3	0.1	0	0.0	3
Rudd	2	<0.1	0	0.0	2
Common smelt	2	<0.1	0	0.0	2
Total	4237		7201		11438

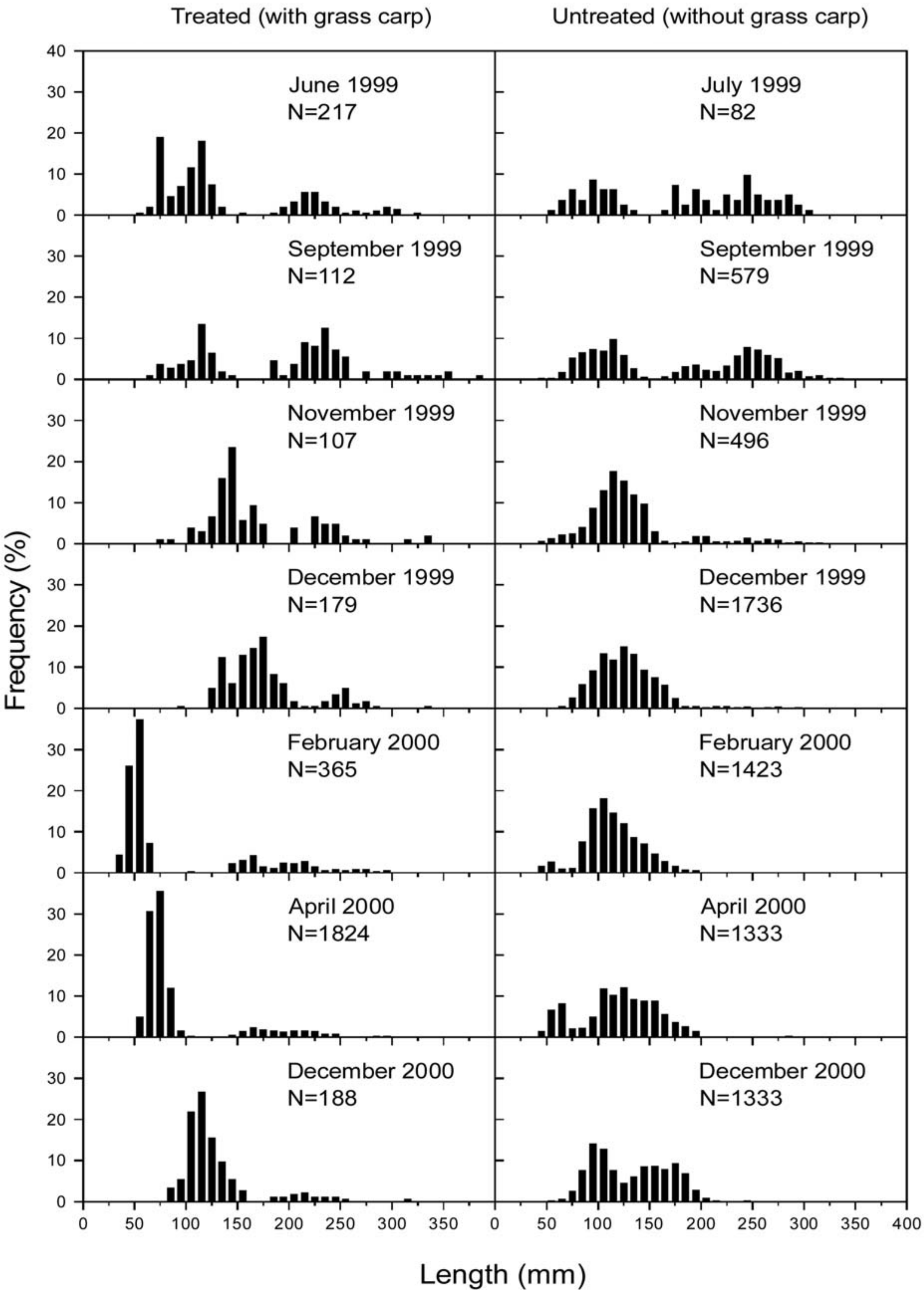

Figure 1. Length-frequency distributions of brown bullhead catfish in two pumped Waikato canals with (treated) and without (untreated) grass carp.

