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Article · September 2018

DOI: 10.3391/mbi.2018.9.3.09

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Management of Biological Invasions (2018) Volume 9, Issue 3: 267–278
DOI: https://doi.org/10.3391/mbi.2018.9.3.09

Management in Practice

Control and eradication efforts of aquatic alien fish species in Lake Caicedo Yuso-Arreo

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Received: 18 May 2018 / Accepted: 1 August 2018 / Published online: 4 September 2018

Handling editor: Matthew A. Barnes

Abstract

Lake Caicedo Yuso-Arreo (Spain) supports dense populations of alien fish species, namely common carp (*Cyprinus carpio*), largemouth bass (*Micropterus salmoides*), pumpkinseed (*Lepomis gibbosus*), and the red swamp crayfish (*Procambarus clarkii*). These introductions have caused a reduced transparency, decreasing submerged vegetation and population decline of native tench (*Tinca tinca*). Alien species were caught and removed for 76 days in 2014 and 2015 with the objectives of eradicating carp and reducing largemouth bass and pumpkinseed populations under 20% of 2014 observed density and biomass. Only two individuals of tench were captured, underlining its scarcity. A total of 27,077 individuals (1089 kg) of alien species were removed, but eradication was not achieved for any species. The largest sizes of carp and largemouth bass almost disappeared, while in 2015 an increase in the abundance of large recruits was observed. A hydroacoustic fish stock assessment was carried out at the end of the action in 2015 to obtain data on fish density and biomass in open water as a mean to compare results to measurements from 2010. Although the density of fish increased from 2010 to 2015, biomass fell drastically. In 2017, the alien species community was controlled again, revealing a substantial recovery from previous control efforts, a change in the size distribution towards smaller specimens and interactions among North American species. Additionally, no tench could be identified and the species is considered locally extinct. Thus, the results from this study suggest the need for ongoing control efforts with increased electrofishing and implementation of alternative control methods such as the introduction of biological control agents to achieve the ecological status improvement and environmental restoration goals.

Key words: fish removal, boat electrofishing, gillnets, hydroacoustics, fish management, ecological status, wetland restoration

Introduction

Freshwater ecosystems, especially in industrialised countries, have been the target of frequent introductions, especially by fish species (Oberdorff et al. 2002; Copp et al. 2005; García-Berthou 2007). Lake Caicedo Yuso-Arreo, henceforth referred to as Lake Arreo, is a peculiar ecosystem in the Iberian context, as it is one of the eight Iberian lakes on a saline chimney (González-Mozo et al. 2000; Camacho et al. 2009). In addition, it is the only n González-Mozo et al. 2000lake in Basque country. In the 19th century, its fish community was composed of trout (*Salmo trutta* Linnaeus, 1758), European eel (*Anguilla anguilla* Linnaeus, 1758), and tench (*Tinca tinca* Linnaeus, 1758) (Madoz 1845). At the beginning of the 21st century however, trout was already absent and the alien largemouth bass (*Micropterus salmoides* Lacépède, 1802) and pumpkinseed (*Lepomis gibbosus* Linnaeus, 1758) were detected in surveys under the Water Framework Directive ecological status monitoring network (Vasco 2004). The fish census carried out in 2010 (Monteoliva et al. 2011b) also detected common carp (*Cyprinus carpio* Linnaeus, 1758) and quantified dense populations of invasive *M. salmoides* and *L. gibbosus*. The densities of these species were significantly higher than that of tench, the only species that could be considered native in the

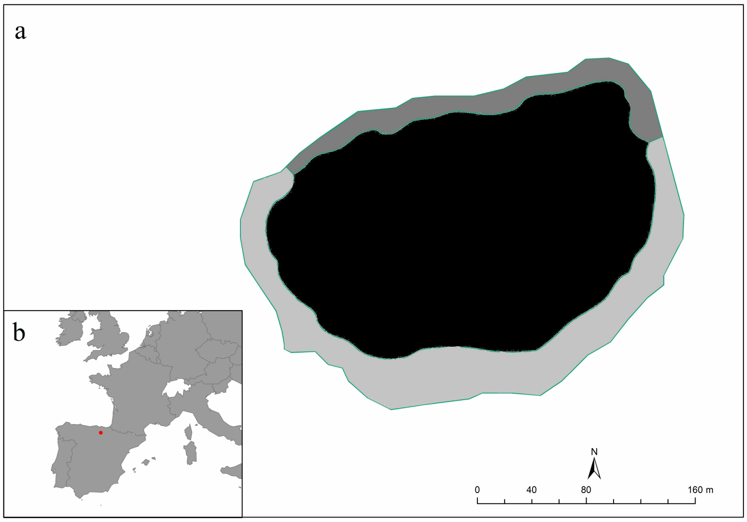


Figure 1. Distribution of fish capture zones (black: pelagic zone; dark grey: slope zone; light grey: helophytes zone) of lake Caicedo Yuso-Arreo (a) and location in Europe (b).

absence of precise data on the historical composition of the community. This species tends to be considered native in most of Europe (Freyhof and Kottelat 2008), although its native distribution in Spain is uncertain (Doadrio et al. 2011).

C. carpio has been introduced to more than 100 countries worldwide as a result of human action (Balon 1995; Badiou et al. 2011). Several negative impacts on recipient ecosystems have been reported for this species, such as an increase in sedimentation, erosion and increasing dissolved nutrients in the water column and thus, an increased phytoplankton growth; a disturbance of the structure of the planktonic community; decreased abundance of submerged macrophytes, macrozooplankton and benthic invertebrates; decreased diversity and abundance of native fish; competition with aquatic birds for food resources, and others (Lougheed et al. 1998; Chumchal et al. 2005; Scheffer 1998). Hysteretic state changes resulting from modulation of the resources available for other species (Badiou et al. 2011) were also reported.

