

Research article

Preliminary assessment of feral goldfish impacts on ponds, with particular reference to native crucian carp

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Abstract

Introductions of an Asian cyprinid, goldfish *Carassius auratus*, are known to pose a genetic threat to crucian carp *Carassius carassius*, which is native to northern parts of central and western Europe, including southeast England. However, there are no known studies in Europe of goldfish impacts on crucian carp growth and life-history traits, nor on the recipient ecosystems. The present study is the first such attempt, and compares the plants, invertebrates and fish biology (growth, condition, reproduction) in six ponds, two containing crucian carp only (allopatry), two containing goldfish only (allopatry), and two with both species (sympatry). Feral goldfish growth was greatest in sympatry with native crucian carp, whereas crucian carp growth was similar regardless of goldfish presence or absence. However, body condition (*LK*) and relative fecundity (per unit of body weight) of crucian carp was greatest in sympatry with feral goldfish. *LK* increased significantly with increasing water conductivity in goldfish but not in crucian carp, and *LK* was not related to pond invertebrate densities in either fish species. Differences in the plant and aquatic invertebrate communities observed in the study ponds could not be attributed to the introduction and establishment of goldfish, however non-native plant and invertebrate species were observed only in ponds containing goldfish. Differences in growth and condition between the two *Carassius* species does not appear to be due to differences in available food, so elevated somatic growth and reproductive output in crucian carp and faster growth in goldfish in sympatry may be due to non-dietary competitive interactions. The present preliminary study highlights the difficulties of assessing 'real world' impacts of non-native species on native species and ecosystems as well as the need for further study of feral goldfish impacts on European pond ecosystems in general and on native congener crucian carp in particular.

Key words: endangered species conservation; sympatric compensatory growth; pet fish; pest species; non-native species

Introduction

One of the major threats to pond ecosystems is the introduction of non-native ornamental fishes (Wheeler 1998; Copp et al. 2005a; Hänfling et al. 2005; Smartt 2007). The first, and still the most prominent, of the ornamental fishes that are released into open waters such as ponds is the goldfish *Carassius auratus* L. (Copp et al. 2005a). A species from eastern Asia, the goldfish was first introduced to Europe, including the United Kingdom (UK), in the late 1600s (Lever 1977). Perhaps as a result of this long history in the UK, the goldfish is ignored in national legislation regarding non-native species (see Copp et al. 2005b) and its distribution in the UK

is uncertain. Both species share the ability survive low oxygen and high temperature conditions (Sollid et al. 2005), and the natural brown variety of goldfish bears a strong physical resemblance with its close congener, crucian carp *Carassius carassius* (L.), which is native to northern parts of central and western Europe, including southeast England (Wheeler 2000). As a consequence of mis-identifications of brown goldfish as crucian carp (Wheeler 2000; Hickley and Chare 2004) and of illegal releases of unwanted pet fish (Andrews 1990; Wheeler 1998; Copp et al. 2005b), the goldfish is now widespread in the UK, both in 'natural' ponds and water courses (Wheeler 1998; Copp et al. 2005a, 2006), noting that virtually all ponds in

the UK were created by human activities (water supply, blacksmithing, extensive fish rearing, military action [i.e. bomb craters], ornament) but for the purposes of this paper ornamental ponds that have been stocked with goldfish are ignored.

