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# *Fish invading deserts: non-native species in arid Moroccan rivers*

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## ABSTRACT

1. Desert rivers are highly dynamic systems in which dry periods, frequently involving the cessation of superficial flow, alternate with violent flash floods. In spite of their territorial importance and high functional and biological diversity, desert rivers have received little attention in the scientific literature, especially in Northern Africa.

2. This study investigated the distribution of non-native fish, their relationship with river damming and their potential impacts on native biodiversity in the main river basins draining arid areas of Morocco (Oued Draa, Oued Ziz and Oued Ghir), based on field sampling covering 84 stream reaches.

3. Thirteen fish species were recorded, eight of which are non-native. Two species (stone moroko, *Pseudorasbora parva*, and bleak, *Alburnus alburnus*) had not been previously recorded in Morocco, while the native sandsmelt (*Atherina boyeri*) had not been cited as an invader. Pumpkinseed (*Lepomis gibbosus*) was the most widely distributed non-native fish.

4. Non-native fish species were associated with reservoirs, colonizing the regulated downstream reaches. In contrast, unregulated upstream reaches tended to be free of non-natives. The low abundance of native fish in reservoirs seems to be caused by the impacts of introduced fish species.

5. Management options for environmental flow are limited, owing to reduced water availability. Non-native fish management should thus focus on limiting the spread of species already introduced and avoiding new introductions, especially into reservoirs.


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KEY WORDS: river; stream; biodiversity; disturbance; distribution; fish; alien species; impoundment

## INTRODUCTION

Arid and semiarid lands, where mean annual potential evapotranspiration is at least twice as high as annual mean precipitation, occupy more than 30% of the world's land surface (Safriel and Adeel, 2005). Some of the most important rivers

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of the world as well as several minor river systems drain, either totally or in part, arid and semiarid areas (Kingsford and Thompson, 2006). These rivers (henceforth 'desert rivers') share the common features of water scarcity with variable duration, often with cessation of superficial water flow, and showing high temporal habitat variability (Stanley *et al.*, 1997). Desert river systems have more diverse hydrological and physicochemical features than those in more mesic areas (Kingsford and Thompson, 2006; Harms *et al.*, 2008).

Fish species in desert rivers are adapted to live in highly fluctuating ecosystems (Stanley *et al.*, 1997; Bunn *et al.*, 2006). Since most of these species lack drought-resistance adaptations, their populations persist during dry periods in permanent pools that act as refugia. Conditions in these pools can be extreme, including hyperthermia, hypoxia and increased biotic interactions (Sternberg *et al.*, 2012). There are also flash floods, which are proportionately more intense and more unpredictable in desert rivers compared with other rivers (Harms *et al.*, 2008). These characteristics usually preclude the establishment of commonly introduced non-native fish species, which have frequently evolved in more stable environmental conditions (Moyle and Light, 1996). However, the alteration of flow regimes resulting from human water uses, especially through river damming, can buffer the temporal variability of desert rivers (Kingsford, 2000) and thus facilitate the establishment and spread of non-native fish (Eby *et al.*, 2003; Pool and Olden, 2014). Once established, non-native fish have driven declines of native species in different arid and semiarid areas of the world (Propst *et al.*, 2008; Clarkson *et al.*, 2012).

Despite being a prominent component of the world's river systems and exhibiting a high diversity in their characteristics, desert rivers have been much less studied than rivers in wetter regions, with most of the existing knowledge derived from studies either in south-western USA or in Australia (Harms *et al.*, 2008). There is a scarcity of information on freshwater fish from Northern Africa, a region that encompasses important desert river systems (Smith and Darwall, 2006; Ribeiro and Leunda, 2012). Rivers in the arid areas of Morocco, Algeria and Tunisia are biogeographically interesting, since they host Mediterranean and Afrotropical affinities (Lévêque, 1990; Smith and Darwall, 2006; Qninba and Mataame, 2009). The latter are relict elements from wet times, when the current hyper-arid Sahara desert was a corridor for several freshwater species (Drake *et al.*, 2011). The scarcity of information on the status of biodiversity in desert rivers is especially worrying in the light of the fragility of these systems. Pressure on water resources is severe in arid regions, where the subsistence of human societies relies on the use of a scarce and often unpredictable water supply (Kingsford, 2000). Northern African desert rivers are changing rapidly, including an increasing number of dams and the intensification of agricultural practices (García *et al.*, 2010).

This study concerned the status of non-native fish species in rivers and reservoirs of arid and semiarid regions of Morocco south of the High Atlas Mountains, based on extensive field sampling. The relationships between the patterns in the distribution of non-native fish and the presence of reservoirs were investigated in order to determine whether these structures facilitate the spread of non-native species. It is predicted that native species should be more prevalent in highly variable natural streams compared with reservoirs and regulated reaches with their relatively stable water levels. This work also considered the possible current and future impacts of non-native fish on Northern African desert rivers and the options for their mitigation.