The centrarchid species *M. salmoides* and *L. gibbosus* are native to North America and have been frequently introduced to reservoirs specifically for sport fishing (Doadrio 2001; Naspleda et al. 2012). In the Iberian Peninsula, they occupy lentic habitats and slow stretches of large rivers, where they reach high densities. Especially *L. gibbosus* is known for its omnivorous diet and negative effect on water clarity as well as being a common prey for *M. salmoides* (Angeler et al. 2002), which is a voracious predator of invertebrates, amphibians, fishes, and even of micromammals and reptilians when reaching larger sizes (Hodgson and Hansen 2005; Shelton et al. 2008; Wasserman et al. 2011; Magoro 2014).

The presence of invasive fish species puts pressure on Lake Arreo, as they are potentially exerting negative impacts on the recipient species community and in the case of *C. carpio* facilitate the eutrophication process (Lougheed et al. 1998; Miller and Crowl 2006). Therefore, a proposal was made to implement corrective measures based on the desired removal of alien species (not only fishes but also the red swamp crayfish (*Procambarus clarkii* Girard, 1852) in the framework of the LIFE TREMEDAL project (LIFE11 NAT/ES/ 000707). Considering the characteristics of the lake, an integrated approach of electrofishing and gillnet techniques was selected for removal of alien species. The specific objectives of removal were: (1) recovery of tench population; (2) common carp eradication; (3) removal of up to 80% of alien fish populations.

Hence, this work investigates if previously defined objectives for Lake Arreo are achievable by applied manual removal techniques (electrofishing and gillnetting) and furthermore, aside from highlighting conducted monitoring and control tasks, presents information about changes within population structures of present fish species two years later. Lastly, this article provides complementary data about feeding activity as well as reproductive status of removed invasive fish, investigating species interactions and exploring potential tasks for the future.

Materials and methods

Study site

Lake Arreo is located in Basque Country (north of Spain, see Figure 1), 655 m above sea level. It is part of the Ebro river basin and covers about 136 ha. Its morphology is simple, with only one basin located on the north side with a maximum depth of 24 m in an area with a steep slope associated with an ENE-WSW positioned fault (Martínez-Torres et al. 1992). The south and west areas are shallow and feature a low slope, allowing the development of a dense helophytic margin dominated by *Phragmites australis* and *Cladium mariscus*. As a result, three different habitats for fish can be distinguished (Figure 1): the pelagic habitat (limited to the superficial zone by hypolimnetic anoxia); the shallow slope habitat (abundant submerged dead tree trunks; without helophytes); and the shallow flat habitat (helophytes constitute a dense refuge for fish). Water transparency was measured using a Secchi disk at the beginning of each session and a multiparametric probe (Hydrolab DS5) was used to measure physico-chemical parameters (water conductivity; water temperature). Meteorological data from the nearest station were gathered for each day on the site (www.ogimet.es).

Goals and objectives

The main aim of conducted control efforts in Lake Arreo was the recovery of the previously present tench population. To achieve this objective and a stable recovery of the previously invaded ecosystem, a complete eradication of the for resources competing common carp (Adámek et al. 2003) was intended. Because of the high densities of other also present alien fish species (pumpkinseed, largemouth bass) that are likely exerting a negative impact on the ecosystem and thus, lowering the chances of recovering tench (Lorenzoni et al. 2002), their populations should be decimated by 80% to eventually lower their densities.

Fishing techniques

In 2014, 15 days between June and September were devoted to fishing as part of five surveys (called ARR14_01 to ARR14_05), and 61 days between May and August as part of 17 surveys (called ARR15_01 to ARR15_17) in 2015. Multi-mesh gillnets (trammel-, benthic- and pelagic nets) were deployed overnight in the pelagic habitat for about 12h. Gillnets conformed to “EN14757:2005: Sampling of fish with multi-mesh gillnets”, with 5 to 50 mm mesh sizes and four additional mesh sizes (70–135 mm) for large fishes (Šmejkal et al. 2015). Electrofishing in shallow habitats was conducted from a boat, using a 13-kW electric power equipment (Hans Grassl EL65II GI). The electric output was a continuous pulse current of 300 V with 80–100 Hz, generating an electric current of approximately 9 A (ranging from 7 to 11 depending on conductivity, depth and helophyte density). Electrofishing paths were positioned with a GPS in order to standardize the effort with fishing duration and were conducted separately for both kind of shallow habitats (helophytes and slope), navigating around the lake parallel to the shore. For every fish, fork length (in cm) and weight (in g) were recorded. Alien fishes were euthanized using an anaesthetic (Eugenol) overdose and taken out of the lake. Tench individuals were excluded from anaesthesia and kept in clean water before being released back into the lake. Capture related variables (gillnets: hours in the water, size and mesh size of gillnets; electrofishing: hours fished, distance covered with the boat) were standardized and the Catch per unit of effort (CPUE) using the numbers of caught fish, and the Biomass per unit of effort (BPUE) using the total mass of collected fish were calculated for every species. A regression model was applied to identify relationships between species' specific CPUE values and abiotic variables. Population sizes were estimated, assuming that the CPUE serves as a surrogate for density and correlates with the abundance of a species, by plotting the standardized CPUE (x-axis) against the accumulative total catch (y-axis) for each sampling and extrapolating a regression line that, once reaching the x-axis indicates the total population size (Leslie and Davis 1939).