The introduced range of goldfish also includes southern Europe (Lorenzoni et al. 2007), Asia Minor (İzci 2004), Canada (Munkittrick and Leatherland 1984) and Australia (Mitchell 1979; Morgan et al. 2004; Morgan and Beatty 2007; Rowe 2007; Baumgartner et al. 2008). The environmental biology of feral goldfish populations has received little study in Europe (i.e. Lorenzoni et al. 2007), which contrasts a larger number of such studies from other continents (e.g. Mitchell 1979; Munkittrick and Leatherland 1984; İzci 2004; Morgan et al. 2004; Morgan and Beatty 2007; Rowe 2007; Baumgartner et al. 2008). Studies of feral goldfish impacts are also more common outside of Europe, where the species is believed to be a major cause of the decline of some fish species in U.S.A. (Deacon et al. 1964), and suggested impacts on native fishes include predation on the fish eggs, larvae, and adults (Scott and Crossman 1973). European studies have suggested that feral goldfish impacts include competition with native fishes (Scheffer et al. 1993) and reproductive interference on native crucian carp (Hänfling et al. 2005), resulting in species displacement (Wheeler 2000; Navodaru et al. 2002; Smartt 2007). However, there have been no studies examining the effect of feral goldfish on pond ecosystems and their most characteristic fish species, the crucian carp. As a consequence of an observed decline in crucian carp distribution within its native English range (C.D. Sayer, G.H. Copp, D. Emson, G. Zięba, M.J. Godard and K.J. Wesley, unpublished), the species has recently been designated a Biodiversity Action Priority (BAP) species for Norfolk (Copp and Sayer 2010). This reflects local (Conservators of Epping Forest 2002; Lambeth Borough Council 2006; Copp et al. 2008a, 2008b) and national (Environment Agency 2003) conservation concern.

The aim of the present, preliminary study was to identify impacts of feral goldfish on native pond organisms, with particular reference to crucian carp. The specific objectives were to: 1) compare the biological traits (age-specific growth, body condition, mean length and age at maturity, gonado-somatic index, relative fecundity) of pond-dwelling populations of crucian carp and of feral goldfish living in

allopatry and sympatry; and 2) assess the composition of aquatic plants and invertebrates in these ponds to identify impacts of pond community structure. We predicted that crucian carp populations living in sympatry with goldfish would demonstrate different growth and reproduction patterns than those living in allopatry. And in light of the past association between goldfish releases and the introduction of other non-native aquatic organisms, e.g. Canadian pondweed *Elodea canadensis* Michaux, (West 1910), we predicted that ponds containing goldfish were more likely to contain other non-native species.

Materials and methods

Study site

Sampling of aquatic plants, aquatic invertebrates, and fishes was undertaken between 23 April and 1 May 2007 in six ponds (Table 1; Figure 1) of the Epping Forest conservation area (Conservators of Epping Forest 2002). Detailed descriptions of these ponds (Table 1) are given elsewhere (Wheeler 1998; Copp et al. 2005b; Tarkan et al. 2009; Tarkan et al. 2010). Past sampling has demonstrated that Fairmeads and Earls Path ponds contained both crucian carp and goldfish in surveys undertaken in 1995, 1996, 1997 (Wheeler 1998) and 2003 (Copp et al. 2005b). Note that Fairmeads Pond was treated with rotenone in early 1998, and a survey in May 1998 revealed only threespine stickleback *Gasterosteus aculeatus* L. after which about 30 crucian carp from a pond near Essendon (Hertfordshire) were re-introduced into Fairmeads Pond. Hawcock and Pizzole Pit ponds contained crucian carp and golden rudd *Scardinius erythrophthalmus* L., respectively, with no goldfish reported, in 1997 (Wheeler 1998) – note that Pizzole Pit was stocked in 1998 with about 50 crucian carp from Hawcock Pond (K.J. Wesley, unpublished). Johnson's Pond contained goldfish but not crucian carp in 1997 (Wheeler 1998) and 2003 (Copp et al. 2005b), and goldfish was the only fish species found in Carroll's Farm Pond in 2003 (Copp et al. 2005b).

Invertebrate sampling was undertaken during the week of 23 April 2007 using UK National Pond Survey methods described in Pond Action (1998). Crucian carp and goldfish were collected by electrofishing (240 V Millstream unit, Honda generator-powered, using a 40×40 cm copper anode) on 31 April and 1 May 2007 (see Tarkan et al. 2009; Tarkan et al. 2010) from a fibreglass,

electric motor-powered boat. Each pond was sampled once over the two-day period, and the entire surface of each pond was electrofished at a constant rate to provide data for catch-per-unit-effort (CPUE) of time (minutes) on fish abundance (see Copp et al. 2005a). Some additional specimens of short body length were collected on 7–8 April 2008, but these were excluded from the CPUE estimates. Details of the sampling and processing of the fish specimens are given in Tarkan et al. (2009) and Tarkan et al. (2010).