## STUDY AREA

The study was conducted in the Draa, Ziz and Ghir basins, the main river systems that drain the southern slopes of the High Atlas (a mountain range, >4000 m asl), east of Jbel Siroua. Annual precipitation, often falling as snow during winter, is relatively high (about 500-600 mm) at high altitudes although eastern sectors are drier than western ones (Figure 1). As elevation diminishes, rivers flow through progressively more arid lands (≤150 mm) eventually infiltrating into the desert. The Oued (river) Draa is the longest river in

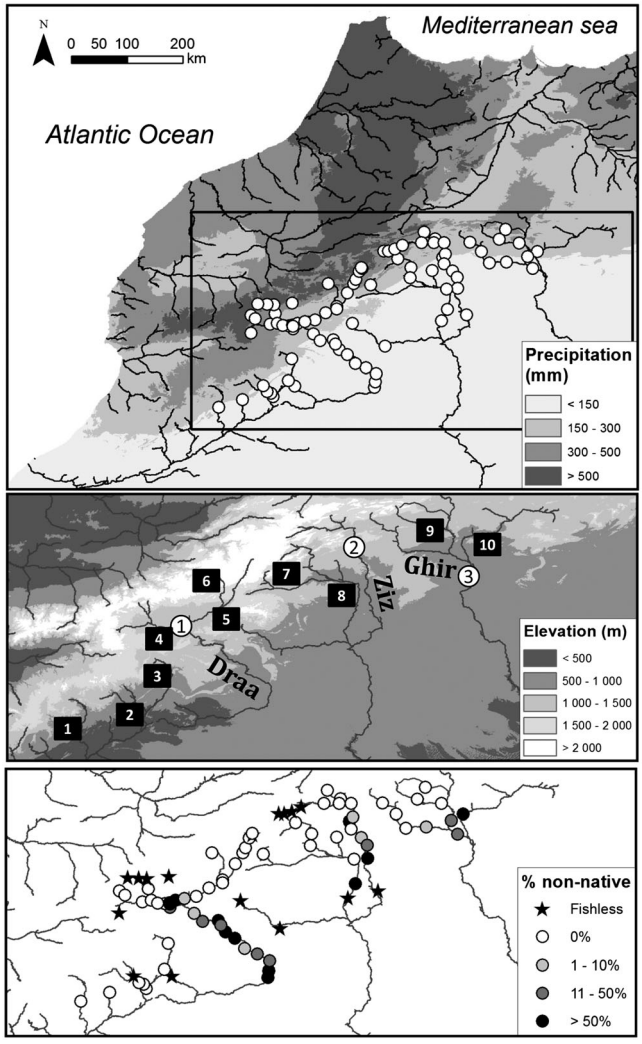


Figure 1. Study area with relevant features, study sites and percentage of non-native fish individuals among fish catches. Upper panel: location of the three basins studied in northern Africa showing the 84 study sites (empty dots). Background tones represent mean annual precipitation. The rectangle indicates the location in subsequent panels. Middle panel: location of large reservoirs (circles) and main tributaries (rectangles) within the study area. Reservoirs: 1- El Mansour Eddahbi; 2- Hassan Addakhil; 3- Djorf Torba. Tributaries: 1- Oued Tata; 2- Oued Tissint; 3- Oued Zguid; 4- Oued Ouarzazate; 5- Oued Dades; 6- Assif M'Goun; 7- Oued Todgha; 8- Oued Rheris; 9- Oued Bouanane; 10- Oued Zelmou. Background tones represent elevation, with higher areas shown by lighter tones. Lower panel: percentage of non-native fish individuals among all fish captured at each site. Sites with no fish indicated with a filled star.

Morocco (~1100 km). It has its own estuary in the Atlantic Ocean (28.68 N, 11.12 W), but superficial flow usually stops about 600 km upstream from the sea. With the name of Oued Dades (in Morocco rivers do not necessarily maintain the same name from source to mouth), it flows for almost 200 km from the High Atlas south-westward. Then, already named Oued Draa, the river turns to flow south-eastward to cross the Jbel Saghro, the most important massif of the Anti-Atlas mountain range. In the region known as Coude du Draa (Draa's Elbow), the course of the river turns again to flow west to the sea, but in this stretch superficial flow usually stops. The middle reaches of the Oued Draa only connect with its estuary during extreme rain episodes (Dłużewski and Krzemień, 2008). The Ziz and Ghir basins, the other two rivers (Figure 1), flow from the High Atlas southwards, directly to the Sahara Desert. Although now completely independent river basins, about 10000 years ago they formed part of one of the ancient lake systems that connected most perisaharian rivers, including the Niger River (Drake *et al.*, 2011). The Oued Ziz and its main tributary Oued Rheris, usually flow independently into the desert, but can connect near the Moroccan–Algerian border (30.64 N, 4.43 W) during high flow episodes. The Oued Ghir enters Algeria shortly after or while joining its main tributaries (Oued Bouanane and Oued Zelmou, Figure 1) and flows for around 250 km before disappearing under the Great Western Erg (*Grand Erg Occidental*, around 29.45 N, 1.45 W).