Open water census methodology

A hydro-acoustic survey was carried out using a scientific split-beam echo sounder (Biosononics-DTX) synchronized to a *Differential Global Positioning System* (DGPS), generating a digital bathymetric model and detecting fish and their acoustic target strength by means of their size (Monteoliva and Schneider 2005). Both were combined with direct sampling (capture) data to generate density and biomass estimates in open non-shallow waters. For echograms registering in vertical position during the mobile echo sounding survey, the basic equation of Love (1977), adjusted for the transducer frequency, was applied to the single echo detections (SED). In shallow waters (less than 5 m depth) the transducer was oriented in horizontal position and echo integration was used instead of SED analysis. In this case, the median size of the fish catches was used to calculate the backscattering cross section and to estimate the fish density and biomass in each analysis segment, using the regression proposed by Kubecka et al. (2009). Global estimates were compared to 2010 data (Monteoliva et al. 2011a), a similar survey prior to fish removal campaigns.

Table 1. Summary of used gillnets incl. mesh size and Catch per Unit Effort (CPUE). Only gillnets that caught fish are listed.

Year	Survey	Date	overall catch	net types	Mesh size	CPUE
2014	1	02.06.2014	125	3x Trammel	2 × 1.5; 3 × 1.5; 5 × 1.5	0.39–0.59
				2x Pelagic	16 × 5	0.12–0.63
				4x Benthic	2 × (4 × 1.5); 2 × (12 × 1.5)	0.24–0.63
	2	16.06.2014	45	2x Trammel	5 × 1.5	0.26–0.14
				2x Pelagic	16 × 16	0.15
				2x Benthic	16 × 1.5	0.25–0.6
	3	06.08.2014	22	Pelagic	16 × 6	0.16
2015	2	12.05.2015	3	Pelagic	16 × 6	0.17–0.20
	7	15.06.2015	2			
	9	29.06.2015	1			
	10	06.07.2015	63			
	11	14.07.2015	1			
	12	20.07.2015	27			
	13	27.07.2015	26			
	14	05.08.2015	8			
	15	10.08.2015	2			
	17	24.08.2015	12			
	Total		337			

Evaluation of control efforts

To enable and observe a potential recovery of the tench population as well as to evaluate the effectiveness of the control and eradication efforts in 2014 and 2015, the status (CPUE, BPUE) of present fish populations was assessed again in 2017 (ARR17_01, 02 and 03) using the same electrofishing approach used in previous years. Specimens were measured, and the sex was determined. The reproductive status of randomly chosen individuals of alien fish species were examined, and gonadal weight was measured to 0.01 g (Jadever SNUG 300). The Gonadosomatic Index (GSI) was calculated as the percentage of gonads per total body weight (Devlaming et al. 1982). The stomach contents of mature but randomly chosen fish species were examined using a stereomicroscope and found items were identified to the lowest possible taxa. Additionally, fish diets were analysed as frequency of occurrence (F% = 100 × A_i × N_-) where A_I was the number of fish containing prey item i and N the total number of fish analysed (excluding those specimens with empty stomachs). These observed data were used to evaluate potential niche overlaps by calculating Pianka's index (Pianka 1974) using the R-package "EcoSymR" (Gotelli et al. 2015).

Additionally, data of the from 2013 and onwards sampled *P. clarkii* was assessed (Asensio 2015) and, as an integral part of the invasive species community, sampled again in 2017 using 6 funnel traps along the hydrophyte zone overnight for 12 hours.

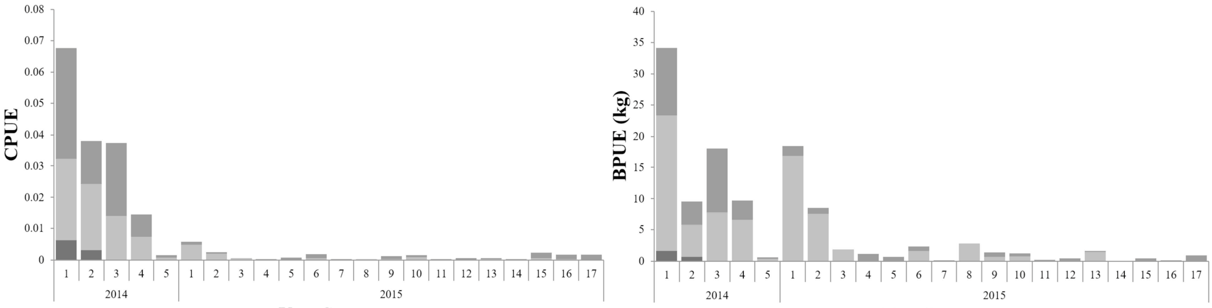
Results

The lake remained stratified during the entire process of removal, with an average epilimnetic conductivity of 1,139 µS/cm in 2014 and 946 µS/cm in 2015. The available habitat for fish was limited to the epilimnion due to the lack of oxygen in deeper strata. Surveys were defined as the unit of effort for data analysis. The total effort for gillnets was 76.3 units (45 m^2 · 12 h) and 25,625 m for electrofishing in 2014, whereas in 2015 the effort was 88.9 units for gillnets and 122,000 m for electrofishing.