Plant and invertebrate sampling

All wetland macrophytes present in each sample area were recorded either by walking and wading through shallow regions and the margins of water bodies, or in deeper water using a grapnel thrown from the bank or a boat. ‘Wetland macrophytes’ were defined as those plants listed as wetland plants in the National Pond Survey methods guide (Pond Action 1998). This included aquatic marginal, emergent, floating-leaved and submerged plants. For sampling macroinvertebrates a 1 mm mesh hand-net was used to sample for a total of 3 minutes, with the total sampling time being divided equally between the major mesohabitats present in the survey area, e.g. areas of distinctively different

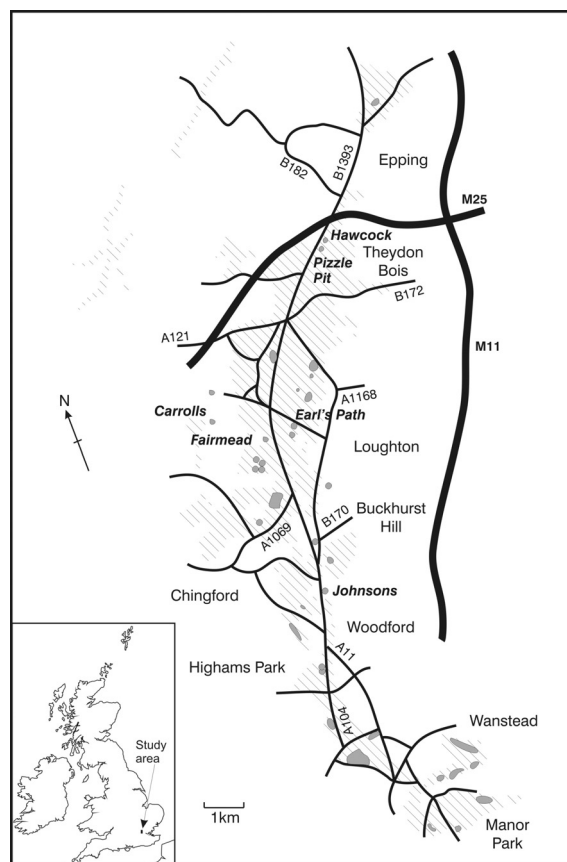


Figure 1. Map of Epping Forest (Essex, England) with the studied ponds labeled by name.

Table 1. Geographical location (Lat = latitude; Long = longitude), area (m²) and mean water depth (m) of study ponds in Epping Forest (Essex, England), with fish species present (CC = crucian carp; GF = goldfish) as follows: crucian carp living in allopatry (CC-allo), goldfish living in allopatry (GF-allo) and these two species living in sympatry (CC/GF-sym). Also given are the catch-per-unit-effort (CPUE) per minute of electrofishing estimates of fish densities and total numbers of specimens captured (GF total = 441; CC total = 252), based on 31 April and 1 May 2007 sampling only; and the mean fish condition (*LK*) with sample numbers (*n*) for GF and CC.

Pond name	Code	Lat (N)	Long (E)	Area	Depth	Fish CPUE			Fish <i>LK</i>			
						GF	CC	nc	GF	nGF	CC	nCC
Fairmeads Pond	CC/GF-sym	51:39:02	00:02:07	453	1.2	0.06	0.41	33	1.007	4	1.321	29
Earls Path Pond	CC/GF-sym	51:39:05	00:02:38	1760	1.5	3.02	0.17	191	1.017	184	1.088	10
Hawcock Pond	CC-allo	51:41:11	00:05:10	1181	0.5	–	†7.27	160			0.902	110
Pizzole Pit Pond	CC-allo	51:40:08	00:04:59	563	0.6	–	1.89	53			1.006	53
Carroll's Pond	GF-allo	51:39:07	00:00:23	706	2.5	10.09	–	222	1.034	221		
Johnson's Pond	GF-allo	51:36:34	00:01:19	800	0.9	0.48	–	34	1.150	34		