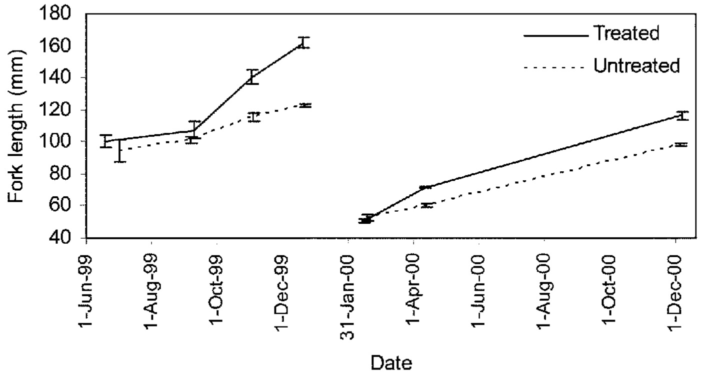

Figure 2. Growth of brown bullhead catfish in two Waikato canals with (treated) and without (untreated) grass carp. Error bars are 95% confidence intervals.

net^{-1} $night^{-1}$. Small numbers of shortfinned eels (<4 eels net^{-1} $night^{-1}$) were generally caught on all sampling dates in the untreated canal.

Biomass catch rates of shortfinned eels were similar in the two canals despite the differences in relative numerical abundance. The larger size of eels in the untreated canal compensated somewhat for their lower density (Table 3B). The biomass of catfish caught was usually greater in the untreated canal. There was no difference in the combined biomass of both species caught. In addition, there was no seasonal trend or change in the fish biomass caught.

Macroinvertebrates

Macroinvertebrates were unevenly distributed among the macrophyte taxa; *Myriophyllum aquaticum* usually had the greatest number of macroinvertebrates (Table 4). There was also variation among seasons; in September, chironomids were found in the treated canal, mostly on *Glyceria maxima* and *Myriophyllum aquaticum*. In January 2000, gastropods were the most numerous macroinvertebrate in the untreated canal, occurring on all plant genera, but were absent from the treated canal despite their presence in June 1999. In the untreated canal, *Glyceria maxima* was never present and *Myriophyllum aquaticum* was sparse, so neither plant species was sampled there. Damselfly nymphs were found in low numbers in both canals associated with both submerged and emergent plant species in spring and summer.

Seven invertebrate taxa were found, including chironomid larvae (*Tanytarsus* sp.), damselfly nymphs (*Xanthocnemis zealandica* (McLachlan)), the introduced gastropod *Physa acuta* Draparnaud, an unidentified hemipteran, leeches (*Glossiphonia* L. sp.), oligochaete worms of the Family Tubificidae (*Branchiura sowerbyi* Beddard), and waterboatmen (*Sigara* sp.) (Table 5).

Mean abundance of macroinvertebrates on macrophytes and in sediments was not different between the canals (Table 5) because of variable distribution among samples. On macrophytes, snails and leeches were the most common species. By September 1999, chironomids had increased dramatically in the treated canal, but had reduced by January 2000. Damselfly nymphs and tubificids were the most common macroinvertebrates on macrophytes in the treated canal, whereas snails and leeches predominated in the untreated canal (Table 5A). In sediment at the start of monitoring in June 1999, macroinvertebrate numbers were not different between the canals, although tubificids were highly abundant in the treated canal (Table 5B).

Grass Carp Growth and Head Width

The mean FL of the released grass carp at the time of stocking was 341.9 ± 5.1 mm, and their mean weight was 485.5 ± 31.2 g (±95% confidence interval; $N = 250$; range 264 to 457 mm FL). The total weight of grass carp at release was estimated to be 121 kg, equivalent to 40 kg ha^{-1} (83 fish ha^{-1}) in the ~3 ha of canal between the pump stations. However, the depth of the canal was not uniform, and the lower 1.5 km was deeper than the upper section and all of the side canals. Assuming that only the lower 1.5 ha of the canal was suitable for grass carp, as macrophytes were not controlled elsewhere, the realized stocking density could have been up to 80 kg ha^{-1} (167 fish ha^{-1}).

