Nowhere to swim to: climate change and conservation of the relict Dades trout *Salmo multipunctata* in the High Atlas Mountains, Morocco

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SUPPLEMENTARY MATERIAL 1 Assessing the somatic condition of the Dades trout *Salmo multipunctata*.

The somatic condition of Dades trout individuals was assessed using the scaled mass index, following Maceda-Veiga et al. (2014):

$$SMI_i = W_i \left[\frac{L_0}{L_i}\right]^{bSMA}$$

where W_i and L_i are the weight and total length, respectively, of individual i, L_0 is a constant length used to standardize body condition values (we used the arithmetic mean of total lengths of all individuals captured; Fig. S1), and bSMA is the scaling component, which we obtained by dividing the slope of the ordinary least squares regression of weight on length (both of them ln-transformed) divided by the Pearson's correlation coefficient of that relationship.

SUPPLEMENTARY MATERIAL 2 Habitat characterization for the Dades trout in the High Atlas Mountains of Morocco

At each surveyed site we measured water conductivity and temperature, and recorded several variables related to the structure of the riverbed and riparian habitats (Table S2). These variables were measured or estimated repeatedly at transects placed at 20 m intervals within the sampled stretch, and mean and/or maximum values (depending on the variable) were taken to characterize sites. To summarize the variability in the resulting habitat dataset, we submitted the 12 habitat variables to a principal components analysis. Elevation was not included in the principal components analysis and was retained as a separate explanatory variable, given its presumed relevance for a high-mountain organism such as the Dades trout. Following the scree plot criterion (i.e. identifying changes in the sequential decrease of eigenvalues along principal components, or PCs) we retained the first two principal components for further analyses, which accounted for almost 45% of the variability of the original dataset. PC1 was related to the size (i.e. volume) of stream habitats (henceforth Size–PC1), as its positive extreme had sites where channels were wider and deeper, with fast-moving waters, large substrate sizes and small coverage of aquatic vegetation. PC2 was mainly related to riparian vegetation cover (henceforth Vegetation–PC2), having sites with high coverage of both woody and herbaceous riparian plants towards its positive extreme, and sites with large proportions of rocky shore towards its negative extreme (Table S2).

SUPPLEMENTARY MATERIAL 3 Assessment of the global conservation status of the Dades trout

The Dades trout (Doadrio et al., 2015) is endemic to Morocco. It lives only in the headwaters of the Dades and M'Goun rivers, on the southern slope of the High Atlas Mountains. We evaluated the species' global conservation status using the IUCN Red List Categories and Criteria, Version 3.1 (IUCN, 2012).

Criterion A: Population size reduction
There is no estimate of the population size of the Dades trout, and therefore it is not possible to establish whether or not there has been a decline in the number of mature individuals. This criterion cannot be applied.

Criterion B: Geographical range
The Dades trout exists in two subpopulations, which are completely isolated from one another. The subpopulations, in the Dades and M'Goun catchments, are separated by a straight-line distance of 65 km, and 200 km along the river channels. Both catchments are part of the Draa River Basin. The species is limited to ≤22 km of stream channels.

In the Dades catchment the species is found only in the N'Ougouni stream, a high mountain stream that is the headwater of the Dades River. The trout occurs from the N'Ougouni source (at 2,375 m altitude) down to an altitude of 2,190 m. The range of this subpopulation is limited to 12,000 m of stream channel.

In the M'Goun catchment the species is found in two right-margin tributaries of the M'Goun (Aflafal and Imigmar streams) as well as in some sectors of the M'Goun main channel. The trout occurs from the Aflafal source (at 2,370 m altitude) down to an altitude of 2,135 m. This subpopulation is distributed across c. 10,000 m of stream channels.

A future decline in habitat suitability for the Dades trout is projected, based on the effects of global climate change. This decline will specifically affect those areas that are currently occupied by the species. The loss in habitat suitability will be less pronounced at higher altitudes, but permanent water streams are not found there. Furthermore, the presence of waterfalls in the M'Goun channel precludes upstream migration of the species. Therefore, a continuous decline in both the area of occupancy and the quality of habitat is projected, which will affect the size of the population and the extent of occurrence.