Agricultural lands are restricted to river banks and are irrigated by complex webs of channels (*seguias*) and occasionally also wells, usually mixing woody (almonds and nuts in high altitudes, date palms in lower lands) and herbaceous crops. Water salinity steadily increases downstream in the three basins, reaching on average 3000 $\mu S\ cm^{-1}$, a threshold implying severe limitations for several crops, at around 800 m asl. There are three large dams in the three basins. The El Mansour Eddahbi dam was built in 1972 on the Oued Draa, with a maximum storage capacity of 529 x $10^6\ m^3$, more than half the average total annual flow of the river (Dłużewski and Krzemień, 2008). The Hassan Addakhil dam was built in 1971 on the main course of the Oued Ziz, with a total capacity of 347 $10^6\ m^3$. The Djorf Torba dam in Algeria was built in 1969 on the main course of the Oued Ghir, with a storage capacity of 299 $10^6\ m^3$. There are also several minor dams (Dłużewski and Krzemień, 2008) and numerous small barriers across

waterways that temporally retain or divert water. A new large dam on the Oued Iriri, a tributary of the Oued Draa near El Mansour Eddaahbi dam, was completed in August 2013, with a capacity of 270 $10^6$ $m^3$. All reservoirs are vulnerable to siltation problems (Lahlou, 1996), with estimates that the El Mansour Eddahbi and Hassa Addakhil reservoirs will be inoperative by about 2030 (Messouli *et al.*, 2008; Busche, 2013).

## DATA COLLECTION AND ANALYSIS

Fish were sampled in March and April 2013 at 84 sites (spring survey), 39 of which were re-sampled in September and October 2013 (autumn survey) (Figure 1). Water conductivity was measured at each site and survey, with a HI 9828 multi-parameter instrument (Hanna Instruments, Italy). At most sites (N = 64) a portable electrofishing device was used (model ELT60 II HI, Hans Grassl GmbH, Schönau am Königssee, Germany). About 100 m of stream (mean 105.6 m; range 35-400 m) was sampled, using a single pass without blocking and a direct pulse current (50-75 pulses $s^{-1}$). Captured fish were kept in a mesh cage within the river, to avoid hypoxia. Whenever electrofishing could not be performed (e.g. in reservoirs or when water conductivity was higher than 6000 μS $cm^{-1}$) fyke, seine or dip nets were used. Fyke nets had two different mesh sizes (3.5 and 7 mm) and were usually set for 24 hours. The seine nets were 5 m in length and 1.5 m in height, with a mesh size of 4 mm.

Captured fish were identified to species, except for native *Luciobarbus*, which were identified only to genus, since taxonomy of Northern African barbels is currently unresolved (Crivelli, 2006). Arguably, barbels found in the Draa basin are *L. lepineyi*, while those in the Ziz and Ghir basins are *L. pallaryi* (J. Freyhof, pers. comm.), but their identity needs confirmation with molecular analyses (e.g. COI gene). Some of the basins may be inhabited by more than one barbel species. Total length was measured to the nearest mm before release, except for a small sample of fish taken for the collection of the Natural History Museum of the Institute Scientifique (Rabat, Morocco). The presence of external parasites or visible infections in captured fish was also noted.

Non-native status of fish species was defined according to the role of humans in the presence of a species in the study area (e.g. transport). Any species occurring in the area due to the direct introduction by humans was considered non-native, even if it is native to other areas of northern Africa. The percentage of non-native fish individuals at each site indicated the level of alteration of fish communities. At sites sampled twice (spring and autumn) these percentages were based on pooled data. The distance of each site along the river to the main reservoir, within each of the three basins, was measured using Google Earth – distance to the dam wall for downstream sites or to the maximum water level in reservoirs (estimated from changes in the vegetation) for upstream sites. Positive values were assigned to upstream distances and negative values to downstream ones. The relationship between this distance gradient and the presence of non-native fish species (presence/absence) was analysed using a generalized linear model with a binomial error distribution and a logit link function, while a simple linear regression was used for the relationship with the percentage of non-native fish individuals. Effect size for the generalized linear model was calculated as the percentage of deviance reduction between the null model (including only the intercept) and the model including distance to reservoir as the explanatory variable. Unregulated tributaries, without reservoirs and joining regulated main rivers downstream from reservoirs (e.g. the Oued Rheris and right margin tributaries of the middle Oued Draa), as well as sites where no fish were captured were excluded from the model.