The regression of grass carp head width to FL at the time of release, combined with 40 fish previously measured by the New Zealand Ministry of Fisheries (unpublished data), was

$$Y = 2.70 + 0.140\ X,$$

where Y = head width in mm and X = FL in mm ($N = 100$, $r^2 = 0.973$, $P < 0.001$). Estimated head widths of the released grass carp ranged from 38 to 67 mm compared to screen opening widths of 38-57 mm (mean 48 mm, 95% confidence interval 2.9 mm, $N = 17$). Although the management objective was to contain the grass carp with the metal screen, 175 (70%) of the 250 grass carp originally stocked had an estimated head width less than the mean screen opening (48 mm) at the time of release. Grass carp needed to be >324 mm FL to be retained by the screen, and as many were less than this, escape through the screen was possible. The levee and pumped outlet, however, probably prevented escape of grass carp into the Waikato River. The period during which grass carp were small enough to escape was brief, as they grew rapidly after their release. Fifteen grass carp were captured 272 days after release. These fish had a mean length of 513.4 ± 22.3 mm, a mean weight of 2795 ± 137 g, and an estimated mean head width of 77 ± 3.4 mm.

DISCUSSION

Grass Carp

Our study achieved control of aquatic macrophytes at a moderate stocking density of 83-167 fish ha^{-1} (Wells et al. 2003), within the range 50-187 fish per vegetated ha recommended for irrigation systems in the southwestern U.S.A. (Cassani 1996). Our estimated initial stocking density of grass carp (40-80 kg ha^{-1}) was lower than in a previous New Zealand study of control of aquatic macrophytes in a drainage canal (350-650 kg ha^{-1}; Edwards and Moore 1975). The final density in our study was up to 470 kg ha^{-1} as individual carp grew almost 6-fold in biomass through growth. Assuming also that our sampling in March was not biased towards

TABLE 3. MEAN CATCH RATES OF BROWN BULLHEAD CATFISH AND SHORTFINNED EELS CAUGHT IN TWO WAIKATO CANALS WITH (TREATED) AND WITHOUT (UNTREATED) GRASS CARP. *P* VALUES SHOW THE DIFFERENCES BETWEEN THE MEANS FOR EACH CANAL DETERMINED BY ANOVA WITH A DUNN-SIDAK MULTIPLE-TEST CORRECTION. $N = 12$ FOR EACH TREATMENT AND DATE EXCEPT FOR JUNE 1999 WHERE $N = 4$ FOR THE TREATED CANAL.

	Catch rate (number of fish net^{-1} night^{-1})								
	Catfish			Shortfinned eels			Catfish and eels		
Site	Treated	Untreated	*P*	Treated	Untreated	*P*	Treated	Untreated	*P*
A. Number of fish net^{-1} night^{-1}									
Jun 1999	31	7	0.007	8	1.0	0.081	39	8	0.007
Sep 1999	10	48	0.007	12	2.8	0.081	22	51	0.041
Nov 1999	9	41	0.307	11	1.8	0.014	20	43	0.740
Dec 1999	15	145	0.075	29	3.1	0.028	44	148	0.270
Feb 2000	30	119	0.162	9	2.7	0.068	39	121	0.232
Apr 2000	152	111	0.366	11	2.5	0.021	163	114	0.997
Dec 2000	16	111	0.015	8	1.4	0.063	23	113	0.028
B. Weight (kg) of fish net^{-1} night^{-1}									
Jun 1999	1.9	0.8	0.180	1.0	0.8	1.000	2.9	1.6	0.835
Sep 1999	1.4	5.6	0.007	3.2	1.5	0.568	4.7	7.1	0.679
Nov 1999	0.7	1.6	0.385	5.2	1.3	0.088	5.9	2.9	0.429
Dec 1999	1.2	4.5	0.226	10.6	2.1	0.088	11.8	6.5	0.710
Feb 2000	0.7	2.5	0.232	2.8	1.7	0.811	3.5	4.2	0.997
Apr 2000	2.8	3.0	1.000	3.0	2.2	0.982	5.8	5.2	1.000
Dec 2000	0.5	4.0	0.005	3.2	1.0	0.174	3.7	5.0	0.958

