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Anthropogenic stressors are driving a steep decline of hemipteran diversity in dune ponds in north-eastern Algeria

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Abstract

In arid North Africa, dune ponds qualify as hotspots of aquatic biodiversity, offering numerous sustainable ecosystem services. Despite mounting anthropogenic pressures that threaten their integrity, the overall consequences of these changes have yet to be documented and no strategy to mitigate potential impacts is being implemented. We monitored four dune ponds in northeast Algeria during five hydrological cycles spanning the period 1996–2013. The analysis revealed a steep decline in species richness (47%) and abundance (94%) over the study period. Remote sensing-based data indicated that marked human-induced changes in and around these dune ponds have over time led to a substantial expansion of built areas and cultivated plots and a reduction in both natural wet- and dry-land habitats. Fish predation by the introduced fish, *Gambusia holbrooki*, may have had both direct and indirect impacts on notonectids. We argue that aquatic hemipterans have undergone an alarming reduction driven by a combination of invasive species, human encroachment, agricultural runoffs, and possibly, climate change.

Keywords Aquatic hemiptera · Climate change · Ecosystem services · Mosquitofish · North Africa · Remote sensing · Temporary ponds

Introduction

Freshwater biodiversity is imperiled worldwide because water is increasingly in high demand by a growing human population and under threat from a range of stressors like pollution, invasive species and climate change (Vörösmarty et al. 2010; Bunn 2016). The high rate of species decline in freshwater ecosystems may qualify them as the most endangered ecosystems (Sala et al. 2000; Dudgeon et al. 2006). Similarly threatened, small water bodies often have a greater diversity of aquatic organisms than lakes and rivers (Williams et al. 2003; Davies et al. 2008) and their importance for rare, endangered or endemic species cannot be overstated (Collinson et al. 1995; Della Bella et al. 2005).

As small water bodies, ponds play a major role in biogeochemical cycles (Downing 2010) and provide essential ecosystem services such as primary production, water purification, and nutrient cycling (Céréghino et al. 2014; Mitsch et al. 2015). Furthermore, temporary ponds have also established themselves as a convenient arena for ecological research (Wilbur 1997) and their typical characteristics, such as shallow waters and small size, suggest a distinct ecological function (Oertli et al. 2002). In addition, over the last two decades, temporary ponds have become the center of a growing interest in the conservation of aquatic organisms and their habitats (Oertli et al. 2005).

As could be expected, water is scarce in North Africa's desert regions like the Maghreb, amounting to a strategic resource. Whereas vast salt lakes are the dominant wetlands in the arid and semi-arid North African Hauts Plateaux and Sahara (Demnati et al. 2017), temporary pools and dune ponds are the most frequent freshwater wetlands along the Mediterranean, especially in northeast Algeria (Samraoui and Bélair 1997, 1998). Dune ponds are not only unique freshwater ecosystems in the North African landscape; they are also biodiversity hotspots and sanctuaries for relict dragonfly and zooplankton species (Samraoui et al. 1993, 1998). However, following a worldwide trend (Brinson and Malvárez 2002), North African freshwater ecosystems have been facing unrelenting anthropogenic pressures in the past decades (Hollis 1992; Bélair and Samraoui 1994).

Despite the large spectrum of ecological services provided (Losey and Vaughan 2006), insects are undergoing a rapid decline worldwide with cascading effects on trophic webs (Thomas et al. 2004; Conrad et al. 2006; Hallmann et al.

2017). Amidst these long-term changes and Anthropocene defaunation, insect conservation has been hindered by a number of obstacles including knowledge gaps (Cardoso et al. 2011; Dirzo et al. 2014). For instance, aquatic hemipterans are considered potential bioindicators of water quality (Jansson 1977; Savage 1990) which may be used in regional or global conservation planning of freshwater biodiversity (Polhemus and Polhemus 2008) but their status and knowledge of their ecology are still fragmentary (Papáček 2001).

The loss and major alterations of local wetlands have been associated with a concomitant disturbing decline in their biota (Samraoui et al. 2012) but efforts to mitigate these downward trends are hampered by an inadequate knowledge of the status of most species. In the last three decades, only two systematic surveys of the hemipterans of Algeria have been carried out, providing much-needed information on the distribution, phenology and status of this much-neglected group of aquatic insects (Tebibel 1992; Annani et al. 2012).

However, this limited information may already be outdated as the spread of the eastern mosquitofish, *Gambusia holbrooki*, as a biological control agent throughout Algeria has had an adverse impact on the indigenous fauna (Haiahem et al. 2017). Mosquitofish have been introduced worldwide (Botsford et al. 1987) but the benefits of such endeavour (mosquito control) remain controversial while the drawbacks are well documented (Hurlbert et al. 1972; Pyke 2008). The present work aims to assess the potential impact of pervasive stressors (invasive fish, human encroachment, pollution, and climate change) on four dune ponds in northeast Algeria by monitoring the status of their aquatic hemipteran communities over a 17-year period.

Materials and methods

Study area

Numidia, in northeast Algeria, has a diversity of aquatic habitats, including freshwater lakes, ponds, lagoons, and brackish marshes (Samraoui and Bélair 1997, 1998). The region encompasses a Biosphere Reserve, the El Kala National Park, and numerous Ramsar sites and Important Bird Areas (Samraoui and Samraoui 2008) (Fig. 1). Numidia's climate is typically Mediterranean, being characterized by a mild and unpredictable rainy season between October and April (600–800 mm), and a hot, dry season exceeding 5 months from May to September. Four dune ponds, all located within Numidia, northeastern Algeria, were selected. The word 'Garaet' (lake/pond) is abbreviated to 'G':

1. G. Estah (36°50.556'N, 7°58.939'E): A temporary pond of 8 ha with *Nymphaea alba*, *Phragmites australis*, *Scirpus lacustris*, *Salix atrocinerea*, and *Iris pseudo-acorus*. Because of the proximity of the Mekhada marsh, the non-native mosquitofish (*Gambusia holbrooki*) was present at Estah at the beginning of the sampling period.
2. G. Dakhla (36°50.674'N, 7°59.077'E): A temporary pond of 8 ha, adjacent to G. Estah with *Phragmites australis*, *Cladium mariscus*, *Scirpus lacustris*, and *Nymphaea alba*.
2. Lac Bleu (36°54'N, 8°20'E): A protected (Ramsar Site) permanent pond of 4 ha located within the El Kala National Park. The vegetation is dominated by *Phragmites australis*, *Nymphaea alba*, and *Ceratophyllum demersum*. Lac Bleu was one of the last strongholds of the Killifish *Aphanius fasciatus* in Numidia.
3. Saulaie: A temporary dune slack, adjacent to Lac Bleu, dominated by *Salix cinerea*, *Iris pseudoacorus*, *Carex elata*, and *Scirpus lacustris*.

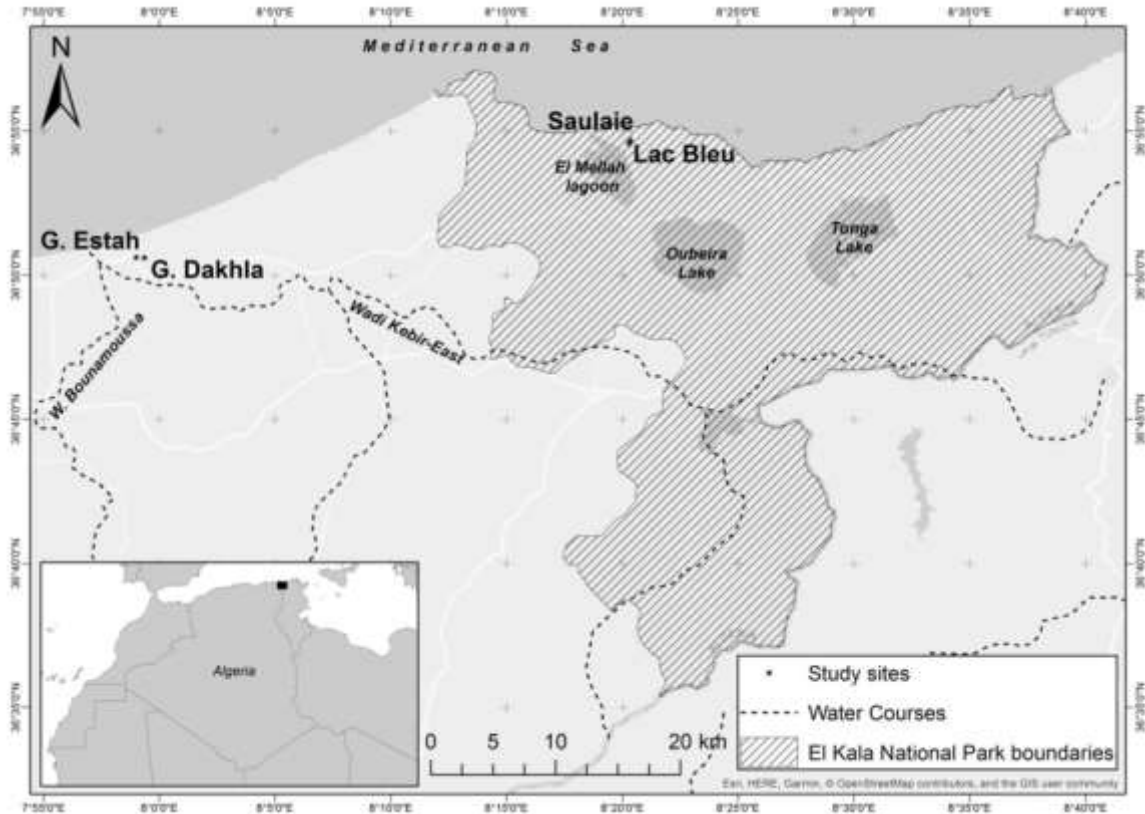
Estah and Saulaie are temporary ponds which dry up during the summer months and early autumn whereas Dakhla dries up only during severe droughts. Estah harboured mosquitofish at the start of the study while the other three dune ponds were initially devoid of mosquitofish until they were invaded in 2010 (Dakhla) and 2012 (Lac Bleu and Saulaie).

Land use and land cover change monitoring

The spatiotemporal dynamics of land use and land cover (LULC) in and around the studied sites (using 1 km buffer zone) were assessed by earth observation (EO) tools. Thus, based on Landsat time series, covering 4 years (1992, 1999, 2007 and 2015), it was possible to produce LULC maps using an object-based approach (images segmentation and classification) and implementing a hybrid nomenclature system that integrates all wetland habitats (according to Ramsar definitions) into the CORINE Land Cover typology. All the resulting products were then integrated into a geographic information system (GIS) and different indicators, related to habitat extents and their trends, were computed and used for further statistical analyses. All workflows for satellite images processing were carried out using the

GEOclassifier 1.4.8 software (Jena- Optronik GmbH 2018) and the spatial analyses ArcGIS 10.3 TM (2014).

Fig. 1 The location of the study sites across eastern Numidia (1: G. Estah, 2: G. Dakhla, 3: Lac Bleu, and 4: Saulaie)



Aquatic sampling

Aquatic hemipterans and fish were collected monthly throughout the year for Lac Bleu, a permanent pond, and covering the ponds' hydrological regimes for the other three temporary sites: the first two cycles spanned the hydroperiods of 1996–1998 (June 1996–May 1998) whereas the last three cycles covered the following seasons: 2010–2013 (June 2010–May 2013). Samples were collected using a dipnet (300 µm mesh size, 35 cm diameter) and were fixed in 5% formaldehyde. Each site was sampled along a 50 m transect using ten dipnet sweeps (3 m long) across all microhabitats along the bank edge. Deeper submerged parts of the study sites were not sampled.

Each sample was preceded by measures of the average water depth, and water temperature, recorded between 9 a.m. and 11 a.m. Water conductivity was only recorded for the last four hydrological cycles using a Hanna instruments HI 8733. In the laboratory, samples were sorted, and Hemiptera were counted and identified to species with taxonomic keys (Tachet et al. 2010) and confirmed using the University of Annaba's Laboratoire de Recherche des Zones Humides reference collection. Because some aquatic sampling could not be performed due to summer drought, only water temperature values from December to February were taken into account, and combined into two distinct periods (1996–1998 and 2010–2013).

Statistical analyses

Hemipteran community structure was investigated using species richness and Simpson's diversity index. Linear regressions were used to explore whether Hemiptera total abundance or species richness changed over time and were thus related to cycle order. One-way ANOVA tests were performed followed by Post hoc (Tukey) tests to distinguish the mean differences which are significantly different. Non-parametric tests were used when assumptions of normality and homogeneity of variance could not be met. All statistical analyses, including a Principal Component Analysis (PCA) were carried out using R (R Development Core Team 2017).

Results

Between 1992 and 2015, there was a notable increase in human activities across the whole eastern Numidian dune system which stretches from G. Estah/G. Dakhla to Lac Bleu/Saulaie. EO-based LULC maps indicated that agricultural lands increased while natural dryland (forests, shrubs and herbaceous vegetation) and wetlands declined (Table 1). Interestingly, changes in land use were not uniform across the dune system. The extension of built-up areas and roads was concentrated around Lac Bleu and Saulaie, which are part of the El Kala National Park, and the town of El Kala and its suburbs (Fig. 2). In contrast, there was a greater expansion of agriculture area and a concomitant larger loss of natural vegetation cover in the vicinity of G. Estah and G. Dakhla (Fig. 3). In addition, surface areas of natural wetlands incurred more habitat loss near these unprotected sites.

There was a marked seasonal change in water depth but fluctuations were similar across years, ranging from 16 cm (Saulaie, August 2012) to 110 cm (Dakhla, February 2013). The overall mean water temperatures of the first two sampling periods (1996–1998 and 2010–2013) were 11.4 ± 1.7 °C and 12.9 ± 1.9 °C, respectively. The increase in water temperature during the second period (1.5 °C) was significant (One-way ANOVA: $F_{1,55} = 8.7$, $p < 0.005$). Mean water conductivity in the second cycle (0.49 mS/cm) was significantly higher than those recorded in subsequent cycles (0.30–0.34 mS/cm) (One-way ANOVA: $F_{3,92} = 9.6$, $p = 1.4 \times 10^{-5}$).

Of significance was the first ever record, during the third hydrological cycle, of *Gambusia holbrooki* at Dakhla. Mosquitofish were able to reach Dakhla between 2000 and 2006, when locals dug a trench linking this latter site to G. Estah. In addition, during the last hydrological cycle, the non-native mosquitofish managed to invade both Lac Bleu and Saulaie but how this was achieved remains unknown.

The five hydrological cycles yielded 18 hemipteran species that were identified from the 7120 recorded aquatic hemipterans (Table 2). There was a downward trend of total abundance (linear regression: abundance = $-122.8 \times \text{cycle} + 724.3$, $R^2 = 0.27$, $p = 0.02$) (Fig. 4a) and species richness (linear regression: species richness = $-1.8 \times \text{cycle} + 13.9$, $R^2 = 0.60$, $p < 0.0001$) (Fig. 4b). Compared to the first hydrological cycle which provided 2181 hemipterans, the fifth and last cycle only hosted 123 hemipterans, displaying a drop in abundance of 94%. Over the same period, species richness decreased by 47%. Only eight species, *Nepa cinerea*, *Corixa affinis*, *Corixa panzeri*, *Hesperocorixa linnae*, *Hesperocorixa moesta*, *Sigara lateralis*, *Anisops sardea*, and *Plea minitissima*, were recorded during the last hydrological cycle. In contrast, Shannon's diversity index showed a relative stability over the first four sampling periods before undergoing a marginal decrease in the last hydroperiod (Kruskal–Wallis: $\chi^2 = 3.84$, $df = 4$, $p = 0.43$; generalized additive model: $F_{2,17} = 1.99$, $p = 0.17$, explained deviance = 18.9%) (Fig. 4c).

A Principal Component Analysis was performed (20 samplings \times 18 species) and four components, representing 63.6% of the total inertia, were retained (Fig. 5a, b). The first component (23.9% of the total variance) was associated with high abundance of Notonectidae and the absence of fish. Dakhla and Saulaie in the first 20 years of sampling were characteristic sites of this first component. This component also included the second cycle of Estah which had its mosquitofish population decimated by a summer drought. The second component (16%) was associated with a high abundance of large-sized corixids and the absence of *Notonecta*. This assemblage was best represented by Dakhla after mosquitofish invaded this site during the third hydrological cycle. The third component (12.3%) opposed a high abundance of mosquitofish to species sensitive to fish predation like *Hesperocorixa moesta* and *Notonecta glauca* while the fourth component (10.9%) was associated with the presence of the rare relict belostomid *Hydrocyrius columbiae* (Supplemental Fig. A).

The impact of mosquitofish on the aquatic hemipterans was uneven, varying according to taxa (Fig. 6). The abundance of Notonectidae declined significantly in the presence of *Gambusia holbrooki* (Kruskal–Wallis: $\chi^2 = 5.2$, $df = 1$, $p = 0.02$) (Fig. 6a) whereas the Corixidae did not seem to be affected significantly (Kruskal–Wallis: $\chi^2 = 0.01$, $df = 1$, $p = 0.93$) (Fig. 6b). However, within the Corixidae, some taxa, like *Hesperocorixa moesta*, were reduced significantly when associated with mosquitofish (Kruskal–Wallis: $\chi^2 = 5.5$, $df = 1$, $p = 0.02$) (Fig. 6c). The mean abundance of other taxa, like *Gerris thoracicus*, declined but an association with mosquitofish was only marginally significant (Kruskal–Wallis: $\chi^2 = 2.5$, $df = 1$, $p = 0.11$).

Table 1 Percent changes in landscape features between 1992 and 2015 around each study sites

Landscape features	G. Dakhla	G. Estah	Lac Bleu	Saulaie
Roads, paths and built-up areas	-1.7	-3.9	57.8	68.9
Agricultural lands	314.7	307.2	7.1	30.9
Natural drylands	-37.6	-39.2	-3.5	-4.6
Natural wetlands (Ramsar definitions)	-9.1	-2.1	-0.8	-0.6

Fig. 2 Changes in landscape cover in a 1 km buffer zone around Lac Bleu and Saulaie in 1992, 1999, 2007, and 2015

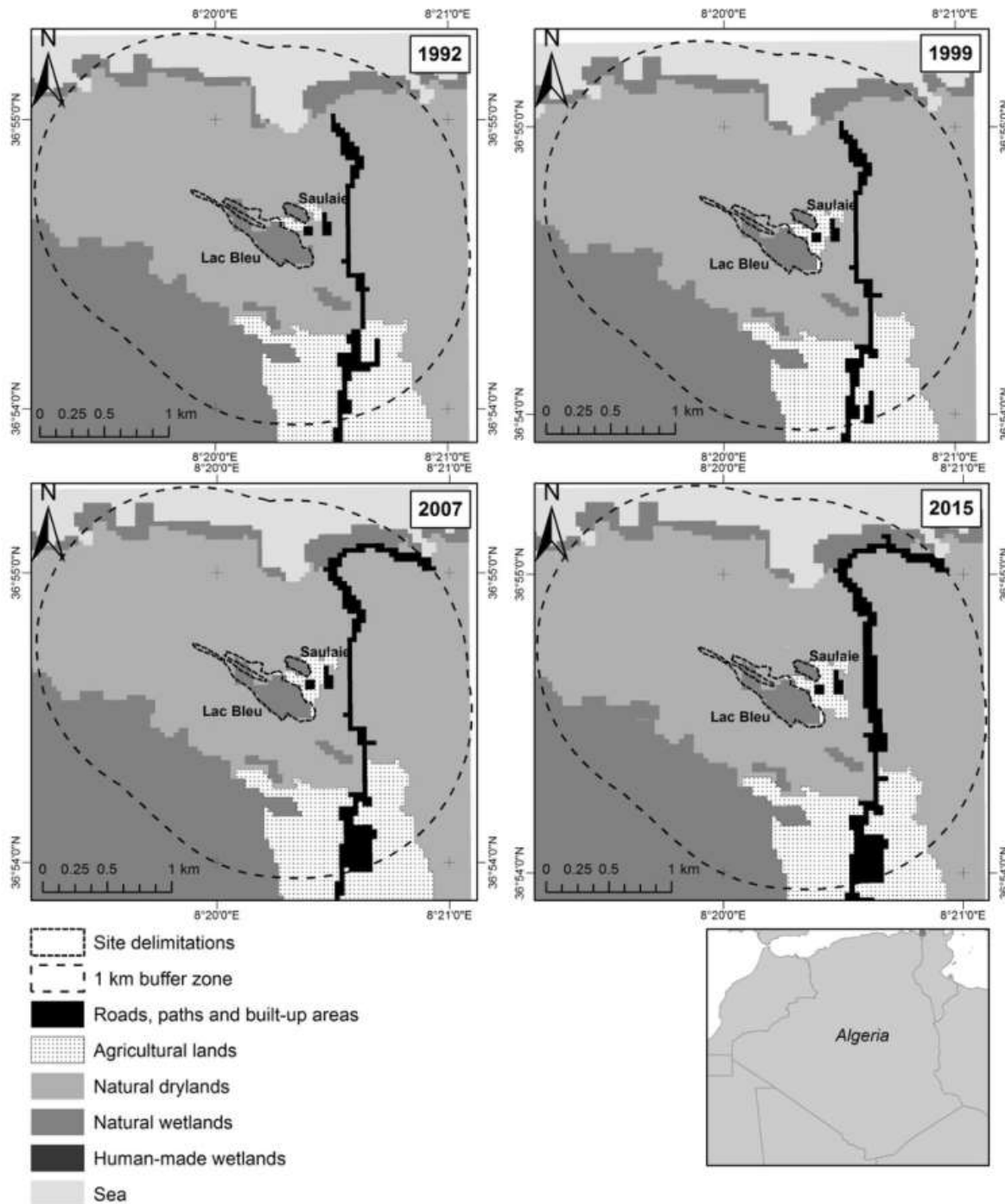
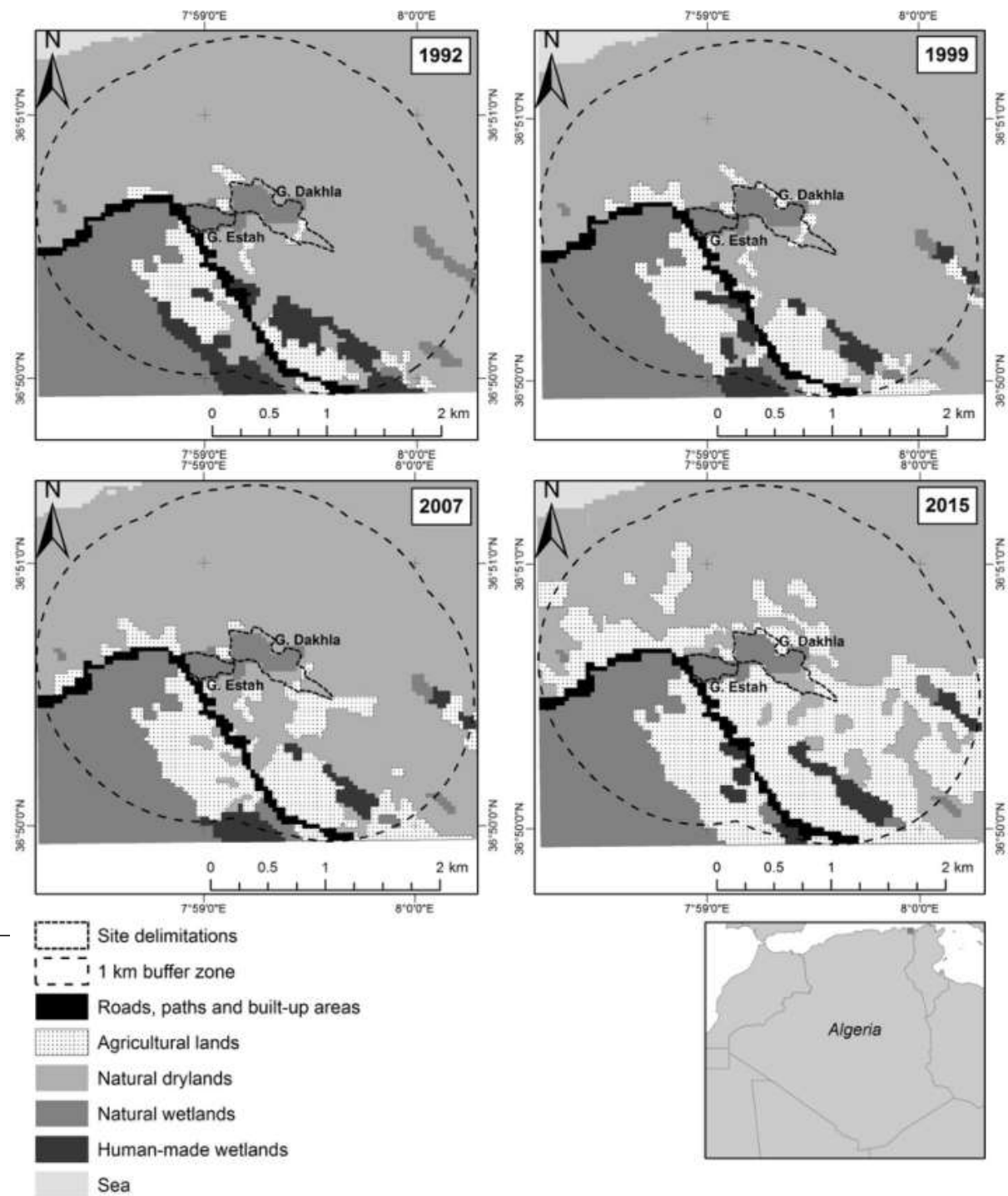


Fig. 3 Changes in landscape cover in a 1 km buffer zone around G. Estah and G. Dakhla in 1992, 1999, 2007, and 2015



Discussion

Dune ponds are essential elements of the Numidian landscape habitat mosaics which provide a rich array of landscape functions (Bélair and Samraoui 1994; Samraoui and Bélair 1997). However, in line with what is happening worldwide, human activities have been eroding landscape functions by altering connectivity between ponds and other landscape elements (Carpenter et al. 2011). The magnitude of the recorded changes in the Numidian dune system weakens the connectivity of the study ponds to other landscape elements, and thus influence ecosystem functions and services (Mitchell et al. 2013).

One basic function of dune ponds, biodiversity support, seemed to have been markedly undermined during the study period. Altogether, 18 species of aquatic hemipterans were

Table 2 Check-list of aquatic hemipterans recorded during the study period

	Species	Code	1996–1998	2010–2012	2012–2013
1	<i>Hydrocyrius columbiae</i> Spinola	Hco	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Dakhla	
2	<i>Nepa cinerea</i> Linné	Nci	Dakhla ^a	Lac Bleu, Saulaie	Lac Bleu
3	<i>Ranatra linearis</i> Linné	Rli	Dakhla	Saulaie	
4	<i>Corixa panzeri</i> (Fieber)	Cpa	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Estah, Dakhla
5	<i>Corixa affinis</i> Leach	Caf	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Estah, Dakhla
6	<i>Corixa punctata</i> (Illiger)	Cpu		Dakhla	
7	<i>Hesperocorixa linnaei</i> (Fieber)	Hli	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah, Dakhla
8	<i>Hesperocorixa moesta</i> (Fieber)	Hmo	Lac Bleu ^a , Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu
9	<i>Hesperocorixa furtiva</i> (Horvath)	Hfu	Saulaie, Estah	Saulaie, Estah, Dakhla	
10	<i>Sigara scripta</i> (Rambur)		Lac Bleu ^a		
11	<i>Sigara nigrolineata</i> (Fieber)		Saulaie ^a		
12	<i>Sigara lateralis</i> (Leach)	Sla	Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah, Dakhla	Estah
13	<i>Parasigara favieri</i> (Poisson)		Saulaie ^a , Dakhla ^a		
14	<i>Micronecta scholtzi</i> (Fieber)		Lac Bleu ^a		
15	<i>Micronecta</i> sp		Lac Bleu ^a		
16	<i>Notonecta glauca</i> Poisson	Ngl	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah	
17	<i>Notonecta meridionalis</i> Poisson	Nob	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah	
18	<i>Notonecta viridis</i> Delcourt	Nvi	Dakhla		
19	<i>Anisops sardea</i> Herrich-Schaffer	Asa	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah, Dakhla	Dakhla
20	<i>Plea minutissima</i> Leach	Pmi	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu
21	<i>Naucoris maculatus</i> Fabricius	Nma	Lac Bleu, Saulaie, Estah, Dakhla	Lac Bleu, Saulaie, Estah	
22	<i>Hydrometra stagnarium</i> (Linné)		Saulaie ^a		
23	<i>Gerris thoracicus</i> Schummel	Gth	Lac Bleu ^a , Saulaie, Estah, Dakhla	Saulaie, Estah, Dakhla	
24	<i>Mesovelgia vittigera</i> Horvath	Mvi	Lac Bleu, Saulaie, Estah, Dakhla		

Known records from Annani et al. (2012) are marked with superscript “a”

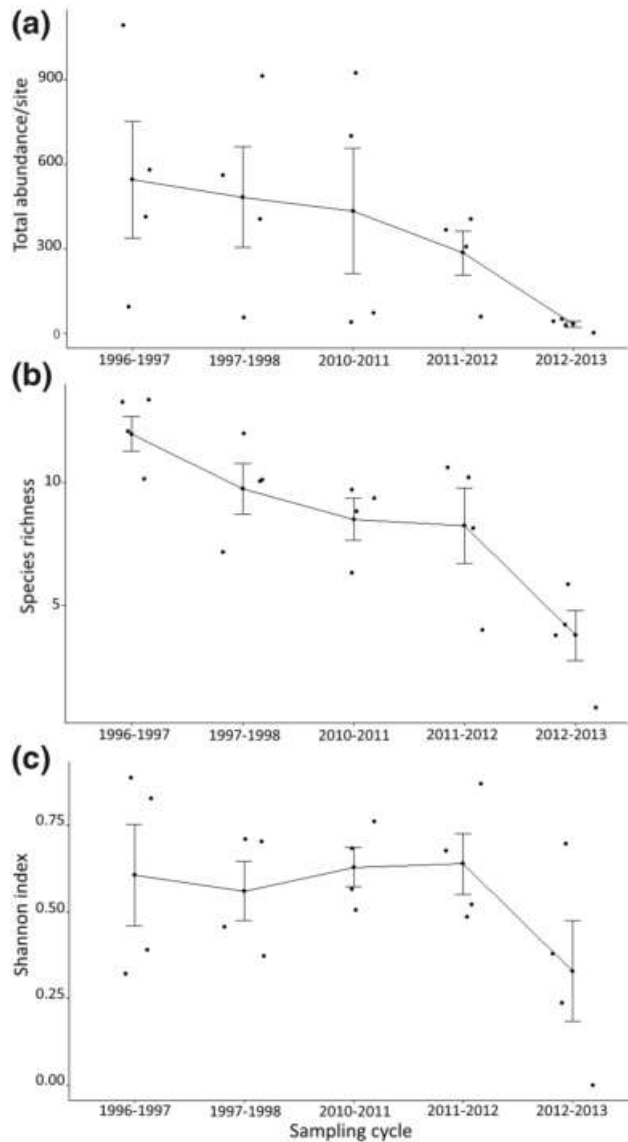
identified with the four study ponds. This number can be put into context by comparing it with the result from another survey which sampled 83 distinct sites across north-eastern Algeria and recorded 35 species (Annani et al. 2012). The high percentage of species recovered from our study (54%) is even more remarkable as Annani et al. (2012)’s sampling included semi-arid areas and both lotic and lentic habitats. This result is congruent with previous work highlighting the remarkable biodiversity of small water bodies, often dominated by hemipterans and coleopterans (Nicolet et al. 2004; Zacharias et al. 2007; Bilton et al. 2009).

However, both the overall abundance and species richness of aquatic hemipterans exhibited a significant decrease in numbers. While the abundance and species richness exhibited a gradual but steep decline over time, Shannon’s diversity index was relatively stable until the last sampling year when it displayed a marginal drop. When abundance varies significantly between samples, the interpretation of results may depend on the choice of the diversity index (Magurran 1988).

Two clear community structures, dominated by notonectids and corixids, respectively, emerged from the multivariate analysis. Although the detailed trophic position of most corixids and notonectids is poorly known (Klecka 2014), their differential distribution across the study ponds and hydrological cycles suggest distinct responses to anthropogenic pressures that may shed some light on the food web structures of dune ponds.

Altogether, three anthropogenic stressors have been identified (invasive fish, human encroachment including agricultural runoff, and global warming) but disentangling the separate impact of each of these recorded stressors on the study ponds would require an experimental approach.

Fig. 4 Trend in abundance (a), species richness (b), and Shannon's diversity index (c) of aquatic hemipterans in the study ponds during five hydrological cycles



However, we will review each factor in turn and attempt to discuss potential impacts and implications.

Invasive fish

Predation is a major driver of food web structure (Zaret 1980). Selective predation by fish or notonectids may reduce the abundance of large zooplankton and alter species composition and diversity of freshwater communities (Batzer and Wissinger 1996; Shurin 2001). In Algeria, it has been shown that predatory mosquitofish can deplete the zooplankton assemblages of both permanent lakes and temporary ponds (Samraoui 2002; Haiahem et al. 2017). Thus, a shortage of zooplankton caused by fish predation may have negative consequences on predatory aquatic insects like notonectids which also rely heavily on this type of prey (Murdoch et al. 1984).

Our study indicated a differential response of notonectids and corixids in the presence of the mosquitofish and a significant relationship between the presence of mosquitofish and notonectids' decline. Notonectids may suffer from a lack of large zooplankton prey, but may also fall prey to fish or avoid habitats with predatory fish via adult dispersal (Cook and Streams 1984; McCauley and Rowe 2010). Lastly, fish and notonectids may

also indirectly influence zooplankton's life history traits through the release of kairomones and thus alter prey dynamics (Chakri et al. 2010). All these factors may have led to the decimation of *Notonecta* species in the study ponds.

In contrast, our study indicated that corixids are less vulnerable to predatory mosquitofish. Whereas notonectids are carnivorous which may increase their vulnerability to competition with mosquitofish for prey, placing corixids in a specific functional feeding group is open to question (Hädicke et al. 2017). Water boatmen have traditionally been considered as organic scrapers (Hutchinson 1993) but recent work indicates they may occupy different trophic niches as predators in littoral and pelagic zones. In addition, they may also occupy benthic substrates as omnivores (Hädicke et al. 2017). Their specific habitat and micro-habitat requirements make them suitable indicators of water quality of lakes (Sav- age 1982). Corixid species composition and diversity may vary according to substrate, organic content, water conduc- tivity, vegetation cover and hydroperiod (Savage 1982; Tully et al. 1991; Bloechl et al. 2010).

Indeed, there is some evidence that corixids are less prone to fish predation than notonectids (Mura et al. 1984). Because of their peculiar head shape, mosquitofish are pre- dominantly surface feeders (Dirnberger and Love 2016) which may make corixids less susceptible because of their bottom-dwelling behavior. Interestingly, surface-dwelling taxa like *Gerris thoracicus* and *Mesovelia vitigera* were extirpated from the study ponds in the latest stages of the study. Notable exceptions to the relative vulnerability of corixids from mosquitofish are the small-size *Hespero- corixa linnaei* and, to a lesser extent, *H. furtiva*. It is known that scent gland secretions of some corixids may confer an effective deterrence against predation (Kovac and Machwitz 1991).

Unfortunately, macroinvertebrates are not the only aquatic organisms that may be undergoing a steep decline in the Numidian landscape. A survey of the amphibians of north-eastern Algeria indicated a precipitous decline of the Algerian newt *Pleurodeles poireti* (Samraoui et al. 2012). A range of factors may be driving the global decline in amphibians (Stuart et al. 2004), but a number of studies have demonstrated that mosquitofish prey on eggs and larvae thus posing a serious threat to this group (Goodsell and Kats 1999; Komak and Crossland 2000).

Human encroachment and agricultural runoff

EO-based LULC maps have shown that agriculture around the study sites has increased in a marked way during the last three decades. This expansion of speculative crops (water melons, peanuts) ushered a greater exploitation of the ground water and an unrestricted use of pesticides. In addition, the study area is located close to one the most industrialized region in Algeria with many industrial com- plexes and plants releasing high loads of trace elements in the atmosphere and the hydrological network. High levels of trace elements (Cd, Pb) have been found in aquatic organ- isms inhabiting the main wadi (river) draining northeastern Algeria (Abdenmour et al. 2000; Belabed et al. 2017).

Based on the recorded water conductivity and the absence of algal blooms, there is no evidence that the study sites have suffered from excess organic matter originating from ferti- lizer use on crops. In contrast, there is a widespread use of pesticides in the region where plant protection is essentially achieved through the unrestrained use of insecticides, fungi- cides and herbicides (Mebdoua et al. 2017). Unfortunately, despite the known detrimental effect of agricultural runoff to human health and the environment (Richter 2002; Berenzen et al. 2005; Rasmusen et al. 2012), Algerian regulations are often not enforced and many pesticides (lindane, hexachloro- cyclohexane, etc.), banned elsewhere, are still in use (Alamir et al. 1984).

To make matters worse, there is a widespread non-com- pliance with prescribed concentration and applications of fungicides which are considered as general biocides (Maltby et al. 2009). Another cause of serious concern is the syner- gistic effect of fungicides on non-target organisms in the presence of insecticides (Nørgaard and Cedergreen 2010) or under high temperatures (Müller et al. 2012). Agricultural runoffs and metal contamination can adversely interfere with the development of aquatic organisms and alter food web stability and ecosystem function (Järup 2003).

Furthermore, EO-based data have shown that the natural vegetation cover has shrunk substantially around the study sites. Part of the maquis (scrubland vegetation) has been converted into cultivated plots but overgrazing may also have played a key role in this process. In addition, unre- stricted access to the riparian zones of ponds by grazing livestock can be costly leading to disturbance, vegetation trampling and a decrease in water quality (Clark 1998; Nader et al. 1998). These factors may lead to the loss of aquatic biodiversity and changes in community structure and func- tion (Fleischner 1994). For example, heavily grazed

ponds can host a lower abundance of aquatic hemipterans, probably through the indirect effect of reduced vegetation cover which may act as a spatial refuge (Bloechl et al. 2010).

Fig. 5 First two principal components of **a** variable factor map and **b** individual factor map. The projected variable “Total” represents total abundance of aquatic hemipterans while codes related to species are found in Table 2. Numbers associated to study sites refer to hydro- logical cycles: 1 = 1996–1997, 2 = 1997–1998, 3 = 2010–2011, 4 = 2011–2012, and 5 = 2012–2013. The inset in 6a represents a scree plot

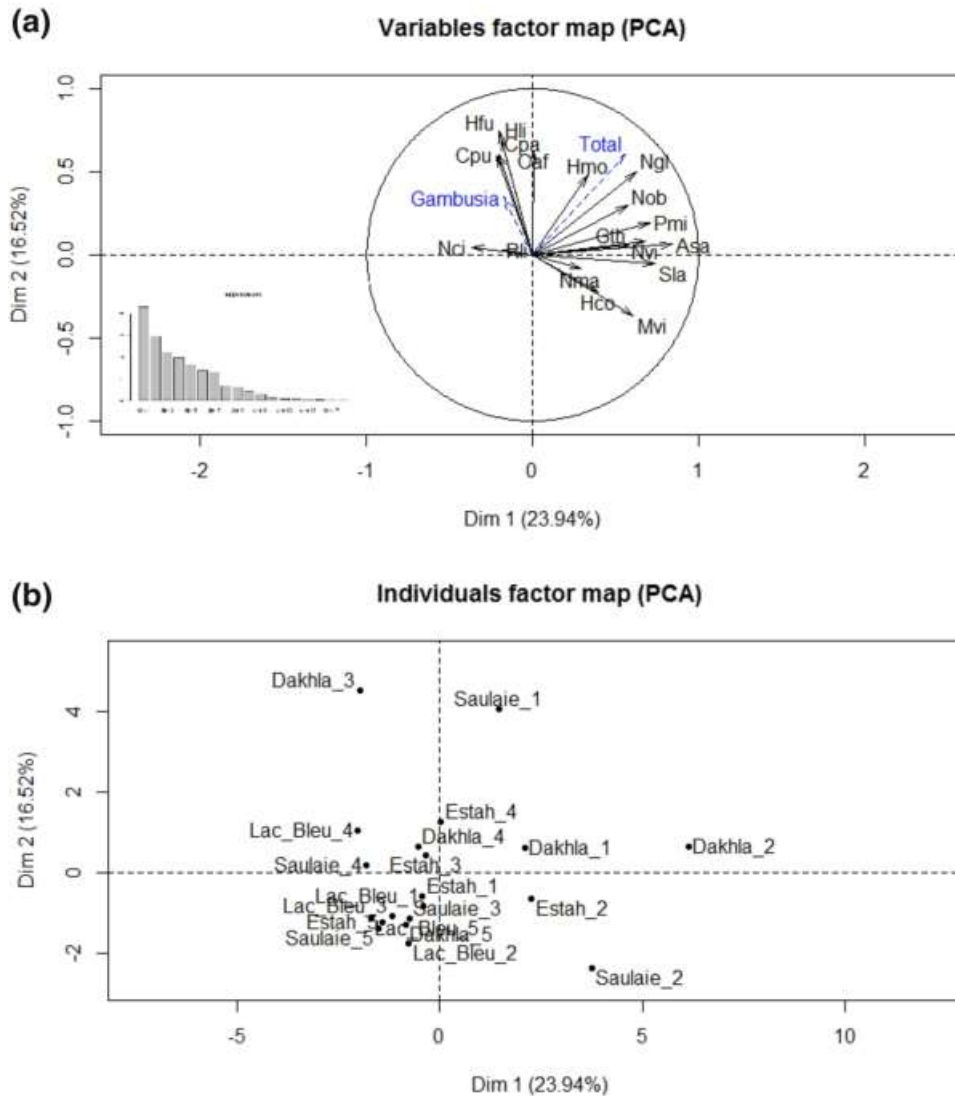
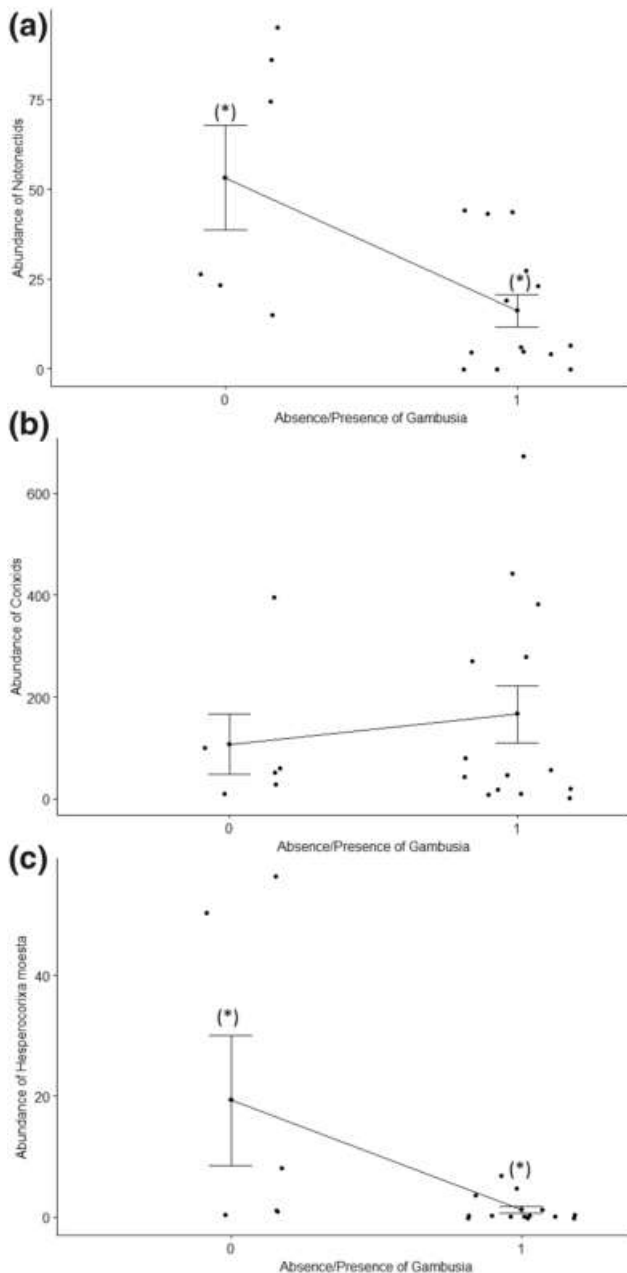


Fig. 6 Mean abundance (and standard error) of Notonectids (a), Corixids (b), and *Hesperocorixa moesta* (c) according to absence/presence of mosquitofish. An asterisk in brackets indicates a significant difference



Climate change

A sustained increase in temperatures across Algeria over the past four decades has been demonstrated by numerous studies (Achite and Ouillon 2016; Zeroual et al. 2017). North Africa is also expected to experience increasing heat extremes that are projected to accelerate and be associated with a temperature increase in excess of 6 °C by the end of the century (Lelieveld et al. 2016). Altered precipitation patterns and climate extremes can affect the development and survival of drought-prone macroinvertebrates and dominant predators with repercussions on community structure and function (Wellborn et al. 1996; Dossena et al. 2012). The second cycle at Estah was a typical example of the changes in community structure that occur following a drought-induced eradication of predatory fish.

The collapse of species richness at the study ponds is coherent with studies of the effect of global warming on ecosystems that exhibit a disproportionate loss of species in higher trophic levels and large body size (Petchey et al. 1999). Although hypotheses about processes driving responses to warming of natural communities are controversial (O’Gorman et al. 2017), increasing temperatures may decrease the amount of dissolved oxygen in surface waters (Carpenter et al. 2011) or affect food webs structure and sta-

bility by altering predator–prey interaction through changes of the ratio of predator body size to prey body size (Shurin et al. 2012; Gibert and DeLong 2014; Tunney et al. 2014).

Conservation

Anthropogenic impacts are affecting the structure and function of ecosystems on a global scale (Biesmeijer et al. 2006; Pereira et al. 2010). Likewise, North African ecosystems are facing multiple stressors that are steadily eroding their diversity and our study confirms and complements previous similar studies which highlighted the magnitude of human activities affecting North African wetlands (Samraoui et al. 1992, 2012; Bélair and Samraoui 1994). This finding raises concerns for the conservation of these vulnerable ecosystems. Loss of biodiversity may lead to simplified ecosystems which can in turn negatively affect ecosystem functioning, stability and productivity (Pimm et al. 1995; Vitousek et al. 1997). Because alterations of ecosystem processes may adversely affect ecosystem services, they may negatively impact human well-beings (Farley and Costanza 2010).

The sudden collapse of the biodiversity of the study ponds raises great concerns as Lac Bleu, the only permanent Algerian wetland, is unique for its rare and relict populations of aquatic organisms. In particular, Lac Bleu was for decades the only sanctuary of *Urothemis edwardsii*, an Afro-tropical relict dragonfly listed as Critically Endangered on both the North African and Mediterranean IUCN Red Lists (Samraoui 2018). Other rare and threatened species include the Endangered Grizzled Pintail *Acisoma inflatum*, another Afrotropical relict dragonfly, the killifish *Aphanius fasciatus*, the endemic ray-finned fish *Pseudophoxinus callensis*, and the Afrotropical relict belostomid *Hydrocyrius columbiae*.

Our study highlights the formal but fairly ineffective protection provided to internationally important wetlands by including them within national parks, MAB Reserves or designating them as Ramsar sites. Both urgent mitigating steps (halt human encroachment, pollution and overgrazing, eradication of invasive species and restoration, etc.) and long-term monitoring of these wetlands are required. In addition, future research should delve deeper into the potential impacts of pesticides and global changes on vulnerable habitats like dune and temporary ponds which are most at risk from water abstraction, drainage, catchment agriculture and unchecked urbanization.

Because of their small size, human encroachment makes ponds particularly exposed to water abstraction, untreated sewage discharges and agricultural runoff. In particular, the presence and concentration of pesticides needs to be studied in more details for the study ponds. Other threats include invasive species, such as mosquitofish which are a threat to freshwater biodiversity that goes often unnoticed (Haiahem et al. 2017).

Conclusions

In arid North Africa, dune ponds are rare aquatic ecosystems that are sanctuaries to rare, endemic and relict populations of aquatic plants and invertebrates. These hotspots of aquatic biodiversity are seriously threatened by a range of anthropogenic stressors which are rapidly depleting their communities and disrupting their structure and function. The monitoring over a 17-year period of four dune ponds in north-eastern Algeria strongly suggests that invasive fish, agricultural runoff, and an unequivocal temperature rise, may have led to a marked loss of species and abundance of their aquatic hemipteran assemblages. These alarming changes cannot go unheeded and they should prompt urgent mitigation steps to halt the fast eroding North African biodiversity.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was approved by the Algerian Ministère de l'Enseignement Supérieur et de la Recherche Scientifique (M.E.S.R.S.) and all procedures followed were in accordance with international ethical standards.

Research involving human participants The research involved no human participant.

Informed consent All the authors are in agreement with the version submitted and are in agreement with its publication in *Journal of Insect Conservation*.

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