## RESULTS AND DISCUSSION

### Native fish fauna

Fish were captured in 68 of the 84 sites visited in the spring survey and in 38 of the 39 sites visited in the autumn survey. In total, 23 401 individual fish were caught (10 937 in spring and 12 464 in autumn), comprising 13 species, five of which (assuming two barbel species) were native to the area (Table 1). Barbels were the most abundant and widely distributed fish in the rivers studied, present in 66 of the 68 sites in which fish were detected and

Table 1. Fish species recorded at 84 sites in Moroccan desert rivers, separated into native and non-native. For each species the number of sites (N sites, from a total of 84 sampled sites, 68 of which had fish) and the basins where it was present are reported. D- Draa basin; Z- Ziz basin; G- Ghir basin

| Family | Species | Common name | N sites | Basins |
|---|---|---|---|---|
| **Native species** | | | | |
| Cichlidae | *Coptodon zillii* | Redbelly tilapia | 3 | D |
| | *Oreochromis aureus* | Blue tilapia | 9 | D |
| Cyprinidae | *Luciobarbus* spp | Barbels | 66 | D, Z, G |
| Salmonidae | *Salmo trutta* | Brown trout | 3 | D, Z |
| **Non-native species** | | | | |
| Atherinidae | *Atherina boyeri* | Sandsmelt | 8 | D |
| Centrarchidae | *Lepomis gibbosus* | Pumpkinseed | 22 | D, Z, G |
| | *Micropterus salmoides* | Largemouth bass | 1 | D (Z*) |
| Cyprinidae | *Cyprinus carpio* | Common carp | 6 | D |
| | *Carassius auratus* | Goldfish | 2 | G |
| | *Pseudorasbora parva* | Stone moroko | 3 | G |
| | *Alburnus alburnus* | Bleak | 2 | G |
| Poecilidae | *Gambusia holbrooki* | Mosquitofish | 4 | D, G |

*Largemouth bass (*Micropterus salmoides*) was not captured in the Ziz basin, but it was reported there by local informants.

clearly dominating fish communities in unregulated reaches, often the only taxon present.

Relict cichlid populations (of blue tilapia, *Oreochromis aureus*, and redbelly tilapia, *Coptodon zillii*) were exclusively recorded in the Draa basin. They occurred with barbel in the Oued Tissint, a saline tributary of the Oued Draa. Blue tilapia was also present in the Oued Draa, up to 800 m asl, possibly limited by cold winter temperatures recorded at higher altitudes. The present occurrence of redbelly tilapia or African jewelfish (*Hemichromis bimaculatus*) in the Ziz and Ghir basins (cited by Qninba and Mataame, 2009) could not be confirmed.

Brown trout (*Salmo trutta*) was recorded in three sites over 1800 m asl, two belonging to the Draa basin (upper oueds M'Goun and Dades) and one in the Oued Sidi Hamza, a tributary of the Oued Ziz. Trout populations from the Draa basin belong to a distinct, ancestral trout lineage (Dades lineage) isolated before the split of the two main groups of lineages (i.e. at least 1.2 million years ago) (Snoj *et al*., 2011). These trout populations are highly vulnerable, owing to their extreme southern location within the trout distribution range and especially sensitive to global warming.

Two other native freshwater fish species occur in the basins studied, but were not taken in field samples. European eel (*Anguilla anguilla*) occur in the Oued Tissint (in the Draa basin), its southernmost distribution limit, although in small and declining numbers (Qninba *et al*., 2011). The Sahara aphanius (*Aphanius saourensis*), is an endemic and critically endangered cyprinodontid (Azeroual, 2010), occurring in a single stream in the Ghir basin in Algeria (Blanco *et al*., 2006), about 200 km south of the study area. It was once more widely distributed, potentially into the Moroccan part of the Oued Ghir, but its range has contracted substantially, partly due to non-native species (Blanco *et al*., 2006).

## Non-native species and their distribution

Eight non-native species were recorded in the study area (Table 1; Figure S1). The Draa and the Ghir basins had five non-native fish species, while only two were found in the Ziz basin. Most fish introductions in Morocco have occurred in the north (Mouslih, 1987), but results show that the desert rivers studied also have several non-native species. Azeroual (2003) cited the presence of two additional non-native fish species in the area, rudd (*Scardinius erythrophthalmus*) and grass crap (*Ctenopharyngodon idella*), but none was captured during the field sampling.

Two non-native species were recorded for the first time in Morocco: stone moroko (*Pseudorasbora parva*) and bleak (*Alburnus alburnus*) (Mouslih, 1987; Azeroual *et al*., 2000; Azeroual, 2003). They occurred only in the Ghir basin (Table 1), with goldfish (*Carassius auratus*). Goldfish were recorded in the 1950s, from the estuary of the Oued Ksob (Furnestin *et al*., 1958), and in the Oued Sebou in the early 1990s (Doadrio, 1994). Generally, the

species is not included in the lists of non-native fish in Morocco (Azeroual *et al.*, 2000). Before the present study, there was scarce information about fish in the Ghir basin, which was not even represented in the reviews of Moroccan freshwater biodiversity (Azeroual *et al.*, 2000; Dakki *et al.*, 2009). These three non-native species had been recorded from Algeria (Kara, 2012), and so probably colonized Moroccan waters spreading from the neighbouring country, possibly from Djorf Torba reservoir. Supporting this, bleak and goldfish occurred at the two sites closest to the Djorf Torba reservoir. Stone moroko have probably spread quickly through the Ghir basin (Figure 2). This species is a highly invasive Asian cyprinid now occupying most of Europe in less than 50 years, after its introduction to Romania in the 1960s (Gozlan *et al.*, 2010). The species has been present in Northern Africa since the 1970s, but previously known localities are far from the populations in the Ghir basin, with the closest located 750 km to the north east, near Algiers (Gozlan *et al.*, 2010). The range of stone moroko in Algeria is probably considerably larger than currently reported in the scientific literature.