the larger fish, this implies a mean growth rate of 8.5 g day^{-1}. This exceeds a previous growth rate estimate in New Zealand of 5.7 g day^{-1} in the Aka Aka canal (Schipper 1983), but is well below the species maximum of 29 g day^{-1} (Shelton et al. 1981, Cassani 1996). The almost complete removal of *Ceratophyllum demersum* by grass and continued presence of *Glyceria maxima* in our study contrasts with previous preference studies in New Zealand. *Glyceria* was rated a "much preferred food" compared to *Ceratophyllum* that was rated only as "palatable to the fish" (Rowe and Schipper 1985).

Mean water temperatures in summer (21-23°C; Wells et al. 2003) are within the optimal range for grass carp feeding (21-26°C; Cassani 1996), and were above the threshold of 16°C for intensive feeding in early summer and autumn (18 to 19°C, respectively). Dissolved oxygen concentrations were generally >4 g m^{-3}, which also enhanced the potential for growth of grass carp and plant consumption (Rottmann 1977).

Resident Fish

The habitat conditions and species richness in our study was poor to begin with, as reflected by the predominant biomass of introduced aquatic macrophytes (Wells et al. 2003), low number of aquatic macroinvertebrate taxa, high abundance of introduced fish, and limited number of native fish species. Grass carp did not appear to degrade the habitat further, and possibly increased dissolved oxygen concentrations in the treated canal by removal of profuse growth of aquatic macrophytes (Wells et al. 2003). Extreme fluctuations in dissolved oxygen have been measured in streams in the Waikato Region with high macrophytes abundance (Wilcock et al. 1998).

Grass carp also had no obvious short-term effect on the abundance and biomass of the two major fish species in the treated canal (brown bullhead catfish and shortfinned eels). The fish populations of the treated and untreated canals appeared to reflect pre-existing differences in fish species and densities that did not change through the course of the experiment. The range of fish species present in the canals was limited compared to the high fish diversity in the adjacent Waikato River (Chapman 1996, Hicks et al. 2005, in press), of which both canals are tributaries. In the absence of barriers to migration, we would expect inanga (*Galaxias maculatus* Jenyns), koi carp (*Cyprinus carpio* L.), common bullies (*Gobiomorphus cotidianus* McDowall), and grey mullet (*Mugil cephalus* L.) in the canals, and a greater abundance of common smelt. The low number of fish species that we found probably resulted from the restricted access to upstream migrants caused by the levee and pump structures at the canals' outlets.

Catfish abundance was lower in the treated canal than in the untreated canal, and the likely cause was eel predation, which may have been facilitated by vegetation removal by grass carp. Increased fish predation following vegetation removal is one effect that has been attributed to grass carp (Mitchell 1986; Cassani 1996). Eels were always more numerous in the treated canal than in the untreated canal, and this did not appear to be an effect of the grass carp stocking.

Catfish were relatively small in our study sites, rarely exceeding 300 mm. In the lower Waikato River, and lakes Waahi and Waikare, catfish frequently exceeded 300 mm in length, with some catfish >400 mm (Patchell 1977). In the untreated canal, where densities were greater, catfish were smaller than in the treated canal. This suggests that the canals provide good breeding habitat, but that the environment for either survival or growth to larger sizes is poor. The goldfish, rudd, and common smelt present in the treated canal were too few to determine if any effect from grass carp had occurred. The growth rate of the benthivorous brown bullhead catfish did not appear to suffer from the removal of the vegetation.

TABLE 4. MEAN NUMBER OF MACROINVERTEBRATES ON DIFFERENT MACROPHYTES IN TWO WAIKATO CANALS WITH (T = TREATED) AND WITHOUT (U = UNTREATED) GRASS CARP. JUNE SAMPLING WAS ONE WEEK AFTER MECHANICAL REMOVAL OF AQUATIC MACROPHYTES, BUT BEFORE THE RELEASE OF GRASS CARP. —, MACROPHYTE NOT PRESENT.