† Note that in Tarkan et al. (2009), the number of crucian carp ‘collected’ (p. 800) refers to the numbers of fish sacrificed rather than the numbers sampled, and that the CPUE value for Hawcock Pond was erroneously stated as ‘50.0’ rather than the correct value given here above.

sediments, submerged tree roots, stands of vegetation with differing structure (see Williams et al. 2004). Samples were live-sorted in the laboratory to remove all individual macro-invertebrates, with the exception of very abundant taxa (>100 individuals), which were sub-sampled. Macroinvertebrates were identified to species level for those groups where reliable distribution data and Red Data Book (a collection of the available information relative to Endangered and Threatened Species) information were available.

Species richness (S) was calculated as the total number of plant or invertebrate species recorded in each pond. Species rarity (R) was calculated using a species rarity index (SRI). This index is conceptually based on the Species Quality Score developed in the 1980s (Foster et al. 1990) and was derived in the following manner: (I) all species present were given a numerical value depending on rarity/threat, (ii) the score of all species in each sample were summed to give a Species Rarity Score, (iii) the Species Rarity Score was divided by the number of species recorded in the sample to give the SRI.

Six rarity categories were recognized and given the following conservation scores: Score 1 = 'Common species'; Score 2 = 'Local' (for invertebrates, either confined to certain limited geographical areas, where populations may be common or of widespread distribution, but with few populations. For plants, recorded from $\leq 25\%$ of $[\leq 705] 10 \times 10$ km grid squares in Britain, as per Preston et al. (2002); Score 4 = 'Nationally Scarce' (recorded from 15–100 of 10×10 km grid squares in Britain); Score 8 = 'Red Data Book – conservation dependent or near threatened'; Score 16 = 'Red Data Book – endangered or vulnerable'; Score 32 = 'Red Data Book – critically endangered'.

The 'Priority' status of the ponds was evaluated, to put the ecological status of the ponds into a national context, using a series of status criteria (http://www.pondconservation.org.uk/pond_hap/prioritypondcriteria.htm); these criteria include the presence of: i) European priority habitats, ii) species of conservation concern, or iii) exceptionally rich assemblages (e.g. occurrence of ≥ 50 macro-invertebrate species in 3-minute samples, three or more Nationally Notable invertebrate species, one of more Nationally Scarce plant, one of more Red Data Book species, one or more species of Biodiversity Action Plan (BAP) designation).

Fish age, growth, body condition and reproduction

Age, growth and body condition of fish were determined as described in Tarkan et al. (2009) and Tarkan et al. (2010). Using the data from these papers, comparisons of growth trajectories were made using the growth index described by Hickley and Dexter (1979): standard lengths (SL) at mean ages (n) were plotted against SL at age ($n+1$) to obtain a straight line for the Walford (1946) method; then, SLs for age were obtained from the formula $l_n = L_\infty (1 - k_n)$ where $L_\infty = l_t / (1 - k)$; l_t = interception on the y axis; l_n = length at age n ; k = slope of the Walford plot (Hickley and Dexter 1979).

Relative body condition (LK) was assessed as per Copp (2003) using Le Cren's (1951) index: $LK = w/w'$, where w is the observed body weight and w' is the expected weight as estimated from the SL-to-weight relationship ($W = a + SL^b$) for the respective species (crucian carp, $a = 0.0268$ and $b = 3.1187$; goldfish, $a = 0.0425$ and $b = 2.962$). An LK value > 1.0 indicates that the individual is in better condition than an average individual of the same SL range, whereas an LK value < 1.0 indicates that the individual is in worse condition than an average individual of the same length. See Copp (2003) and Tarkan et al. (2009) for further details.

Four reproductive indices from Tarkan et al. (2009) and Tarkan et al. (2010) were examined: relative fecundity (RF), gonado-somatic index (GSI), mean age at maturity (AaM) and mean standard length at maturity (LaM). RF values were calculated as per Bagenal (1978), and gonado-somatic index (GSI) as: $GSI = 100 \times \text{ovary weight} \div \text{total body weight}$. AaM was determined as per DeMaster (1978), with the modified version of this formula (see Trippel and Harvey 1987) used to calculate LaM. Because these latter two indices can be calculated at the population level only, statistical comparisons of LaM and AaM between allopatry and sympatry were not possible due to the low number of study sites available in this preliminary study.