Sandsmelt (*Atherina boyeri*) is a native species in Morocco, inhabiting wetlands and the lower reaches of rivers (Azeroual, 2003; Francisco *et al.*, 2008), but is non-native to the study area (Table 1), Sandsmelt is unlikely to have naturally colonized the study area, since it was mainly recorded in relatively high altitude reaches (>1100 m asl) and about 850 km of mostly dry river bed far from the sea sources. The species occurred in high numbers in El Mansour Eddahbi reservoir, where it formed large schools. It was also recorded in two watercourses just upstream of the reservoir, and occasionally along the Oued Draa, below the dam (Figure 2). However, sandsmelt were rare and always scarce outside the reservoir. Inland, landlocked sandsmelt populations, from intentional or accidental releases, occur in endorheic lagoons (Fernández-Delgado and Hernando, 1982) and reservoirs (Pérez-Bote, 2002) in Spain and several reservoirs and lakes in Turkey

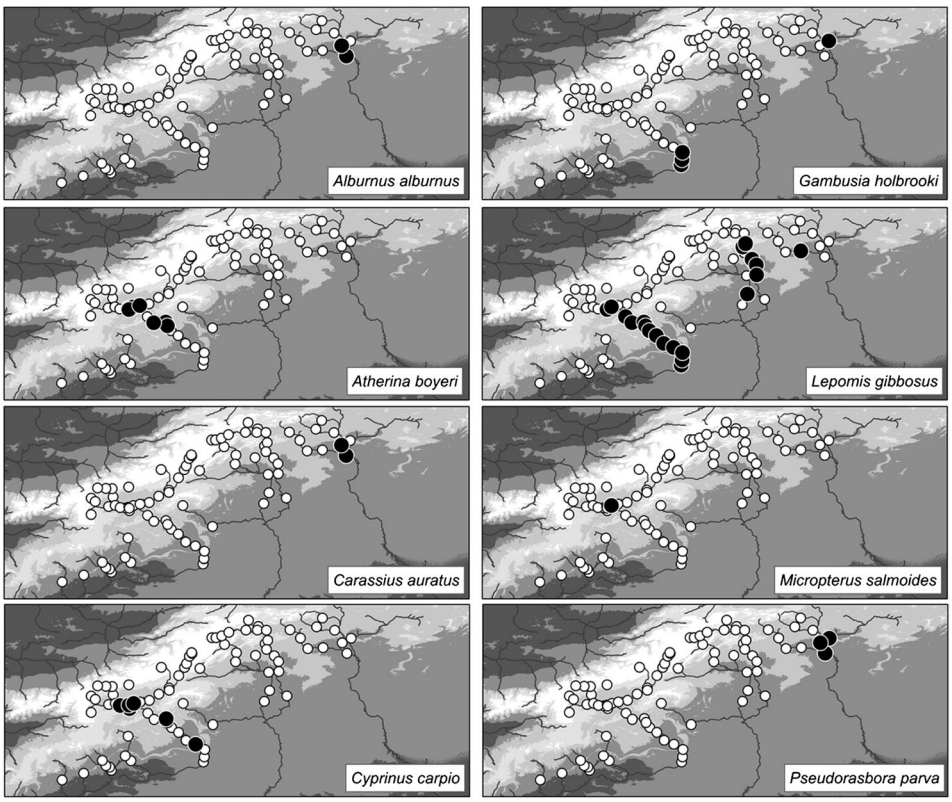


Figure 2. Distribution of eight non-native fish species (filled dots) in the three river basins, showing elevation (for legend, see Figure 1, middle panel).

(Innal and Erk'akan, 2006). However, sandsmelt had not been cited previously as a non-native species within Morocco.

The distribution of common carp (*Cyprinus carpio*) followed a similar pattern to sandsmelt, although the species was rare, with only 12 individuals caught. All captured carps belonged to the mirror-like pool of artificially selected varieties (see Figure S1). Carp was introduced to Morocco in the mid-1920s and is at present common in many water bodies, from the sea level to high altitude lakes (Mouslih, 1987).

