

Turbidity generation and biological impacts of an exotic fish *Carassius auratus*, introduced into shallow seasonally anoxic ponds

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(Received 30 July 1994, Accepted 27 November 1994)

Over the last decade, goldfish *Carassius auratus* L., have been introduced into lakes and ponds in the Montreal region. Controlled experiments compared the impact of goldfish in both mud- and gravel-bottomed outdoor pools, with either caged or non-caged vegetation. High levels of turbidity were generated by foraging goldfish in mud pools ($P < 0.01$). All non-caged submersed plants (*Potamogeton*) showed extensive grazing damage and all of the unprotected submersed and emergent forms were uprooted. Data from Stoneycroft pond where a feral goldfish population reached 15–17 000 individuals ha^{-1} , confirmed the experimental findings showing goldfish to be benthic herbivores, causing a visible increase in turbidity and decrease in aquatic vegetation. Gut analysis revealed goldfish to have little diet overlap with native amphibians. High turbidity should reduce the success of predators feeding on goldfish, and may decrease the foraging success of other competitors. The sporadic distribution of goldfish in Canada may be linked to site characteristics, specifically the susceptibility of the area to turbidity generation. © 1995 The Fisheries Society of the British Isles

Key words: goldfish; habitat modification; benthic feeding; turbidity generation.

INTRODUCTION

Introduced species can have dramatic impacts upon native ecosystems (Zaret & Paine, 1973; Simberloff, 1981; Bertness, 1984; Groves & Burdon, 1986; Mooney & Drake, 1986). Both direct effects such as predation and indirect effects such as habitat modification by an exotic can change native floral and faunal communities (Simberloff, 1981). However, of the hundreds of species introduced into North America, relatively few have been identified as causing serious harm. Mills *et al.* (1993) estimate that for the Great Lakes, only 10% of all exotics (across all taxa), and 50% of exotic fish have had ‘demonstrably substantial impacts’. These figures do not indicate that the remaining fish and other taxa have had no impact, rather that any effects have gone largely unstudied or ignored because of their limited effects (Mills *et al.*, 1993).

Goldfish have been introduced both accidentally and deliberately into almost every state and province in North America, and in Quebec they have been introduced over the last few decades. Although considered vulnerable to predation, goldfish are highly tolerant of environmental stress including prolonged periods of total anoxia (Walker & Johansen, 1977; Hochachka, 1980; Van den Thillart *et al.*, 1983). This ability allows them to colonize a wide variety of habitats including small ponds that would otherwise lack fish. In similar shallow pond conditions in Finland, Crucian carp *C. carassius* L., have achieved

abundant numbers which can dominate the ecology of the aquatic community (Holopainen & Pitkanen, 1985; Holopainen *et al.*, 1988). Despite the long history of goldfish in N. America, dating at least as far back as the late 1800s (Scott & Crossman, 1973), almost nothing is known of the potential impacts of this species.

The introduction of common carp *Cyprinus carpio* L., into N. America, a bigger cousin capable of hybridizing with goldfish, has had largely adverse effects, including the destruction of vegetated breeding habitat used by both fish and birds, and an increase in turbidity (Cahoon, 1953; Crivelli, 1983; Fletcher *et al.*, 1985; Panek, 1987). High turbidity can damage gill membranes, reduce feeding efficiency, alter behaviour and migration patterns, and cause the death of both eggs and larvae of aquatic organisms (Stuart, 1953; Cordone & Kelly, 1961; Lemly, 1982; Wilber, 1982; Lloyd, 1987).

This study used controlled experiments in outdoor artificial pools to investigate whether goldfish can cause significant increases in turbidity and a reduction in macrophytes when introduced into shallow pond systems. The second part of our work reports the invasion of a shallow seasonally anoxic Quebec pond by goldfish. Goldfish population size, composition, and diet are reported along with the potential for diet overlap between goldfish and red-spotted newts *Notophthalmus viridescens viridescens* (Rafinesque) using gut content analysis. Newts are typically the keystone vertebrate predators of shallow seasonally anoxic pond communities in N. America (Morin, 1981), while goldfish are reported to be omnivores feeding on a variety of aquatic organisms and vegetation (Scott & Crossman, 1973). We therefore expected food competition between newts and goldfish, especially at times of high goldfish abundance.