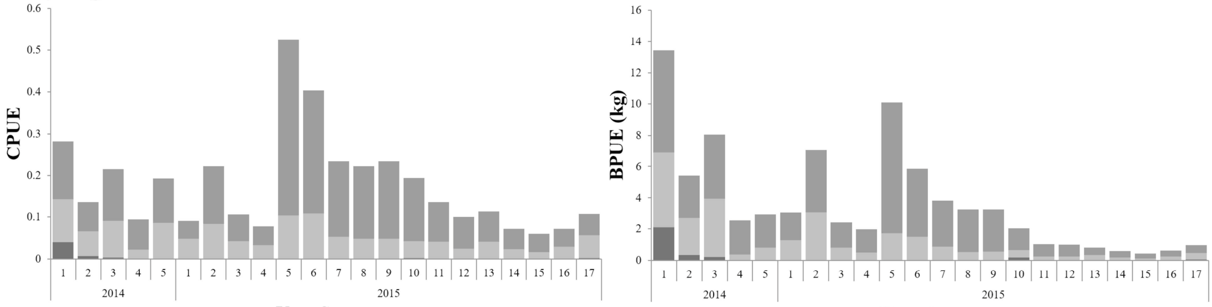
The total catch of individual fish in 2014 and 2015 using electrofishing amounted to 6,063 specimens in the slope zone and 20,679 in the helophyte zone. The use of different gillnet types with different mesh sizes resulted in the catch of 337 fish from the deep zone (Table 1). Gillnets proved to be ineffective in removing high quantities of fish in the pelagic zone. Therefore, and because boat electrofishing was unable to sample in the epipelagic zone, only pelagic nets were used in 2015. The total biomass taken out of the lake was 1,089 kg. The percentage of total biomass showed the following distribution: *C. carpio* 45.3% (due to the 46 large sized mature individuals), *L. gibbosus* 37.3% (due to abundance), *M. salmoides* (17.4%) and *T. tinca* (0.05%). The total number of caught specimens showed a different distribution. *L. gibbosus* was the most abundant species (73.2%), followed by *M. salmoides* (23.6%), *C. carpio* (3.2%) and finally two individuals of *T. tinca* (0.01% of the total).

The standardized CPUE values varied between days and surveys. For *C. carpio*, CPUE values (Figure 2a)

a) ***C. carpio***



b) ***L. gibbosus***



c) ***M. salmoides***

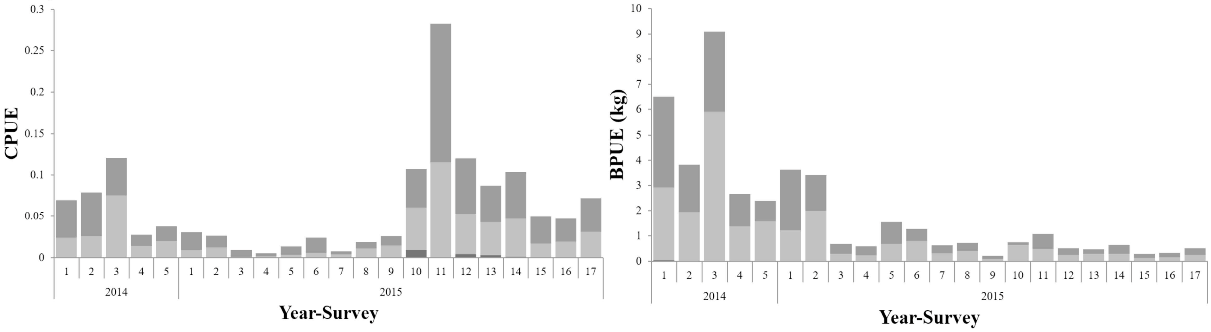


Figure 2. Development of Catch per Unit Effort (CPUE) and Biomass per Unit Effort (BPUE) in 2014 and 2015 surveys. Black: pelagic habitat; dark grey: slope habitat, light grey: helophytes habitat. Numbers on the x-axis indicate the survey for 2014 and 2015.

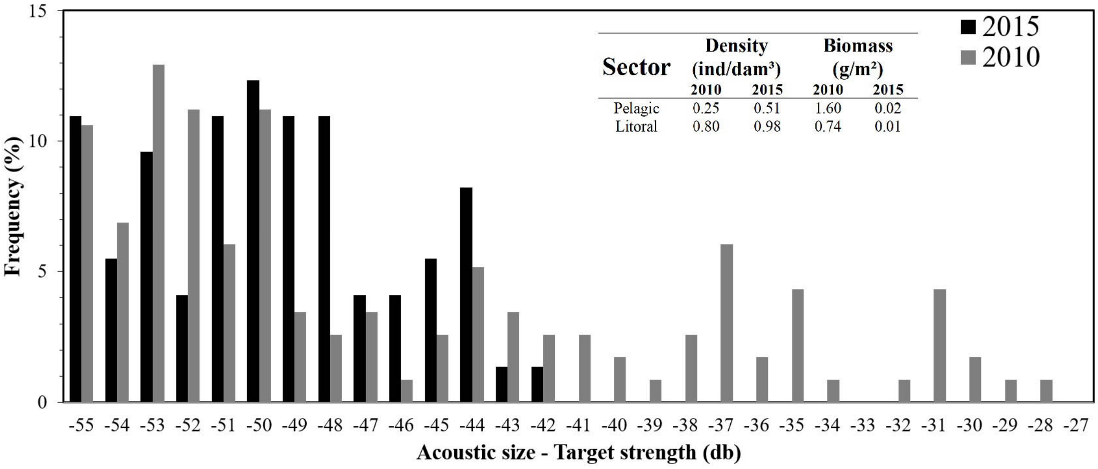
dropped quickly in all habitats after effort accumulation, remaining at very low levels. Catches of carp were scarce in the deep zone, and the average size was generally higher in the slope zone than in the helophytes zone. However, from June 2015 onwards, a marked increase in *L. gibbosus* catches (Figure 2b) was observed, especially in the helophytes zone. After that date, CPUE and BPUE dropped progressively with increasing removal. *M. salmoides* CPUE (Figure 2c) experienced a high increase from July 2015 on, but BPUE did not. The annual number of *Procambarus clarkii* caught increased from 2013 (2,250 individuals, 16 traps, 72 hours, CPUE: 1.953) to 47,450 individuals in 2014 (50–54 traps, 2,136 hours, CPUE: 0.444) and to 70,500 in 2015 (50–70 traps, 86,400 hours, CPUE: 0.014) (Asensio 2015) but CPUE decreased strongly. The applied regression model revealed that *C. carpio* catches related significantly to conductivity and air temperature (inversely). *L. gibbosus* catches related significantly to turbidity and *M. salmoides* catches to water temperature and conductivity (Table 2).

