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Moroccan desert rivers: fish on the arid extreme of Mediterranean streams

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SUMMARY

Northern Africa presents a continuous aridity gradient related to geographic position and elevation that marks a change in river dynamics, from typical Mediterranean regimes to ephemeral desert water courses, in which prolonged dry periods without superficial flow alternate with violent flash floods. The region is also a spatially and temporally dynamic border area, occupied by a biota of mixed Palearctic and Afrotropical affinities. Here we describe the fish fauna of the main desert river basins in Morocco, highlighting its conservation status and suggesting possible research lines to be developed in the area. We focus in the basins of Oueds (= rivers) Draa, Ziz and Ghir, which drain the southern slopes of the High Atlas mountain chain, and use both our own field data from extensive surveys and already published information.

The studied basins contain nine native species, including cold-water species (two trout species), taxa with Mediterranean affinities (*Luciobarbus*, *Aphanius*) and three Afrotropical relict cichlids. Two species, the Dades trout (*Salmo multipunctata*) and the Sahara aphanius (*Aphanius saourensis*) are in critical need of conservation efforts. Eleven non-native species have been recorded in the area, of which eight are apparently established. Non-native species are closely linked to reservoirs from where they seem to have excluded native species. Flow regulation facilitates the colonization of downstream reaches by non-natives, while unregulated river reaches are dominated by native species. Authorities should work towards avoiding new introductions and the spread of already established non-native species.

Preserving, and ideally recovering the bio-geographic mosaic of Northern African river basins should be an international conservation target.

Keywords: Desert rivers, Sahara Desert, Atlas Mountains, Fish conservation, Invasive species, Reservoirs

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ملخص

تتميز شمال إفريقيا بتدرج مستمر في الجفاف المرتبط بالموقع الجغرافي و بالارتفاع الذي يغير أداء الأنهار من أنظمة متوسطية تقليدية إلى أودية صحراوية غير منتظمة سريعة الزوال. إذ تتناوب فيها فترات جفاف طويلة بدون تدفق سطحي مع فيضانات عنيفة. فالمنطقة هي أيضا، جغرافيا و زمانيا، منطقة حدودية ديناميكية تستوطنها كائنات حية مختلطة تنتمي في أصلها إلى مناطق مختلفة بيوغرافيا.

هنا، نقوم بجرد أنواع الأسماك التي تتواجد في أحواض الأنهار الصحراوية الرئيسيّة في المغرب و نبرز حالة محافظتها و اقتراح خطوط البحث التي يمكن تطويرها في المنطقة. سنركز على أحواض وادي درعة، و وادي زيز، و وادي غير، و التي تجري عبر المنحدرات الجنوبية لسلسلة الأطلس الكبير، و ذلك من خلال الاستعانة ببياناتنا الميدانية الخاصة المستقات من مسوحاتنا الواسعة النطاق و من المعلومات التي سبق نشرها.

تستوطن في الأحواض المدروسة تسعة أنواع من الأسماك المحلية، بما في ذلك نوعان من التروتات التي تعيش في المياه الباردة، و عدة أنواع من فصيلتي لوسيوباربوس و أفانيوس المتوسطية الأصل و ثلاثة أنواع من السيكليد التي تعتبر من مخلفات المناخ الإستوائي الذي كان سائدا في المنطقة. صنفان، تروتة دادس و أفانيوس الصاورا، في حاجة ماسة إلى جهود خاصة للمحافظة عليها من الإنقراض. من جهة أخرى، تم جرد أحد عشر نوعا من الأسماك الغير محلية، ثمانية منها استقرت نهائيا على ما يبدو. هذه الأسماك الدخيلة مرتبطة ارتباطا وثيقا بالخزانات المائية حيث يظهر أنها استأصلت الأنواع المحلية. السيل المنتظم يسهل استيطان الأسماك الدخيلة لسافلة الأنهار، بينما تهيمن الأنواع المحلية في الأودية الغير المنتظمة.

ينبغي على السلطات المعنية أن تعمل على تجنب إدخال أنواع جديدة من الأسماك الغير المحلية و أن تحد من إنتشار تلك التي تم إدخالها. يجب أن تكون صيانة، و إذا أمكن، ترميم الفسيفساء البيوجغرافية للأنهار في شمال إفريقيا، من الأهداف الدولية للمحافظة.

كلمات مفاتيح : أودية الصحراء، جبال الأطلس، المحافظة على الأسماك، الأنواع الغازية، الخزانات.

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ON THE BORDER

The borders of biogeographical regions are rarely sharp in space, while being often also temporally dynamic. The north of Africa constitutes a biogeographical mosaic, due to its bridge position between the Afrotropical and Palearctic realms. The Sahara Desert separates the two realms by setting up a wide and extreme border, but also an extraordinarily dynamic one. The Saharan area has alternated dry and wet periods during the last millennia and these environmental changes have driven biodiversity patterns as well as the landscape occupation by human societies (Drake *et al.*, 2011; Brito *et al.*, 2014).

Streams and rivers in Northern Africa reflect the border character of this territory, both in their functioning and in the biogeographical affinities of their biota. Large parts of Morocco and the coastal fringe of Algeria and Tunisia have a typical Mediterranean climate, which can be humid in the mountain ranges and towards the Atlantic Ocean. However, towards the south and the east the environmental conditions become progressively drier and the characteristic seasonality of Mediterranean-climate precipitations is blurred. This rainfall variability is translated to the flow regimes of river systems, which vary from permanent Mediterranean rivers to ephemeral streams without marked seasonal flow patterns. The complex biogeographical history of Northern Africa has also favoured that its environmental mosaic is inhabited by a biota, including freshwater fish, with a mix of Palearctic and Afrotropical affinities (Lévêque, 1990; Smith and Darwal, 2006; Brito *et al.*, 2014). The latter are relict elements from wetter times, when the current hyper-arid desert acted as a corridor for several freshwater species (Drake *et al.*, 2011).

Despite being a prominent component of the world's river systems, rivers in arid areas have been much less studied than rivers in wetter regions (Harms *et al.*, 2008; Hillyard *et al.*, 2015), a lack of knowledge that has specifically been highlighted for Northern Africa (Smith and Darwal, 2006; Ribeiro and Leunda, 2012). The scarcity of information on the status of biodiversity in the area is critical, since rivers in Northern African are experiencing important recent transformations, including an increasing number of dams and the intensification of agricultural practices (García *et al.*, 2010).

In this work, we describe the freshwater fish fauna inhabiting the main river basins that drain the southern slopes of the High Atlas mountain range, running into the Sahara Desert. We identify the main threats for the conservation of freshwater fish in the area and define the future research pathways to increase our knowledge on, and promote the conservation of, the diverse and fragile biodiversity of the area.