Pumpkinseed (*Lepomis gibbosus*) was the most widespread non-native fish in the area, found in all three surveyed basins (Figure 2). It was introduced to Morocco in the 1950s from North America (Mouslih, 1987), but the species had been present in Algeria since 1910, when it was introduced from France (Kara, 2012). In the study area, the species was abundant in reservoirs and close to reservoirs in upstream river stretches. Pumpkinseed also occurred at almost all river sites, often in high numbers, where flows were regulated by an upstream dam. This highly adaptable species may exploit anthropogenically altered aquatic systems (Fox *et al*., 2007). In the regulated parts of the Oued Draa and Oued Ziz, dams reduce environmental variability and act as a source of colonizing individuals. However, there was one site in the unregulated Oued Rheris with a pumpkinseed population that probably originated from a direct introduction (Figure 2). This site is separated by about 200 km of mostly dry river bed and highly saline stretches from the nearest pumpkinseed populations in the Oued Ziz. Pumpkinseed occurred in sites with high water conductivity, up to 22 900 μS $cm^{-1}$ (~13 ppt salinity), within the tolerance range reported for the species in estuarine habitats (≤17 ppt, Moyle, 2002). The species was particularly abundant in the Oued Rheris site (average of 53 fish per fyke net per day), where conductivity was higher than 10 000 μS $cm^{-1}$. Pumpkinseed may have arrived recently in the Ghir basin, because it was detected in only one site during the autumn survey and the population was almost completely dominated by young-of-the-year fish (average total length = 39.6 mm; range 30-71 mm; N = 42).

Mosquitofish (*Gambusia holbrooki*) were found mainly in the Oued Draa around the Coude du Draa, where surface water usually disappears and conductivity is high (>10000 μS $cm^{-1}$), reflecting the high tolerance of the species (Ruiz-Navarro *et al*., 2013). Mosquitofish was especially abundant in the lowest sampled site along the Oued Draa. The species was not recorded in the right margin tributaries of the middle Draa (Oued Tissint and Oued Tata), although Azeroual (2003) reported its presence in the Oued Tata, where only barbels were found. Mosquitofish was present in the Oued Zelmou, within the Ghir basin, with an abundant stone moroko population. Mosquitofish was introduced to Morocco in the late 1920s (Mouslih, 1987), arriving soon after in Algeria (Kara, 2012). Breeding facilities for the species for malaria control were established in 1928 in Rabat and Casablanca, followed by breeding centres across the country for widespread introduction (WHO, 2007). Mosquitofish stocking is still recommended in Morocco for malaria prevention (WHO, 2007).

Largemouth bass (*Micropterus salmoides*) was only recorded in one of the three sites surveyed in the El Mansour Eddahbi reservoir. However, information provided by local fishermen indicated that the species is also present also in Hassan Addakhil reservoir.

### Reservoirs and non-native species

Reservoirs are critically important for non-native fish in Moroccan desert rivers. Presence of non-native species had a clear sigmoidal response to the gradient of distance to the reservoir (Wald statistic = 12.6; N = 54; $P < 0.001$; 47.2% variation explained), while the percentage of non-native individuals steadily increased along this gradient [F = 40.7; N = 50 (i.e. excluding reservoir sites); $P < 0.001$; $R^2 = 0.46$] (Figure 3). Upstream sites had only non-native species when near reservoirs but downstream sites were dominated by non-native species independently of distance to the reservoirs. Only one out of 15 sites below dams had no non-native fish species: this was a site in the Oued Ziz strongly affected by organic pollution (effluents from the sewage treatment plant in the