Open water census methodology

Comparison of hydroacoustic estimates in 2010 and after control efforts in 2015 revealed major changes of partial fish community in Lake Arreo, likely induced by removal efforts. Density increased considerably in the pelagic sector and moderately in

Table 2. Multiple stepwise regression analysis of Catch per Unit Effort (CPUE) and environmental variables. ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.

Dependent variable	Adjusted R^2	F (ANOVA)	Selected independent variables	Coefficient	Standard deviation	Student t
CPUE *C. carpio*	0.54	45.00**	Intersection	0.000	0.078	–
			Conductivity	0.707	0.079	8.97**
			Mean air temperature	−0.188	0.079	−2.39*
CPUE *L. gibbosus*	0.14	13.42**	Intersection	0.000	0.107	–
			SD transparency	0.394	0.108	3.66**
CPUE *M. salmoides*	0.22	11.29**	Intersection	0.000	0.102	–
			Water temperature	0.402	0.103	3.91**
			Conductivity	0.261	0.103	2.53*
CPUE *T. tinca*	0.03	3.12^{ns}	Intersection	0.000	0.114	–
Total CPUE	0.12	4.45**	Intersection	0.000	0.108	–
			Water temperature	0.223	0.110	2.02*
			Conductivity	0.281	0.117	2.40*
			SD transparency	0.346	0.118	2.92**



Sector	Density (ind/dam³)		Biomass (g/m²)	
	2010	2015	2010	2015
Pelagic	0.25	0.51	1.60	0.02
Litoral	0.80	0.98	0.74	0.01

Figure 3. Frequencies of acoustic sizes (target strength) in lake Caicedo Yuso-Arreo from 2010 and 2015. Table: Hydroacoustic density and biomass estimations for respective years.

the littoral, whereas biomass fell drastically in both sectors. Frequency distribution of acoustic sizes (target strength) changed also (Figure 3) from 2010, prior to removal, to 2015, showing the disappearance the largest size fishes.

Population shifts and evaluation of efforts

Initial population sizes were calculated under the assumption of CPUE being an indicator of population density, and the results for each year of removal are listed in Table 3. The measured turbidity showed an increase during the removal efforts in 2015 (3.0 to 1.9 m) and decrease in 2017 (1.6 to 2.3 m). Results of length and weight shifts of removed species for all years are presented in Figure 4, showing an increase in *M. salmoides* recruits from 2014 to 2015

Table 3. Estimation of annual population sizes for targeted species based on Catch per Unit Effort (CPUE) and accumulated annual catchments.

Species	Year	Pop. size	R^2
L. gibbosus	2014	66671.1	$R^2 = 0.4162$
	2015	52062	$R^2 = 0.1151$
	2017	23449.2	$R^2 = 0.9614$
C. carpio	2014	797.9	$R^2 = 0.9034$
	2015	45.1	$R^2 = 0.5284$
	2017	10.9	$R^2 = 0.9865$
M. salmoides	2014	2303.9	$R^2 = 0.6315$
	2015	1384.9	$R^2 = 0.2317$
	2017	525.7	$R^2 = 0.8884$