BIOGEOGRAPHICAL CONTEXT

Here, we focus on the fish fauna of the Draa, Ziz and Ghir basins, the main river systems that drain the southern slopes of the High Atlas east of Jbel (= mountain) Siroua (Figure 1a). Annual precipitation, often falling as snow during winter, are relatively high (about 500-600 mm) in this mountain range with elevations over 4000 masl in Jbel M'Goun, although eastern sectors tend to be drier than western ones (Figure 1b). As elevation decreases, rivers enter in progressively more arid lands to ultimately disappear infiltrated in the desert (Schulz and Judex, 2008). Oued (= river) Draa, with around 1100 km, is the longest river in Morocco. It has its own estuary in the Atlantic Ocean (28.68N, 11.12W), but superficial flow usually stops around the town of Mhamid, some 600 km upstream from the sea. With the name of Oued Dades (rivers in Morocco do not necessarily maintain the name form source to mouth) it flows for almost 200 km from the High Atlas south-westward to Ouarzazate. Soon after that city, and already named Oued Draa, the river turns to flow south-eastward across 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

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to flow west to the sea, but in this stretch superficial flow usually stops. Middle reaches of Oued Draa only connect with its estuary during extreme rain episodes (Dłużewski and Krzemień, 2008). Ziz and Ghir basins direct their water flow from the High Atlas southwards to the Sahara Desert. They formed part of one of the ancient lake systems that connected most perisaharian rivers, including the Niger River, some 10,000 years ago (Figure 2). Oued Ziz and Oued Rheris, its main though largely unconnected tributary, usually infiltrate before joining together (30.64N, 4.43W) near the Moroccan-Algerian border. Oued Ghir enters Algeria shortly after or while joining its main tributaries (Oued Bouanane and Oued Zelmou) and, now named Oued Saoura, flows for around other 250 km before disappearing under the Great Western Erg (*Grand Erg Occidental*, around 29.45N, 1.45W).

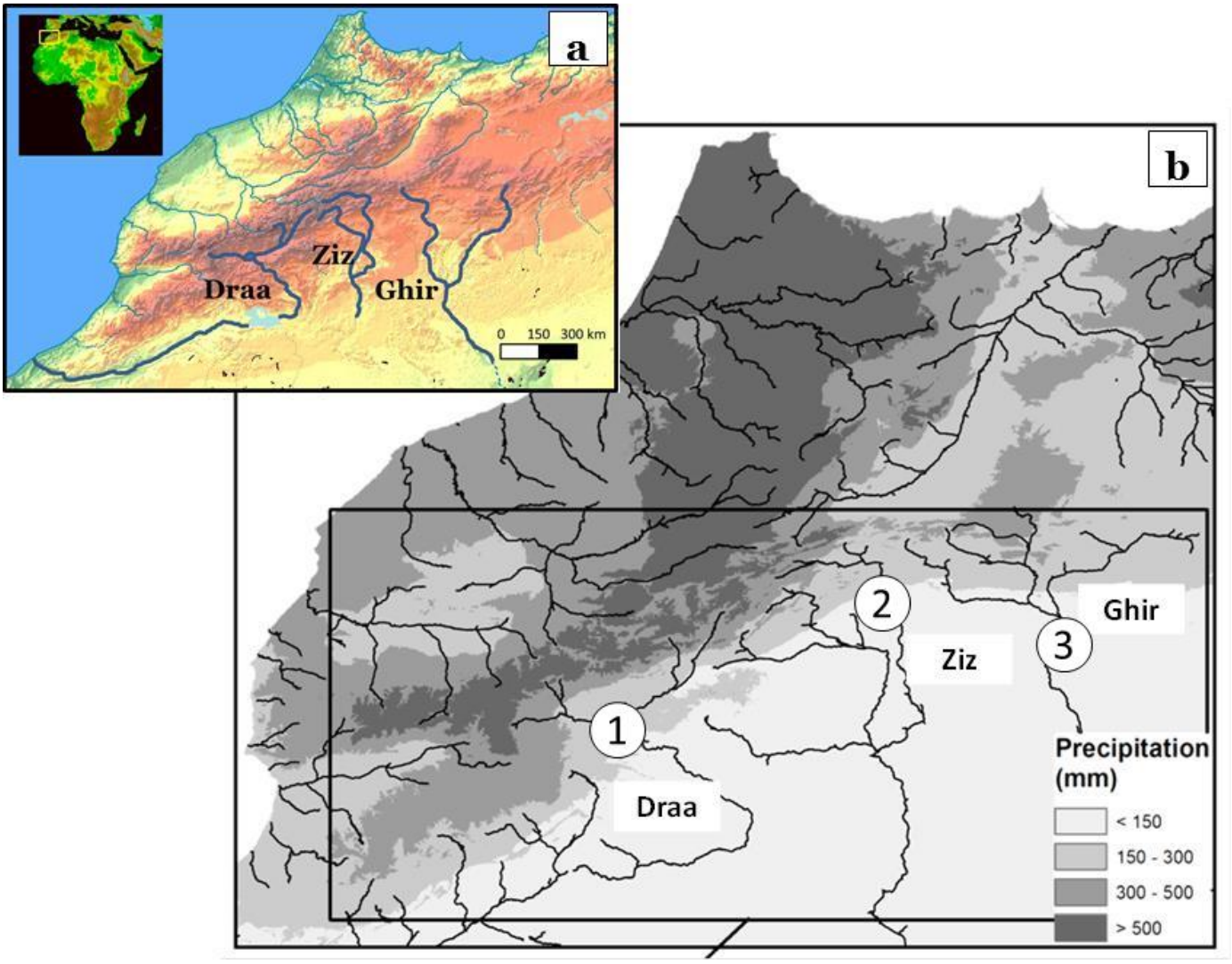

Figure 1. a) Topographic map showing the location of the three river basins described in this study. b) Mean annual precipitation in the studied rivers in the context of North-western Africa. Numbered circles represent large reservoirs: 1- El Mansour Eddahbi; 2- Hassan Addakhil; 3- Djorf Torba. The rectangle marks the area reproduced in Figure 5.