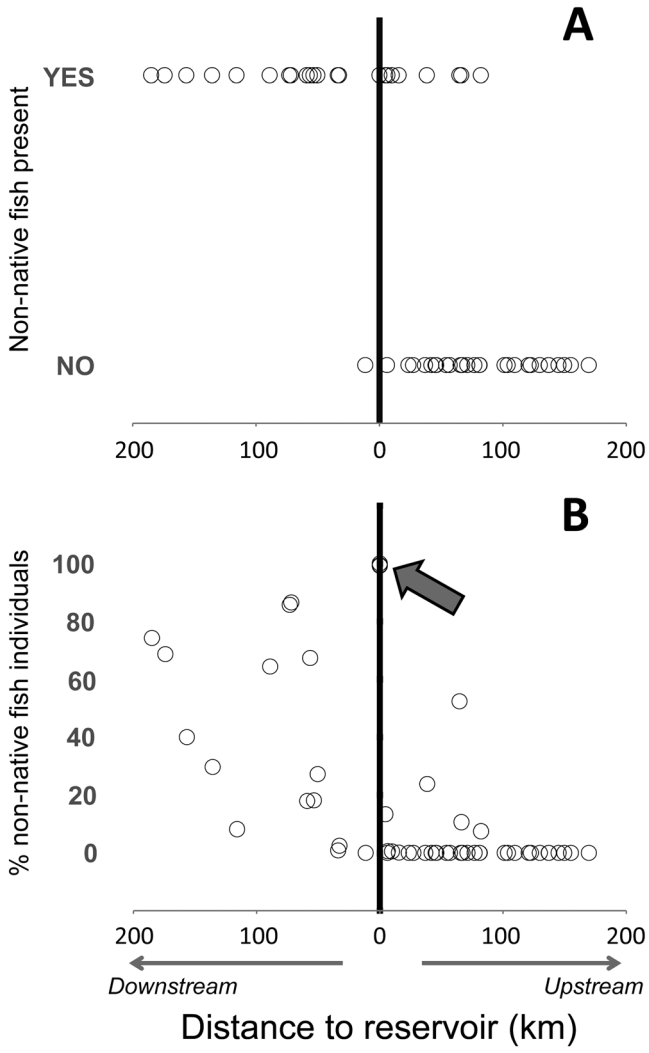


Figure 3. Relationships of non-native fish species with a gradient of distance to reservoirs, showing negative distance values for downstream stretches and positive values for upstream sites. A) Position of sites with and without non-native fish species along the gradient. B) Variation in the percentage of non-native fish individuals along the gradient. The grey arrow marks the four reservoir sites included in the study.

city of Errachidia) that was almost fishless (only one barbel captured).

Reservoirs favour invasion by being preferred sites for official and uncontrolled introductions (Johnson *et al.*, 2008; Clavero and Hermoso, 2011). Reservoirs hold sport fishing activities, encouraging stocking of game and forage fish. Moreover, environmental conditions of reservoirs are more stable than in neighbouring river systems, especially in arid and semiarid regions (Godinho *et al.*, 1998; Clavero *et al.*, 2013). Non-native fish species are generally not adapted to the high variability of desert rivers, but can establish self-sustaining populations in reservoirs (Pool and Olden, 2014). The four reservoir sites were dominated by non-native fish species (Figure 4). Similarly, most introduced fish species were in reservoirs in arid areas of eastern Algeria (Chaibi *et al.*, 2012). Results showed that reservoirs were also effective sources for colonization of the regulated downstream reaches by non-native species (Figure 3). Reductions in flow variability caused by dams, including fewer flash-flood episodes, favour the establishment of non-native species, mostly absent from unregulated rivers (Eby *et al.*, 2003; Clavero *et al.*, 2004). This was reflected by the relatively poor colonization of upstream unregulated river sectors by non-native fish species in this study, probably because of the effects of floods (Meffe, 1984; Pool and Olden, 2014). Fish introduced to the Ghir basin colonized further upstream (up to 66 km) than in the Draa or Ziz basins. This is probably related to the shallower gradient of the Oued Ghir and its main tributaries, but also to the different pool of species present. Stone moroko or bleak may colonize running water systems more effectively than largemouth bass or common carp. Also, non-native species could be favoured by the existence of relatively small dams, with a capacity up to 2 x $10^6$ $m^3$ (Anonymous, 2013), which were probably artificially stocked, since local informants repeatedly explained that those small reservoirs contained 'large fish'.

## Potential impacts

The impacts of non-native species are often difficult to identify owing to the co-occurrence of several drivers of biodiversity loss (Didham *et al.*, 2005). In the study area impacts of non-native species were confounded in time and space by altered flow regimes and more intensive agricultural practices. The presence of non-native fish was also much more common in lower reaches, and thus their effects could also be confounded by the natural longitudinal gradient. Furthermore, there is no information on the composition and structure of freshwater fish communities before dam construction or when non-native fish arrived, rendering evaluation

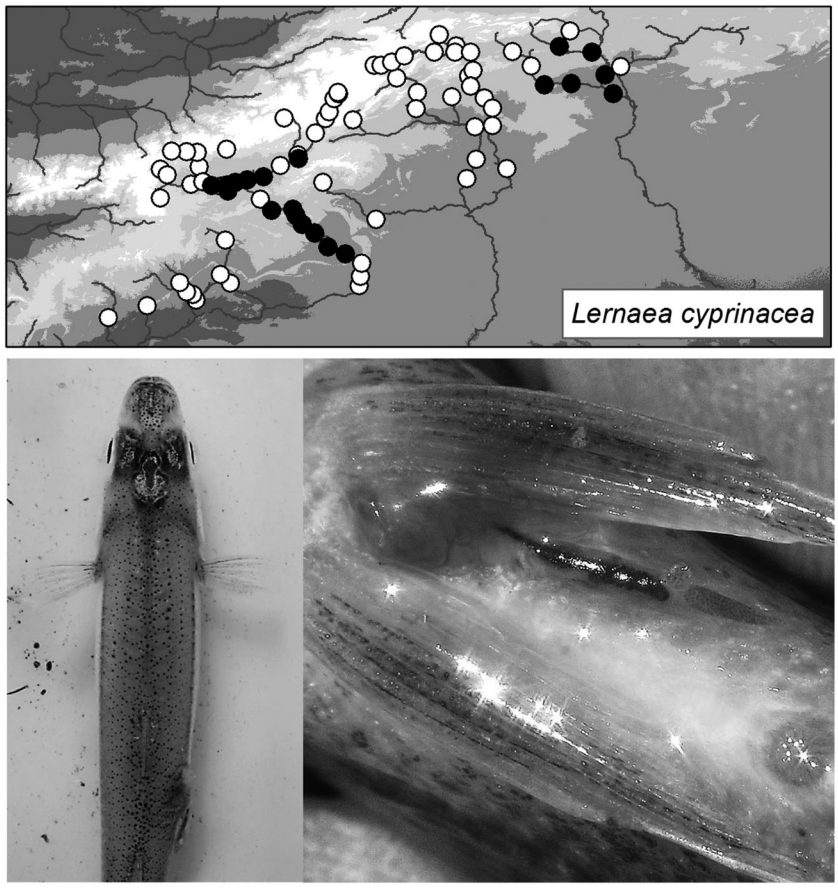


Figure 4. Upper panel: distribution of *Lernaea cyprinacea* in the study area. Background tones represent elevation, with higher areas shown by lighter tones (see Figure 1). Photographs: *Lernaea cyprinacea* anchored on a sandsmelt (left) and between the pelvic fins of a pumpkinseed (right).

of non-native fish impacts particularly difficult (Ribeiro and Leunda, 2012).

There were indications that non-native fish had an adverse effect on Moroccan desert river fish. There were few native species and in small numbers in reservoirs. Four reservoir sites were sampled (three in El Mansour Eddahbi and one in Hassan Addakhil) to capture 990 fish, including only five native fish (barbels; Figure 3). Barbels thus constituted 0.5% of the catch in reservoirs, while they were 91.6% of the catch in river stretches. Most Mediterranean barbels in the genus *Luciobarbus*, particularly those inhabiting desert rivers, are habitat generalists. They occupy environments that can change from a small, hot and crowded pool to a river with very high flow several times within a year. There should be no impediments for barbels to occupy reservoirs but they are rare in them, probably excluded by largemouth bass predation as recorded elsewhere (Clavero *et al.*, 2013). The depletion of native prey populations by introduced piscivorous fish often favours new introduced species (Noble, 1981), probably explaining the stocking of sandsmelt in the El Mansour Eddahbi reservoir. Mosquitofish is one of the main threats to the Sahara aphanius in the Algerian part of the Ghir basin (Azeroual, 2010). The probable direct impact of non-native fish on native species, particularly of mosquitofish, pumpkinseed and stone moroko on barbels and cichlids, remains to be analysed. In the absence of pre-invasion or environmentally similar reference conditions, the study of these interactions will require specifically designed experimental approaches.

Non-native fish can also introduce fish parasites and other diseases (Gozlan *et al.*, 2005; Peeler *et al.*, 2011). Fish infected with the anchor worm *Lernaea cyprinacea*, a parasitic copepod, were

found at 21 sites in the Draa and Ghir basins, the first report of the species for Morocco. This included 152 parasitized fish, mostly barbels (73.7%), pumpkinseeds (21.7%) and sandsmelts (4.6%). The distribution of anchor worms was significantly associated with the presence of non-native fish species ($2 \times 2$ table $\chi^2 = 16.89$; d.f. = 1; $P < 0.001$; N = 68, i.e. excluding fishless sites). *Lernaea cyprinacea* was present in all reservoir sites, common in downstream sites and rare in upstream ones (Figure 4). Its introduction may have been associated with the introduction of non-native fish. It is the most widely distributed of more than 100 anchor worm species, with an almost cosmopolitan range explained largely by human-aided colonization linked to fish introductions (Lester and Hayward, 2006). The species had been recorded previously in Egypt (Mahmoud *et al.*, 2009) and in central and southern African countries (Avenant-Oldewage, 2012), usually associated with non-native fish stocking.

The spread of stone moroko may be linked with the arrival of the rosette agent (*Sphaerothecun destruens*), an intracellular parasite that causes high mortality in salmonids and cyprinids (Andreou *et al.*, 2012), and has led to declines of native fish elsewhere (Gozlan *et al.*, 2005).

## Management implications

Most non-native fish were associated with reservoirs and modified flow regimes. The management of flow regimes to mimic natural frequency and magnitude of floods could be a powerful tool for controlling non-native species populations in river reaches below dams (Freeman, 2002). This is unrealistic in arid Morocco, since water is a limiting resource for human populations and reservoir releases are strictly controlled (Messouli *et al.*, 2008). There is only one other option – the avoidance of new introductions. Official stocking would need to cease, as well as reduction of uncontrolled introductions through policy and education strategies. It is especially important to avoid introducing new non-native species or any non-native species into the large reservoir recently built on the Oued Iriri (Draa basin) (Figure 1).

Where stocking occurs, rigorous audits of fish stocking activities should be carried out to stop the spread of non-native species (Davies *et al.*, 2013). This may avoid the introduction of species already present in the country to Moroccan desert rivers (Mouslih, 1987), including species causing serious economic impacts, such as the Asian clam (*Corbicula fluminea*) (Clavero *et al.*, 2012). Stone moroko should be the target of these audits (Davies *et al.*, 2013), to prevent the spread of this invasive, high-impact species (Gozlan *et al.*, 2010) throughout unoccupied desert basins and other river systems in Morocco.

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