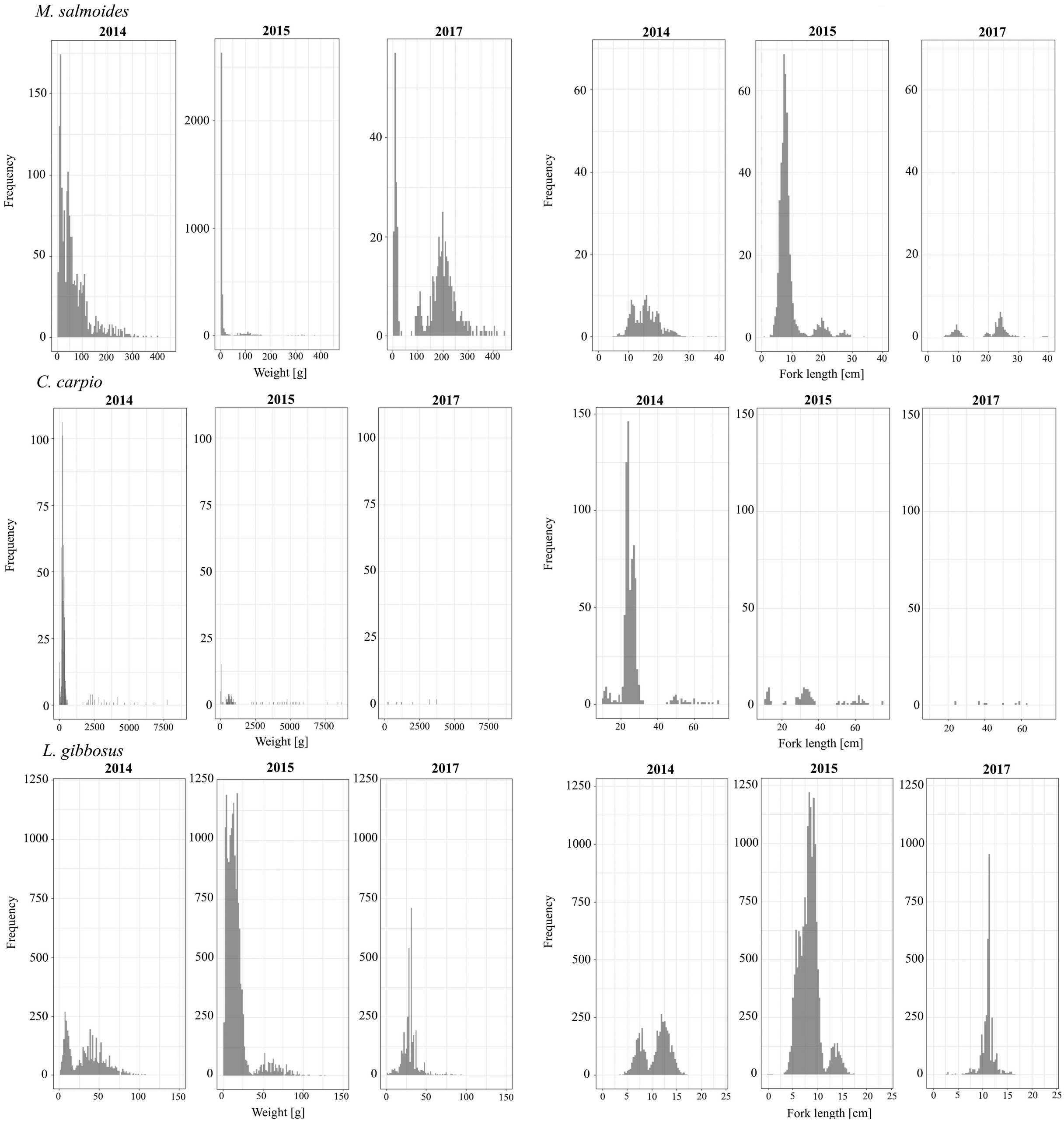


Figure 4. Changes within the population in regard to fork length and weight distribution of removed fish over the years 2014, 2015 and 2017.

and a balanced distribution among immature and mature individuals in 2017. From 2014 to 2015, the carp population remained similar in length and weight distribution with an overall decimation of the population, while the few individuals caught in 2017 were all mature. The removal of *L. gibbosus* in 2014 resulted in an increase of recruits in 2015. In 2017, the population stabilized in between the two distributions of recruits and mature specimens from 2015.

In 2017, the effort for electrofishing accumulated to 15,500 m. Overall, 11 individuals of *C. carpio* (20.8 kg), 3,250 specimens of *L. gibbosus* (97.7 kg) and 499 individuals of *M. salmoides* (83 kg) were sampled, making up a total of 3,760 fish (201.5 kg). 47 crayfish weighing 1,310 g in total were caught with a CPUE of 0.653. No individuals of *Tinca tinca* could be observed. Stomach contents of *C. carpio* was identified with detritus being the dominant component (F%: 45%). *L. gibbosus* diet consisted mostly of Coleoptera (F%: 45.7), Orthoptera (F%: 14.3), *P. clarkii* (F%: 14.3) and smaller frequencies of aquatic invertebrates and diverse insects. The diet of *M. salmoides* was less diverse, with a high abundance of *P. clarkii* (F%: 82.1), followed by Araneae (F%: 21.4), *L. gibbosus* (F%: 17.9) and Odonata (F%: 14.2) (see Table 4). The niche (diet) overlap for the two predatory Centrarchidae was estimated as 0.2352 (Pianka's index) for *L. gibbosus* and *M. salmoides* and therefore generally low (< 0.4). Spawning individuals were observed for every alien species from May onwards. Reproductive investment varied among species (Figure 5), with average GSI values of 4.3% for *C. carpio*, 8.7% for *L. gibbosus* and 3.5% for *M. salmoides*.

Discussion

The eradication of alien fish populations has usually been accomplished with biocides (such as rotenone; see e.g. Britton et al. 2011), which are strongly restricted in Europe and which are normally used only in relatively small and enclosed water bodies (European Commission 2014). In the case of Lake Arreo, it could affect the rare tench if used. Hence, physical removal (Britton et al. 2011) by e.g. commercial harvesting, manual removal as well as gillnetting have been shown to positively minimize alien fish populations (Gliwicz and Rowan 1984; Bahls 1992; Knapp and Matthews 1998; Colvin et al. 2012), although need to be chosen carefully (Nuñez et al. 2012). In the late 20th century, new theories about management of natural resources focused on preserving indigenous biodiversity, reducing the stocking with potentially invasive species, and biologists began to focus on restoration and renaturalization (Parker et al. 2001). In more recent works, electrofishing was used in combination with gill netting (Parks Canada 2016), resulting in a rapid recovery of extirpated zooplankton species (Schindler and Parker 2002; Sarnelle & Knapp 2004). These successful case studies lasted three or four years at least, but targeted lakes were higher and usually shallower with simpler fish assemblages (usually with only one non-native species) than that in Lake Arreo.

Effectiveness of applied techniques

In the case of Lake Arreo, gillnets were identified as less effective than electrofishing. Indeed, boat electrofishing proved to successfully remove fish from the littoral area. However, it was not suitable for gathering especially small-sized fish swimming in between dense helophytes.

Table 4. Identified dietary components for *L. gibbosus* (N = 38), *M. salmoides* (N = 38) and *C. carpio* (N = 11). Results are displayed as frequency of occurrences [F%] in percentages.