	Mean number of macroinvertebrates per sweep net sample											
	Ceratophyllum		*Glyceria*		*Ludwigia*		*Myriophyllum*		*Paspalum*		*Potamogeton*	
Taxon	T	U	T	U	T	U	T	U	T	U	T	U
June 1999												
Chironomids	0.0	0.0	0.0	—	—	—	0.0	0.0	—	—	0.0	—
Damselfly larvae	0.0	0.2	0.0	—	—	—	0.0	0.2	—	—	0.0	—
Gastropods	0.0	7.0	0.2	—	—	—	1.6	10.4	—	—	0.0	—
Leeches	0.0	0.0	0.0	—	—	—	1.6	0.8	—	—	0.0	—
Tubificids	0.0	2.0	0.0	—	—	—	0.0	0.0	—	—	0.0	—
No. of samples	5	5	5	0	0	0	5	5	0	0	2	0
September 1999												
Chironomids	—	2.3	87.6	—	—	3.0	93.6	—	—	12.0	—	—
Damselfly larvae	—	8.6	1.2	—	—	0.0	2.0	—	—	7.0	—	—
Gastropods	—	22.3	0.2	—	—	7.0	0.3	—	—	5.0	—	—
Leeches	—	0.3	3.6	—	—	0.0	146.3	—	—	6.0	—	—
Tubificids	—	0.3	0.0	—	—	0.0	0.0	—	—	0.0	—	—
Waterboatmen	—	5.0	0.8	—	—	0.0	0.0	—	—	0.0	—	—
No. of samples	0	3	5	0	0	1	3	0	0	1	0	0
January 2000												
Chironomids	—	0.0	1.2	—	0.0	0.0	—	0.0	0.0	0.0	—	—
Damselfly larvae	—	0.0	4.0	—	8.0	0.0	—	1.5	1.0	1.0	—	—
Gastropods	—	25.0	0.0	—	0.0	28.8	—	37.5	0.0	77.0	—	—
Leeches	—	2.6	0.2	—	0.0	18.6	—	5.5	0.0	5.0	—	—
Tubificids	—	0.8	3.4	—	20.0	4.2	—	0.0	0.0	10.0	—	—
Waterboatmen	—	0.0	1.8	—	0.0	0.2	—	0.0	8.0	0.0	—	—
No. of samples	0	5	5	0	1	5	0	2	1	2	0	0

Macroinvertebrates

Removal of aquatic macrophytes by grass carp had a profound impact on macroinvertebrate abundance in the treated canal. We can approximate the loss by comparing the difference in percentage of the area covered by aquatic macrophytes (Wells et al. 2003). Before the study, macrophytes often covered 80% of the surface area of the treated canal before mechanical clearing (NIWA Hamilton, unpubl. data). In January 2000, rooted macrophytes covered 78% of the surface area of the untreated canal, but only 17% of the treated canal (Table 1). Thus the area covered by rooted aquatic macrophytes was reduced by about 80% following grass carp introduction. As macrophytes almost always carried macroinvertebrates, the loss of macroinvertebrates associated with the macrophytes was probably similar.

Gastropods were especially reduced in the treated canal. Not only were they absent from all plant genera that remained, but so was the *Ceratophyllum demersum* that comprised the most abundant plant in the untreated canal, confirming that it was an important habitat for gastropods. *Myriophyllum aquaticum*, also a habitat for gastropods, was also substantially reduced in abundance in the treated canal in January 2000.

Extensive marginal *Glyceria maxima* remained in the treated canal, but this was not used significantly by gastropods. The loss of gastropods from the treated canal represents a substantial loss of an important food source to fish and wildfowl (e.g., Hill et al. 1987). Grass carp ingest macroinvertebrates such as chironomids (Mitchell 1980), probably as vicarious intake with the plants on which the macroinvertebrates live.

The initial species richness of macroinvertebrates was very low (4-6 taxa). Lowland Waikato streams with macrophytes generally have 11-30 taxa (Collier et al. 1998), with biomasses ranging from 44-371 g m^{-2} (Collier et al. 1999). The taxa that we found are hardy and common throughout the region and New Zealand, so were of little regional or national significance.