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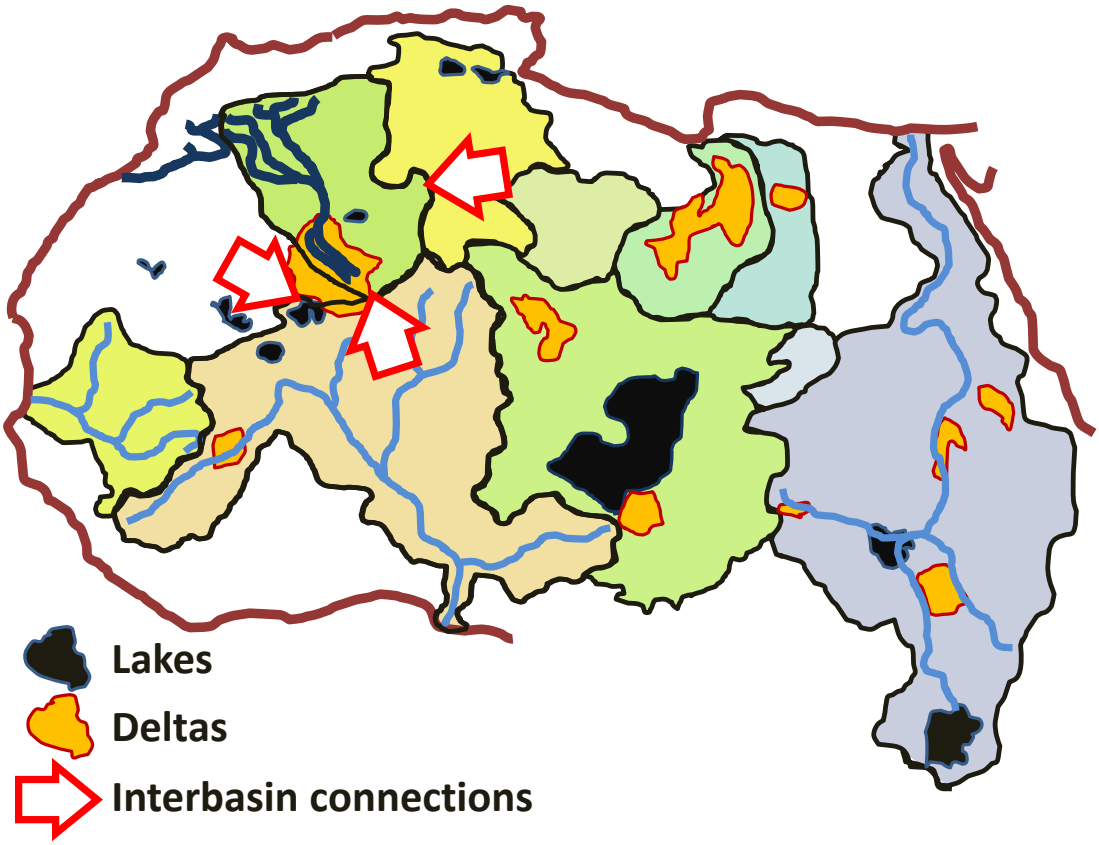

Figure 2. Configuration of main drainages in Northern Africa with the situation of megalakes and inland deltas around 10,000 years ago. Oueds Draa, Ziz and Ghir are marked in dark blue. Note that Oueds Ziz and Ghir were part of the same basin, forming a common inland delta. Senegal, Niger and Nile rivers are shown in light blue. Arrows mark the probable interbasin connections affecting the studied rivers. Relict Afrotropical elements found in Mediterranean areas of Northern Africa probably dispersed through these connections. Modified from Drake *et al.* (2011).

Due to the scarcity of precipitation, rainfed agriculture is not possible in the area. Agricultural lands are distributed along river banks, 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 (Figure 3). Water salinity steadily increases downstream in the three basins, reaching on average 3000 $\mu S \times cm^{-1}$, a threshold implying severe limitations for several crops, at around 800masl (Figure 3). There are three large dams in the studied basins (Figure 1). El Mansour Eddahbi dam was built in 1972 in Oued Draa, south of the city of Ouarzazate, with a maximum storage capacity of 529 million m^3, more than half the average total annual flow of the river. Hassan Addakhil dam was built in 1971 in the main course of Oued Ziz, north of the city of Errachidia, with a total capacity of 347 million m3 (Figure 4). The Djorf Torba dam, in Algeria, was built in 1969 in the main course of Oued Ghir, with a storage capacity of 299 million m^3. There are also several minor dams and numerous less-sophisticated barriers across waterways to temporally retain or derive water. A new large dam, with a capacity of 270 million m^3, was finished in August 2013 in Oued Iriri, a tributary of the Oued Draa, near El Mansour Eddahbi dam. All reservoirs in the area have important siltation problems and it has been estimated that both El Mansour Eddahbi and Hassan Addakhil reservoirs are expected to be inoperative for this reason around 2030 (Messouli *et al.*, 2008; Busche, 2013).

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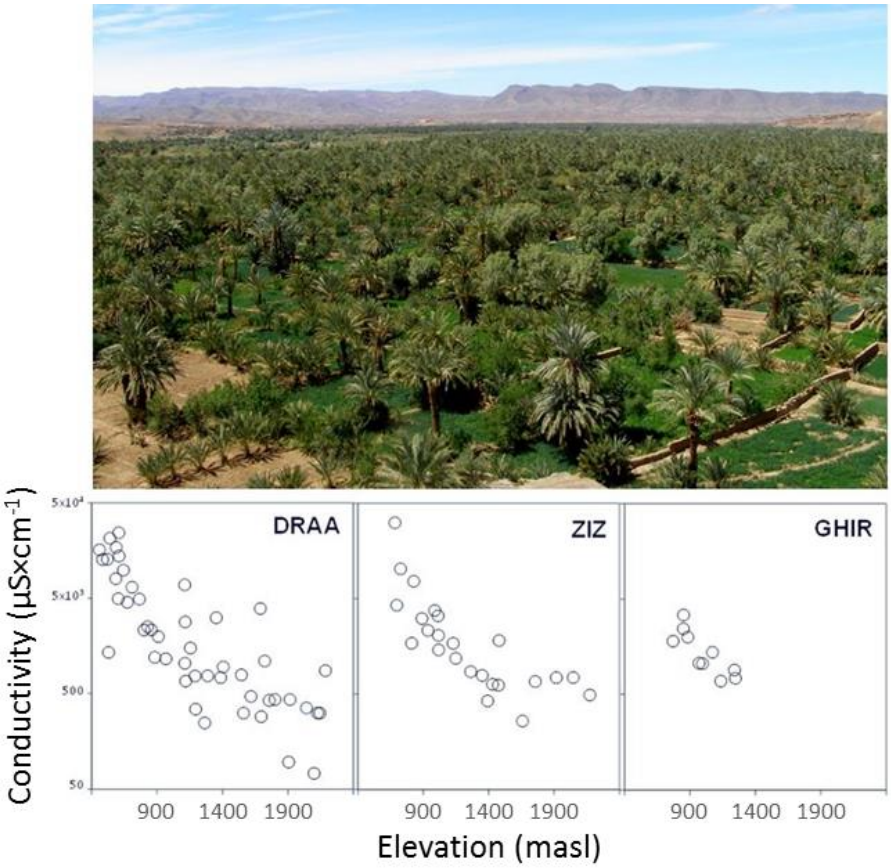

Figure 3. Above: Palm tree mixed plantations in Tamnougalt, Draa Valley. Below: Relationship between elevation and water conductivity in the three studied river basins. Note that the Y-axis has a logarithmic scale

Figure 4. Hassan Addakhil Reservoir, Oued Ziz, near the city of Errachidia

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FISH DATA

The data on fish distribution used in this article derive mainly from three extensive field campaigns, although they were complemented with a review on the technical literature dealing with fish in the study area.