Component	*L. gibbosus*	*M. salmoides*	*C. carpio*
P. clarkii	14.29	82.14	0
L. gibbosus	0	17.86	0
Odonata	0	14.29	0
Mollusks	2.86	0	0
Hymenoptera	20	3.57	0
Heteroptera	11.43	0	0
Snails	0	0	0
Araneae	2.86	21.43	0
Diptera	5.71	0	0
Odonata	5.71	0	0
Orthoptera	14.29	0	0
Coleoptera	45.71	0	0
Formicidae	2.86	0	0
unid. Insects	51.43	0	0
detritus	42.86	3.57	100
fisheggs	8.57	0	0
plant material	5.71	0	0

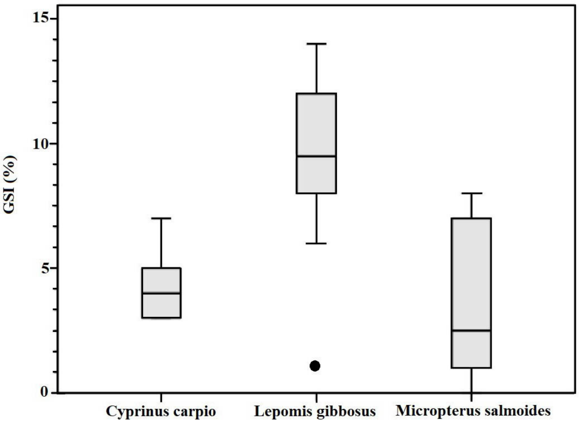


Figure 5. Gonadosomatic Index, i.e. percental weight of gonads for *C. carpio* (N = 9), *L. gibbosus* (N = 26) and *M. salmoides* (N = 22) caught in lake Caicedo Yuso-Arreo.

The total effort applied on Lake Arreo was not enough to eradicate present carp, but the aimed reduction in abundances of populations to low levels was achieved. Recruitment and environmental variables (meteorological factors, water surface temperature, conductivity and transparency) were considered as the causes for variations in CPUE because while most of the effort was made in 2015, field work in 2014 had likely started after the onset of the reproductive season. Furthermore, the density-dependent survival in the immature phase of fish is a key factor in regulating fish populations (Rothschild 1986).

Density-dependent growth due to competition for food in immature fishes has been described for many species (e. g. Beverton and Holt 1957; Rochet 1998; Post et al. 1999; Jenkins et al. 1999) and is suggested as a common and important mechanism in the regulation of fish populations (Lorenzen and Enberg 2002). Hence it is likely, that mature individuals present in the lake in between the end of removal efforts in 2014 and the beginning of the 2015 removal period probably had high reproductive potentials, and successive population reductions liberated more resources for immatures, thus allowing them to maintain high growth and increased survival rates.

In this context, the CPUE of *M salmoides* was observed to remain consistent, but the BPUE decreased. This was due to the presence of increasingly small sized individuals captured by that time, frequently seen in dense shoals. For *L. gibbosus* and *C. carpio*, a significant decrease in CPUE and BPUE was observed.

Classic depletion models (Leslie and Davis 1939) expect the consecutive observed CPUE to fall proportional when plotted against the accumulated catches, but in Lake Arreo, the CPUE tended to stabilize at low levels. The assumed constant catchability and zero natural mortality combined with the recruitment or migration make estimations of initial population sizes difficult, but it can be assumed that populations of all species successfully decreased. The observed CPUE stabilization can hence be due to several reasons: 1) a prolonged removal period (translating into recruitment); 2) inability of fishing techniques to affect fishes hidden in the helophytes; 3) lack of information about migration patterns between refuge and fishable zones; and 4) inconsistent catchability due to changing environmental factors.

Overall, the reduction of non-native fish populations was very high, especially in terms of biomass. BPUE (considered a predictor for total biomass) indicated a reduction of 98% from the beginning to the end of the management effort, whereas CPUE (predictor of density) reduced by 81%. Thus, it can be highlighted that the initial aims were achieved except for the eradication of carp. Because of the successful removal of large parts of the non-indigenous fish community, a positive effect on transparency and submerged macrophytes was expected for the next years. Especially the reduction of carp biomass (> 75% of total biomass) benefits aquatic vegetation (Bajer et al. 2009) and water clarity (Schrage and Downing 2004) and likely has immediate, long-lasting effects such as a clear-water phase in spring allowing for hydrophytes to recover (Lammens 2001).

Restoration of tench population

T. tinca population density in 2015 was very low, as only two individuals were caught. Thus, it can be assumed that the present population faces a high risk of extinction, but its recovery could be supported by the reduced pressure of non-native species. Additionally, this species typically occurs in low-density populations, has resistance to low oxygen levels and an omnivorous diet (Doadrio et al. 2011), factors that should contribute to maintain a viable population in the Lake Arreo. Nonetheless, having caught no individual of *T. tinca* in 2017 points towards a probable extinction of this species in Lake Arreo. Therefore, population reinforcement by stocking from viable populations would be another considerable measure.