METHODS

HABITAT MODIFICATION

To avoid the accidental introduction of an exotic into local aquatic systems, wading pools were used to conduct the tests for turbidity generation and habitat modification. An experimental facility was built at the St Lawrence Valley Natural History Ecomuseum in Ste-Anne-de-Bellevue. A fenced enclosure (7 × 13.5 × 2 m high) with a sand floor was constructed containing 18 hard-bottomed plastic pools (each 1.5 m diameter, 1.76 m² surface area, and 0.3 m deep), arranged in three rows of six. Each pool was recessed into the floor, and protected from predators by two electric shock lines around the entire enclosure, and wires strung above the pools. Nine pools were filled with 2–4 cm of St-Rosalie clay, the typical substratum of ponds in the area, while the others had 2–4 cm of pre-washed coarse gravel (0.5 cm grade) added. Pools were filled with water from a natural well on the site and maintained with rain water.

On 7 and 8 July 1990, approximately equal numbers of uniformly sized specimens of burr-reed (*Sparganium* spp.) and pondweed (*Potamogeton* spp.) were collected, potted, and introduced into 12 of the 18 pools. This potting procedure recreated natural rooting conditions. These species were chosen as previously they had been two of the most abundant plants in Stoneycroft before the goldfish invasion. Flowering condition as well as the number and length of all leaves were recorded for each burr-reed plant upon introduction. For pondweed only the number of main-shoots was noted for each plant before introduction. Then plants in three mud and three gravel pools were protected by a 1 × 1 cm mesh wire cage (30 cm tall, 40 cm diameter). This mesh size minimized the possible effects of shading and poor water circulation, while denying goldfish access to the plants. Five medium [4.5–7.0 cm fork length (F.L.)], and three large goldfish (7.5–10.5 cm

F.L.), with a total combined mass of 60 g, were introduced into each pool giving a total biomass of 340 kg ha⁻¹. This was considered a reasonable approximation of values found for goldfish in the wild. It is much lower than the 600 kg ha⁻¹ of fish reported as being necessary to cause a significant increase in turbidity within a shallow lake (Meijer *et al.*, 1990).

Experiments started on 24 July 1990 and ran until 3 September 1990 when the experiment had to be terminated because of a predator consuming a large number of the fish in the enclosure. Temperature and turbidity were sampled at mid-day, every day, during this period. Turbidity was recorded at mid-water column by measuring the percent light transmittance at 415 µ with a Beckman spectrophotometer. These readings were then converted into nephelometric turbidity units (NTUs) using a standard curve derived by the authors.

Temperature was measured initially at the mid-water level of each pool until 29 July 1990, when it was decided to measure at both the surface and substratum level. Temperature was taken using a standard mercury thermometer with 1° C graduations.

At the end of the experiment plants were removed and their general condition noted. Grazing damage and effect of turbidity upon the plants was assessed by comparing final numbers and lengths of leaves, root condition, and/or numbers of main shoots (as appropriate) to the initial values.

FIELD SITE AND WILD POPULATION

Data for a feral goldfish population came from Stoneycroft Pond, in the grounds of Macdonald Campus (Ste-Anne-de-Bellevue, Quebec). This seasonally anoxic water body occupies an area of <1 ha and has a substratum of fine St-Rosalie clay. The pond is highly variable with a maximum depth in early spring of approximately 1.25 m, but an average depth during the summer of <30 cm. Goldfish were observed first in 1983 and disappeared during the winter of 1988–89. The source and numbers involved during the initial introduction is unknown.

Mark recapture estimates were made in the fall, following Davis & Winstead (1980). Fish were caught using a 20 m seine in early September, counted, fin clipped, measured [fork length (F.L.) and total length (T.L.)], and then released. Subsequent seine hauls were conducted 1 to 2 weeks later with marked and unmarked fish being counted.

DIET

Diets were determined for fish and newts captured between April and October of each year. Most captures were made during the course of undergraduate field exercises making schedules erratic. Goldfish were collected on three occasions in 1986 (23 September, 22 October and 13 November), and twice in 1988 (22 June and 28 October). Newts were sampled on the same dates as goldfish for 1986, five times in 1987 (15 April, 8 May, 22 June, 22 September, 27 October), and only once in 1988 (22 June) and 1990 (30 May). Fish and newts were preserved in 75% formalin, sexed, weighed, measured (T.L. and F.L.), and gut contents analysed volumetrically. Gut contents were identified to the level of order using Merritt & Cummins (1978) and Pennak (1989). Groups comprising less than 1% of the total gut contents of both goldfish and newts were grouped under the category of 'other'. Empty guts were recorded but removed from the analysis when calculating overall frequency or volume.