We conducted two field trips during 2013, the first one between March and April, and the second between late September and early October. Overall, these two campaigns expanded for over 80 days (62 in spring and 20 in autumn) and counted with the participation of 13 people, to sample 88 sites. Thirty-nine of those sites were sampled in the two field trips (Figure 5). The third field campaign covered the upper reaches of the Oued Dades and Oued M'Goun, the main sources of Oued Draa (Figure 5). It was developed during 14 days in August 2014 and resulted in the sampling of 34 sites. Most of these sites had to be reached on foot, aided by mules to transport the sampling equipment

Sampled sites varied from high-altitude streams (up to 2660 masl.) to isolated permanent or semi-permanent water bodies in the desert (Figure 6). Fish communities were sampled mainly by means of electrofishing, fyke nets and seine nets. Electrofishing involved the use of a portable device (model ELT60 II HI, Hans Grassl GmbH, Schönau am Königssee, Germany). We sampled around 100 m of stream (mean 105.6 m; range 35-400 m), using a single pass without blocking. Captured fish were kept in a meshed cage within the river, to avoid hypoxia. Nets were used whenever electrofishing could not be performed (e.g., in reservoirs or with water conductivity higher than 6000 µS/cm). Fyke nets had two different mesh sizes (3.5 and 7mm), and were usually set for 24 hours. The seine nets were 5m in length and 1.5m in height, with a mesh size of 4mm.

Overall, we captured almost 24000 fish, which were identified to species level, measured for total length to the nearest millimetre and released, except for a sample of voucher specimens of each species, which were deposited in the collection of the Natural History Museum of the Institute Scientifique (Rabat, Morocco) and in the Natural History Museum of Lisbon (Lisbon, Portugal).

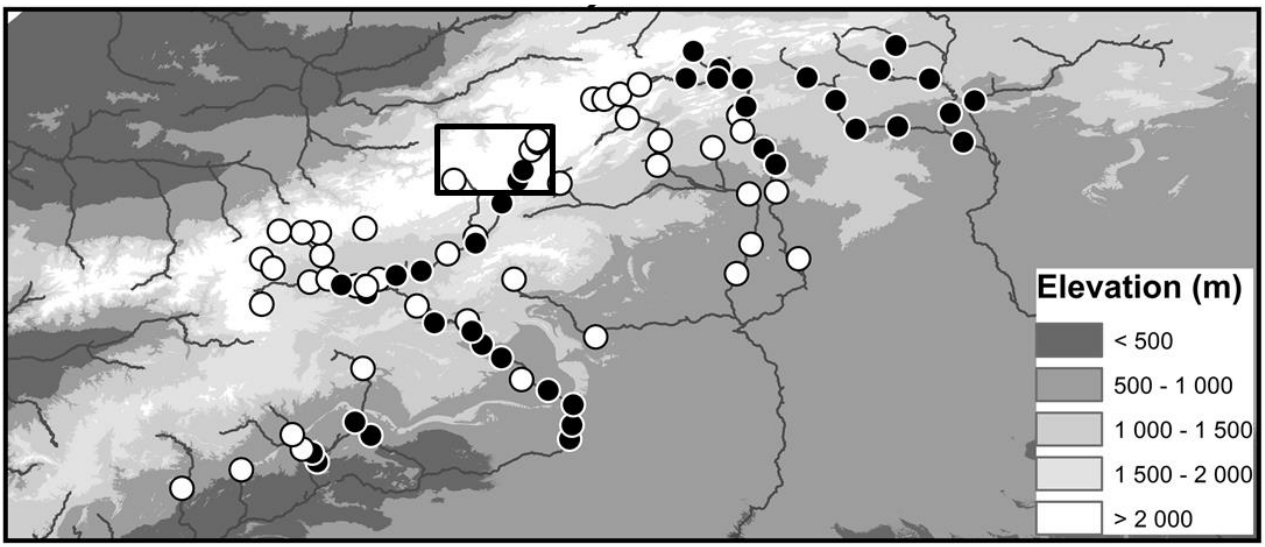

Figure 5. Location of the 88 sites sampled in 2013. The 39 sites revisited in the autumn survey are noted by filled dots. Background tones represent elevation. The rectangle marks the area in the upper M'Goun and Dades rivers where 34 additional sites were sampled in August 2014.

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Figure 6. Different sampled environments. 1) Upper Oued Dades at an altitude over 2100. 2) Middle reaches of Oued Ghir, near the town of Boudnib. 3) Lower, saline reach of Oued Rheris, to the south of Rissani. 4) Isolated pool in an ephemeral water course draining to the Lake Iriki area (Draa basin), near Foum-Zguid.

NATIVE FISH

The studied river basins have at least nine native freshwater fish species (Table 1). During our field work we were able to detect 6 of them, the rest being cited in the literature.

Barbels

Barbels of the genus *Luciobarbus* were the most common and most widely distributed fish taxon in the study area. Overall, we captured 17700 barbel individuals, constituting almost 3 out of every 4 captured fish. The taxonomy of Northern African *Luciobarbus* and other related genera (e.g. *Carasobarbus*) is in the process of being resolved (Doadrio *et al*., 2016; Brahimi *et al*., 2017). 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.; Doadrio *et al*., 2015). On the other hand, it is also possible that some of the basins are inhabited by more than one barbel species (e.g., the possible presence of *L. magniatlantis*). Outside of the Draa basin, *L. lepineyi* is also present in small coastal rivers, such as Oued Noun (Brahimi *et al*., 2016), which reaches the Atlantic north to the mouth of the Draa. *Luciobarbus pallaryi* is now known to be synonymous to *L. antinorii*, described for rivers in Tunisia (Gante, 2011). This suggests that the species would be widely distributed in aquatic systems east to the Draa basin, including Oued Zouzfana, in the Moroccan-Algerian border, and several basins flowing towards the Sahara in Algeria and Tunisia. This pattern can be explained by the configuration of Northern African

drainages and their contact areas during the last wet phase in the area (see Figure 2).

Barbels exhibit a broad environmental plasticity in the study area, being detected in virtually every aquatic environment inhabited by fish. They were only absent at the highest sectors, even though *L. lepineyi* was present at elevations over 2000 masl. in Oued M'Goun and Oued Dades. We observed barbel populations in isolated permanent pools in desert biotopes (e.g. in Oued Rheris, Ziz basin, near Erfoud) and in very saline systems, such as Oued Tissint, in the Draa basin, where conductivity surpassed 16000 µS×cm^{-1} (salinity over 11 PSU).

Table 1. List of fish species present in the studied basins, identifying the basins where each one of them is present. D- Draa basin; Z- Ziz basin; G- Ghir basin. Species highlighted in bold and with coloured background are those detected during field campaigns, while the absence of these features or a basin code in parenthesis denote that the information was obtained from the literature or from local informants.