Extent of occurrence (EOO)
EOO is the area contained within the shortest continuous imaginary boundary that can be drawn to encompass all the known, inferred or projected sites of present occurrence of a taxon, excluding cases of vagrancy (IUCN, 2012). IUCN's Standards and Petitions Subcommittee recommends the use a minimum convex polygon (MCP) to calculate the EOO. The IUCN guidelines for using the Red List Categories and Criteria state that EOO may exclude 'discontinuities or disjunctions within the overall distribution of the taxa'. However, for calculating EOO for criterion B1 the guidelines strongly discourage this because disjunctions and outlying occurrences accurately reflect the extent to which a larger area of geographical distribution reduces the likelihood that the entire

population of the taxon will be affected by a single threatening process (IUCN Standards and Petitions Subcommittee, 2016).

Therefore, following the recommendations of IUCN, the EEO of the Dades trout (i.e. the MPC with all the known, inferred or projected sites of present occurrence of the species) is 218.5 km^2. However, we stress that the strict observance of IUCN guidelines regarding the calculation of EOO may result in an underestimation of the extinction risk of the Dades trout, as frequently happens with riverine organisms (see criticism and discussion below).

Area of occupancy (AOO)
AOO is a parameter that represents the area of suitable habitat currently occupied by the species. IUCN recommends calculating AOO as the area occupied by the species at a scale of 4 km^2 cells as the reference scale in all types of habitat distribution, including taxa with linear ranges, such as riverine species (IUCN Standards and Petitions Subcommittee, 2016). Calculated in this way, the AOO of the Dades trout is 40 km^2, 16 $km^2$of which are in the Dades catchment, and 24 km^2 in the M'Goun catchment.

Assessing whether criterion B is met
Criterion B1 is met for the category Endangered (EN) because the estimated EOO of the Dades trout is <5,000 km^2, and the population is severely fragmented and exists in fewer than five locations (a), and a future decline is projected (b) for extent of occurrence (i); area of occupancy (ii); area, extent and/or quality of habitat (iii); and the number of mature individuals (v).

Criterion B2 is met for the category Endangered because the estimated AOO of the Dades trout is <500 km^2, and the population is severely fragmented and exists in fewer than five locations (a), and a future decline is projected (b) for extent of occurrence (i); area of occupancy (ii); area, extent and/or quality of habitat (iii); and the number of mature individuals (v).

EN B1 ab(i,ii,iii,v) + 2 ab(i,ii,iii,v)

Criterion C: Small population size and decline
There is no estimate of the population abundance of the Dades trout, and therefore it is not possible establish the population size, or whether or not it has declined. This criterion cannot be applied.

Criterion D: Very small or restricted population
There is no estimate of the population abundance of the Dades trout, and therefore it is not possible establish the population size. Criterion D1 cannot be applied.
However, the Dades trout has a very restricted area of occupancy and it exists in only two locations.

Assessing whether criterion D is met
Criterion D2 is met for the category Vulnerable (VU) because the species has a very restricted area of occupancy, it exists in fewer than five locations, and there is a plausible anthropogenic threat.

VU D2

Criterion E: Quantitative analysis
There is no quantitative analysis to determine the species' probability of extinction, and therefore it is not possible to make a criterion E assessment.

Criticism and discussion

Spatial criteria used in IUCN assessments for freshwater taxa
Criterion B uses EOO, AOO and number of locations, in conjunction with several subcriteria, to evaluate the extinction risk associated with restricted spatial distribution. However, the approaches used for calculating EOO and AOO have been criticized regarding their applicability to freshwater species.

Many concerns have been expressed about the use of MCPs without introducing distribution discontinuities (as recommended by IUCN's Standards and Petitions Subcommittee) to assess the conservation status of freshwater species (Keith & Marion, 2002; Simaika & Samways, 2010). When the MCP is calculated for riverine species the resulting polygon is composed mainly of terrestrial environments, which are of course completely unsuitable for the focal aquatic species. The dominance of terrestrial environments in the polygon is larger when the species occupies isolated stream reaches, either within a river basin or in multiple basins. Simaika & Samways (2010) suggested that the area of the subcatchments occupied by a freshwater species would be a better metric for EOO than MCP polygons. They proposed that IUCN redefine the EOO of freshwater species as 'the sum of the smallest hydrological units identified, of presently known, inferred or projected occurrences of a taxon, excluding cases of vagrancy, that are used to estimate the threat to a taxon' (Simaika & Samways, 2010). Similar approaches were chosen for freshwater fish in France (Keith & Marion, 2002) and for lampreys in Belgium (Verreycken et al., 2014). In the case of the Dades trout the EOO measured with an MPC encompasses an area of 218.5 km^2, which is composed mainly of mountain summit environments that are covered by snow during winter and completely dry in summer, and have no permanent water courses. If the EOO were calculated as the sum of the area of the subcatchments in which the Dades trout was found or is inferred to be present (Simaika & Samways, 2010) its area would be 33.3 km^2 (9 km^2 and 24.3 km^2 in the Dades and M'Goun basins, respectively). Alternatively, Mace et al. (2008) consider it inappropriate to include in EOO calculations habitats that are totally unsuitable for the focal species. In fact, thousands of assessments have calculated EOOs by summing the area of different polygons, excluding those areas that were not considered to be suitable habitat (Joppa et al., 2016). If the EOO were calculated as the sum of the areas of the MCPs constructed separately for the two known Dades trout populations, its area would be 16.4 km^2 (5.9 km^2 and 10.5 km^2 in the Dades and M'Goun basins, respectively). Thus, excluding unsuitable habitats from the EOO calculation would result in a >90% reduction in the EOO of the Dades trout (Fig. A).

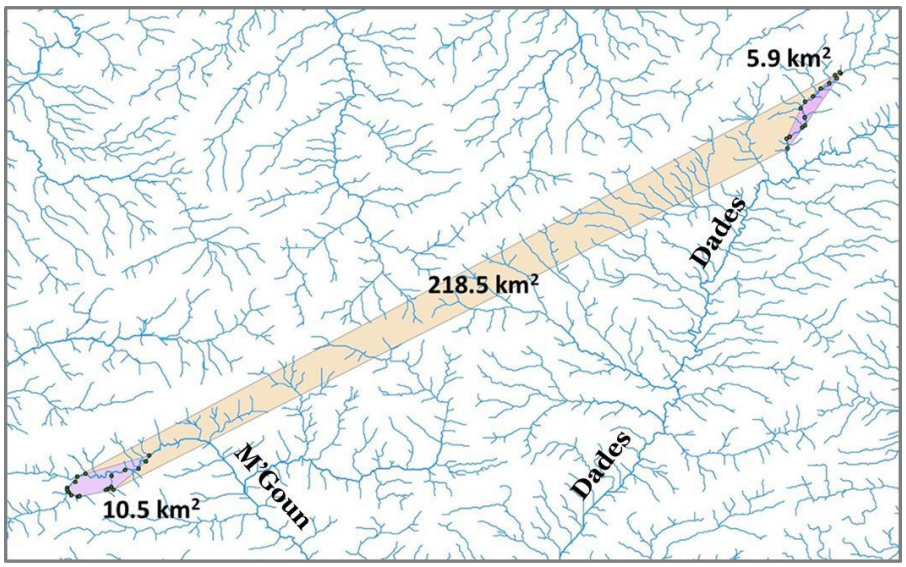

FIG. A EOO of the Dades trout, using either a single MCP (218.5 km^2) or the sum of the MCPs constructed for each of the two isolated extant populations (16.4 km^2). In the second case, unsuitable mountain summit habitats are excluded from the EOO.

AOO is defined as the area within the EOO that is occupied by a taxon, excluding cases of vagrancy (IUCN, 2012). AOO reflects the fact that a taxon will not usually occur throughout the whole of its EOO, which may contain unsuitable or unoccupied habitats. The size of the AOO is a function of the scale at which it is measured. To standardize it, IUCN's Standards and Petitions Subcommittee recommends the use of a grid-based method, performed by overlaying uniform-sized grids of 2×2 km on the range of a species and summing the area of the cells in which the species occurs (IUCN Standards and Petitions Subcommittee, 2016). The applicability of a grid-based AOO measurement is thought to be especially problematic for riverine organisms. River-dwelling organisms have linear ranges, following water courses, a feature that is not captured by grid-based occupancy measurements, which tend to overestimate the size of habitat occupied. This overestimation leads to subsequent misinterpretation of associated extinction risk. This is clearly the case for the Dades trout. The AOO calculated by overlaying a grid of 2×2 km on the range of the species is 40 km^2. However, the area actually occupied by the freshwater channels where the trout lives is c. 5.4 ha (c. 0.05 km^2). This means that 99.9% of the AOO of the Dades trout estimated following IUCN guidelines is composed of unsuitable terrestrial habitats.

A threat category for the Dades trout

The Dades trout is amongst the river salmonids with the smallest distribution globally. Its range has been sampled extensively and is now more fully understood. It is distributed across ≤22 km of stream channels in two isolated locations. The species is threatened as a result of its limited and isolated distribution, and a future decline in its distribution is projected. In our view, the spatial metrics used in the standard IUCN assessment overestimate the distribution of the Dades trout and lead to an underestimation of its extinction risk. Furthermore, the Dades trout, as with other fluvial species, is particularly vulnerable because a threat can rapidly affect the entire area occupied by a population (e.g. a single upstream pollution event could easily affect a

whole river downstream). We propose that the Dades trout should be categorized as Critically Endangered because:

- The estimated EOO is <100 km^2 (after modified measurements), the population is severely fragmented and the species exists in fewer than five locations (a), and a future decline is projected (b) in EOO (i); AOO (ii); area, extent and/or quality of habitat (iii); and in the number of mature individuals (v).

- The estimated AOO is <10 km^2 (after modified measurements), the population is severely fragmented and the species exists in fewer than five locations (a), and a future decline is projected (b) in EOO (i); AOO (ii); area, extent and/or quality of habitat (iii); and in the number of mature individuals (v).

CR B1 ab(i,ii,iii,v) + 2 ab(i,ii,iii,v)

Summary
Strictly observing IUCN guidelines for criterion B, the Dades trout should be categorized as EN B1 ab(i,ii,iii,v) + 2 ab(i,ii,iii,v).

However, we propose a more flexible interpretation of the guidelines, allowing for the ecological soundness of distribution metrics, which leads to the categorization of the species as CR B1 ab(i,ii,iii,v) + 2 ab(i,ii,iii,v).

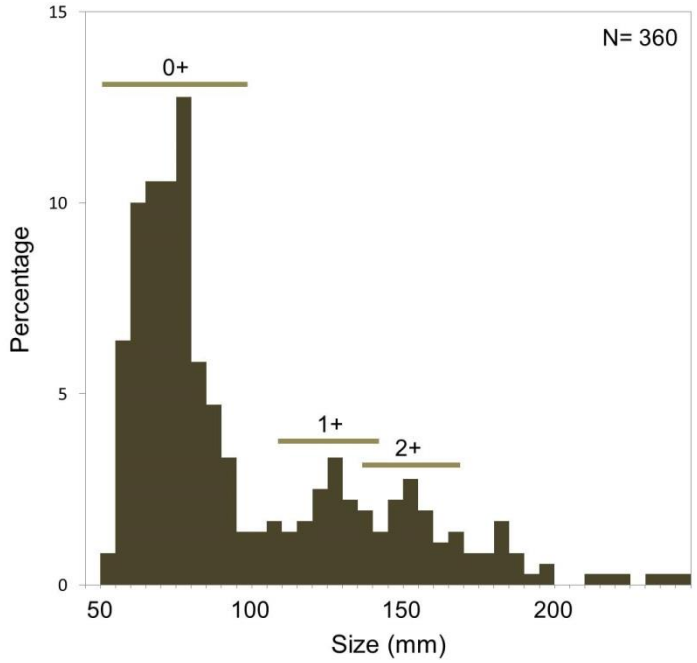

FIG. S1 Distribution of the sizes (total length) of Dades trout *Salmo multipunctata* individuals captured during August 2014. The estimated range of sizes of various cohorts (0+, 1+ and 2+) is indicated.

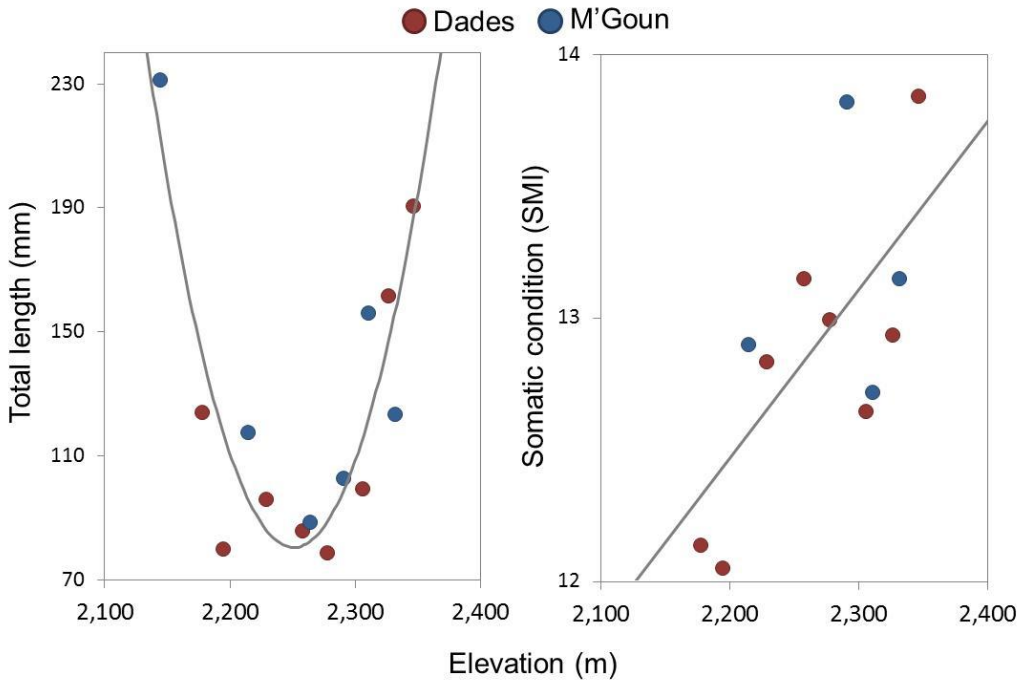

FIG. S2 Mean total length and mean somatic condition (scaled mass index, SMI) of Dades trout in the Dades and M'Goun rivers, according to elevation, within the altitudinal range occupied by the species. Unimodal (left) or lineal (right) relationships are shown in accordance with the results of generalized linear modelling (Table 1).

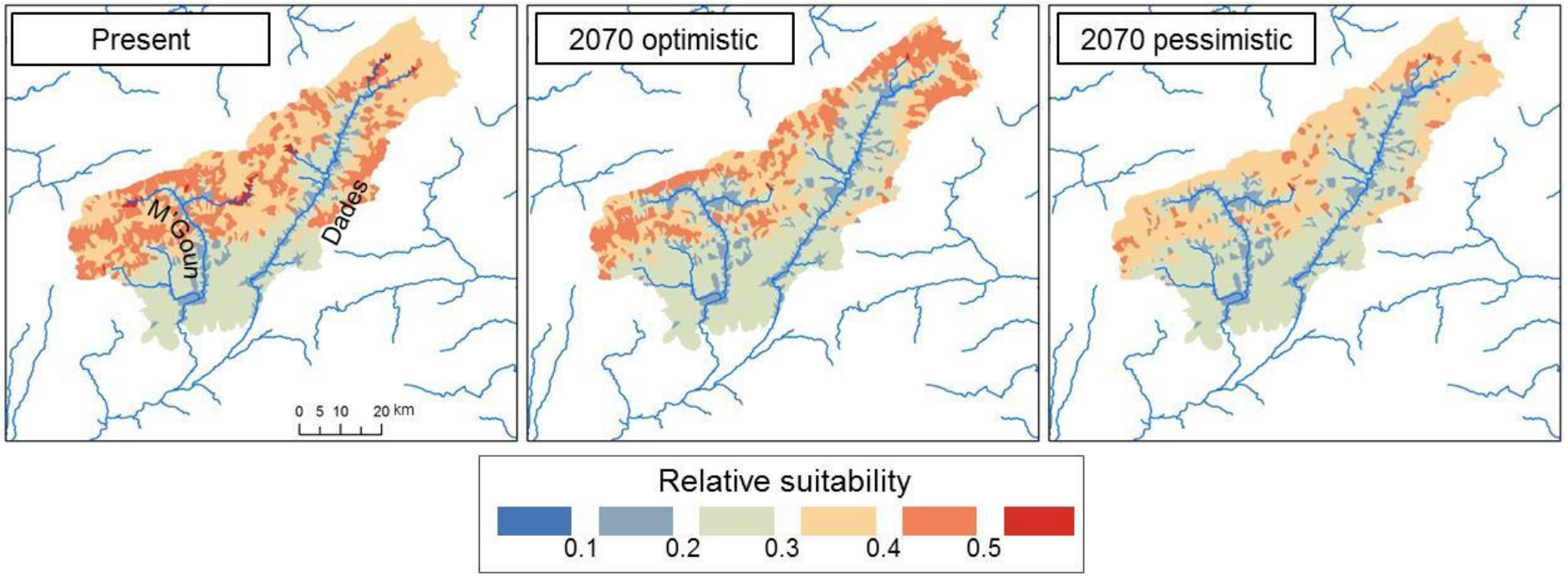

FIG. S3 Estimated present and forecast future habitat suitability for the Dades trout across subcatchment units in the Dades and M'Goun basins. Future suitability is forecast under two contrasting (optimistic and pessimistic) climate scenarios. Suitability is shown only for subcatchments with minimum elevation >1,500 m.

TABLE S1 Details of stream reaches in the Dades and M'Goun basins selected a priori as being potentially suitable for the Dades trout. The selection was based on a minimum elevation of 1,900 m and on the examination of series of aerial photographs to ensure the existence of permanent waters.

Basin	Length (km)	Min. elevation (m)	Max. elevation (m)	Initial Y	Initial X	Final Y	Final X	Sampled	Trout presence/absence
Dades	30	1,900	2,062	31.6121	−5.8607	31.8142	−5.7709	Yes	Absent
Dades	4.5	2,040	2,165	31.6553	−5.8828	31.6568	−5.9181	No	
Dades	14	2,024	2,550	31.6931	−5.8913	31.7561	−5.9951	Yes	Absent
Dades	1.4	2,670	2,734	31.8103	−5.8948	31.8097	−5.9072	No	
Dades	1.8	2,759	2,809	31.8331	−5.8891	31.8421	−5.8999	No	
Dades	1.2	2,178	2,275	31.7623	−5.8451	31.7697	−5.8509	No	
Dades	1	2,028	2,068	31.75	−5.8253			No	
Dades	0.7	2,215	2,215	31.867	−5.7702			No	
Dades	12	2,157	2,373	31.8674	−5.7391	31.9242	−5.6959	Yes	Present
Dades	0.6	2,188	2,188	31.8592	−5.7126			Visited	Absent
Dades	0.6	2,302	2,302	31.8642	−5.6894			Visited	Absent
Dades	4	2,330	2,370	31.8696	−5.6861	31.8828	−5.6681	Yes	Absent
M'Goun	30.5	1,900	2,660	31.5004	−6.1185	31.552	−6.3886	Yes	Present
M'Goun	2.3	2,193	2,360	31.5988	−6.2892	31.5843	−6.2889	Yes	Present
M'Goun	1.2	2,290	2,342	31.583	−6.3261	31.5792	−6.3165	Yes	Present
M'Goun	1.4	2,443	2,505	31.5977	−6.3761	31.5973	−6.3857	No	
M'Goun	5	2,054	2,306	31.6249	−6.2101	31.6461	−6.1788	No	
M'Goun	10.5	1,953	2,174	31.5906	−6.1832	31.6412	−6.1343	Visited	Absent
M'Goun	4.3	2,053	2,212	31.6109	−6.1347	31.6276	−6.1071	Visited	Absent
M'Goun	18	2,111	2,523	31.6028	−6.124	31.6481	−6.0166	No	
M'Goun	10.3	2,121	2,760	31.5021	−6.2768	31.5151	−6.3652	Yes	Absent
M'Goun	12.6	1,912	2,246	31.4152	−6.30049	31.4486	−6.3867	No	

TABLE S2 Habitat variables recorded at each surveyed site, and their relationships (factor loadings) with the two main gradients of variations in habitat features (Size–PC1 and Vegetation–PC2), as defined through a principal components analysis. Factor loadings >0.5 in absolute values are shown in bold. Factor loadings <0.33 in absolute values are not shown.

Variable	Unit, transformation	Size–PC1	Vegetation–PC2
Mean channel width	m	**0.80**	
Riparian woody cover	%		**0.83**
Riparian herbs cover	%	-0.46	**0.62**
Rocky shores	%		**−0.61**
Mean depth	cm	**0.82**	0.44
Maximum depth	cm	**0.62**	0.48
Substrate	Adapted Wentworth scale (1–8)	**0.54**	
Water velocity	Semi-qualitative scale (0–2)	**0.63**	
Periphyton cover	Semi-qualitative scale (0–2)		
Aquatic vegetation cover	Semi-qualitative scale (0–2)	**−0.51**	0.45
Relative temperature	°C, residuals of the regression of measured temperature on solar time of the day	−0.36	
Conductivity	$\mu S\ cm^{-1}$, square-root transformed		
Eigenvalue		3.01	2.34
% variance		25.1	19.5