Applicability to Other Canals

The metal screen at the downstream end of the treated canal was initially an ineffective means of containing most of the grass carp, and some grass carp might have escaped from the canal because of their size at release. However, after 9 months of growth, mean head width was 77 mm, and thus carp were retained. Containment is an important issue in the use of grass carp for weed control in New Zealand as it has also been in the U.S.A. (e.g., Loch and Bonar 1999). For future releases, we recommend that a thorough investigation of screen size is carried out before stocking, and that only fish sufficiently large to be retained by the screen are released.

The treated canal (Churchill East Canal) was one of the more suitable for grass carp in the region as it was a large,

Table 5. Mean number of macroinvertebrates (A) on macrophytes and (B) in sediment in two Waikato canals with (treated) and without (untreated) grass carp. June sampling was one week after mechanical removal of aquatic macrophytes, but before the release of grass carp. Probability of differences between treated and untreated canals for each date was determined by ANOVA with a Dunn-Sidak multiple-test correction. $N = 5$ for each canal and date.

	Mean number of macroinvertebrates per sample								
	June 1999			September 1999			January 2000		
Taxon	Treated	Untreated	*P*	Treated	Untreated	*P*	Treated	Untreated	*P*
A. On macrophytes (number per sweep net sample)									
Backswimmers	0.0	0.0	1.000	0.0	0.0	1.000	0.0	1.6	0.704
Chironomids	0.0	0.0	1.000	143.8	4.4	0.660	1.2	0.0	0.779
Damselfly larvae	0.0	0.4	0.704	2.4	6.6	0.929	5.8	1.0	0.385
Gastropod snails	1.8	17.4	0.190	0.4	15.8	0.634	0.0	99.6	0.156
Leeches	1.6	0.8	1.000	91.4	1.4	0.796	0.2	25.4	0.695
Tubificids	0.0	0.2	0.967	0.0	0.2	0.967	7.4	9.0	1.000
Waterboatmen	0.0	0.0	1.000	0.8	3.0	0.684	3.4	0.2	0.577
All taxa combined	3.4	18.8	0.273	238.8	31.4	0.364	18.0	136.8	0.183
Number of taxa in each sampling period	2	4		5	6		5	5	
B. In sediment (number per surface sediment sample)									
Chironomids	0.0	0.0	1.000	11.8	6.8	0.975	2.4	0.0	0.818
Leeches	0.0	3.2	0.818	1.8	0.0	0.734	0.0	0.0	1.000
Tubificids	50.6	50.4	1.000	11.6	0.4	0.699	196.4	6.4	0.093
All taxa combined	50.6	53.6	1.000	25.2	7.2	0.408	198.8	6.4	0.093
Number of taxa in each sampling period	1	2		3	2		2	1	

had permanent water of >1 m depth, had reasonable water quality compared to other Waikato canals, and had a pump station that limited the chance of grass carp escape. Most New Zealand canals are either too shallow in summer, are hypertrophic and lack sufficient oxygen, or do not permit containment of the grass carp.

The lack of a robust sampling programme before the release of grass carp and only 18 months data after the release limits the strength of our conclusions, and therefore the applicability of our results to other sites. Grass carp could have had further impacts in the longer term as they grew in size and exhausted their food supply. We also do not know how the fish populations behaved prior to grass carp release or what the influence of side canals that were ungrazed by grass carp had on our results.

Sporadic kills of grass carp limit their utility of grass carp for macrophyte control in New Zealand canals. In the treated canal, 62 grass carp were found dead 25 February 2001 about 14 days after 65 mm of rain had fallen in a 29-h period. The preceding weather had been warm and dry for several weeks (Environment Waikato, unpubl. data for the Kaihere Catchment at Maungakawa). Grass carp were also killed in Simpsons Drain, Hauraki, after each of three separate stocking attempts. In December 1997, a pulse of water was observed in Simpsons Drain that had low pH (2.8) and low dissolved oxygen (0.8 g m^{-3}; Wells et al. 2003).

We conclude that where they can be contained, where water quality will allow their survival, and where complete macrophyte removal is an acceptable outcome, grass carp are suitable for aquatic macrophyte control in lowland canals, which normally have low biotic values. The longevity of grass carp in canals, however, remains questionable because of periodic deoxygenation.

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