Family	Species	Common name	Basins
Native species			
Cyprinidae	***Luciobarbus lepineyi***	**Barbel**	**D**
Cyprinidae	***Luciobarbus pallaryi***	**Barbel**	**Z, G**
Cichlidae	***Coptodon zillii***	**Redbelly tilapia**	**D** (G)[1]
Cichlidae	***Oreochromis aureus***	**Blue tilapia**	**D**
Cichlidae	*Hemichromis bimaculatus*	African jewelfish	(G) [1]
Salmonidae	***Salmo multipunctata***	**Dades trout**	**D**
Salmonidae	***Salmo trutta***	**Brown trout**	**Z**
Cyprinodontidae	*Aphanius saourensis*	Sahara aphanius	(G)[2]
Anguillidae	*Anguilla anguilla*	European eel	(D)[3]
Non-native species			
Atherinidae	***Atherina boyeri***	**Big-scale sandsmelt**	**D**
Centrarchidae	***Lepomis gibbosus***	**Pumpkinseed sunfish**	**D, Z, G**
Centrarchidae	***Micropterus salmoides***	**Largemouth bass**	**D** (Z)[4]
Cyprinidae	***Cyprinus carpio***	**Common carp**	**D**
Cyprinidae	***Carassius auratus***	**Goldfish**	**G**
Cyprinidae	***Pseudorasbora parva***	**Stone moroko**	**G**
Cyprinidae	***Alburnus alburnus***	**Bleak**	**G**
Cyprinidae	*Scardinius erythrophthalmus*	Rudd	(D)[5]
Cyprinidae	*Ctenopharyngodon idella*	Grass carp	(D)[5]
Poeciilidae	***Gambusia holbrooki***	**Mosquitofish**	**D, G**
Salmonidae	*Oncorhynchus mykiss*	Rainbow trout	(D)[6]

Sources 1: Qninba and Mataame (2009); 2 : Blanco et al (2006); 3: Qninba *et al.* (2011) ; 4: local informants; 5: Azeroual (2003); 6: local informants and web pages

The ecological plasticity of barbels in Moroccan desert rivers is paired with a huge morphological variability (Figure 7). The variation in relative head size, body slenderness, fin lengths and other features does not seem to correspond to a binary species differentiation (i.e. *L. pallaryi* vs. *L. lepineyi*). Whether or not the environmental and morphological variabilities are related, and whether there is a cause-effect link between them is a relevant matter for future research. Equally interesting is finding out whether morphological variability is related to the severe isolation process experienced by fish populations in desert environments (e.g. Brahimi *et al*., 2016).

Figure 7. Examples of the morphological variability of barbels within the study area.

Cichlids

Cichlids conform the most widely spread group of Afrotropical relict fish in Northern Africa, which also include African catfishes of the genus *Clarias* (Lévêque, 1990; Hillyard *et al*., 2015).

Two cichlid species, the blue tilapia (*Oreochromis aureus*) and redbelly tilapia (*Coptodon zilii*) were found in the Oued Draa basin (Figure 8). The redbelly and blue tilapias occur in sympatry in Oued Tissint, a saline tributary of Oued Draa, where they also coexist with *Luciobarbus lepineyi*. The blue tilapia is also present in Oued Draa's main channel.

The redbelly tilapia has a wide distribution around the Guinea Gulf, with several relict populations in the Sahara Desert, the Maghreb and the Levant (Drake *et al*., 2011) (Figure 9). The genetic consequences of the several connection and isolation processes involving Afrotropical fishes in Northern Africa offer a very interesting research line that has just started to be explored. The first results included in the Master Thesis of Jolita Dilyté show that genetic patterns are complex and that the taxonomy of tilapias in North Africa is far from being resolved. Dilyté (2014) found that redbelly tilapias from North Western Africa belong to two different lineages, one found mainly in coastal areas and the other one present both in Morocco and in the Senegal River, in Mauritania, Senegal and Mali.

Moroccan blue tilapias have been in other works identified as the mango tilapia (*Sarotherodon galileus*) (Qninba and Mataame, 2009; Dilyté, 2014). These two taxa are complex and difficult to identify, so that confusion and misidentifications are possible. Here, we follow the advice by J. Freyhof (pers. comm.), who identifies Moroccan oreochromine cichlids (*sensu* Dunz and Schliewen, 2013) as blue tilapias, based on morphological characters. However, this issue should be clarified for future studies.

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Dilyté (2014) described a similar genetic pattern for Northwest African blue tilapias (which she named *Sarotherodon*) to that of the redbelly tilapia: a coastal lineage and a common lineage shared in Morocco and the Senegal River basin. However, in the case of the blue tilapia the Moroccan populations had a high genetic singularity, which deserves further exploration.

Figure 8. From top to bottom: Redbelly tilapia (*Coptodon zillii*) from Oued Tissint; Blue tilapia (*Oreochromis aureus*) from Oued Draa; mixed sample of juveniles of blue and redbelly tilapias from Oued Tissint.

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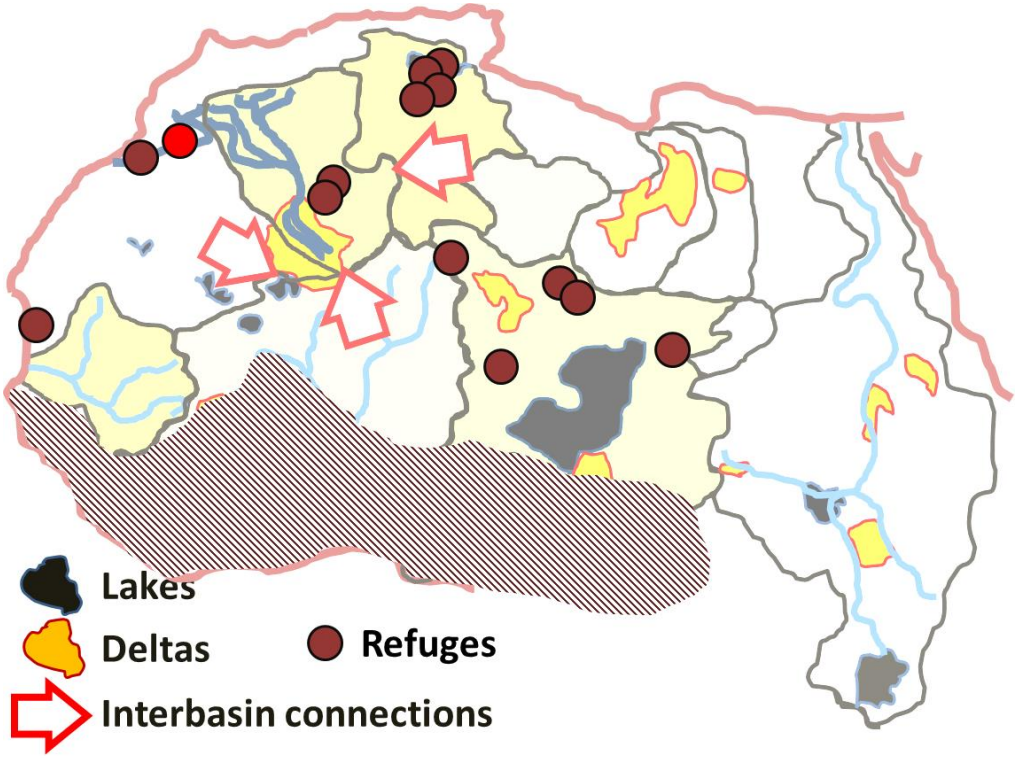

Figure 9. Presence of the redbelly tilapia (*Coptodon zillii*) in Northern Africa, showing the continuous distribution area (shaded area) and the relict populations (refuges, brown dots), modified from Drake *et al*. (2011). The background map is the same as that in Figure 2. The red dot marks the population in Oued Tissint. The population of the lower Draa is in agreement with the information presented by Qninba and Mataame (2009), based on individuals collected in the 1940s. However, Dilyté (2014) only recorded blue tilapias (*Oreochromis aureus*) in the lower reaches of Oued Draa.