RESULTS

ENCLOSURE EXPERIMENTS

Before the introduction of goldfish into the wading pools, turbidity levels were low, but differed significantly (Mann–Whitney U-test $P < 0.01$) between substratum types; gravel pools 3.3 ± 2.1 NTUs (mean \pm S.E.), mud pools 10.6 ± 8.2 NTUs. Following the goldfish introduction, turbidity levels in all the mud

bottomed pools increased by a factor of 10 (116.6 ± 152.5 NTUs). Turbidity in gravel bottomed pools did not change significantly from their pre-introduction levels (Kruskal-Wallis $P > 0.05$), and these pools always remained much clearer (7.4 ± 6.1 NTUs) than the mud pools.

The difference in turbidity between the two types of substrata resulted in different temperature regimes for mud and gravel pools. Mud pools were significantly cooler (Mann-Whitney U-test $P < 0.01$) at the substratum level than gravel pools. Mud pools also had a surface temperature marginally (Mann-Whitney U-test $0.01 < P > 0.05$) warmer than gravel pools. There was no significant (Mann-Whitney U-test $P > 0.05$) difference between the surface ($27.4 \pm 2.8^\circ\text{C}$) and substratum ($27.4 \pm 2.7^\circ\text{C}$) temperatures of gravel pools. However the substratum temperature ($26.2 \pm 2.5^\circ\text{C}$) of mud pools was significantly cooler than at the surface ($28.0 \pm 2.8^\circ\text{C}$). On some days this temperature differential within the mud pools reached 3.0°C , despite the pools' shallow (25 cm) depth.

The significant increase in turbidity in the mud pools had no significant effect on the survival of the plants within those pools. When the growth or loss of caged emergent and submersed plants was compared between turbid and non-turbid pools, no significant differences were found (ANOVA $P > 0.05$) for either plant type.

Uncaged *Potamogeton* showed a reduction in total number of stems by the end of the experiment ($-69.7 \pm 23.7\%$), while caged *Potamogeton* showed an increase in the total number of stems ($34.5 \pm 9.8\%$) (ANOVA $P < 0.01$). Fish were not observed to feed on any of the emergent plants, and there was no significant reduction (ANOVA $P > 0.05$) in the numbers or size of leaves between caged and non-caged plants.

All uncaged plants (100%), both emergent and submersed, were uprooted by foraging goldfish, while all plants taken from caged pools remained securely potted.

FIELD OBSERVATIONS OF A WILD POPULATION

Before the introduction of goldfish in 1983, Stoneycroft was free of suspended sediment with a thick carpet of submersed vegetation (100% coverage) and a broad band of emergent growth along the shores. Following the introduction of goldfish, turbidity levels increased (reducing visibility to only a few cm), emergent plant growth was reduced and submersed vegetation disappeared (to 0% coverage). After a winterkill eliminated the goldfish in 1988–89, Stoneycroft rapidly recovered with water clarity improving, submersed plant growth returning to 100% coverage of the substratum, and a rapid increase in emergent growth.

The goldfish population of Stoneycroft pond fluctuated widely. Mark-recapture estimates were $14\,601 \pm 2622$ in 1986, 5135 ± 1227 in 1987, and $13\,864 \pm 2622$ in 1988.

Over the 3 years of sampling, 783 fish were measured. Over half (52.9%) of these fish were ≤ 4 cm F.L., and only 11.2% were > 8 cm (age 1+, determined from a random sample of 20 individuals). This population structure suggests heavy winter mortality, with a rapid increase in young of the year as the goldfish spawned during the spring and early summer.

TABLE I. Table of gut contents showing percent by volume and frequency of occurrence for red-spotted newts for the years 1986–89 in Stoneycroft Pond

Diet group		1986–89 average		1986	1987	1988	1989
		Frequency total (%)	Volume (%)	Volume (%)			
Mollusca	Gastropoda	49 (33.8)	15.1	5.8	14.4	21.3	30.2
	Pelecypoda	8 (5.5)	3.0	4.6	1.1	11.9	0.0
Annelida	Oligochaeta	2 (1.4)	1.4	0.0	2.1	0.0	0.0
	Hirudinidea	14 (9.7)	6.2	0.0	9.3	0.0	4.0
Crustacea	Cladocera	36 (24.8)	16.1	4.6	18.7	0.0	50.0
	Amphipoda	27 (18.6)	4.8	12.4	2.8	7.8	0.0
Insecta	Chironomidea	76 (52.4)	15.3	17.2	16.7	13.6	1.1
	Corixidae	16 (10.4)	3.5	4.2	4.1	1.1	1.1
	Dytiscidae	10 (6.9)	0.9	0.0	0.2	4.8	0.7
	Ephemeroptera	31 (21.4)	4.3	11.4	2.8	2.9	5.3
	Notonectidae	1 (0.7)	0.7	4.6	0.0	0.0	0.0
	Tricoptera	8 (5.5)	2.2	5.3	2.1	0.7	0.0
	Zygoptera	23 (15.9)	8.7	21.2	8.6	0.0	0.5
	Dipteran pupae*	11 (7.8)	3.2	0.0	3.7	5.9	0.0
	Moulted skin	33 (22.8)	8.4	2.3	8.2	18.8	2.5
Mud		0	0	0	0	0	0
Vegetation		21 (14.5)	2.2	0.5	1.7	7.3	0.1
Others		20 (13.8)	3.0	2.4	2.8	2.8	4.7
Total sampled		154	—	29	95	20	10
Empty stomach		9	—	7	2	0	0

*This is a mixed category of all unknown dipteran pupae.

