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Drivers of change and conservation needs for vertebrates in drylands: an assessment from global scale to Sahara-Sahel wetlands

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Abstract
Drylands range across more than half of the global terrestrial area and harbour about a quarter of continental vertebrate species, many of them endemic. However, this fauna is being increasingly threatened, in particular the one that inhabits deserts, one of the last biomes on earth. This work tracks the most relevant global change drivers acting on drylands, especially in deserts and arid regions, the conservation actions being developed, and the research needs for vertebrate conservation, following IUCN standardised classification schemes. Using the Sahara-Sahel wetlands as case study, it is provided a detailed examination of these aspects to support regional biodiversity conservation and human welfare. Deserts and arid regions are threatened by the synergistic effects of increasing development of urban areas, agriculture, energy production, mining, transportation and service corridors, resulting in pollution, invasive species, human intrusions and disturbance, biological resource overuse and in general, natural system modifications. In addition, climate change together with social underdevelopment of many desert-range countries places the mitigation of threat factors in a large and complex web of global-local societal challenges. Conservation actions targeting land/water and species protection and management, as well as education, awareness, capacity building, and legislation measures to increase livelihood development, are being developed. Additional research efforts are need to enhance biodiversity conservation planning, monitoring biodiversity and land-degradation status (based on Essential Biodiversity Variables), and quantification of socioeconomic factors associated with sustainable use of natural resources and human development. Sahara-Sahel wetlands are important life-support systems for both humans and vertebrates, the last vulnerable to listed global threats. They offer framework scenario to revert current environmental and societal challenges in deserts. Long-term conservation of desert vertebrate biodiversity requires appropriate policy instruments to promote sustainable use of natural resources. Raising environmental alertness within local communities of uniqueness of desert biodiversity is needed to promote policy change.

Keywords: *Biodiversity threats, climate change, conservation actions, land degradation, research needs, sustainable human development*

1. Introduction

Drylands represent about 54% of the Earth's land surface and are inhabited by 2 billion people (AI-Aridity Index <0.65; Figure 1; UNEP 2006). They harbour about 25% of continental vertebrate richness (7000 species of amphibians, reptiles, birds and mammals; Brito & Pleguezuelos 2020), comprising highly adapted and specialised species that are found nowhere else, and displaying high rates of endemism and local hotspots of biodiversity (approximately 1000 of these species are endemic, distributed in 300 families; Mace et al. 2005). Within drylands, most deserts and arid regions (hyper-arid and arid categories of AI; Figure 1) still classify as one of the

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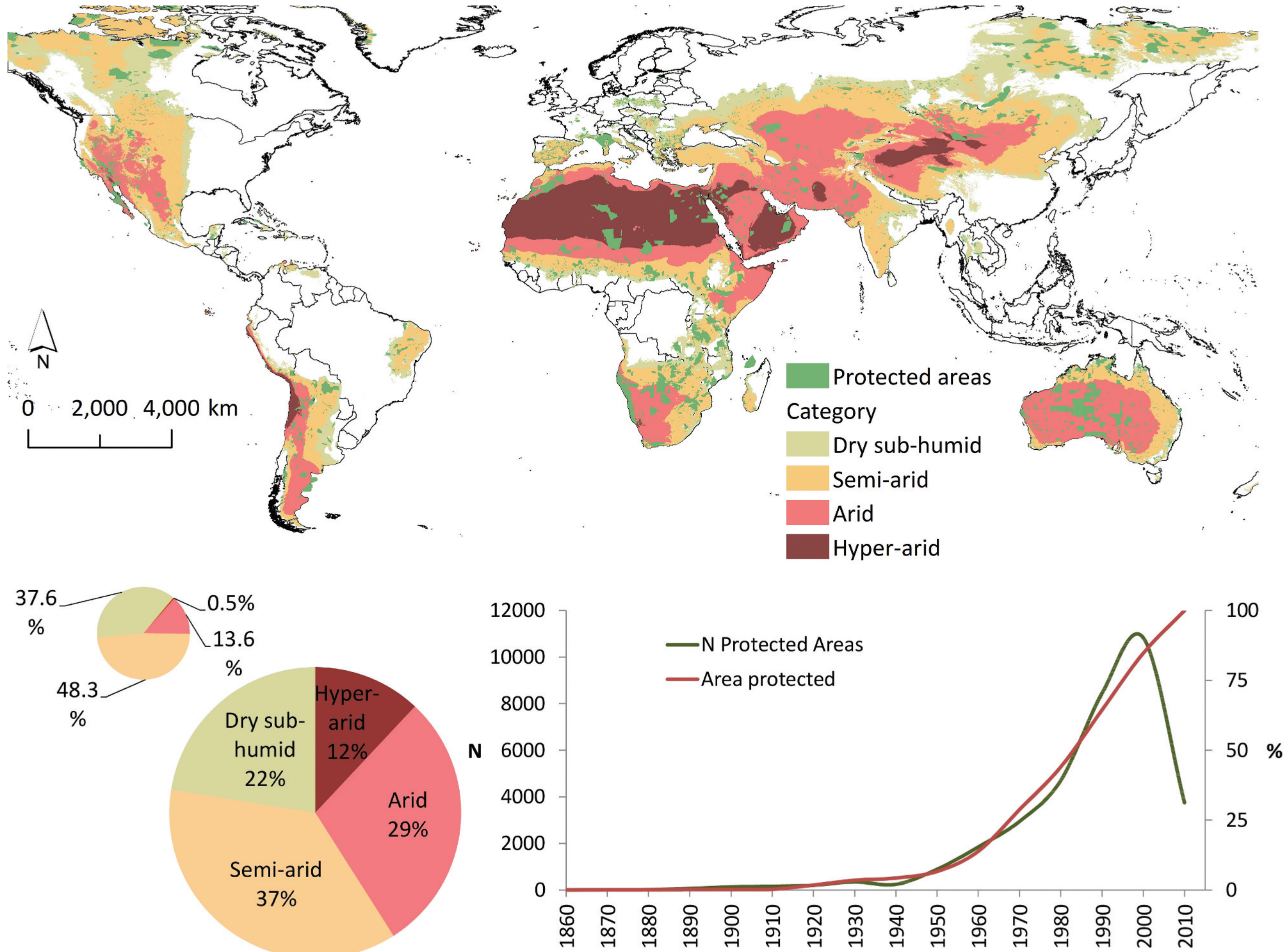

Figure 1. Global distribution of drylands (top: aridity index < 0.65; Trabucco & Zomer 2009), relative proportion of dry sub-humid, semi-arid, arid and hyper-arid categories (bottom left) and percentage of protected areas in drylands afforded by each category (left small inset), and cumulative number of protected areas and their area established in drylands (bottom right) (IUCN and UNEP-WCMC 2019).

last wild biomes on Earth (Ellis & Ramankutty 2008; Watson et al. 2018), but they are threatened by the impact of global change. These impacts include increasing human activities and intrusions, exploitation and progressive aridity conditions (UNEP 2006; Davies et al. 2012; Brito & Pleguezuelos 2020), causing negative consequences in the ecosystem services provided by these biomes, such as food, water and human culture, as well as, the good physical and mental health of human individuals and societies thriving there (Castro et al. 2018). As a result, deserts and arid regions are currently home to some of the most endangered vertebrates (e.g., Durant et al. 2014) and poor and vulnerable people worldwide (UNEP 2006). Actually, human poverty and regional insecurity have been associated with decline of local wildlife in deserts (e.g., Brito et al. 2018). Furthermore, the magnitude and velocity of climate change in deserts are predicted to be strong and fast (Loarie et al. 2009), which will likely cause additional biodiversity declines and impoverishment of local people. Desert-adapted species may even be the most vulnerable ones with respect to other terrestrial biomes (Vale & Brito 2015). Climate-related adversities are also likely to spark regional human conflicts and further biodiversity loss (Brito et al. 2018) associated with human migration, fast-growing human population rates, and the ethnically fractioned societies that characterise many countries where deserts are found (Schleussner et al. 2016; Mach et al. 2019).

Deserts and arid regions remain poorly studied in comparison to other biomes (Brito & Pleguezuelos 2020), but there are a growing number of studies reporting threats to biodiversity and conservation actions being developed to revert biodiversity loss (e.g., Brito et al. 2014). Still, available data are mostly fragmented and there is a clear lack of systematic reporting of those threats and conservation actions. As such, the present work aims to track the most relevant global change drivers acting on drylands, especially in deserts and arid regions (following Section 2), the local conservation actions being developed (Section 3), and the research needs for vertebrate conservation and sustainable human development (Section 4) following IUCN (2019) standardised classification schemes of Threats, Conservation Actions, and Research Needs. The aim of this overview is to provide elements in a systematic way that allows the main patterns found to be comparable with other terrestrial biomes and thus allow setting optimised conservation priorities (Salafsky et al. 2008). Then, using the isolated wetlands of the Sahara-Sahel as an illustrative case-study, it is aimed to provide a detailed examination of these aspects in biodiverse-rich and fragile areas of deserts, and outline the future research priorities to support regional conservation planning and sustainable human development (Section 5). Finally, the main conclusions are outlined (Section 6).

2. Threats on vertebrates in deserts and arid regions

Deserts and arid regions are mainly threatened by the synergistic effects of two rather recent processes, the recent and increasing human intrusion in this biome with exploitation purposes, and climatic change (UNEP 2006; Davies et al. 2012; Brito et al. 2016, 2018; Ward 2016). The combined pressures exerted by threats linked to human intrusion, like urbanisation, traffic, farming, overgrazing, water overexploitation and salinization, and natural resource extraction, are leading to the degradation of world's deserts (UNEP 2006; Ward 2016), including their native biodiversity. Deserts do not regenerate quickly and human impacts can remain in this biome for decades (Abella 2010). Furthermore, the naturally stressed biota and water scarcity that characterise the desert biome poses environmental challenges to sustainable human development and natural resource use. In this section, the direct threats acting on deserts and arid regions are listed and particular focus is given to the ones affecting vertebrate populations. Threat listing follows IUCN (2019) classification schemes (Table I).

2.1. Residential and commercial development

The nomadic lifestyle was the only way humans had to survive in deserts for centuries (apart from oases), because it was resilient and adaptive to unpredictable rainfall (UNEP 2006). Permanent housing and urban development are relatively recent (from 20 to 40 years; pers. observ. of the authors) and expanding processes in desert environments, causing loss of natural habitats and overexploitation of natural resources (Shochat et al. 2010). For instance, biodiversity decline in the coastal areas of the Arabian Peninsula is linked to economic development and urbanisation, as well as to overexploitation of natural resources, both resulting from growing human population and lifestyle changes (Tourenq & Launay 2008). Urban expansion is threatening desert habitats and unique vegetation communities in South-western Peru (Polk et al. 2005), and the percentage of building cover in the Arizona desert (USA) has been associated to negative impacts on both diversity and abundance of desert reptiles (Ackley et al. 2015).

Although wilderness and wildlife tourism frequently favour biodiversity conservation, compared to some other land use systems, this activity can also have detrimental impact on desert biodiversity (Green & Giesie, 2004). Indeed, while tourism can have a symbiotic relationship with nature conservation (Budowski 1976), growing tourism industry "comes with its own set of risks and challenges" (World Bank 2012; p. 7). The negative effects of wildlife tourism in deserts can arrive from access roads, built of facilities, extensive water consumption, direct impacts on vegetation (by trampling, habitat clearing, specimen collection), and changes in animal behaviour (e.g., changes in activity or feeding patterns) (see Novelli et al. 2006). Off-road vehicles are particularly harmful for fragile arid areas, leading to soil compaction and affecting biocrusts, direct effects on vegetation, and accelerating water and wind erosion. In addition, off-road mobility creates noise and disturbance, which can have negative effect on desert vertebrates, even leading to reduced breeding success (Webb & Wilshire 2012). Tourism and related economic opportunities also attract local people to certain areas. In Kunene region (Namibia), for example, increasing local interest on tourism has created an over-utilisation of local resources and pastures in many places, causing serious impacts on environment, livestock and native species especially during dry seasons and droughts (Saarinen 2016).

2.2. Agriculture and grazing

Farmland surface has increased dramatically in some deserts, causing habitat loss and fragmentation, and groundwater overexploitation. These processes affected large portions of coastal areas of the Arabian Peninsula, Libya or the African Sahel

Table I. Selection of direct threats acting on drylands, local conservation actions being developed, and research needs for biodiversity conservation and sustainable human development. Numbering and nomenclature follow IUCN (2019) classification schemes of Threats, Conservation Actions, and Research Needs.

Direct threats	Conservation actions	Research needs
1. Residential and commercial development 1.1 Housing and urban areas 1.3 Tourism and recreation areas *2. Agriculture and grazing* 2.1 Annual and perennial non-timber crops 2.3 Livestock farming and ranching *3. Energy production and mining* 3.1 Oil and gas drilling 3.2 Mining and quarrying *4. Transportation and service corridors* 4.1 Roads and railroads 4.2 Utility and service lines *5. Biological resource use* 5.1 Hunting and collecting terrestrial animals *6. Human intrusions and disturbance* 6.1 Recreational activities 6.2 War, civil unrest and military exercises *7. Natural system modifications* 7.2 Dams and water management/use *8. Invasive and other problematic species, genes and diseases* 8.1 Invasive non-native/alien species/diseases 8.2 Problematic native species/diseases *9. Pollution* 9.1 Domestic and urban waste water 9.2 Industrial and military effluents 9.3 Agricultural effluents 9.4 Garbage and solid waste 9.6 Excess energy *11. Climate change and severe weather* 11.1 Habitat shifting and alteration 11.2 Droughts 11.3 Temperature extremes *12. Other options* 12.1 Other threat	*1. Land/water protection* 1.1 Site/area protection 1.2 Resource and habitat protection *2. Land/water management* 2.1 Site/area management 2.2 Invasive/problematic species control *3. Species management* 3.1 Species management 3.2 Species recovery 3.3 Species re-introduction 3.4 *Ex-situ* conservation *4. Education and awareness* 4.1 Formal education 4.2 Training 4.3 Awareness and communications *5. Law and policy* 5.1 Legislation 5.2 Policies and regulations 5.3 Private sector standards and codes *6. Livelihoods, economic and other incentives* 6.1 Linked enterprises and livelihood alternatives 6.2 Substitution *7. External capacity building* 7.1 Institutional and civil society development 7.2 Alliance and partnership development 7.3 Conservation finance	*1. Scientific research* 1.1 Taxonomy 1.2 Population size, distribution and past trends 1.3 Life-history and ecology 1.4 Harvest, use and livelihoods 1.5 Threats 1.6 Conservation actions *2. Conservation planning* 2.1 Species action/recovery plan 2.2 Area-based management plan *3. Monitoring* 3.1 Population trends *4. Other* 4.1 Land-degradation status and trends 4.2 Quantifying socioeconomic factors

(UNEP 2006; Tourenq & Launay 2008). Intensive farming in deserts will also result in behavioural modifications of native animal speciesfor instance, changing the predator-prey natural balance, as suggested for the Near East (Shapira et al. 2008).

Grazing is a major cause of land degradation across deserts, especially at its margins (ECOWAS & SWAC-OCDE 2006); for example, livestock numbers increased dramatically in the arid lands on Mongolia during the 1990s, following the political changes in the country, threatening the native biodiversity of this fragile environment (Reading et al. 2006). Excess of pastoral activity affected the threatened populations of Houbara Bustard (*Chlamydotis undulata*) in the north-western fringe of the Sahara (Brito et al. 2014), and cattle grazing and browsing have damaged sensitive desert scrubs and riparian habitats in the Chihuahuan Desert in Mexico (UNEP 2006). In the north-western margin of the Sahara, thousands of water cisterns were built for watering livestock, which attract desert vertebrates; they represent a place to reptiles and mammals to forage and find shelter, but at the same time, increase the likelihood of later deathly entrapment within those cisterns. Although cisterns can provide a place for amphibian reproduction, they also increase the possibility of entrapment through falls into structures of high and smooth walls made of reinforced concrete (García-Cardenete et al. 2014); they also change the variety and quality of amphibian breeding sites, i.e., by being suddenly drained, causing additional pressures over already scattered populations in desert habitats (Burkett & Thompson 1994; García-Cardenete et al. 2014).

2.3. *Energy production and mining*

The exploitation of natural resources is growing across world's deserts, through industrial mining, oil and gas drilling (Harfoot et al. 2018), and recently by photovoltaic and wind power stations (Kamp et al. 2016), which is threatening the locally fragmented and remnant biodiversity. For example, the highest mountain system in Mauritania (Kediet ej Jill) and the surrounding rock outcrops are partially falling apart by the intense iron ore extraction (Brito et al. 2016; per. observ. of the authors), even before these habitats are scientifically explored. Prospection for new oil sources in Niger was the major reason for population collapse of Critically Endangered Addax (*Addax nasomaculatus*) (Duncan et al., 2014), and increasing mining activities in the Central Basin desert of Iran further threatens the last wild populations of the Asiatic cheetah (*Acinonyx jubatus venaticus*) (Khalatbari et al. 2017). In the Atacama Desert (Chile), cooper mining has steadily grown in recent decades, implying accelerated groundwater withdrawal in unsustainable way that negatively affects natural areas or territories claimed by indigenous communities (Oyarzún & Oyarzún 2011; Romero et al. 2012). Abandoned mine shafts, acting as pit-falls, were estimated to cause 10–28 million reptile deaths per year in the arid northern South Australia (Pedler 2010). Promoters of solar energy through very large photovoltaic power generation systems are increasingly targeting world deserts because of the large proportion of the Earth covered by hot deserts and with high insolation levels: it is estimated that using only a 4% of these areas for installing photovoltaic systems would result in an energy production equalling current world energy consumption (Komoto 2015). However, these systems would also include threats to biodiversity through habitat loss and additional human presence in deserts (Pizzo 2011), as observed in the large semi-arid grassland steppes of Kazakhstan (Kamp et al. 2016). Likewise, the dry coastal areas of North and East Africa, and the Middle East were identified as mostly suitable for the large-scale production of biofuels derived from microalgae, theoretically without directly competing with food production and areas of high biodiversity value (Correa et al. 2019). However, and similarly to the solar energy, industrial development in these regions represents increasing human presence in previously undisturbed areas and additional pressure over ecosystem integrity. For instance, while protected areas were excluded from the selection sites for microalgae production (Correa et al. 2019), as a rule, the representation and persistence of Sahara-Sahel biodiversity in protected areas is clearly not optimised and thus, it is vulnerable to additional industrial developments (Brito et al. 2016).

2.4. *Transportation and service corridors*

Accessibility to world's deserts is growing and linear infrastructures are an increasingly common feature in most desert landscapes, mostly through roads but also by railways and pipelines. These features threaten local biodiversity by increasing vehicle-collision probability, modifying animal behaviour, and by allowing the spreading of invasive species and the increasing human use of previously remote areas (Ibisch et al. 2016). For example, road collision is currently one of the most important threats to the critically small Asiatic cheetah populations in Iran (Khalatbari et al. 2017) or to the populations of Ground turtle (*Gopherus agassizii*) in the Mojave Desert (Boarman & Sazaki 2006). The expansion of road networks and also the growing usage of four-wheel-drive vehicles is increasing the accessibility to previously remote areas in most world deserts, which combined with the spreading of firearms, is amplifying the impacts of overhunting and poaching (see below).

2.5. *Biological resource use*

The spread of firearms from the beginning of the twentieth century and of the four-wheel-drive vehicles from the middle of the same century dramatically increased the impact of hunting activities (Newby 1980). These threats affected large body-sized vertebrates, and lead to the extinction or to the critically conservation status of many mammals and birds (Ripple et al. 2016; Gross 2019). In the Sahara-Sahel, of 14 large vertebrates that occurred until the past century, the majority have disappeared from more than 90% of their range, and four are now extinct in the wild (Durant et al. 2014). Among others, species affected include Addax, Dama gazelle (*Nanger dama*), Cuvier's gazelle (*Gazella cuvieri*), Slender-horned gazelle (*G. leptoceros*), Dorcas gazelle (*G. dorcas*), Red-fronted gazelle (*Eudorcas rufifrons*), Barbary sheep (*Ammotragus lervia*), Saharan cheetah (*Acinonyx jubatus hecki*), African savanna elephant (*Loxodonta africana*), and Houbara bustard (Brito et al. 2018). In the Arabian Desert, the Leopard

(*Panthera pardus*), the Arabian Tahr (*Arabitragus jayakari*), and the Arabian oryx (*Oryx leucoryx*) are also threatened (Tourenq & Launay 2008). Some species are also particularly persecuted, such as medium-size canids or venomous snakes, while others are captured due to exploitation or superstitious reasons, such as the Egyptian cobra (*Naja haje*), the African savanna elephant or the West African crocodile (*Crocodylus suchus*); the latter was extinct from several isolated populations across the Sahara (reviewed in Brito et al. 2011a).

2.6. *Human intrusions and disturbance*

Human intrusion and disturbance in deserts and arid regions is increasing and reasons are varied, from recreation and exploitation activities (discussed above) to conflict reasons. The recent increase in global conflicts stresses the urgent need for managing and reducing the impacts of conflicts on biodiversity (Brashares et al. 2014), as conflicts create ungovernable political spaces. Within dryland countries, the phenomenon is particularly worrying in West Asia and North Africa, where indexes of peace and terrorism are particularly disturbing (Figure 2; IEP 2018a, 2018b). In the Sahara-Sahel range countries, the absolute number of conflicts has grown 565% over the last 20 years and the rush of extremist groups to control remote desert areas promotes human presence in places that previously were only crossed by nomads; these conflicts are prompting regional declines in endangered mammals (reviewed in Brito et al. 2018). In Libya, the conflict that followed the fall of the Gaddafi regime, which fragmented the country and promoted an increase in the number of uncontrolled fire arms and military vehicles circulating in the desert, was associated with an increase in the number of Dorcas gazelle illegally killed. Illegal off-take of African savanna elephant in Mali, pertaining to the northernmost population in Africa, also increased when regional security conditions deteriorated. Vast regions of the Sahara-Sahel are also affected by the presence of landmines (lasting well after conflicts ended), smuggling and human migrant routes (Brito et al. 2018); for instance, the decline of Addax in Niger was associated with the human migration wave that followed the Libyan turmoil (Brito et al. 2018). Thus, megafauna decline in the Sahara-Sahel resulting from conflicts is a common feature in the region and has affected many other vertebrates (Durant et al. 2014).

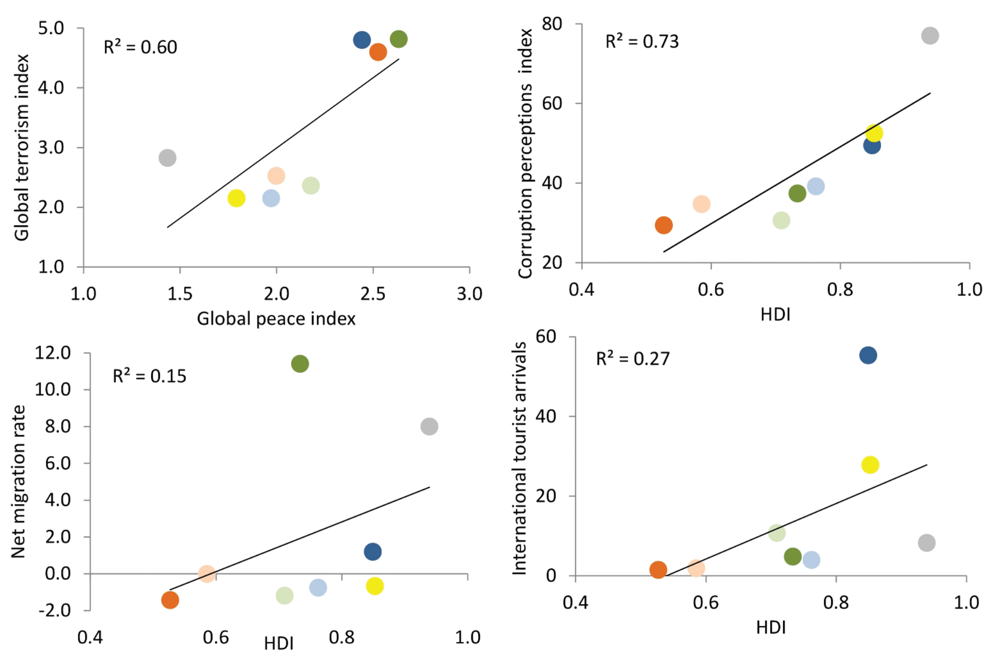

Figure 2. Relationships between average regional values of socioeconomic indicators in 70 dryland countries. Global peace (low values = more peace) and global terrorism (low values = less terrorism) indexes (top left), human development (HDI) and corruptions perception (low values = more corruption) indexes (top right), and net migration rate (per 1,000 people) (bottom left), and international tourist arrivals (millions) (bottom right). Regions: North America (Dark blue), South America (Light blue), Europe (Yellow), North Africa (Dark Orange), South Africa (Light Orange), West Asia (Dark green), East Asia (Light green), and Australia (Grey). Indexes and data from IEP (2018a, 2018b), UNDP (2018), UNWTO (2018), and Transparency International (2019).

2.7. *Natural system modifications*

Water overexploitation for human and livestock consumption threatens local desert fauna. For instance, water shortage for watering livestock during the dry season are linked to increased pressure over fragile West African crocodile populations scattered in isolated mountains of Mauritania (Brito et al. 2011a). The extraordinary micro-endemism levels of the desert springs fed by the Great Australian Basin (GAB) are threatened by groundwater use, with extraction partially exceeding recharge rates and drastically degrading the groundwater-dependent ecosystem (Murphy et al. 2013). Dams, large-scale diversions, and surface and ground-water abstractions have turned the Colorado River (USA) one of the most regulated rivers globally, with negative impacts in water availability along the hydrographic network (less than 8% of the wetlands remaining) and associated habitat loss affecting endemic fishes (reviewed in Datry et al. 2017). River salinization is a phenomenon associated with reductions of water availability that can have negative effects, particularly in fauna from desert rivers. In Australia, increasing salinity of seasonal wetlands has been linked to diversity loss in amphibian communities and to reduced breeding success of waterbirds, the former affected mostly during the embryonic and larval stages and the latter due to changes in their food, nesting habitats, and vegetation cover (Datry et al. 2017).

2.8. *Invasive and other problematic species, genes and diseases*

The expansion of infrastructures in fast developing arid regions benefits invasive species that impact native and fragile desert communities through competition for natural resources, predation, diseases spread or habitat modification (Tourenq & Launay 2008). In Australia, introduced mammals have also threatened the biodiversity of the same rangelands through habitat degradation and competition by the alien herbivores, such as Rabbit (*Oryctolagus cuniculus*), Bezoar (*Capra aegagrus*), Horse (*Equus ferus*), Camel (*Camelus dromedarius*), Wild boar (*Sus scrofa*), and predators, such as Feral cat (*Felis lybica*) and Red fox (*Vulpes vulpes*) (Edwards et al. 2004), the Feral cat being particularly well distributed in the arid and semi-arid regions of this continent (Legge et al. 2017). As a consequence, arid Australia has the world's worst modern mammalian extinction record, largely attributable to competition from these introduced herbivores (Pedler et al. 2016) and from predation by introduced carnivores (Woinarski et al. 2015). In new farmlands in arid regions of Algeria, the invasive Cattle egret (*Bubulcus ibis*) is spreading, hoarding up the already scarce resources (Bachir et al. 2011). In Morocco, the community of non-native fishes (11 species) in desert rivers, closely linked to reservoirs, already overcomes that of native fishes (nine species; Clavero et al. 2015), while more than 10% of the ant diversity observed in 11 oases comprises invasive species (Taheri et al. 2020).

2.9. *Pollution*

Waste waters from domestic and urban areas, as well as effluents from agricultural and industrial facilities are increasingly affecting the water quality of desert rivers. In arid and semi-arid regions of the south-western United States, flows of historically seasonal streams are now perennially dominated by municipal and/or industrial effluent discharges, particularly in urbanised watersheds (Brooks et al. 2006). Effluents with high concentrations of nutrients (e.g., nitrogen pollution) and contaminants (e.g. mercury, pesticides) can strongly affect desert fauna, especially fishes and amphibians (reviewed in Datry et al. 2017). For example, faecal pollution and excessive water eutrophication during the dry season constitute threat factors to the West African crocodile populations inhabiting isolated mountains of Mauritania (Brito et al. 2011a). Pollution from natural resources exploitation is also escalating as a result of the growing number of high-energy and water-consumption industries located in arid regions. For instance, uninhibited discharge of industrial wastewater in the Tengger and Mu Us Deserts (China) are damaging the local ecosystem, in some cases irreparably (Dou et al. 2015). Many deserts and arid regions are located in low human development countries (Figure 2) that generally lack recycling infrastructures, which implies additional pressures from garbage disposal. The extent and radiance from light pollution associated to urban development is also affecting deserts, especially in the Sahara-Sahel and Atacama deserts (Kyba et al. 2017), with negative impacts in public health and ecosystems. Extreme cases of pollution in deserts can also occur as a consequence of armed conflicts, as observed during the deliberate environmental damage perpetrated in the first Gulf War (Iraq) or the poisoning of water sources during the Darfur conflict (Sudan) (UNEP 2009).

2.10. *Climate change and severe weather*

In general, drylands are expected to expand under the current trends of global warming. Recent projections of the Fifth Coupled Model Intercomparison Project (CMIP5) under representative concentration pathways (RCPs) RCP8.5 and RCP4.5 yield an expansion of global drylands of 50% and 56%, respectively, by the end of this century (Huang et al. 2016). This will stress both the adaptation capacity of the involved biodiversity and the climatic boundary conditions for the occurrence of desertification. Climate change will increase extinction rates of organisms in the future and is projected to be more severe in deserts in comparison to other biomes (Loarie et al. 2009). Deserts experienced an overall increase in temperature of 0.5–2°C between 1976 and 2000, a much higher value than the average global temperature increase (0.45°C), which has been attributed to the higher atmospheric concentrations of greenhouse gases (UNEP 2006). For example, predictions for North Africa and the Middle East imply that climate warming will affect mostly summer temperatures, extending the number of warm days and nights and intensifying temperature extremes, and the maximum temperature during the hottest days could potentially reach almost 50°C by the end of the century (Lelieveld et al. 2016). Current and future climate warming would affect the phenology and distribution of many species, and in synergistic combination with other human-induced threats in drylands (see above), will probably lead to range contraction and species extinction. Given that desert-adapted species already live close to their physiological limits, they may be the most vulnerable ones, as suggested for the Sahara-Sahel endemic vertebrates (Vale & Brito 2015). Ecological niche-based models projecting biodiversity distribution under climate-change scenarios predict dramatic losses of suitable climates with potential consequences in species diversity. For example, the Tassili n'Ajjer National Park of Algeria is predicted to lose about 50% of current mammal richness, with only about 10% species gain (Thuiller et al. 2006). Quantifications of range shifts or population trends of the Sahara species reported negative projections driven by the ecophysiological traits of the organisms, and examples cover from fishes to mammals (Brito et al. 2014).

2.11. *Other options*

Land degradation is the outcome of desertification, in turn caused by diverse human activities including processes related to climate change (Millennium Ecosystem Assessment 2005; Cherlet et al. 2018). All desertification processes converge to loss of ecological functions and structural attributes of the concerned ecosystems. These include declines in Net Primary Productivity (NPP) and biomass, increased soil erosion by runoff or wind deflation, and greater sparseness in vegetation cover. These and other effects result often in a simplified (i.e. degraded) version of the original ecosystem, but they may even drive it to trespass thresholds beyond which it loses its identity and becomes a new community, which has been extensively documented in the Chihuahuan Desert (Huenneke et al. 2002) and in the steppes of the Maghreb (Slimani et al. 2010; Martínez-Valderrama et al., 2018). Dry sub-humid, semi-arid and arid zones are the focus areas of the United Nations Convention to Combat Desertification (UNCCD), and for that reason, quantifying their land degradation has been a recurrent target over the years. It is estimated that land degradation affects from 10% to 20% (Millennium Ecosystem Assessment 2005) to 20–30% (FAO 2011) of such dryland zones. In spite of occurring after several desertification syndromes (e.g., Hill et al. 2008), a relatively small set of Global Change Issues have been identified to drive land degradation. The most widespread and which therefore often concur in the same region are aridity, surface and groundwater stress, human population change and density, low-income level, high input agriculture and livestock density (Cherlet et al. 2018). Nevertheless, when states and trends of land degradation are measured independently, the proportion of the latter result is usually small. For example, 21% of degraded land were reported in the north-western Maghreb drylands (Del Barrio et al. 2016), but only 1% were of actively degrading land. This illustrates the spatial pattern of land degradation, which operates through hotspots embedded in a landscape matrix of variable degrees of maturity, rather than as a diffuse occurrence across the whole territory. The above cited Maghrebian dryland zones have an important human population, and for that reason, most desertification studies have focused on them. Nevertheless, while desertification never leads to proper deserts, it may also occur in hyper-arid zones. It does so normally through the concentration of human activity in areas that are not prepared to host permanent settlements, neither to sustain high agricultural productivity. Top-down policy drivers aiming at stabilising nomadic populations cause the former. This creates gradients of overexploitation and waste around the resulting settlements, which are particularly apparent in countries where the prevailing culture is nomadic, such as

Mauritania or Mongolia (UNEP 2006). Often coupled to this policy, oases agriculture is progressively intensified using either fossil groundwater (Alcalá et al. 2015) or surface water diverted from its natural sinks, which are usually wetlands (Zhang et al. 2012). The immediate outcome is an ephemeral richness that conforms perfectly the paradigm of desertification.

Many deserts and arid regions are located in developing nations, especially in Africa and Asia, where most of these countries rank as Low or Medium Human Development (Human Development Index < 0.7; UNDP 2018; Figure 2). Nearly half of the 40 most highly underfunded countries for biodiversity conservation are covered by deserts and arid regions (Waldron et al. 2013). These countries currently lack the resources and capacities, and in some cases the commitment, to make the strong structural changes needed to tackle the threat factors listed above. The assistance to relieve human pressures that could be provided by NGOs is not present and, when existing, it is largely underfunded (reviewed in Brito et al. 2018). The combined low income, lack of perspectives on social development, and poor human rights enforcement stimulate human migration, particularly in Africa, East Asia and South America nations (UNDP 2018; Figure 2). Poor governance and high corruption levels are systemic to many countries covered by deserts and arid regions, especially in Africa, Asia and South America nations (corruption index < 50; Transparency International 2019; Figure 2), which contribute to environmental destruction and lack of societal accountability. For instance, significant declines in Addax population in Niger occurred because the restrictions imposed by the health, security and environment regulations were not respected by oil companies and subcontractors, including the army in charge of securing activities, which represents an environmental crime that was left unpunished (Brito et al. 2018). Conflict and social insecurity are escalating at the global level and affect particularly deserts and arid regions located in North Africa and West Asia nations (but also North America; IEP 2018a, 2018b; Figure 2). These factors are known to promote illegal wildlife killing and trafficking, and accelerate biodiversity decline (Brashares et al. 2014). As side effect, conflict and social insecurity deter potential and prospects of tourism that could contribute significantly to poverty alleviation and, thus, increase local socioeconomic conditions and human well-being. This is evident in many African countries, which display extremely low international visitor numbers (UNWTO, 2018; Figure 2). As such, reversing the current threat factors acting on deserts and arid regions is a problem embedded in a large and complex web of "glocal" (global-local) societal challenges (Brito et al. 2018).

3. Conservation actions being developed on deserts and arid regions

Most world deserts are among the last wilderness areas at global level that can still be considered mostly intact (Watson et al. 2018), i.e., less affected by the main threatening factors to the biodiversity, the habitat loss and degradation, and where implementing conservation actions would be most cost-effective (Durant et al. 2014; Brito et al. 2016). Because of climatic constraints, more than the 90% of the tropical deserts of the world remain uncultivated have rather low economic value, and the protection of these areas for biodiversity conservation is rather inexpensive (Durant et al. 2014). In this section, the main conservation actions being developed on deserts and arid regions are listed. Conservation Action listing follows IUCN (2019) classification schemes (Table I).

3.1. Land/water protection

The percentage of deserts and arid regions that are formally designated as protected areas is gradually increasing (Figure 1; UNEP 2006; Davies et al. 2012). For instance, Niger declared the largest reserve of Africa for the protection of the Addax population, but local biodiversity hotspots with high endemicity rates associated with the rare perennial wetlands, remain mostly unprotected, as are the cases of the mountain rock pools of Mauritania and the desert springs of the Australian GAB (Vale et al. 2015; Rossini et al. 2018). Protected areas established in deserts and arid regions are highly biased for semi-arid and dry sub-humid regions and only a very small fraction (<0.5%) are located in the hyper-arid category of the AI, despite this category representing about 12% of the global arid regions (Figure 1). Area prioritisation for biodiversity conservation begins to be available for some organisms and specific deserts (e.g. Watson et al. 2009; Brito et al. 2016), but these efforts need to be extended to other biodiversity levels and areas (see below).

At the local scale, community-based natural resource management (CBNRM) projects are building awareness of the environment and the cultural, economic and ecological importance of biodiversity and ecosystem services for human well-being (Pailler et al. 2015), as in the cases of the high Andes of Peru, Namib desert in Namibia or the Mongolian Gobi Desert (Davies et al. 2012); these efforts combining biodiversity conservation and human well-being need to be extended to other world's deserts. For instance, in face of rapid suburban development affecting the grasslands of the Chihuahan desert (North America), conservation of functioning ranch represents a viable means of sustaining ecological function of this desert; community-based adaptive management involving ranchers and environmental agencies would function to conserve biodiversity of these landscapes (Curtin et al. 2002). Actions directed at improving education and awareness on the local biodiversity can be a rewarding path to enhance desert conservation. Local communities have a good perception of the surrounding biodiversity, and stimulating collaboration with researchers, environmental managers and ecotourism agencies, may be of cultural benefit for them, generate alternative income sources, and improve their understanding of the ecosystem services afforded by deserts (UNEP 2006; Brito et al. 2014). Wildlife conservancies on private or communal properties can complement the function of the areas protected by governmental agencies, as has been implemented for arid regions in Namibia (Barnard et al. 1998; Kavita & Saarinen 2016).

3.2. *Land/water management*

In its functional concept, ecological corridors favour the movement of fauna from one area to another, and in the context of the harsh desert conditions, with populations of organisms rather scarce and patched, a conservation priority is protect already known corridors, and identified and proposed new possible conservation corridors (Brito et al. 2016). Telemetry studies can identify movement of desert organisms and help for creating desert corridors, as proved for the desert-dwelling Mountain sheep (*Ovis canadensis*) in California (Bleich et al. 1994). Modern procedures of graph and circuit theory are being used to quantify landscape connectivity in the Sonoran Desert favouring species of conservation concern, and at the same time mitigating the spread of invasive species, like the Bullfrog (*Lithobates catesbeianus*) (Drake et al. 2017).

Management actions are being developed to control invasive species, such as with feral cats or rabbits in Australia (Pedler et al. 2016). In 2015, the Australian government announced the target of killing 2 million feral cats by 2020 (Australian Government 2015), and the measure attracted significant public interest. However, the scientific basis for it is being questioned (Doherty et al. 2019).

3.3. *Species management*

Conservation actions directed at managing or restoring populations of regionally extinct or threatened species are occurring in the world's deserts. For example, extensive conservation efforts were developed to save the two remaining natural populations of the Numbat (*Myrmecobius fasciatus*), in Australia, while conservation breeding and reintroduction programs have succeeded in establishing six populations in its former range (Davies et al. 2012). In Chad, concerted actions between local administrations, the environmental authorities of Abu-Dhabi, and the Sahara Conservation Fund (www.saharaconservation.org) allowed the recent reintroduction of the Scimitar oryx (*Oryx dammah*) in the Ouadi Rimé-Ouadi Achim Game Reserve, after decades of being considered Extinct in the Wild (IUCN SSC Antelope Specialist Group 2016). Morocco is developing an *ex-situ* breeding facility (M'cissi Reserve) of large ungulates (Oryx, Addax) and the Ostrich to be reintroduced in the north-western fringes of the Sahara, while captive breeding and releasing programmes of Houbara Bustard are being successful, although they are aimed at maintaining hunting activities, by falconry, on this large bird (UNEP 2006). Reintroduction and restocking of wild species is a first step for the restoration of ecosystem function in deserts (Durant et al. 2014), but such operations require detailed decision processes and are costly, lengthy and logistically difficult, reinforcing that local extinction should be avoided whenever possible (Brito et al. 2018). For instance, the first reintroduction attempt of 24 Mhorr gazelles (*Nanger dama mhorr*) in southern Morocco was affected by feral dogs (killing seven individuals) and poaching (chasing released individuals), which represent major obstacle to reintroduction projects in the region (Abáigar et al. 2019).

There are ways to reduce the accidental entrapment of desert organism in anthropogenic infrastructures by on-site, cost-effective management measures. The barrier effect by fencing is a cost-effective mitigation measure used by managers to reduce mortality from road vehicles. Roadside fencing and animal underpasses in desert roads when they intercept washes have reduced their impact on the fauna, as deduced from the study of Ground turtle in the Mohave Desert (Peaden et al. 2017). In Iran, these measures are being planned for the Semnan-Mashhad highway (N44), stretching along the northern boundary of Touran Biosphere Reserve, where road collision is a major cause for population decline in Asiatic cheetah (Khalatbari et al. 2017). Dense wire mesh in the inlet and overflow slits of the modern water cisterns for watering livestock could prevent wild desert organisms from being caught, and simple ramps in the settling tanks could facilitate the escape of trapped individuals, while not restricting livestock from watering; in the West Sahara, this mitigation measure has reduced 66% of amphibian and reptile mortality from trapping (Pleguezuelos et al. 2017). However, the management of desert spring in North America and Central Australia must include disturbance produced by livestock to maintain the native fish fauna, probably because a long history of disturbances by native mammals and aboriginal humans in these habitats (Kodric-Brown & Brown 2007).

3.4. Education and awareness

Actions directed at people to improve their education and awareness on the local biodiversity can be the most rewarding path to enhance the conservation of deserts, an in general most biomes. Local communities have a good perception of surrounding biodiversity (e.g., Hammiche & Maiza 2006; Miara et al. 2019), and stimulating collaboration with researchers, environmental managers and developing agencies may be of cultural benefit for them, generate alternative income sources, and improve their understanding of the ecosystem services afforded by deserts (UNEP 2006; Brito et al. 2014). There are governmental agencies and multiple other organisations and NGOs providing research, formal education and advanced training in desert biodiversity, and environmental protection, such as the Desert Studies Center (California; http://nsm.fullerton.edu/dsc/), Desert Research Learning Center (Sonora; https://www.nps.gov/im/sodn/drlc.htm), Desert Research Unit (Arizona; https://snre.arizona.edu/facilities/dru) and the Desert Research Institute in North America (Nevada; http://www.dri.edu/); the Desert Ecology Research Group (Sydney; http://www.desertecology.edu.au/) and Desert Knowledge Australia in Australia (https://www.dka.com.au/); and the Desert Research Foundation (http://www.drfn.org.na/) and the Gobabeb Desert Research and Training Centre in Namibia (http://www.gobabebtrc.org/) (Brito & Pleguezuelos 2020). Local actions enhancing knowledge, skills and information exchange for practitioners, stakeholders and other relevant individuals are also being developed across multiple deserts, and examples come from the Coalition for Sonoran Desert Protection (https://www.sonorandesert.org/), Namib Desert Environmental Education Trust (http://www.nadeet.org/namib-desert-environmental-education-trust-nadeet), and Sahara Conservation Fund (https://www.saharaconservation.org/). The latter has several programmes to recover threatened vertebrates in the Sahara-Sahel (e.g., Addax, vultures, giraffes, ostrich) and specifically involves local communities in management actions.

3.5. Law and policy

Specific legislation to protect biodiversity of deserts and arid regions is relatively rare and is often restricted to developed countries. Examples include the California Desert Protection Act of 1994, which established the Death Valley and Joshua Tree National Parks and the Mojave National Preserve in the California desert, or the Environment Protection and Biodiversity Conservation Act of 1999 (EPBC Act) of the Australian government to identify and protect desert threatened ecological communities. Still, increasing efforts to develop legislation and policies relating to Protected Areas in deserts are emerging. For instance, Botswana and South Africa have developed concerted efforts to develop policy harmonisation to promote greater transboundary harmonisation in the management of the Kgalagadi Transfrontier Park, regarding natural resource management and local community benefits (Moswete 2009; Thondhlana et al. 2015).

Under the Minerals Act (1992) and the Environmental Management Act (2007) Namibia, a mainly arid country, developed environmental legislation to regulate mining activities, which were later reinforced by the Policy on Mining and Prospecting in Protected Areas and National Monuments (1999) and the Minerals Policy (2003) (Ministry of Environment and Tourism 2010). Despite these regulations, conflicts between mining activities intruding keyareas for local communities, such as in the case of the Ju/'hoansi people inhabiting the Kalahari Desert along the border between Namibia and Botswana, indicate that current legal regimes to protect indigenous peoples are still inadequate (Harring 2012). In developing nations that rely extensively on mineral exports to sustain economy, environmental pressures steaming from mining activities still need better regulation. Companies exploiting natural resources need to engage in Corporate Social Responsibility (CSR) (Málovics et al. 2008) and work together with wildlife authorities of range countries to align strategies and operations with universal principles on human rights, labour, environment and anti-corruption (reviewed in Brito et al. 2018). The United Nations Global Compact (www.unglobalcompact.org) provide guidelines to companies to promote sustainable and equitable use of natural resources, while actively support the recovery of threatened species, the management of protected areas, and the effective capacity building of the wildlife services in the countries where extraction operations are conducted.

Countries where conflict and social insecurity are causing environmental damage need to develop measures to stimulate the disarmament of civilians, militias and extremist groups, while firearms and ammunition embargos to non-governmental buyers need to be imposed. The implementation of the United Nations Arms Trade Treaty (https://www.un.org/disarmament/convarms/arms-trade-treaty-2/) provides an umbrella for such actions, and encouraging examples arrive from West African countries, which have already ratified the Treaty and are in the process of integrate it into their national security systems (Brito et al. 2018). International legal instruments are also need to reduce or mitigate the environmental impacts of military activities, including site-based protection of critical natural resources and areas of ecological importance during armed conflicts (Plant 1992; UNEP 2009).

3.6. *Livelihoods, economic and other incentives*

Tourism in natural areas, especially ecotourism, is one of the economic activities based on the ecosystem services provided by deserts and arid regions with the potential to preserve the desert biome while supporting local cultures, traditional livelihoods and sustainable development of homestay communities (reviewed in Santarém et al. 2020a). Deserts display many opportunities to promote ecotourism, such as the wetlands of Mauritania for bird- and crocodile-watching (Santarém et al. 2018), the Wadi Rum of Jordan (Goudie & Seely 2011), the Little Sandy Desert of Australia (Webb 2002), the Khorn and Biabanak deserts of Iran (Eshraghi et al. 2010), Sossusvlei in the Namib-Naukluft National Park of Namibia (Baker & Mearns 2017) or the Chilean deserts (Borsdorf et al. 2012). Ecotourism has been suggested as a substitution of environmental damaging activities, solving conflicts derived from intense pastoralism in the arid regions of Mongolia (Reading et al. 2006). Goals towards an effective conservation of semi-deserts in Kazakhstan include involving stakeholder in conservation, and a greater allocation of funds to protection and management areas (Kamp et al. 2016).

3.7. *External capacity building*

International cooperation to create or providing non-financial support and capacity building to local communities in deserts and government agencies are forming the basis to facilitate partnerships and networks of organisations. For instance, the Nature Conservancy is promoting capacity building for biodiversity and conservation in the southern Gobi Desert to protect the world's largest remaining populations of Khulan (*Equus hemionus*), Mongolian gazelle (*Procapra gutturosa*), Goitered gazelle (*Gazella subgutturosa*), wild Bactrian camel (*Camelus ferus*), and Siberian ibex (*Capra sibirica*) from the negative impacts of growing local mining activities (The Nature Conservancy 2016). The project attempted to facilitate and coordinate the assistance to the Mongolian Ministry of Environment, Green Development and Tourism (MEGDT) in building their internal capacity to manage several constraining factors, and to mitigate the impacts of rapid and unsustainable development; examples are the lack of biological data at regional and local scales, cooperative data sharing, and landscape scale assessments. By a recent agreement signed between Morocco and the Ministry of Environment Qatari, the latter country has engaged with the Haut Commissariat aux Eaux et Forêts et la Lutte Contre la Désertification of Morocco for the implementation of a reintroduction program of Sahara fauna in its natural habitats by recruiting additional custodians who will be responsible for monitoring at the regional level under the guidance of Moroccan forest officers. In Australia, the BHP Billiton Foundation's is promoting an indigenous-led partnership to address the impacts of destructive wildfires, and invasive noxious weeds and feral animals, across 10 deserts of Australia, supported by regional and international conservation organisations (Jupp et al. 2015; BHP 2018).

4. Research needs on deserts and arid regions

Deserts and arid regions are highly appealing for biodiversity and evolutionary research, but their usual large size and remoteness, and in some cases long-term social insecurity, contribute substantially to a generalised lack of knowledge, particularly in the African Sahara and Central Asia deserts (Brito & Pleguezuelos 2020). Still, research efforts in deserts have increased exponentially over the last decades and are now mostly based in the use of contemporary tools and analytical processes, including molecular (DNA sequencing and genotyping) and geomatic (Global Navigation Satellite Systems and Geographical Information Systems) tools. Research is enabling the mapping of biodiversity distribution patterns and land degradation status and trends (e.g., Brito et al. 2014; Del Barrio et al. 2016), but these studies are also exposing knowledge gaps on these topics. The following research needs in deserts and arid regions follows the IUCN (2019) classification scheme (Table I).

4.1. Scientific research

Molecular-based studies across the world's deserts are unravelling cryptic diversity and geographic structuring in genetic diversity that should be preserved (Brito & Pleguezuelos 2020). For example, conservation of the threatened Cuvier's gazelle in the northern Sahara should consider the preservation of the recently described mountain and lowland ecotypes to maintain the overall adaptive potential of the species (Silva et al. 2017). In the desert springs of the Australian GAB, molecular studies have uncovered massive numbers of endemic forms in aquatic invertebrates (Murphy et al. 2013). Although the systematic status of these genetic demes and the evolutionary drivers of such diversity in many cases still remain unknown (Brito et al. 2014), the results of multiple studies are increasingly suggesting that the diversity in deserts is still largely underestimated. Most likely, scientific research will continue revealing additional biodiversity in the desert biome.

The classic perception that deserts accumulate few species with large distributions is being increasingly replaced by molecular evidence showing that they display larger numbers of species and in some cases with narrow distributions, often limited to local hotspots of biodiversity (e.g., Murphy et al. 2013, 2015; Vale et al. 2015; Rossini et al. 2018). Multiple patterns emerge in the distribution of biodiversity in deserts and arid regions: it is spatially structured and apparently related to environmental variation, mountains and wetlands constitute biodiversity refugia (especially for aquatic and mesic species), high biodiversity levels are found along ecological corridors, and the vast empty-quarters (unpopulated areas) and dune massifs are crucial refugia for threatened species (Brito & Pleguezuelos 2020). Still, knowledge about biodiversity distribution in deserts and arid regions is highly skewed toward North America and Australian deserts, while the Sahara-Sahel, the Horn of Africa, the Arabian Peninsula, and Central Asia, remain poorly sampled (Brito & Pleguezuelos 2020). Additional scientific research is needed to fill out these knowledge gaps in biodiversity distribution. For instance, the recent technological advances in the use of environmental metagenomics (eDNA) for biodiversity inventory has the potential to uncover biodiversity levels and distribution in drylands (e.g., Egeter et al. 2018). Satellite Remote Sensing tools also have the potential to support biodiversity conservation in data-deficient areas, especially in large and remote areas that are hard to sample (Owen et al. 2015; Pettorelli et al. 2016).

4.2. Conservation planning

The identification of priority areas for biodiversity conservation needs to be extended to regional/national scales and for world deserts. Reserve design targeting desert freshwater diversity needs to consider the effects of hydrology and species' ecology on population connectivity (Murphy et al. 2015). The assessment of the conservation status under the IUCN Red List criteria is still poorly developed in desert-dwelling species, and needs to be extended to regional/national scales (Rossini et al. 2018; Burriel-Carranza et al. 2019). Species-based Action Plans outlining the main actions needed to preserve and/or recover threatened biodiversity are basal to the developed optimised conservation in world deserts. So far, most Action Plans have been derived for imperilled fauna, such as the Ground turtle or the Addax (USFWS 2011; Rabeil 2016), but these need to be expanded to other threatened species and/or complete taxonomic groups. For instance, Australia developed specific Action Plans for the birds and mammals of the country (Garnett et al. 2011; Woinarski et al. 2014). Likewise, there are very examples of Action Plans dedicated to desert territories, covering distinct biodiversity levels, and examples come from developed nations (e.g., US-BLM 2005). Additional research efforts are need to cover these gaps in conservation planning of desert biodiversity.

Community-based Wildlife Management and CBNRM programmes allow building awareness of the environment and the cultural, economic and ecological importance of biodiversity and ecosystem services, and developing a deeper understanding of the local needs and contexts (Brito et al. 2018). In fact, natural heritage can provide a constructive and positive identity to be proud of, especially through inspiring young future "green activists". While there is no doubt that support is needed to effect major societal and policy change, including from organisations, such as the World Bank/GEF, United Nations Convention to Combat Desertification, or the European Development Fund, better integration of environmental conservation with equitable socio-economic development into efficient peace strategies is still required.

4.3. Monitoring

Under the context of global change, monitoring of biodiversity status and trends has become a top priority research field to conserve species and ecosystems management (Navarro et al. 2017; Haase et al. 2018). Various scientific disciplines contribute essential information that enhances the understanding of land degradation and desertification at different temporal and spatial scales. These include studies from plot scale to global assessments, the collection of biophysical and socio-economic data, and the establishment of models to predict potential transformation pathways in future decades. Field-based monitoring efforts remain spatially and temporally fragmented and there are generalised taxonomic biases, although contemporary techniques (e.g., Satellite Remote Sensing and geomatic tools) allowed widening the range of data acquisition. For instance, deserts and arid regions represent huge knowledge gaps in biodiversity status and trends (Brito & Pleguezuelos 2020), being almost excluded from global initiatives to map biodiversity time series (e.g., Bruelheide et al. 2018; Dornelas et al. 2018). Still, the growing scientific research in deserts and arid regions is building-up a bulk of biodiversity data, ranging from raw distribution data to species phylogenies and ecosystem-level data, which creates a challenge in the assemblage of the scattered knowledge on biodiversity status and trends (Brito et al. 2014).

Earth observation provides spatially explicit information on the Earth surface. Remote sensing data are important components of monitoring strategies, as they provide objective, repetitive and synoptic observations across large areas (Graetz 1996; Hill et al. 2004). Since decades earth observation data are used to characterise land degradation in dryland areas (Stellmes et al. 2015). Information extracted from remote sensing data can be employed for instance to assess the extent and condition of ecosystems and to monitor changes in their conditions over time periods (Foley et al. 2005; Turner II et al. 2007). These data enable observing long-term trends and short-term disturbances across large areas. Thus, the use of earth observation data contributes to the understanding of dynamics and responses of vegetation to climate and human interactions (DeFries 2008). There are numerous studies that map the condition of drylands worldwide using Earth observation imagery. Many of these studies differ for instance in the spatial, temporal, and spectral characteristics of the Earth observation data used, as well as in the indicators and methods applied and the period of observation (Stellmes et al. 2015; Dubovyk 2017). These differences in study design make it difficult to harmonize results and provide a global picture of the state of drylands. The third Atlas on desertification aimed at filling this gap by providing a synoptic summary of dryland condition (Cherlet et al. 2018). Moreover, a wide range of different sensor systems (multi- and hyper-spectral, LiDAR, RADAR) exist that work on different platforms (UAVs, airborne, satellite) and are characterised by different temporal repetition rates. The variety of remote sensing data offers new opportunities in monitoring drylands both with high spatial and temporal resolution that meet the requirements of the often highly heterogeneous dryland areas. But these manifold capabilities make it even more important to develop ecosystem and sensor-independent indicators that may be compared across scales and ecosystems.

This urgent need is addressed by the efforts of the scientific community to establish a set of Essential Biodiversity Variables (EBVs). EBVs are defined as derived measurements to study, report, and manage biodiversity change, focusing on status and trend in elements of biodiversity, and are structured in six classes: genetic composition (e.g., intraspecific genetic diversity, effective population size), species populations (e.g., species abundances), species traits (e.g., morphology, phenology), community composition (e.g., community abundance, taxonomic diversity), ecosystem functioning (e.g., primary productivity), and ecosystem structure (e.g., ecosystem distribution) (https://geobon.org/). The use of Essential Biodiversity Variables (EBVs) allows structuring biodiversity monitoring globally and to harmonise and standardise biodiversity data from disparate sources (Kissling et al. 2017; Jetz et al. 2019). As such, more effort should be placed in reporting biodiversity status and trend framed in the EBV context. Despite the low visitation rates of deserts in relation to other biomes, citizen science based-data could help overcoming current knowledge gaps (Chandler et al. 2017).

4.4. Other

Land condition (in terms of ecological maturity) and biodiversity are related by positive feedbacks, which are likely to be under hysteresis. In other words, loss of species depends on ecosystem condition, and will be slower for mature than for degraded states. This is probably critical in desert environments because of the slow progression of ecological secondary succession, and finding associated thresholds is required to ensure success of conservation policies (Ward 2016). Such thresholds should not only refer to biodiversity, as done, for example, in the IUCN Red Lists of Ecosystems (https://iucnrle.org/), but also to its drivers. For example, stable isotopes highlight processes of water recharge in aquifers under arid climate (Malki et al. 2017); hence, may be useful as indicators of exploitation intensity. Exploitation controls land condition and, largely, its spatial structure. Thus, the paradigm that considers biodiversity as an attribute of pristine ecosystems in the outback of human influence should be upgraded to consider humans as a part of desert ecosystems. Humans simplify natural ecosystems to maximise NPP at the expense of biomass. In the deep desert, this is done through a spatial structure that is coupled to rainfall. In permanent settlements and oases, that alteration occurs in radial gradients. Either way, the resulting spatial pattern controls biodiversity not only through local ecosystem changes, but also by creating a new spatial structure that impacts ecological connectivity, hence ecosystem persistence, at several spatial scales (Okin et al. 2009). Further, an intriguing hypothesis of desertification in deserts would be that land degradation gradients around settlements are very long, because both of the low NPP inherent to the environment and of the increased exploitation connectivity associated to off-road vehicles. As a result, such areas of influence might coalesce (or have done it already in some regions) with more facility than in more humid regions.

At a regional level, it is necessary to foster the engagement of local people in biodiversity conservation by promoting a sustainable natural resource management. Ecotourism and sustainable tourism industry have a potential to support nature conservation and increase human well-being, and studies in southern Africa suggest that local communities are often aware of the potential role of tourism in improving livelihoods (Mbaiwa & Stronza 2011; Chiutsi & Saarinen 2017). However, ecotourism development that is often based on long-haul flights should not be envisaged as a solution for global environmental and climate change that deserts are facing, but it can offer a regionally sustainable tool to contribute positively to local conservation and the well-being of communities living within deserts (Santarém et al. 2020a, 2020b, 2021). In this respect, future research should focus on how to optimise benefit creation and distribution between ecotourism operators and local communities and how to foster environmental responsibility in tourism-community relations. Furthermore, research is needed on the development of adaption measures to deal with global changes impacting ecotourism activities, human development, and biodiversity conservation in arid environments (Tervo-Kankare et al. 2018). In addition, ecotourism in drylands may generate specific environmental, economic and sociocultural impacts that need to be considered when developing tourist activities (Santarém et al. 2020a). This calls for stronger sustainability governance in implementation and management of tourism projects (Saarinen & Gill 2019). This means that the tourism industry needs to develop advanced environmental and social responsibility; especially as the industry usually does now own those natural and/or cultural attractions it uses and sells for tourists. Finally, the implementation of ecotourism projects is challenged in many deserts due to regional insecurity and conflict (see above), which translates into high vulnerability and strong regional variation in visiting rates among world deserts (Figure 2). For these reasons, amongst others, tourism based on ecosystem services provided by deserts still remains under-explored (Santarém et al. 2020a, 2020b, 2021).

5. A case-study: the Sahara-Sahel wetlands

Isolated wetlands are critically important life-support systems in deserts and arid regions for both humans and wildlife (Datry et al. 2017). During the wet season they are inundated and provide support to local people directly with water, food resources and fertile lands, while during the dry season they act as water source for nomadic communities and livestock migrating from more arid regions. In the Sahara-Sahel, they constitute local biodiversity hotspots that are vulnerable to human activities and climate change (Brito et al. 2014; Vale et al. 2015). Using the wetlands of the west Sahara-Sahel as case study, here we detail the major threats affecting them, the available knowledge about biodiversity distribution patterns and the evolutionary processes regulating these patterns, and the research priorities to support regional conservation planning and sustainable human development.

5.1. Direct threats acting on wetlands and conservations actions in need of development

Biodiversity in the Sahara-Sahel ecoregions of Africa is being eroded due to habitat conversion and unsustainable human development (reviewed in Brito et al. 2014). Recent increase in conflicts and resource exploitation has accelerated decline and stressed the need for developing effective policies to reduce impacts on biodiversity (Brito et al. 2018). All Sahara-Sahel range countries are developing nations and some, such as Algeria, Mauritania, and Morocco, are amongst the 40 most highly underfunded countries for biodiversity conservation (Waldron et al. 2013). Algeria and Mauritania are also amongst the top-five countries unable to retain top talents and brain drain deprives them from the human resources needed to drive and implement the structural changes needed for reverting biodiversity loss while promoting sustainable human development (WEF 2014). These are also amongst the least visited countries by international tourists in the world (UNWTO 2018), which hampers local development, exacerbates social-economic pressures, and contributes to migration crisis (UNEP 2006).

Wetlands in the west Sahara-Sahel offer a framework scenario to revert current environmental and societal challenges. They display biological and cultural resources that can be used to build awareness of the surrounding environmental, economic, and ecological importance of biodiversity and ecosystem services (Figure 3). They may be used to frame sustainable development, while promoting biodiversity conservation through community-based ecotourism (CBE) programmes. Protected areas together with local community-based conservation are key tools for securing Sahara-Sahel biodiversity under climate change scenarios (Brito et al. 2018), sustainable economic development, and regional peace and stability. West Sahara-Sahel wetlands provide benchmark case-study to investigate if and how CBE could contribute to improve socioeconomic welfare of populations, and ultimately to preserve cultural and natural heritage (Brito et al. 2011a, 2014, 2018; Vale et al. 2015).

Studies developed in Algeria, Mauritania, and Morocco have emphasised the importance of protecting local wetlands and oases for biodiversity conservation. It has been preliminarily shown (mostly in Mauritania) that: 1) They constitute local biodiversity hotspots and refugia to relict populations of distinct Palaearctic or Afro-tropical species (crocodiles and baboons are notable examples; Brito et al. 2011a; Vale et al. 2015), and promote speciation (Brito et al. 2014); 2) Population isolation and genetic differentiation within species occurred in mountains, with cryptic lineages being formed by relict populations associated to aquatic or mesic environments (Leite et al. 2015; Metallinou et al. 2015; Gonçalves et al. 2018; Dilytė et al. 2020; Gonçalves & Brito 2020), probably induced by the strong regional climatic oscillations since the

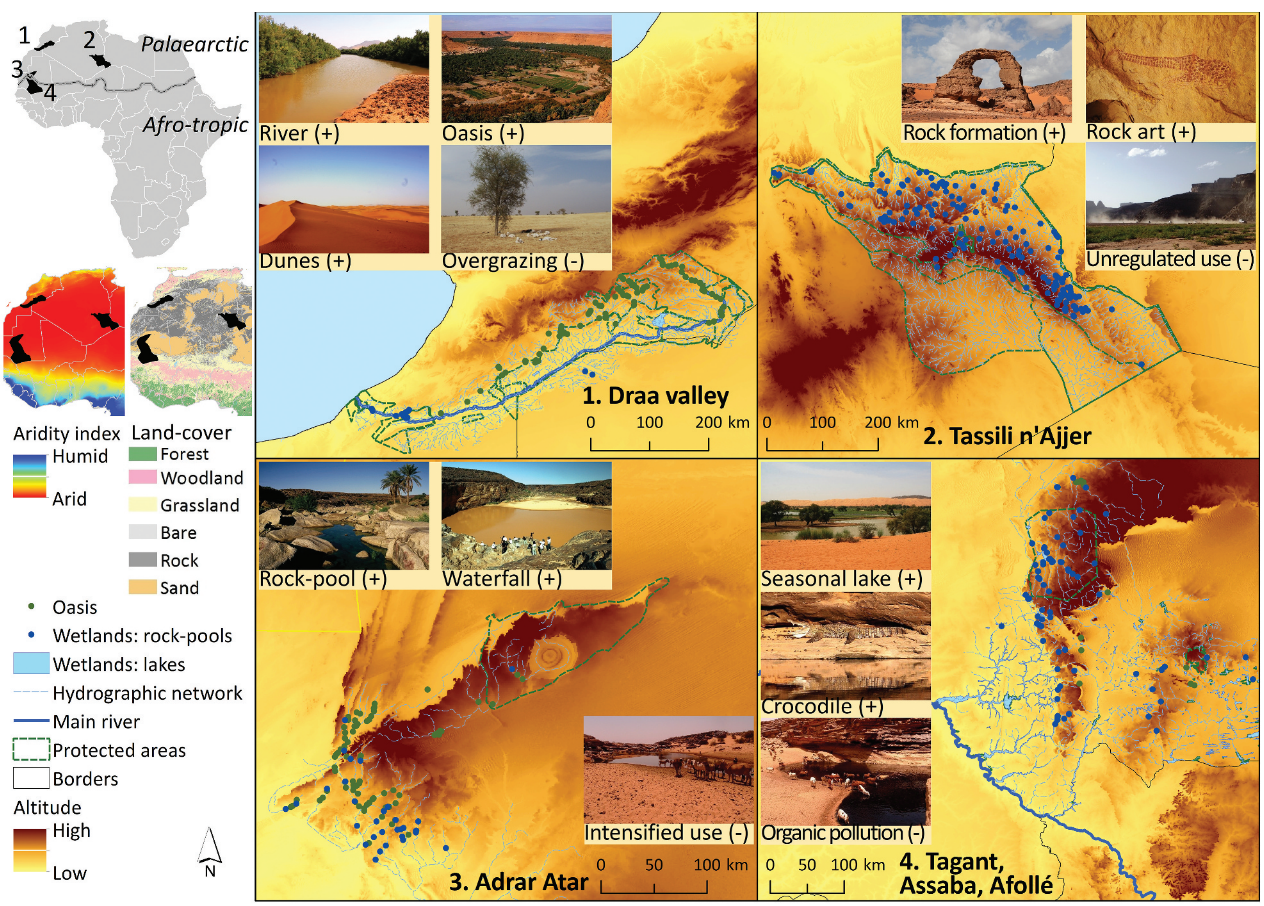

Figure 3. The wetlands of the west Sahara-Sahel. Location of four hydrographic networks in the African context (left insets), distribution of 696 wetlands and 181 oases, and a selection of pictures of values (+) and pressures (-) associated to wetlands.

Pliocene (5.3–2.5 Mya) (Brito et al. 2014); 3) In wetlands, preliminary estimates of genetic and community composition EBV were related with primary productivity and permanent water (Vale et al. 2015; Gonçalves et al. 2018), while species populations EBV were linked to rainfall and temperature variation (Vale et al. 2014; Leite et al. 2019); 4) The available quantifications of genetic and community composition in wetlands are insufficient to provide a robust identification of priority conservation areas (Brito et al. 2016); 5) Environmental metagenomics (eDNA) has potential application for EBV quantification in arid regions (Egeter et al. 2018), but optimised field sampling designs and eDNA processing methods still need further development; and 6) Ecosystem structure EBV are diverse (Campos et al. 2012), but trends in ecosystem function and structure are still unavailable.

West Sahara-Sahel wetlands are isolated remnants of the Green Sahara that have progressively contracted and became spatially isolated along hydrographic networks during the Holocene. Based on a limited set of samples, it has been shown that wetlands are presently nodes of ecological networks (inter- and intra-specific populations linked by functional attributes), where connectivity fluctuates according to seasonal and inter-annual climate variations (Velo-Antón et al. 2014). During the rainy season of humid years, suitable dispersal corridors are formed along raging streams, partially connecting isolated wetlands and allowing gene flow and metapopulation dynamics within sub-basins (Campos et al. 2012). Still, it is unknown how dispersal abilities and distinct levels of water dependence may relate with gene flow dynamics and population structure of concerned species. Water availability is apparently related with dispersal events (Velo-Antón et al. 2014), but landscape features shaping the distribution of genetic diversity are mostly unknown.

Recent land-use changes have increased pressure on ecosystems, directly by extracting natural resources and indirectly by degrading the network nodes and their embedding landscape matrix (Brito et al. 2014). In Mauritania, activities for excavating pools or pumping water are increasing and water overexploitation for livestock causes seasonal shortages, faecal contamination, and excessive eutrophication (negatively impacting also public health) (Brito et al. 2011a; Vale et al. 2015; Campos et al. 2016). Yet, the relationships between threat status in wetlands and genetic, species and community composition EBV have not been formally described, and land-condition status and trends remain unmapped.

Conservation actions developed so far have focused in the: i) designation of protected areas, like the Tassili n'Ajjer Cultural Park in Algeria, the Iriqui National Park and Ait Oumribet Natural Park in Morocco, and the El Agher and Guelb er Richât National Parks in Mauritania (the later only proposed); ii) the recognition of UNESCO World Heritage Sites, like the Tassili n'Ajjer in Algeria, Ancient Ksour of Chinguetti and Ouadane in Mauritania, and the Oasis of Southern Morocco (Man and Biosphere Reserve); and iii) the identification of Ramsar sites, like the “La Vallée d'Iherir” in Algeria, the “Lac Gabou et le réseau hydrographique du Plateau du Tagant” in Mauritania, and the “Embouchure de l'oued Dr'a” and “Moyenne Dr'a” sites in Morocco. In addition, Morocco has designated a series of Biological and Ecological Interest Sites (SIBE), such as the “Oasis de Tissint”, “Msseyed”, “Oued Mird”, and “Oued Tighzer” (Figure 3). While these actions may support local biodiversity conservation, scenarios of conservation planning in the Sahara-Sahel showed that optimised conservation networks needed to maximise spatial representation of overall biodiversity patterns and processes, and minimise conflicts with human activities, are in need of development (Brito et al. 2016). In fact, