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Local extinctions and range contraction of the endangered *Coenagrion mercuriale* in North Africa

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Freshwater biodiversity is currently threatened worldwide. In North Africa, 24.4% of Odonata are regionally threatened with extinction. In this region, freshwater resources are particularly scarce and an increasing shortage of water is expected. To better understand the current threats to the endangered North African damselfly *Coenagrion mercuriale* we updated information on extinct and extant populations in North Africa and characterized these localities with regard to their topography, climate and anthropogenic use (anthrome). The *C. mercuriale* populations are being lost and this damselfly is experiencing range contraction. In Morocco nearly 45% of the populations have become extinct in recent decades and in Tunisia a single extant population remains. This species, which occupied predominantly areas of high value for human settlement, is now mainly restricted to high altitude areas. Nevertheless, the extant populations remain under threat of extinction due to increasing demand for water, changes in agricultural practices and land conversion.

Keywords: anthromes; climate; conservation; Coenagrionidae; dragonfly; freshwater biodiversity; Morocco; Odonata; Tunisia; water demand

Introduction

Freshwater biodiversity is seriously threatened worldwide and is the over-riding conservation priority during the International Decade for Action – 'Water for Life' – 2005 to 2015 (e.g. Dudgeon et al., 2006; Vörösmarty et al., 2010). The preservation of freshwater diversity is more important than preserving individual species because of the impact freshwater biodiversity has through promoting economic development and the maintenance of ecosystem services (Sullivan & Meigh, 2005; United Nations Development Programme, 2006). Vörösmarty et al. (2010) estimated that nearly 80% of the world's population is exposed to high levels of threat to water

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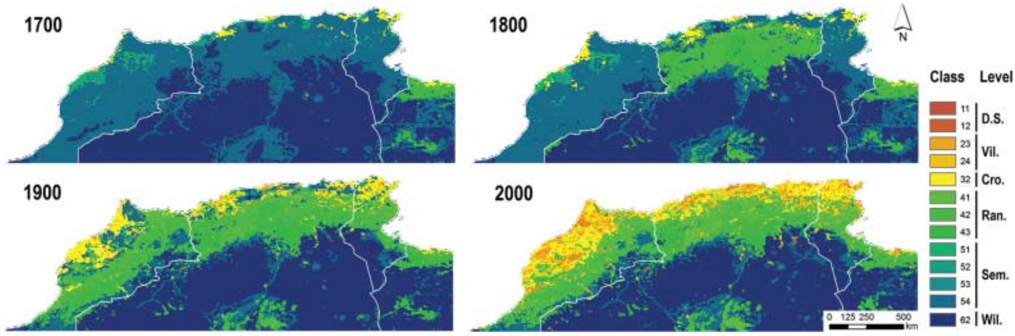

Figure 1. Temporal dynamics in anthropogenic biomes (1700–2000) in the study area. Acronyms represent anthrome levels: D.S., Dense Settlements; Vil., Villages; Cro., Croplands; Ran., Rangelands; Sem., Seminatural; Wil., Wildlands. Numbers represent anthrome classes (designation in Table 2). Adapted from Ellis et al. (2010).

security. Moreover, geographic areas with little or no technological investments are the most vulnerable to water security and biodiversity threat risks. The Middle East and North Africa (MENA) region represents the most water-scarce region in the world, with one half of the population living under conditions of water stress and the per capita water availability expected to halve by 2050 (Droogers et al., 2012). Droogers et al. (2012) estimated that 78% of the water shortage was likely to be as a consequence of changes in socioeconomic factors with only 22% attributable to climate change, highlighting the massive impact of human activities on water availability.

Humans have restructured the terrestrial biosphere for a number of uses, such as agriculture, forestry and urbanization (Foley et al., 2005; Matson, Parton, Power, & Swift, 1997; Vitousek, Mooney, Lubchenco, & Melillo, 1997), leading to changing patterns of land-surface hydrology, biogeochemical cycles, primary productivity and species' composition and abundance. Ellis and colleagues (Ellis, Goldewijk, Siebert, Lightman, & Ramankutty, 2010; Ellis & Ramankutty, 2008) characterized terrestrial biomes based on global patterns of sustained, direct human interaction with ecosystems and designated them as anthromes or anthropogenic biomes. The observed changes in anthromes in the last four centuries reveal a rapid conversion of wilderness areas to human settlements, following the increase of the human population. The Mediterranean basin has been inhabited by humans for thousands of years (Blondel, Aronson, Bodiou, & Boeu, 2010), leading to marked impacts on the ecosystems therein. Major changes in human population numbers were observed in the northern Maghreb between 1900 and 2000, with the Moroccan population increasing more than sixfold, the Algerian population increasing more than sevenfold and the Tunisian population increasing more than fivefold (Fargues, 1986; Taboutin, Vilquin, & Biraben, 2002). For instance, the northern Maghreb in 1700 was mostly occupied by Wildlands and Seminatural anthromes (Figure 1), but by 2000, those anthrome classes had almost disappeared, giving rise mainly to Rangelands and Croplands, but also to Villages and Dense Settlements (Figure 1). Moreover, these anthropogenic changes were not gradual; their rate increased over time and the gains observed in any of the classes Rangelands, Croplands, Villages and Dense Settlements were due to intensification of land use and increase of human population densities, to the detriment of more natural areas (Ellis et al., 2010). The negative impacts on biodiversity are in need of quantification.

As result of human-mediated changes, North African odonates are currently under a threat of extinction (García, Cuttelod, & Malak, 2010; Juffe-Bignoli & Darwall, 2012). Of the 82 North African odonate species assessed by IUCN in 2010, nearly a quarter are threatened with extinction at the regional scale, and a further 10% are Near Threatened (Samraoui et al., 2010). The major causes behind these species' decline were habitat loss and degradation, largely due to water abstraction and dam construction, together with pollution.

Coenagrion mercuriale (Charpentier, 1840) is a Western Palaearctic damselfly, present in Western Europe (Austria, Belgium, France, Germany, Italy, Liechtenstein, Luxembourg, Netherlands, Portugal, Spain, Switzerland and UK) and North Africa (Morocco, Algeria and Tunisia). At the global level the species is considered as Near Threatened and in North Africa this species is classified at regional level as Endangered due to its small area of occupancy, fragmented population and ongoing population declines (Samraoui et al., 2010). It is present in lotic habitats such as small brooks and springs with abundant water and riparian vegetation (Jacquemin & Boudot, 1999). The distribution of *C. mercuriale* in Morocco, where two-thirds of all known populations are found, is described in Jacquemin & Boudot (1999), with additions from El Haissoufi, Bennas, L'Mohdi, & Millán (2010) and Boudot & De Knijf (2012), yielding a total of 29 localities. This species has been recorded from only six localities in Tunisia (Boudot et al., 2009; Dumont, 1977; Gadeau de Kerville, 1908; van Helsdingen, Willemse, & Speight, 1996; and Paul Schrijvershof in litt.), of which only two localities have records of *C. mercuriale* being present after 2000: Dougga (in an archaeological site 5 km SSW Teboursouk) and Oued el Gdim. In Algeria only nine localities inhabited by *C. mercuriale* have been recorded (Khelifa et al., 2011; Mahdjoub et al., 2014; Martin, 1910; Morton, 1905; Samraoui & Corbet 2000; Samraoui & Menaï 1999; Selys-Longchamps 1871; van Helsdingen et al., 1996). The IUCN red list assessment of *C. mercuriale* in North Africa lists four populations in Morocco, five in Algeria and three in Tunisia as probably extinct (Samraoui et al., 2010).

In the present work we studied *C. mercuriale* distribution in North Africa and quantified the environmental and anthropogenic variability of potential habitats in northern Morocco to address three main objectives. (1) To update the distribution of *C. mercuriale* in North Africa and address the question of whether local extinctions have occurred and if there is any underlying geographical pattern. (2) To characterize the topoclimatic variability of northern Morocco, and compare it with that of the localities with records for this taxon; we predict a reduction of the area of occupancy of the extant populations in comparison with the area of occupancy of historic (extant and extinct) populations. (3) To characterize the variability in anthromes in northern Morocco; we predict that populations that had become extinct were in anthromes with dense human settlements and intensive land use. Our results provide insights on the current conservation status of *C. mercuriale* and frame it in an environmental and anthropogenic context.

Methods

Fieldwork

Three visits to North Africa were made during the middle of the *C. mercuriale* flying season, when the greatest numbers of adults can be observed. There were two visits to Morocco (June 2011, June 2012) totalling 36 days; and one visit of seven days to Tunisia (end of May 2012). Two people visited the localities from which previous records of *C. mercuriale* were available and searched those sites and additional streams, brooks and wetlands in the surrounding areas. Each location was sampled for up to one hour, depending on the complexity of the habitat, accessibility, and dimensions of the water body. Localities were considered to have extant populations when adult specimens of *C. mercuriale* were found (including observations of single specimens) and considered to have extinct populations when the species had been recorded from that locality previously but no specimens were found and unsuitable conditions were observed. The conditions that were considered unsuitable were: dry water course, no permanent water available,

Table 1. Localities visited in Morocco in the present study.

Locality	Latitude	Longitude	Reference	Population	Alt. (m)	H.P.D. 2000	Anthrome			
							1700	1800	1900	2000
Oued 1 km N Tammast 70 km SE Marrakech	31° 3’ 35.8” N	7° 41’ 0.1” W	New locality	Extant	2166	25	54	54	42	41
Ponds and marshes 2.5 km N of the Zad Pass on road Azrou to Midelt	33° 1’ 49.6” N	5° 4’ 9.0” W	New locality	Extant	2133	40	54	54	41	41
Aguelmane Sidi Ali	33° 4’ 32.0” N	4° 59’ 58.8” W	Jacquemin & Boudot 1999	Extant	2075	42	54	54	42	41
Oued Amalouk in the upper catchment of Oued Guigou	33° 5’ 59.7” N	5° 5’ 36.3” W	Boudot & De Knijf 2012	Extant	2054	39	54	54	42	41
Oued Guigou 9.5 km S Timhadite	33° 8’ 56.4” N	5° 3’ 30.7” W	New locality	Extant	1923	39	54	54	42	41
Aguelmane n’Tifounassine	33° 9’ 14.3” N	5° 5’ 44.7” W	Jacquemin & Boudot 1999	Extant	1914	39	54	54	42	41
Oued Guigou 6 km south of Timahdite along the N 13 (P = 21)	33° 10’ 36.2” N	5° 4’ 21.7” W	Jacquemin & Boudot 1999	Extant	1886	39	54	54	41	41
Oued Guigou south of Timahdite	33° 11’ 20.5” N	5° 3’ 50.0” W	Boudot & De Knijf 2012	Extant	1880	39	54	54	41	41
Oued Guigou 4.5 km south of Timahdite along the N 13 (= P 21)	33° 11’ 33.5” N	5° 3’ 52.9” W	Boudot 2008	Extant	1871	39	54	54	41	41
Oued Aguersit 14 km NNW Boumia	32° 50’ 29.9” N	5° 9’ 50.7” W	New locality	Extant	1784	42	54	54	42	41
Southern branche of Oued Fellat below Aït Badi 15.5 km WNW of the Col du Zad; forest area	33° 1’ 56.5” N	5° 14’ 12.2” W	Boudot & De Knijf 2012	Extant	1784	39	54	54	42	32
Tizi n’Znou;Spring and rivulet on Eastern bank of Oued Ansegmir about 500 m below the bridge	32° 31’ 13.7” N	5° 4’ 47.2” W	Boudot & De Knijf 2012	Extant	1704	42	54	54	42	41
Road to Almis des Marmouchas 30 km W Outat Oulad El Hadj	33° 22’ 27.1” N	4° 1’ 20.2” W	Boudot & De Knijf 2012	Extant	1698	13	54	54	42	42
Oued Kiss E side of Tizi n’Rechou between Boumia to Karrouchane	32° 46’ 6.4” N	5° 12’ 3.2” W	Jacquemin & Boudot 1999	Extant	1645	42	54	54	42	41
Oued Bouhets 14 km N Boumia	32° 51’ 16.9” N	5° 4’ 37.1” W	New locality	Extant	1622	42	54	54	41	24

Tributary of Oued Tizguit 2 km NNE Ifrane	33° 32’ 57.8” N	5° 5’ 48.8” W	New locality	Extant	1606	41	52	52	32	23
Valley of Oued Tizguit 1.5 km N Ifrane	33° 33’ 10.4” N	5° 6’ 43.1” W	New locality	Extant	1580	41	52	52	32	23
Valley of Oued Tizguit 1.5 km NW Ifrane	33° 33’ 6.6” N	5° 6’ 42.6” W	New locality	Extant	1577	41	52	52	32	23
Oued Tizguit at Val d’Ifrane	33° 33’ 14.3” N	5° 6’ 55.4” W	Jacquemin & Boudot 1999	Extant	1560	41	52	52	32	23
Dayet Iffer at NE d’Ifrane	33° 36’ 28.5” N	4° 54’ 34.1” W	Dumont 1972	Extant	1536	50	54	54	41	41
Oued Boulajoul at bridge on road P 21 SE of Col du Zad	32° 52’ 48.0” N	4° 57’ 13.0” W	Jacquemin & Boudot 1999	Extant	1477	42	54	54	42	41
12 km east of Khenifra, tributary of oued Chbouka	32° 55’ 35.0” N	5° 33’ 31.7” W	Ferreira et al. 2014	Extant	1151	42	54	54	54	32
Brook 500 m N Maijo (= Laiaden) 8.8 km SE Chefchaouen	35° 6’ 42.2” N	5° 11’ 20.2” W	New locality	Extant	790	101	54	54	54	23
Brook 28 km E Meknes	33° 53’ 29.5” N	5° 14’ 33.1” W	New locality	Extant	653	88	54	54	54	31
Midelt	32° 41’ 36.9” N	4° 44’ 43.6” W	Jacquemin & Boudot 1999	Extinct	1437	42	54	54	41	24
Oued Bou Ijdjii south S 303, between the springs of the Oued Oum Er Rbia et l’Aguelmane Azigza	33° 1’ 32.9” N	5° 28’ 34.8” W	Jacquemin & Boudot 1999	Extinct	1403	42	54	54	54	32
Chefchaouen; Jbel Khizana; Bouztate; complex of springs, streams and swamps at 15 Km from Fifi	35° 0’ 13.2” N	5° 12’ 4.1” W	El Haissoufi et al 2010	Extinct	1304	101	54	54	54	23
Oued Gheraia (Assif n’Ighighayane) downstream of Asni	31° 16’ 13.0” N	7° 57’ 43.5” W	Lieftinck 1966	Extinct	1098	78	54	54	42	32
Aïn (ayn) Atrouss about 20 km SW from Fès on the road to Al Hajeb (Hajab)	33° 57’ 54.0” N	5° 10’ 6.2” W	Jacquemin & Boudot 1999	Extinct	446	88	54	54	32	23
Oued Mda along the P 23, 20 km W from Ouezzane	34° 48’ 41.2” N	5° 47’ 4.1” W	Jacquemin & Boudot 1999	Extinct	160	162	54	54	32	32
Aïn (ayn) Deffali: swamp, springs and oueds along the P 28, 12-15 km N of the village	34° 41’ 38.0” N	5° 34’ 28.5” W	Jacquemin & Boudot 1999	Extinct	120	162	54	54	32	32

(*Continued*).

Table 1. Continued

Locality	Latitude	Longitude	Reference	Population	Alt. (m)	H.P.D. 2000	Anthrome			
							1700	1800	1900	2000
Arbawa (oued Khefecha spring and small marsh)	34° 54’ 22.1” N	5° 54’ 57.2” W	Jacquemin 1994; Jacquemin & Boudot 1999	Extinct	90	226	54	54	32	32
Oued Moulouya at “Pont International”, at P 27 near Machra Safsaf (Çafçaf)	34° 54’ 54.2” N	2° 37’ 30.1” W	Jacquemin & Boudot 1999	Extinct	43	118	52	52	51	31
Oued Akrach S from Rabat down from the road towards Aïn el Aouda (Ayn al Awda)	33° 54’ 20.7” N	6° 48’ 47.3” W	Jacquemin & Boudot 1999	Extinct	39	1966	51	51	51	32
Tributary of the oued Loukkos between Ksar El Kebir and Larache 16 km NW Larache	35° 3’ 30.4” N	6° 4’ 3.4” W	Ocharan 1992	Extinct	19	179	54	32	32	32
Tétouan	35° 32’ 52.9” N	5° 25’ 49.0” W	Navas 1934	Extinct	14	214	54	54	54	23
Estuary of the Oued Loukkos (Lekkous) near Larache (al Arach)	35° 12’ 20.2” N	6° 8’ 9.5” W	Jacquemin & Boudot 1999	Extinct	1	179	54	32	11	11

Table 2. Topoclimatic and anthrome factors (1900 anthromes grid) used for the characterization of the environmental and anthrome variability of northern Morocco.

Code	Description	Units	Range (min–max)
ALT	Altitude	m	–64–4016
SLOP	Slope	%	0–67.8
ATEM	Annual average temperature	°C	8–242
MTEM	Minimum temperature of coldest month	°C	–150–13.2
PWET	Precipitation of wettest month	mm	8–205
TWAR	Maximum temperature of warmest month	°C	220–461
APRE	Annual average total precipitation	mm	33–1182
PDRI	Precipitation of driest month	mm	0–29
TSEA	Temperature seasonality	Dimensionless	1635–8240
PSEA	Precipitation seasonality	Dimensionless	19–110
TAR	Temperature annual range	°C	109–420
11	Urban (distance to)	°	0–6.03
12	Mixed Settlements (distance to)	°	0–3.55
23	Rainfed Villages (distance to)	°	0–4.45
24	Pastoral Villages (distance to)	°	0–3.96
32	Residential Rainfed Croplands (distance to)	°	0–3.82
41	Residential Rangelands (distance to)	°	0–2.21
42	Populated Rangelands (distance to)	°	0–1.50
43	Remote Rangelands (distance to)	°	0–3.10
51	Residential Woodlands (distance to)	°	0–5.01
52	Populated Woodlands (distance to)	°	0–4.56
53	Remote Woodlands (distance to)	°	0–6.79
54	Inhabited Treeless & Barren Lands (distance to)	°	0–0.82
62	Wild Treeless & Barren Lands (distance to)	°	0–3.98

eutrophic standing waters, polluted waters, concrete irrigation channels (without any sediment or vegetation). Locality coordinates were georeferenced with a GPS (Table 1, Figure 2).

All localities ($n = 6$) with recorded populations in Tunisia were visited (Figure 2). In Morocco we visited nearly 90% of the localities ($n = 26$, Table 1) with previous records of *C. mercuriale* but, due to time constrains, we were not able to visit the localities Jbel Outka and Oued Sidi Raba (Jacquemin & Boudot, 1999) (Figure 2).

Environmental factors

Two sets of environmental factors or ecogeographical variables (EGV) were selected to characterize environmental variability (Table 2). These sets included one topographical grid (USGS, 2006) that was used to derive the variable Slope, with the "Slope" function of ArcGIS v.10.1 (ESRI, 2012), and nine climate grids (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005). All EGVs had an original square pixel size of 30 arc-sec (about 1 × 1 km). Altitude values of extant and extinct localities were extracted by intersecting localities with the altitude grid using the "Extract Multi Values to Points" tool of ArcGIS v.10.1 (ESRI, 2012).

Anthropogenic factors

To characterize anthrome variability, we used the anthromes grid corresponding to the year 1900 – square pixel size of 5 arc-min (about 10 × 10 km) (Ellis et al., 2010). To convert the categorical anthromes variable into continuous variables, one binary grid was created for each anthrome present in the study area. The Euclidean distance of each grid cell to the closest anthrome was calculated for each individual anthrome (13 anthrome types; Table 2) using the "Euclidian Distance" tool of ArcGIS v.10.1 (ESRI, 2012). Additionally, we used two anthromes

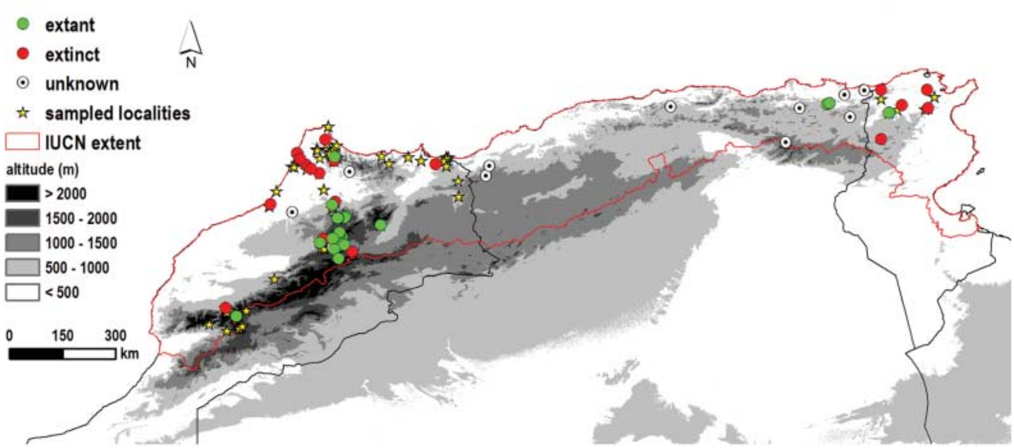

Figure 2. Distribution of *Coenagrion mercuriale* in the study area, including population status (extant, extinct or unknown), sampled localities without *C. mercuriale* records or observations, and the known extent of occurrence in North Africa according to IUCN (Odonata Database Africa, 2006). The Algerian population was classified as extant based on the work of Khelifa et al. (2011) and Mahdjoub et al. (2014).

grids (1900 and 2000) (Ellis et al., 2010) to quantify the availability of anthromes by century in northern Morocco (latitude above 27° 39.0′N) and identify which anthromes *C. mercuriale* populations occupy. Anthrome classes of extant and extinct localities in 1900 and 2000 were extracted by intersecting localities with the corresponding anthromes grid using the "Extract Multi Values to Points" tool of ArcGIS 10.1 (ESRI, 2012). Additionally, human population density values in 2000 were extracted for extant and extinct localities by intersecting localities with the correspondent Population Density Grid, v.3 (CIESIN & CIAT, 2005).

Two spatial principal components analysis were performed with the principal components analysis extension of ArcGIS v.10.1 (ESRI, 2012), to depict the topoclimatic (hereafter PCAtc) and anthrome (hereafter PCAa) variability of the study area. The PCAtc included 11 variables: ALT, SLOP, ATEM, MTEM, PWET, TWAR, APRE, PDRI, TSEA, PSEA and TAR (Table 2). The PCAa included 13 variables: 11, 12, 23, 24, 32, 41, 42, 43, 51, 52, 53, 54 and 62 (Table 2). For representation purposes, the values of the two first two principal components (PC1 and PC2) of each analysis were extracted to each 10 × 10 km square of northern Morocco by intersecting the centroid of each square with the PC1 and PC2, and plotted in the corresponding graph characterizing the variability of the study area. PC1 and PC2 values of extant and extinct localities were extracted by intersecting localities with the PC1 and PC2 grids respectively using the "Extract Multi Values to Points" tool of ArcGIS v.10.1 (ESRI, 2012).

Results

We recorded local extinctions and verified a range contraction of the endangered *Coenagrion mercuriale* in North Africa. In Tunisia, only one population of *C. mercuriale*, from the six previously recorded localities, was classified as extant (Oued el Gdim, Figure 2). Despite the 2009 records of *C. mercuriale* in Dougga, no specimens of any dragonfly species were found, in spite of good weather conditions and apparent habitat suitability for *C. mercuriale* and other odonates. The stream in Dougga was dry in parts of the water course and water flow might have been diverted for an extended period of time during construction works, moreover there was water extraction for domestic use. Water extraction for human consumption or irrigation was observed

Table 3. Number and percentage of *Coenagrion mercuriale* localities by anthrome class and anthrome classes availability (number of 10 km squares and percentage) in northern Morocco.

	Coenagrion mercuriale			Availability in Morocco	
	1900	2000			
Anthrome class	Known (%)	Extant (%)	Extinct (%)	1900 (%)	2000 (%)
11: Urban	1 (2.70)		1 (7.69)	7 (0.13)	26 (0.47)
23: Rainfed Villages		5 (20.83)	3 (23.08)	64 (1.16)	400 (7.23)
24: Pastoral Villages		1 (4.16)	1 (7.69)	9 (0.16)	162 (2.93)
31: Residential Irrigated Croplands		1 (4.16)	1 (7.69)		90 (1.63)
32: Residential Rainfed Croplands	9 (24.32)	2 (8.33)	7 (53.85)	722 (13.04)	895 (16.17)
41: Residential Rangelands	7 (18.92)	14 (58.33)		530 (9.57)	942 (17.02)
42: Populated Rangelands	12 (32.43)	1 (4.16)		1439 (25.99)	1318 (23.81)
51: Residential Woodlands	2 (5.41)			93 (1.68)	
54: Inhabited Treeless & Barren Lands	6 (16.21)			1438 (25.98)	770 (13.91)
Other anthromes				1234 (22.29)	933 (16.85)
Total	37 (100.00)	24 (100.00)	13 (100.00)	5536 (100)	

in Tunisia at nearly all water bodies seen during sampling. In Morocco, we found 24 extant localities of which 11 represent new records for *C. mercuriale*. One of the new populations found (Oued 1 km N Tammast 70 km SE Marrakech) is now the southernmost population known (latitude 31° 3.6′N, Table 1, Figure 2). It is the furthest new locality from previous records (35 km straight line). All other localities are within the vicinity of previous records ($<$ 15 km straight line). Thirteen previously known populations were considered extinct (Table 1, Figure 2). Currently this taxon is found mainly ($>$ 95% of localities) at altitudes above 1500 m asl (Figures 2, 3) mostly in the Middle Atlas mountain range, while lowland ($<$ 500 m asl) populations were extirpated.

The quantification of the availability of anthromes by century in northern Morocco revealed a reduction in wilderness areas and an increase in human populated areas (Figure 1, Table 3). In 1900, 35% of northern Morocco anthromes were Wildlands and Seminatural Lands, 50% were Rangelands and 13% Croplands, with Villages and Dense Settlements occupying less than 2% of the land (Ellis et al., 2010). By 2000, Villages and Dense Settlements represented more than 14% and Croplands 20% of anthromes. Wildlands and Seminatural Lands percentage was reduced to half in a century, while Rangelands registered a small decrease, as conversion of Rangelands to more human-dominated anthromes was balanced by the loss of wilder areas.

The conversion of lands from wilder areas to more human populated areas took place at the localities where *C. mercuriale* has been recorded. In 1900, 22% of the localities with records of *C. mercuriale* were located in Seminatural Lands, 51% in Rangelands and 24% in Croplands. In 2000, no populations of *C. mercuriale* were known to occur in Seminatural Lands. Extant populations occurred mainly in Rangelands (62%), and then in Croplands (12%) and in Villages (25%). Extinct populations of *C. mercuriale* used to occur in areas occupied by Croplands (62%), Villages (30%) and Urban areas (8%) in 2000, and generally were in areas with higher human densities than the localities with contemporary extant populations (Table 3, Figure 3A, 3B).

We recorded extinction of populations of *C. mercuriale* in areas where land conversion took place and also in areas in which there was no change in the anthrome class during the last century. All previously recorded populations of *C. mercuriale* at low altitudes ($<$ 500 m asl) that we visited in Morocco were extinct (Figure 3); it is notable that, of these localities, only a few had

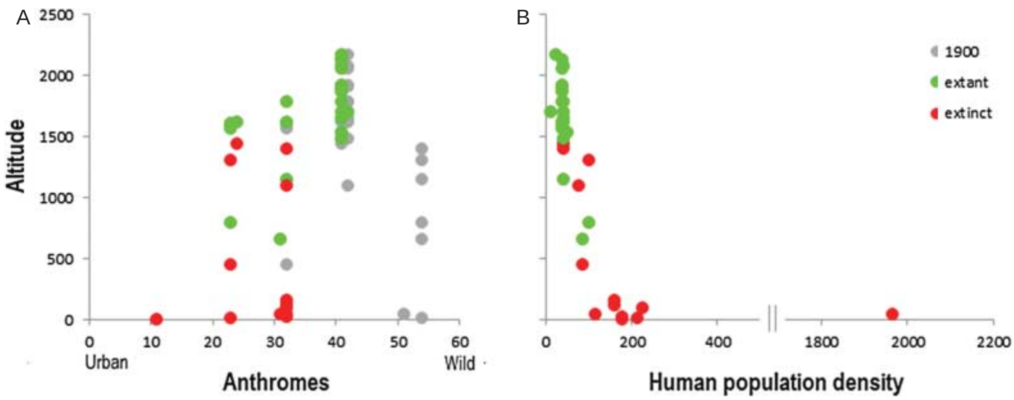

Figure 3. Localities with extant and extinct *Coenagrion mercuriale* populations in northern Morocco according to variation in (A) anthrome classes and altitude, and (B) human population density and altitude (anthromes class designation in Table 2). Grey dots (1900) represent 1900 anthrome classes of all localities with population records. Detailed information on anthrome class changes from 1900 to 2000 is presented in Table 1.

changed from Seminatural Lands to Cropland or Villages, while the majority were already used as Croplands by 1900, being under continued human pressure for a long time (Figure 3A). In higher altitudes (i.e. 500–1500 m asl), we observed more marked changes in anthromes in localities with records of *C. mercuriale*, with all ($n = 5$) Seminatural Lands transformed to Croplands or Villages that was associated with the loss of 50% of the known populations. Above 1500 m asl some changes in anthromes were observed also; within Rangelands there was an increase of human density with most Populated Rangelands localities being converted in Residential Rangelands. In some cases, Rangelands were converted to Croplands and some Croplands were converted to Villages, in which populations of *C. mercuriale* become more prone to extinction due to increased water demand (Figure 3A).

A subset of the available topoclimatic and anthrome conditions of the study area is currently occupied by extant populations, and this subset is smaller than the one that known populations of *C. mercuriale* (extinct + extant) occupied prior to our survey (Figure 4). The two first axes of the topoclimatic and anthrome PCAs explained 79.1% and 63.9% of the topoclimatic and anthrome variability, respectively (Table 4) and were used to summarize topoclimatic and anthrome variability of Northern Morocco (Figure 4A, B). *Coenagrion mercuriale* seems to be absent in areas of high temperatures (either maximum temperature of warmest month > 36°C or annual average temperature > 20°C) and it is present in localities exhibiting high precipitation (either annual average total precipitation > 270 mm or total precipitation of wettest month > 35 mm) in the study area (Figure 4A, Table 4). The current situation is that most of the populations are extinct in areas with variable precipitation, while most of the populations in localities with variable year temperature (the variables temperature seasonality and temperature annual range) persist (Figure 4A). In 1900, *C. mercuriale* was mostly present in open areas with high primary productivity anthromes (Figure 4B) and absent in Wild Treeless & Barren Lands.

Discussion

Coenagrion mercuriale is currently facing major range contraction in North Africa, with our detailed surveys indicating that nearly half of the known populations have become extinct over

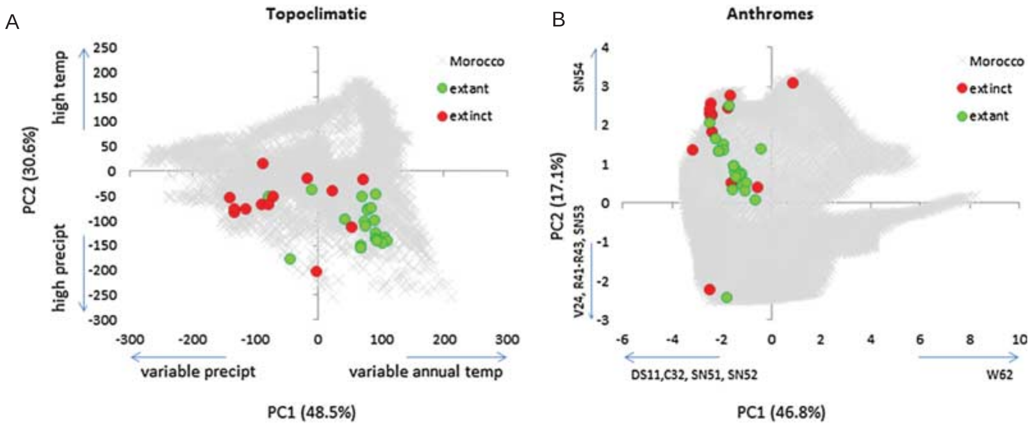

Figure 4. Localities with extant and extinct *Coenagrion mercuriale* populations according to variability in topoclimatic variables (A) and anthrome classes in 1900 (B), in northern Morocco. Topoclimatic and anthrome variability measured by principal component analysis (PCA). Localities are displayed over the first two axes of the PCA and percentage of explanation of each axis is given. Interpretations of the factors expressed in each axis are provided (see Table 2 for codes of anthrome classes).

the past few decades. This species is currently known to exist as a single population in Tunisia, and in Morocco a reduction of 45% from previously known populations was observed. The contemporary status of the Algerian populations remains unknown, with exception of one extant population in the Seybouse River (Khelifa et al., 2011; Mahdjoub et al., 2014).

In northern Morocco, no extant population of *C. mercuriale* was found at low altitudes, most probably due to habitat degradation as result of human pressure in that region. Recent extinctions of lowland populations have been suggested in other organisms with similar distributional ranges, e.g. Lataste's viper, *Vipera latastei* (Brito et al., 2011). Population extinctions took place in both unchanged and converted land during the last century. Extinctions of populations located in low altitude Croplands might be result of long term effects of variations in water regimes and degradation of water quality. On the other hand, the fact that some populations that were in Seminatural Lands in 1900 are presently located in Croplands might indicate that the land conversion was recent and shows some degree of resilience in *C. mercuriale.* These extant populations of *C. mercuriale* might represent opportunities for conservation if swift action was to be taken. However, conservation in Croplands is unlikely to be implemented, let alone be successful, given the high demand for water for agricultural use that results in frequent stream diversions and, intermittent flows, as this species requires permanent slow-flowing water. Nevertheless local solutions should be investigated urgently, aiming for the conservation of those freshwater communities within the Cropland anthromes. An example of one such community lies in the tributary of Oued Chbouka, near Khenifra, as this place not only hosts a thriving population of *C. mercuriale* but is also the only known location of *Onychogomphus boudoti*, a recently described critically endangered odonate (Ferreira et al., 2014).

Although high altitude populations of *C. mercuriale* were apparently less affected by local extinction, in comparison to low altitude populations, evidences of several conservation threats were also observed at higher altitudes. Most of the Rif and portions of the Middle Atlas were Seminatural Lands in 1900 and have been converted to Croplands or Villages, leading to the extinction of at least four populations. The need to feed a rapidly growing human population has been leading to the conversion of wilder areas into Croplands. In addition to fruit and vegetable cultivation, the production of cannabis, once traditional and restricted to certain areas of the Rif

Table 4. Loading scores on the first three axes (PC) of two principal components analyses, one for topoclimatic data (above) and one for anthrome data (below).

Topoclimatic data % Eigen values	PC1 48.541	PC2 30.608	PC3 13.148
Altitude	0.325	–0.217	–0.246
Slope	0.060	–0.148	–0.023
Annual average total precipitation	0.015	–0.512	0.481
Precipitation of driest month	0.170	–0.173	–0.179
Precipitation seasonality	–0.338	0.156	0.299
Precipitation of wettest month	–0.061	–0.427	0.538
Annual average temperature	–0.141	0.392	0.224
Temperature annual range	0.515	0.145	0.205
Maximum temperature of warmest month	0.276	0.438	0.400
Minimum temperature of coldest month	–0.331	0.214	0.115
Temperature seasonality	0.522	0.141	0.177
Anthrome data	PC1	PC2	PC3
% Eigen values	46.819	17.053	11.803
11: Urban	0.382	–0.102	–0.019
12: Mixed Settlements	0.116	–0.151	0.537
23: Rainfed Villages	0.005	0.002	0.001
24: Pastoral Villages	0.048	0.326	0.416
32: Residential Rainfed Croplands	0.357	0.144	0.116
41: Residential Rangelands	0.180	0.297	0.301
42: Populated Rangelands	0.036	0.318	0.190
43: Remote Rangelands	–0.267	0.514	–0.072
51: Residential Woodlands	0.369	–0.080	0.193
52: Populated Woodlands	0.378	0.089	–0.014
53: Remote Woodlands	0.239	0.481	–0.517
54: Inhabited Treeless & Barren Lands	–0.091	–0.333	–0.089
62: Wild Treeless & Barren Lands	–0.512	0.171	0.286

(Ketama, Bab Berret), has expanded, and large areas in the north of Morocco are now being used for its production (Chouvya & Afsahib, 2014; Labrousse & Romero, 2001). Fertile land is being allocated to cannabis cultivation and it is progressing towards the rich agricultural areas, at the expense of food products. In parallel, the production of *Kif*, the local cannabis variety adapted to the dryness of the Rif region, is being replaced by water-intensive monoculture of hybrids (Chouvya & Afsahib, 2014). These changes alter the water regimes of the local streams, intensifying the water scarcity problem of the region. Further research on the status of populations in the Rif is urgently needed as during our fieldwork only a single specimen of *C. mercuriale* could be found in the Rif in a stream running between cannabis fields. In the Middle Atlas the populations of *C. mercuriale* are numerous and conflicts between human activities and its conservation are less evident. This is mostly because many locations remain in areas of Rangelands, where human pressure and water demand remain limited.

In both time frames (1900 and 2000), *C. mercuriale* principally occupied areas of high value for human settlement: Residential Rangelands and Croplands, which are preferred also for human settlement and agriculture (Ellis & Ramankutty, 2008). *Coenagrion mercuriale* populations typically occupy small rivers, brooks, streams and springs with aquatic and riparian vegetation, favouring areas of reduced slope (slow flowing water courses). These habitat characteristics are found mostly in fertile valleys and floodplains, which are typical of areas widely used as Croplands (Daily, 1999; Ellis & Ramankutty, 2008; Huston, 1993). The areas of wilderness in northern Morocco are located mainly in the south and south-east of the study area, where climatic conditions are mostly unsuitable for *C. mercuriale*, being characterized by high aridity, bordering the Sahara desert. Nevertheless, the new finding of the southernmost population, which expanded the limit of *C. mercuriale* distribution range, testifies to the incompleteness of the information available. It is highly improbable that this new population results from a colonization event in the last decades, considering the topology of the region and the low dispersal ability of the species (Keller & Holderegger, 2013; Rouquette & Thompson, 2007). Although the southern region is considerably more arid than the Middle Atlas, further streams might still hold relict *C. mercuriale* populations, and research is needed to delimit accurately the species distribution range and to set conservation priorities. Furthermore, this southernmost population could be at risk of the increasing arid conditions forecast for north-western Morocco, as predicted for other taxonomic groups (Martínez-Freiría, Argaz, Fahd, & Brito, 2013).

Extant populations of *C. mercuriale* are mostly restricted to high altitude areas with variable average year temperature in comparison to the previous range. Until the 1990s, this taxon occupied a wider range, occurring in both low and high altitude areas, and in areas with stable or variable average year temperature. This apparent current preference of the species for variable average year temperature might actually reflect the lower extent of habitat degradation/land conversion of high altitude areas in comparison with low altitude areas. Nevertheless the current reduction of *C. mercuriale* to a subset of the environmental variability range once occupied by the species translates to a reduction in habitat availability and indicates that the realized ecological niche of the species is currently reduced. The effects of this range contraction on the genetic diversity and adaptation ability of *C. mercuriale* to environmental change are unknown. Further ecological/physiological studies are needed to understand how the extant populations will cope with the predicted climate change for the region.

Concluding remarks

Coenagrion mercuriale is an odonate threatened with extinction in North Africa, which lives in lotic ecosystems and tends to occupy areas of high value for human settlement. Odonates restricted to lotic ecosystems are potentially more threatened than odonates from lentic ecosystems, as their geographic ranges tend to be smaller (Clausnitzer et al., 2012). To assist conservation of *C. mercuriale* in North Africa more studies are needed. Several basic ecological aspects that are crucial for the design of a conservation plan remain unknown, namely life cycle duration, dispersal ability, connectivity between populations and reproductive traits as oviposition site selection in North Africa. Currently, there are no known conservation actions in place on those countries targeting *C. mercuriale* despite its classification as endangered in the North African red list (Samraoui et al., 2010).

Urgent efforts should be directed to the conservation of the only extant population in Tunisia, and to the screening of any potential freshwater habitat to ascertain if any other populations might exist in that country. Moroccan populations, despite being more numerous, are seriously threatened by habitat loss and degradation due to water extraction, degradation of water quality, changes in land use and agricultural practices. In Algeria, the distribution and conservation status of *C. mercuriale* is poorly known, and it might be facing a similar high risk of extinction as in the neighbouring countries. The *C. mercuriale* populations are being lost at an alarming rate, but it is only one of many organisms that live in freshwater ecosystems of North Africa, facing a high risk of extinction. Its current conservation status is most likely indicative of the current situation of many freshwater organisms in these fragile ecosystems. The conservation of this species would promote the maintenance of the habitats it occupies and thus allow the persistence of other similarly threatened freshwater organisms.

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Disclosure statement

The authors declare that no financial interest or benefit exists arising from the direct application of their research.

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