GUT CONTENTS

Newts had 14 food types comprising at least 1% total volume of their diet (Table I), while goldfish concentrated on only six food groups (Table II). Goldfish were mainly herbivorous ($P < 0.01$ Kruskal–Wallis: Table II), with vegetation comprising 44.6% by volume of their diet, and occurring in 71.4% of the guts. Goldfish ≤ 8 cm and those > 8 cm ate approximately equal quantities of vegetation (Kruskal–Wallis $P > 0.05$) and did not differ significantly in their consumption of mud (Kruskal–Wallis $P > 0.05$) (Table III). Larger fish consumed significantly more cladocerans (8.1%) than smaller fish (1.9%: $P < 0.01$ Kruskal–Wallis), which consumed more chironomids (22.6%) than the larger fish (1.5%: $P < 0.01$).

Newts ate significantly less vegetation than goldfish ($P < 0.01$: Kruskal–Wallis), but instead fed primarily upon significantly more cladocerans, chironomids, and gastropods ($P < 0.01$ Kruskal–Wallis: Tables I and II). Cladocerans, an open water prey item, formed the largest portion by volume of the newt diet in both 1987 (18.7%) and 1989 (50.0%) (Table I).

DISCUSSION

Turbidity in the mud pools showed a rapid 10-fold increase as a byproduct of the goldfish suck, spit, and pick mode of benthic feeding. Goldfish will suck up

TABLE II. Table of gut contents of Stoneycroft pond goldfish, showing the overall percent by volume and frequency of occurrence for the years 1986–89, and percent by volume for each individual year during that period

Diet group		1986–89 average		1986	1987	1988
		Frequency total (%)	Volume (%)	Volume (%)		
Crustacea	Cladocera	12 (11.4)	3.9	4.6	7.8	0.0
Insecta	Chironomidae	24 (22.9)	15.8	6.3	19.5	19.3
	Corixidae	4 (3.8)	2.6	0.0	4.0	3.3
	Dipteran pupae*	3 (2.9)	3.4	0.0	5.9	3.7
Mud		22 (21.0)	20.9	17.1	8.5	34.1
Vegetation		75 (71.4)	44.6	63.3	41.9	33.7
Others		15 (14.3)	0.3	0.6	0.4	0.0
Total sampled		164	—	44	70	50
Empty guts		59	—	15	35	9

*This is a mixed category of all unknown dipteran pupae.

TABLE III. Goldfish guts contents showing percent by volume, broken down by size for those fish ≤ 8 cm and those > 8 cm

Diet group		Size class	
		Fish ≤ 8 cm	Fish > 8 cm
Crustacea	Cladocera	1.9	8.1
	Copepoda	0.0	1.8
Insecta	Corixidae	1.9	4.1
	Chironomids	22.6	1.5
	Dipteran pupae*	3.5	3.1
Mud		16.8	29.3
Vegetation		45.5	42.6
Number sampled		114	50
Empty guts		44	15

*This is a mixed category of all unknown dipteran pupae.

a mouthful of benthos, which is then spat out forming a cloud of suspended sediment from which they pick any edible portions. Carp have also been reported to feed in this manner (Scott & Crossman, 1973). The effectiveness of the turbidity generated by the goldfish in preventing predation was evident after a single avian predator (possibly a green heron *Butorides striatus*), managed to enter the enclosure and within 48–72 h consumed all 48 fish from the clear water pools but only 50% of the fish from the turbid pools.

Many authors have reported a decrease in macrophyte production resulting from increased turbidity (Swale, 1964; Edwards, 1968; Wetzel & McGregor, 1968; Patrick, 1972). Hanson & Butler (1990) showed that the removal of fish from a shallow prairie lake caused a dramatic improvement in water transparency, in turn supporting increased macrophyte growth. However, the turbidity seen in our enclosures had no significant effects upon plant growth or

survival. The pools were shallow, and therefore even the high levels of turbidity generated during the trials were not sufficient to block light penetration to the bottom of the pools completely. However, all plants from the mud pools were covered with a fine film of clay, which under more natural or deeper situations may have impeded long term growth, especially during the spring when initial plant regrowth from the substrate takes place.

Gut contents of the experimental fish could not be examined. However, in the non-caged pools, the fish were actively herbivorous, feeding intensely upon any small vegetative structures that they could nip or tear. Not all vegetation was accessible to the goldfish for feeding. The stronger emergent plants used in the trials were immune to the effect of direct grazing. However, fish foraging amongst the substratum of the plant pots caused the uprooting of all unprotected plants. This uprooting is probably partially responsible for the loss of emergent growth around the shores of Stoneycroft during the time of the goldfish invasion. In this larger system, wave action would have washed any uprooted plants either into deeper water or onto shore, causing their death. The loss of rooted plants would further destabilize the pond bottom, freeing sediments for suspension and further increasing the level of turbidity.

At the ecosystem level, the high turbidity, removal of large quantities of macrophytes, and the possible reduction of larger zooplankton caused by high turbidity levels, could have a cascading effect, causing a phytoplankton bloom (Carpenter *et al.*, 1985; Scheffer *et al.*, 1993), and thereby further reducing the water transparency (Meijer *et al.*, 1990). High turbidity can also bind nutrients and essential elements, rendering it unavailable for use by the biological community (Heath & Franko, 1988), thereby countering any increased availability in nutrients caused by the defaecation of goldfish or through the removal of macrophytes.

The significantly cooler substratum temperature of the mud pools indicates that the depth of penetration of incoming solar radiation was reduced significantly. This decrease in light would not only reduce community productivity, but also offer a refuge to goldfish from potentially lethal summer temperatures (36 and 38° C: Heinicke & Houston, 1964) that could occur in a shallow pond system.

In Stoneycroft Pond, the goldfish formed a dense, probably food-limited population similar in size and structure to those seen for the crucian carp in Finland (Holopainen & Pitkanen, 1985; Holopainen *et al.*, 1988). As with crucian carp, goldfish numbers in Stoneycroft were determined probably by the intra-specific competition for food reserves necessary to survive winter (Holopainen & Hyvarinen, 1985).

Wild goldfish gut contents showed little diversity in their diet, with benthic chironomid larvae the only common invertebrate food. The large quantity of detritus (second only by volume to vegetation) could have been ingested as a byproduct of the goldfish benthic foraging, however they may also consume detritus for its own nutritional value. While not normally a good food source for fish, detrital aggregate is consumed by many species, especially cyprinids (Bowen, 1979, 1983). With the large numbers of goldfish recorded in Stoneycroft, it is possible that some switched to detritivory because of intense competition for limited food resources. The 2 years when goldfish numbers were

high (1986 and 1988) were also the 2 years with the highest ingestion of detritus. Conversely the year of lowest goldfish numbers was the year when mud was of the least importance in their diet.

Newts had a more varied diet than goldfish, feeding on benthic and pelagic invertebrates. *Daphnia* was the most important food (by volume) in two of the 4 years. *Daphnia* abundance in newts stomachs declined as goldfish populations increased. The decline in the importance of *Daphnia* in the diets of newts may have been because of reduced visibility causing lower feeding efficiency, or it could represent an actual drop in *Daphnia* numbers due to the high numbers of goldfish generating an increase in turbidity which would cause damage to their feeding, respiratory, and/or natatorial tracts (Moghraby 1977, Hart 1986).

Like the crucian carp, the ability of goldfish to withstand harsh environmental conditions and to reproduce rapidly has helped this species colonize a variety of habitats including oxygen-deficient ponds previously unoccupied by fish. Yet despite the widespread distribution of the species, it occurs sporadically throughout N. America. Direct food competition between goldfish and the red-spotted newt (the typical dominant vertebrate predator in local anoxic ponds) appears to be minimized by goldfish herbivory.

Initial colonization of a water body by goldfish probably would be associated with high predation losses since the fish will be predator-naïve and conspicuously coloured. However in ponds with a suitable substratum, the high turbidity levels generated by even a small number of benthically foraging goldfish (Richardson & Whoriskey, 1992) could offset some of those disadvantages (Breitburg, 1988) and facilitate colonization.

This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC), and Fonds pour la formation de Chercheurs et l'Aide à la Recherche (FCAR). M. Richardson was sponsored by a NSERC graduate scholarship. We thank Bob Wootton for his help with preliminary drafts of the paper, Pierre Borassa for technical help, Mike Kaluski for a reliable goldfish supply, and the St. Lawrence Valley Natural History Society (J. R. Bider, President) for allowing the installation of our enclosure on their site.

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