Relationships among fish density, invertebrate density and plant parameters, plant richness, rarity scores, water chemistry (pH and conductivity) were tested using linear regressions, whereas relationships among scale size (radius length), relative fecundity, egg diameter and SL were tested using non-linear (power curve) regressions. Differences in LK

values between each population were performed with Analysis of Covariance (ANCOVA). Fish *LK* has been reported to correlate to water conductivity (used as a surrogate measure of water productivity) in some but not many freshwater fish species, being geographically variable within species (see references cited in Copp 2003), so regression analysis was used to test for this possible relationship, as well as for the possible influence of invertebrate abundance. Mean calculated SL values for differences between allopatry and sympatry, between back-calculated SLs and observed SLs and between mean relative fecundity values of the populations were tested using Students' *t* tests (Zar 1999).

Results

The growth trajectories revealed that goldfish growth was faster when living in sympatry with crucian carp ($t = 8.73$, $P < 0.01$) than in allopatry (Figure 2). Crucian carp growth was only slightly faster when living in sympatry with goldfish, but less so compared to goldfish growth in sympatry with crucian carp (Figure 2). *LK* values showed that crucian carp are plumper in sympatry (Table 1; ANCOVA, $F = 10.90$, $P < 0.01$) with the lowest *LK* in crucian carp living alone (Table 1, Figure 3). However, there was no significant difference in *LK* for goldfish in sympatry and allopatry (ANCOVA, $F = 2.31$, $P > 0.05$). The *LK* of crucian carp and goldfish living in sympatry did not differ significantly (ANCOVA, $F = 0.04$, $P > 0.05$); in allopatric goldfish populations, the *LK* value for goldfish was significantly higher than in allopatric crucian carp (ANCOVA, $F = 19.19$, $P < 0.01$). *LK* increased with increasing water conductivity in goldfish ($LK = 1.258 \times 10^{-4} \mu\text{S} \cdot \text{cm}^{-1} + 3.74$, $r^2 = 0.91$, $F = 19.85$, $df = 3$, $P = 0.047$) but not in crucian carp ($F = 0.115$, $df = 3$, $P > 0.75$). *LK* was not related to invertebrate density in either fish species ($Ps > 0.20$).

LaM values were generally similar for both females and males, regardless of the presence or absence of the other species. However, in males, the estimated AaM value in crucian carp was almost one year younger in the presence of goldfish, which showed a similar but less pronounced pattern. In both species, RF was much higher in sympatry than in allopatry ($t = 4.178$, $P < 0.001$ for goldfish; $t = 6.620$, $P < 0.001$ for crucian carp), with values for goldfish being almost the double of the native species (Table 2).

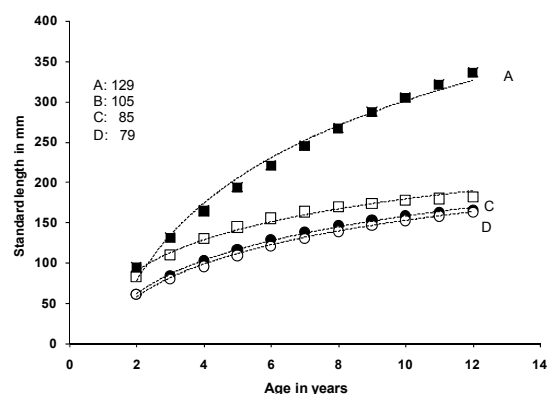


Figure 2. Growth curves based on back-calculated standard lengths (SL), using the Walford (1946) method together with calculated growth indices (Hickley and Dexter 1979: letters A–D, with the number of specimens indicated), for goldfish (squares), and crucian carp (circles) in ponds of Epping Forest (Essex, England) living in allopatry (open symbols) and in sympatry (filled symbols).

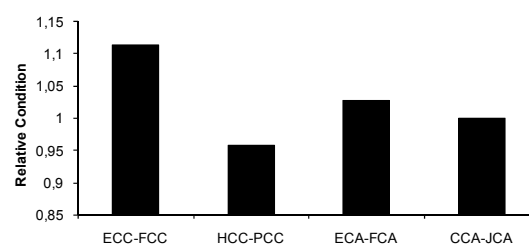


Figure 3. Le Cren (1951) relative fish body condition (*LK*) in ponds of Epping Forest (Essex, England) for crucian carp living in sympatry (ECC-FCC) and in allopatry (HCC-PCC) with goldfish, and goldfish living in sympatry (ECA-FCA) and in allopatry (CCA-JCA) with crucian carp.

GSI was higher in sympatry than in allopatry for goldfish, though not significantly (*t* tests, $Ps > 0.05$), but this was not the case for crucian carp (Table 2). None of the ponds were of sufficient biological quality to be recognised as Priority Ponds under the UK BAP. There were no significant relationships between fish abundance and invertebrate and plant indices (*F* test, P values > 0.05), but plant richness and rarity scores tended to be higher with higher crucian carp CPUEs (Table 1). By contrast, the opposite tendency was observed for goldfish CPUEs. Indeed, non-native plant species, as well as the non-native tadpole snail *Physella acuta* (Draparnaud), were present only in ponds containing goldfish, either in allopatry or in

Table 2. Mean standard length (SL, mm) at maturity (LaM), mean age (years) at maturity (AaM) and mean relative fecundity (RF) and gonado-somatic index for crucian carp in ponds of Epping Forest (Essex, England), where they were living in allopatry (CC-allo) and in sympatry (CC-Sym) with goldfish, and goldfish living in allopatry (GF-allo) and in sympatry (GF-sym) with crucian carp (derived from data in Tarkan et al. 2009, Tarkan et al. 2010).

Species combination	Male			Female				
	n	LaM	AaM	n	LaM	AaM	GSI	RF
CC-allo	86	55.0	2.20	100	45.0	2.05	8.4	119.2
CC-sym	51	52.5	1.50	40	50.0	1.50	6.4	231.0
GF-allo	126	59.6	1.45	114	56.7	1.35	7.1	251.7
GF-sym	66	56.1	1.10	65	54.2	1.20	9.0	455.8

Table 3. Summary of water chemistry and aquatic invertebrates (mean values for aquatic invertebrates are given for sympatry and the two types of allopatry) and plants in ponds (FM = Fairmeads; EP = Earl's Path; HC = Hawcock; CP = Carroll's; PP = Pizzole Pit; JP = Johnson's) sampled the week of 23 April 2007 in Epping Forest, England (see Table 1).

Water chemistry	Sympatry		Crucian only		Goldfish only	
	FM	EP	HC1	PP	CP	JP
Conductivity ($\mu\text{S}\cdot\text{cm}^{-1}$)	273	359	288	311	789	1371
pH	6.7	6.8	7.1	7.4	8.7	8.2
Invertebrates						
Species richness 'S' (total)	30	28	27	28	23	34
Species richness (non-native) ²	1	1	0	0	0	1
Species Rarity Score	34	32	31	28	24	35
Species Rarity Index	1.13	1.14	1.15	1.00	1.04	1.03
Total number of invertebrates netted ³	871	251	358	480	522	224
Mean number of invertebrates	561		419		373	
Conservation value	Mod.	Mod.	Mod.	Low	Mod.	Mod.
Plants						
Submerged ⁴	5.5	3	10	15	62	0
Floating-leaved	6.0	1.0	0.1	28.0	0.5	0
Emergent	12	12	20	12	38	6
Total cover ⁵	24	16	30	55	98	6
Species richness 'S' (total) ⁶	24	17	21	20	14	7
Species richness (non-natives)	1	2	0	0	1	0
Species Rarity Score	28	18	23	22	16	7
Species Rarity Index	1.17	1.06	1.10	1.10	1.10	1.00
Conservation value	High	Mod.	Mod.	Mod.	Mod.	Low

¹Contained palmate newt *Triturus helveticus*;

²Excludes the ubiquitous non-native freshwater shrimp *Crangonyx pseudogracilis*;

³Indicates relative abundance, not true abundance per unit area and excludes organisms recorded in absence presence only (see Annex 1);

⁴Cover of submerged, floating-leaved, emergent and total were estimated in the field, so values given are not the sum of all individual species values in the column above;

⁵Total cover is not the sum of submerged, floating and emergent but is estimated separately;

⁶Excludes *Salix* spp. and algae.

sympatry with crucian carp (Table 3). The non-native freshwater shrimp *Crangonyx pseudogracilis* Bousfield is now considered ubiquitous to inland waters of the Britain and was present in all ponds surveyed (Appendix 1). Goldfish were present in ponds of both lower and higher water conductivity, where crucian carp was present only in ponds of lower water conductivity (Table 3). No significant relationships were found between the density (CPUE) of either fish species and invertebrate species richness. Unadjusted invertebrate *S* and SRI appeared to

decrease with increasing goldfish density, but this was not true when *S* and SRI were adjusted for invertebrate density.

Discussion

In this preliminary study, the composition of pond organisms could not be attributed to the presence of goldfish, though it should be noted that non-native plants and animals were found only in ponds containing goldfish. Whereas, the observed differences in crucian carp body

condition and relative fecundity may be due to goldfish presence. Crucian carp growth is known to be influenced by environmental factors, such as temperature and food availability, with adverse effects having been attributed to intra-specific competition in cases of food shortage (Holopainen et al. 1997). Temperature difference among study ponds do not appear to be a major factor explaining our results, as the ponds are situated within a few kilometers of each other, and the fastest growing goldfish were in a well-shaded pond (Earl's Path). Similarly, food availability did not appear to be important, as crucian carp growth was similar in both allopatry and sympatry with goldfish (Figure 2), and no relationship was found between invertebrate densities and the body condition (*LK*) for either species – indeed the non-significant relationships in both species were of weakly decreasing *LK* with increasing invertebrate density. The positive relationship between water conductivity and *LK* in goldfish could be interpreted as reflecting a growth response to greater productivity, however this relationship was not found in crucian carp, which in northern Sweden is known to have a distribution correlated with water pH (Öhman et al. 2006), and the applicability of this relationship geographically limited and appears to be coincidental (see Copp 2003).

Coexistence of crucian carp and goldfish may even incite these two congeners to maximize their growth potential. Relative to allopatric populations, sympatric crucian carp were plumper, i.e. elevated *LK* value (Figure 3), and represent the fastest-growing crucian carp so far recorded for England. Shifts in the allocation of energetic resources between somatic and gonadal growth are well known in fishes, in particular those introduced outside their native range (e.g. Copp and Fox 2007), and crucian carp living in multispecific fish communities are known to have increased GSI relative to mono-specific existence (Aho and Holopainen 2000). Males of both crucian carp and goldfish matured earlier and at smaller size in sympatry than in allopatry (Table 2), and this was also seen in females, except for age at maturity in female crucian carp. Compared with crucian populations elsewhere at similar latitudes (Tarkan et al. 2009), growth rates in the present study were intermediate. Similarly, fast-growing sympatric goldfish in our study (Figure 2) had intermediate growth rates relative to populations elsewhere in Europe (Tarkan et al. 2010), whereas the growth rate of

allopatric goldfish populations (Figure 2) was slow relative to other European populations of this species.

The faster incremental growth in goldfish and greater plumpness in crucian carp observed in sympatric populations were expected to influence reproductive output. This was supported by the relative fecundities observed (Table 2). However, no consistent pattern was observed in length or age at maturity for sympatry. Variations in reproductive output have been reported for introduced species (e.g. Copp and Fox 2007), and increased fecundity was observed in both species in sympatry in the present study, with almost double the number of eggs per body weight relative to females existing in allopatry. Also in sympatry, male crucian carp matured almost a year earlier with did those in allopatry. Comparative data for feral goldfish in Europe are scarce, but in the warm climate of Lake Trasimeno, Italy (Lorenzoni et al. 2007), the *RF* of goldfish was lower, and mean AaM was higher, than observed in the ponds of Epping Forest (Tarkan et al. 2010). This runs contrary to life-history theory (Atkinson 1994), which predicts that ectotherms will experience faster juvenile growth, precocious maturity, and a shorter life-span, in response to elevated water temperatures. Fast juvenile growth and precocious maturation have been linked to invasiveness potential in pumpkinseed *Lepomis gibbosus* (L.) introduced to European waters (Copp and Fox 2007). This pattern, which appears to prevail despite differences in local food availability and fish density, may also apply to goldfish, but insufficient data are available at present to test this hypothesis. For example, the majority of papers on feral goldfish report length at age data (seven populations besides these Epping Forest ponds), with data on reproduction limited to Lake Trasimeno, Italy (Lorenzoni et al. 2007) and these three Epping Forest ponds (Tarkan et al. 2010). Length at age varies greatly, with the fastest rates reported in feral populations of Australia (Mitchell 1979, Morgan and Beatty 2004) and Turkey (İzci 2004). Whereas, female goldfish in these Epping Forest ponds mature at younger mean ages (1.0, 1.2, 1.7) and shorter mean standard lengths (50.0, 54.2, 63.4 mm) than those in Lake Trasimeno (2.1 years, 129.2 mm SL).

Wider ecosystem impacts have been attributed to introductions of goldfish, including a decrease in invertebrate numbers (Richardson and Whoriskey 1992), the local eradication of

aquatic macrophytes through direct consumption, and the alteration of aquatic community composition associated with nutrient re-suspension due to the species' benthic feeding habits (Richardson et al. 1995; Cowx 1997). Indeed, recent research has found the growth of cyanobacteria to be stimulated during its passage through goldfish intestines (Kolmakov and Gladyshev 2003).

In conclusion, differences in the plant and aquatic invertebrate communities of the ponds in the present study could not be attributed directly to the introduction and establishment of goldfish, which contrasts the somewhat more apparent ecosystem impacts reported elsewhere (e.g. Mitchell 1979; Richardson et al. 1995; Kolmakov and Gladyshev 2003). However, in support of our prediction, and with the exception of the ubiquitous freshwater shrimp *Crangonyx pseudogracilis*, all non-native plant and invertebrate species were encountered only in ponds containing goldfish (Appendices 1 and 2). The present, preliminary study did reveal a possible goldfish impact on crucian carp biology, though these manifestations of competitive interaction do not appear to be related to food abundance. Both body condition and relative fecundity in crucian carp were greater in ponds co-inhabited with goldfish. Egg diameter in the English populations has been found to be significantly smaller, and mean relative fecundity higher, than in the Lake Trasimeno (Italy) population (Lorenzoni et al. 2007), which suggests a trade off between these two traits under different environmental conditions (Tarkan et al. 2010). Because crucian carp egg diameter was similar in allopatry and in sympatry with goldfish (Tarkan et al. 2009), crucian carp coexistence with goldfish appears to lead to greater allocation to growth in weight and subsequent higher relative fecundity. However, crucian carp relative fecundities are approximately half those of goldfish, regardless of allopatric or sympatric existence. Thus, in addition to their genetic contamination of crucian carp populations through hybridization (Wheeler 2000; Hänfling et al. 2005; Smartt 2007), goldfish have the potential to out-reproduce crucian carp by two-fold, given similar food resources. These biological pressures, combined with loss of habitat due to various pressures (including changes in landuse; Sayer et al., unpublished), appear to be key factors contributing to the decline of crucian carp in parts of its native range.

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Supplementary material

The following supplementary material is available for this article.

Appendix 1. List of aquatic invertebrates (summarized in Table III) observed in ponds of Epping Forest (Essex, England) during the week of 23 April 2007, with their status, rarity score, description.

Appendix 2. List of aquatic plants (summarized in Table III) observed in ponds of Epping Forest (Essex, England) during the week of 23 April 2007, with their status.

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