Procambarus clarkii

Because the control of *P. clarkii* has been shown to be a long and difficult process, the continuous application of trapping to control the abundance of *P. clarkii* cannot be considered as effective and thus, other techniques need to be explored. Although *P. clarkii* was not directly sampled as part of the last control and eradication effort, an action for evaluation of its eradication was carried out from 2013 to 2015 (Asensio 2015). The presence of this species is of integral importance as this species is a common food source of *M. salmoides* and *L. gibbosus*, two species with which it shares a common co-evolution and life-history. Additionally, it is known for its devastating effects on recipient ecosystems (see e.g. Gherardi and Acquistapace 2007). Placing the traps for crayfish was practiced the same way in all the years by positioning them on the muddy ground in the shallow zone between patches of hygrophytes. The capture and CPUE values decreased between 2013 and 2014, but not during 2015, although the mean size of individuals was lower. These results hint towards a successful decimation (~ 72%) of the population to a certain threshold, below which it was impossible to progress by applying only one technique, for which reason other potential control techniques should be examined. In addition, it was concluded that baiting and placing the traps closer to the surrounding marshland might result in higher CPUE rates.

The overall turbidity showed a strong increase after high values in the beginning of 2015 followed by decreasing values in 2017, likely linked to the lack of control efforts in 2016 and a successive recovery of present alien species. It should be noted that the presence of *P. clarkii* and fish such as *C. carpio* has often been linked to an increased turbidity

(Rodríguez et al. 2003). Nonetheless, it is not possible to determine a causality between observed turbidity and presence nor successful decimation of *P. clarkii* and *C. carpio* in Lake Arreo. Additionally, the presence of *P. clarkii* has been linked to facilitating establishment and increased population growth of other aquatic invasive species, for what reason the abundance of *P. clarkii* for the control and thus eradication of *M. salmoides* and *L. gibbosus* should be reduced.

Population shifts and evaluation of efforts

In 2017, the decreasing catchability of *L. gibbosus* specimens (day 1: 2,284 individuals; day 2: 590; day 3: 376) and *M. salmoides* specimens (day 1: 281; day 2: 131; day 3: 87) is in consensus with catches from 2014 and 2015, but also revealed the recovery of both species' populations. Considering that a reduction of *L. gibbosus* and *M. salmoides* populations was achieved, it is not surprising, that the length and weight distribution of alien fish in Lake Arreo differed from the previous years. Increased density but decreased biomass between 2010 and 2015, most likely affected these species' reproductions, making immature survival after 2015 the key factor for the recovery of populations in 2017 and the future years. Having caught, in 2017, only 11 carp (27–64 cm; 302–3,750 g) from which eight had fully developed gonads, showed the effectiveness of previous efforts, but also signified that the population of carp was on the verge of recovering. Thus, having achieved neither the population recovery of tench, nor the aimed eradication of carp, has major implications for the future. For once, because the applied efforts of carp were effective but not sufficient, control and management should be continued. With the observed effectiveness of electrofishing, it is likely that future efforts to eradicate carp will also affect other alien fish species, further reducing their populations. In the case of *P. clarkii*, due to its long invasion history and threat to European freshwater environments, several potential control techniques have been assessed in the past (Gherardi et al. 2011; Lodge et al. 2012; Souty-Grosset et al. 2016) and could be considered. Especially approaches like the introduction of biological control agents (Aquiloni et al. 2010) or increased electrofishing and funnel trapping after having trimmed back the abundant hydrophyte zone, should be explored.

Conclusion

It is likely that dense populations of *L. gibbosus* and *P. clarkii* are nurturing the population of *M. salmoides* and as the abundance of crayfish adds to the diet of *L. gibbosus*, enables both species of predatory fish to recover and generate high abundances and biomasses as observed in 2017. The very low diet overlap combined with the observed diet make it likely that the three present North American species are forming a highly linked trophic web with low competition, leaving the bottom feeding carp, the only species that can be considered as almost eradicated, outside. Nonetheless, with no individuals of *T. tinca* caught in 2017, it can be assumed that a population recovery of this species was not achieved, while the invasive species have been successfully reduced.

Positive effects of removal of non-indigenous invasive species such as lower population densities of invasive species can be enhanced in a near future by additional fishing effort (mainly by electrofishing). These works should be undertaken before the onset of the reproductive season to avoid or reduce density-dependent effects. This combination of electrical techniques and trapping of crayfish is postulated as an optimal strategy for the control and/or eradication of highly abundant invasive fish populations, as a key contribution to the recovery of the lake's ecological status, but additional methods such as the introduction of a biological control agent (e.g. the European eel, *Anguilla anguilla*; see Aquiloni et al. 2010) and the cutting back of zones that serve as a refuge for targeted species (e.g. the hydrophyte zone) should also be considered. Lastly, the interactions among species with a common origin, as in the case of Lake Arreo *L. gibbosus*, *M. salmoides* and *P. clarkii,* need to be investigated more thoroughly and especially a highly prolific invader such a *P. clarkii* needs to be controlled among invasive fish.

Acknowledgements

Our thanks go to Gonzalo Alonso, José Manuel Gómez, Ana Aja, and especially to David Corta and Ana Gracia for field work and support. We would also like to acknowledge the effort and useful comments provided by the two anonymous reviewer and Dr. Matthew Barnes. Financial support was provided by the LIFE+ TREMEDAL Project (Inland wetlands of Northern Iberian Peninsula: Management and restoration of mires and wet environments. LIFE11 NAT/ES/000707, European Union) and more recently by the County Council of Araba (Technical Assistance for the Restoration of the Aquatic Ecosystem in the Lake Caicedo Yuso ZEC ES2110007 during Post LIFE TREMEDAL project). Thanks for promoting and supporting this work to URA (Ur Agentzia, the Basque Water Agency), HAZI (Foundation of the Basque Government for the rural, littoral and food development) and the Natural Heritage of County Council of Araba, particularly to Javier Pérez and Joseba Carreras. Funding was also provided by the Aquainvad-ED project (2020 Marie Sklodowska-Curie ITN-2014-ETN-642197).

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