Records of the blue tilapia in the area were scarce prior to our work. Qninba and Mataame (2009), based on specimens collected in the 1930s and 1940s, only recorded its presence (also as *Sarotherodon*) in small tributaries of the Draa's right margin, near the town of Akka. However, we found this same species in several sites along the middle reaches of Oued Draa, reaching an elevation of 800 masl. The distribution of this Afrotropical species might be limited in the area by cold winter temperatures registered at higher elevations. It is also possible that the blue tilapia is currently expanding its range in the area as a consequence of global warming and/or to the buffering effect of damming on flow fluctuations (Clavero *et al*., 2015). The blue tilapia is known to be an efficient invader in several areas (Canonico *et al*., 2005), and thus it is plausible that it would expand its range in the study area under more favourable environmental conditions. This possible expansion process would be an interesting line of research, especially in relation with the interactions of the blue tilapia with other species, either native (barbels) or introduced (e.g. pumpkinseed sunfish, *Lepomis gibbosus*).

We could not confirm previous information on the presence of redbelly tilapia or African jewelfish (*Hemichromis bimaculatus*) in the Ghir basin, which had been reported from the Algerian part of the basin in the early 20th century (Qninba and Mataame, 2009).

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Trout

The brown trout (*Salmo trutta*) has a vast distribution area, one of the largest among freshwater fish worldwide (Jonsson and Jonsson, 2011). This distribution range has been shaped by complex processes of contractions and expansions associated with events of Pleistocene glaciations, giving rise to different genetic lineages (Bernatchez, 2001). The large and increasing knowledge on brown trout genetics has not clarified its taxonomy. While some authors consider the brown trout a single, complex species (Jonsson and Jonsson, 2011), others rather see it as a species complex that contains several taxa (Kottelat and Freyhof, 2007).

The brown trout, *sensu lato*, has its southernmost populations in mountain systems of Morocco and is present in two areas within the studied basins: the upper Draa basin (Oued M'Goun and Oued Dades) and the upper Ziz basin (Oued Sidi Hamza). Trout populations in the Draa basin belong to an ancient, independent genetic lineage (Dades lineage) described by Snoj et al., (2011) (Figure 10). Following those findings, Doadrio *et al.* (2015) described the Dades trout as a new species, *Salmo multipunctata*. Snoj *et al.* (2011) suggest that the Dades trout became isolated at least 1.2 million years ago. Oueds Dades and M'Goun are part of the Draa River basin, which meets the sea at a low latitude (28.6°N), a feature that has probably precluded its colonization by more recent trout southward expansions, which involved exclusively the Atlantic lineage (see Figure 10). The trout population in Oued Sidi Hamza belong to this Atlantic lineage, and we conservatively maintain it within the "umbrella" species *S. trutta*, even though there is a clear and urgent need to clarify the taxonomy of trout in Northern Africa. Clavero *et al.* (2017) discuss on the conservation problems of not having a clear taxonomic framework in the region (e.g. unclear definition of conservation status).

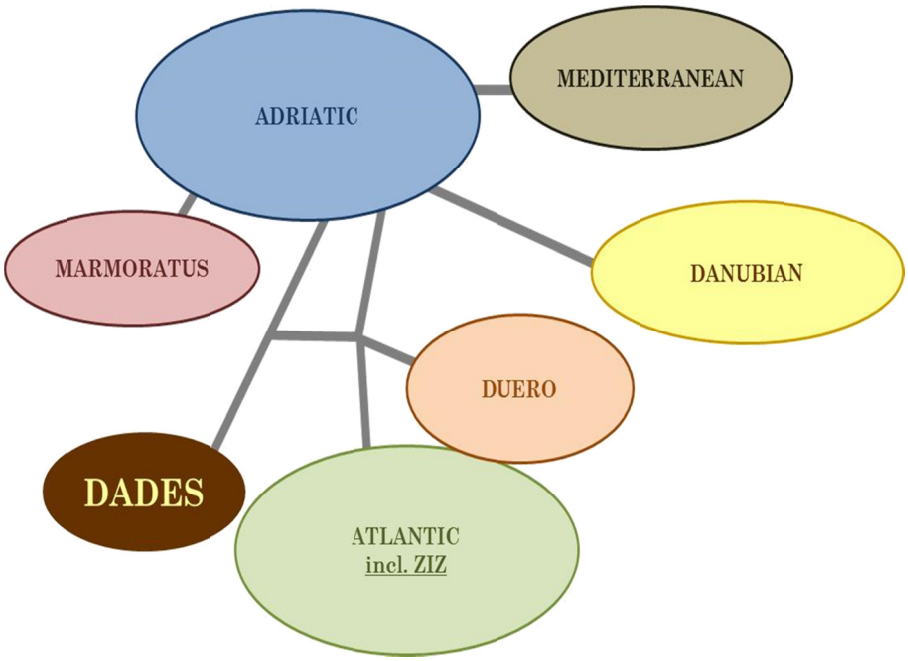

Figure 10. Hypothesized relationships among brown trout lineages, based on the variability of the control region of the mitochondrial DNA. Distances among lineage groups roughly reflect genetic distances, although only in a qualitative way. Drawn based on the results of Snoj *et al.* (2011).

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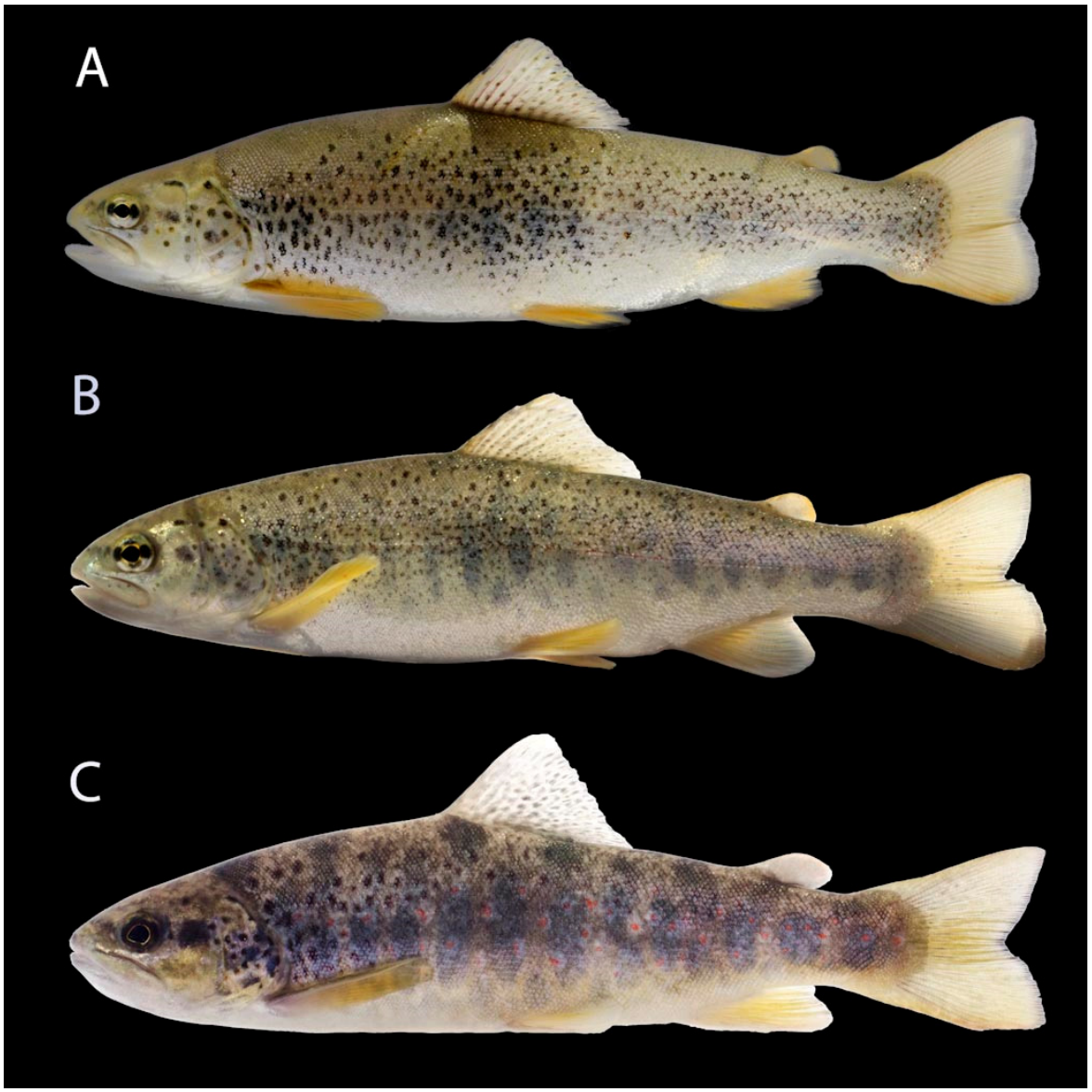

Figure 11. Dades trout (*Salmo multipunctata*) from (A) Oued M'Goun and (B) Oued Dades, and (C) brown trout (*Salmo trutta*) from Oued Sidi Hamza, Ziz River basin.

The Dades trout (Figure 11) is a critically endangered species with a tiny distribution range, probably among the smallest of any stream salmonid worldwide (Clavero *et al*., 2017). It occupies less than 22 km of stream reaches in a narrow elevation band (roughly 2150 to 2375 masl), being thus extremely vulnerable to warming climatic conditions and to any possible catastrophic event. Clavero *et al*. (2017) propose specific measure to enhance its conservation chances, including habitat restoration and improvement (involving stream channels, riparian vegetation and the drainage areas), the establishment of new population nuclei and the start of a captive breeding program. Of critical importance to maintain the integrity of the Dades trout uniqueness is avoiding any trout stocking in the Draa basin, involving either trout from other Moroccan lineages or American trout.

There is still a lot of work to do with the Dades trout, involving both knowledge generation and active conservation. Regarding research lines, we still know very little about the ecology and behaviour of this species. Genetic tools could be used to quantify the level of isolation of the two extant popu-

lations of the species, which are currently separated for some 200 km of stream reaches. Also, introducing genetic markers different from the mitochondrial DNA control region (see Figure 10) would be useful for clarifying the position of the Dades trout within the brown trout complex, as well as the complex itself.

Oued Sidi Hamza originates in an abundant and constant water source, which provides high flow of cold water across the year, allowing the maintenance of abundant and healthy trout populations. Brown trout probably occupied the endorheic Ziz basin through a river capture event, which are widespread in the High Atlas (Babault *et al.*, 2012). The populations of origin could belong the Oum Er-Rbia or the Moulouya basins, the headwaters of which are in contact with those of the Ziz.

Aphanius and eel

The Sahara aphanius (*Aphanius saourensis*) was only recently described as a new species from the lower reaches of Oued Soura, the name that Oued Ghir takes when entering Algeria (Blanco *et al.*, 2006). The Sahara aphanius is a sister taxa of the Iberian species of the genus (*A. iberus* and *A. baeticus*). It is thought that the species would have been once widely distributed in the basin, but by the time of its formal description (based on specimens captured in 2004), the species was known from a single locality, in which it was severely threatened by invasive mosquito fish (*Gambusia holbrooki*), with "densities of *Gambusia* to *Aphanius* being more than 100 to one" (Blanco *et al.*, 2006). An expedition in 2013 was unable to find the Sahara aphanius, in spite of a large sampling effort in its type locality and surrounding water bodies, and the species is now considered to be Extinct in the Wild (Bacha and Freyhof, 2017). The species is still held in captivity in different European countries, a stock that could be managed for a future creation of wild populations. However, this scenario seems difficult, due to the maintenance of the extinction driver (i.e. widespread presence of invasive fish species) in the area (Bacha and Freyhof, 2017).

Qninba *et al.* (2011) reported the presence of the European eel (*Anguilla anguilla*) on Oued Tissint, in the Draa basin. The finding is surprising and very interesting, because it expanded the known distribution of the species in Africa some 200 km southwards (the previous southern limit was set at Oued Massa) and because to reach Oued Tissint an eel must have swum upstream through several hundred kilometres of Oued Draa's main channel, which only sporadically has superficial flow. This finding highlights the interest of investigating the lower reaches and the mouth of Oued Draa, which has been only sparsely surveyed by fish biologists.

NON-NATIVE FISH

Eleven non-native fish species have been reported in the studied basins (Table 1; Figure 12). Of these, we could detect eight species during the field explorations, some of which (stone moroko, *Pseudorasbora parva*, and bleak, *Alburnus alburnus*) being first species records for Morocco (Clavero *et al.*, 2015). We did not capture any rudd (*Scardinius erythrophthalmus*) or grass carp (*Ctenopharyngodon idella*), which had been cited by Azeroual (2003) in El Mansour Eddahbi dam (Oued Draa). We could neither detect the presence of the rainbow trout (*Oncorhynchus mykiss*), which is known to have been introduced in the 1990s in Oued Oussikis River, a tributary of Oued Dades, close to the range of the Dades trout. The introduction took place in the Aït Yazza reservoir and rainbow trout apparently thrived until the reservoir became almost totally silted, disappearing thereafter (after interviews with locals and http://www.sud-maroc.com/2010/12/vallee-doussikis-et-peche-a-la-truite/ accessed October 18th 2017). It is very important for the conservation of the Dades trout to avoid any possible future restocking of this species.

Figure 12. Non-native fish species detected during the field campaigns. Left column, top-down: pumpkinseed sunfish (*Lepomis gibbosus*), largemouth bass (*Micropterus salmoides*), goldfish (*Carassius auratus*), stone moroko (*Pseudorasbora parva*). Right column, top-down: eastern mosquitofish (*Gambusia holbrooki*), bleak (*Alburnus alburnus*), big-scale sand smelt (*Atherina boyeri*), common carp (*Cyprinus carpio*)

The Draa and the Ghir basins had 5 non-native fish species each, while only 2 were found in the Ziz basin (Table 1). Pumpkinseed (*Lepomis gibbosus*) is the most widely distributed non-native fish in the study area, being also the only non-native species detected in the three studied basins. At the time of the field campaigns (2013) the introduction of pumpkinseed into the Ghir basin was apparently recent, since it was found in a single locality, in low abundance and with a population dominated by small size classes (Clavero *et al*., 2015).

The big-scale sandsmelt (*Atherina boyeri*) is native to the Moroccan coastal areas, including wetlands and low river reaches (eg, Francisco *et al*., 2008), but has been introduced in the study area. The species is abundant in El Mansour Eddahbi dam, where it forms large schools. We also detected the species in two water courses upstream the reservoir, though very near to it, and occasionally along Oued Draa, below the dam, but always in small numbers (Clavero *et al*., 2015).

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Non-native fish species are clearly associated to reservoirs in the study area, and native species are apparently excluded from these artificial environments through the interaction with non-native ones (Clavero *et al.*, 2013). For example, barbels constituted 0.5% (5 fish out of 990 individuals) of the catch in the 4 reservoirs sites sampled during the field campaigns, while they were 91.6% of the catch in river stretches. But the relationship between non-natives and reservoirs spread out of the reservoir boundaries. Non-native species easily colonize the regulated downstream reaches, in which they are omnipresent and frequently abundant. Colonization of upstream (i.e. unregulated) reaches by non-native species seems much more difficult (Clavero *et al.*, 2015). In spite of this, some non-native fish species have apparently colonized Morocco from the Djorf Torba reservoir, in Algerian territory. Thus, it seems that managing reservoir outflows to mimic natural (and extreme) flow regimes could be a powerful management option to control the proliferation of non-native species. However, modifying flow regulations is very difficult in this dry area in the area, due to the high human demand for the small water availability. Non-native fish management should thus focus on limiting the spread of already introduced species and avoiding new introductions, especially into reservoirs, which act as efficient invasion foci.

The impacts of non-native fish species can be direct (as the exclusion of native fish from reservoirs) or indirect, for example through the introduction of associated parasites and pathogens (Peeler *et al.*, 2011). During the field campaigns we detected the presence of an ectoparasitic copepod, the anchor worm (*Lernaea cyprinacea*), in several barbel, pumpkinseed sunfish and big-scale sandsmelt individuals in the Draa basin (Figure 13). *Lernaea cyprinacea* has an almost cosmopolitan range due to its association to fish introductions (Lester and Hayward 2006), but our observations were the first made for the species in Morocco (Clavero *et al.*, 2015). The distribution of this parasite is very similar to that of non-native fish, being present in all reservoir sites, common in downstream sites and very rare in upstream sites, being restricted to areas close to the El Mansour Eddahbi reservoir.

Figure 13. Parasitic anchor worm *Lernea cyprinacea* in the Draa basin, infecting big-scale sandsmelt (above) and pumpkinseed sunfish (below)

The introduction and expansion of the stone moroko could also by responsible of the impacts generated by the rosette agent (*Sphaerothecun destruens*), an intracellular parasite that causes high mortality in salmonids and cyprinids (Andreou *et al.*, 2012). A first analysis of stone moroko samples from the Ghir basin was negative for the presence of the rosette agent (Sana *et al.*, 2017). However, this negative result has to be taken cautiously. Sana *et al.* (2017) found the rosette agent with low prevalence in areas where it is known to be present and to have important impacts, such as the United Kingdom. In that case the authors obtained 1 positive sample out of 20, while in the sample from the Ghir basin the result was 20 negatives. Anyway, the absence of the rosette agent in Northern Africa is preliminary good news that we hope could be confirmed in the future.

CONCLUDING REMARKS

The high historical environmental dynamism of the Sahara Desert has favoured a blurred limit between the Palearctic and Afrotropical biogeographic realms in northern Africa (Brito *et al.*, 2014; Leite *et al.*, 2015). Our study area is one of the clearest examples of that admixture of biotas. The fish fauna have cold-water species with Palearctic affinities (trout), Mediterranean elements (*Luciobarbus*, *Aphanius*) and Afrotropical relicts (cichlids). In the headwaters, fish coexist with cold-welling Palearctic taxa (e.g. white-throated dippers, *Cinclus cinclus*), while the lower reaches host Egiptian cobras (*Naja haje*) and Honey badgers (*Mellivora capensis*). The Nile crocodile (*Crocodylus niloticus*) was present in the lower Draa until the beginning of the 20th century (Brito *et al.*, 2011). Preserving, and ideally recovering the biogeographic mosaic of Northern African river basins should be an international conservation target.

In our specific study area, conservation efforts are urgent for the Dades trout (Clavero *et al.*, 2017) and the Sahara aphanius (Bacha and Freyhof, 2017). It is also relevant to avoid the introduction of new non-native species, as well as avoiding the expansion of those already established through their introduction to basins where they are not present yet.

AUDIO-VISUAL MATERIALS

The Youtube channel Peces Desierto (https://www.youtube.com/channel/UCw5elNrmQKffW-YHASHJOPA) offer different audio-visual materials related with the development and the results of our research in Moroccan desert river basins. The main two pieces are:

- **Peces en el desierto / Fish in the desert**. (30 min., in Spanish, with English or French subtitles). A group of enthusiastic naturalists pursue the fishes and other aquatic animals that live in the most arid area of Morocco. The troubles for surviving in such a hostile environment interwine with the difficulties to do science when the taste for pure knowledge is lost. https://www.youtube.com/watch?v=V1adwIsKmYs
- **Sin lugar hacia el que nadar / Nowhere to swim to**. (9 min., in Spanish with English subtitles) A research team goes into the canyons of the rivers Dades and M'Goun, tirelessly searching one of the most ancient, unknown and threatened trout on Earth, the Dades trout. https://www.youtube.com/watch?v=h-ImQx3rFmU

AUTHORS CONTRIBUTIONS

MC, JE, MR, JC and MD developed the field work. JE made all the photographs and audio-visual materials. MC lead the writing, aided by all other authors.

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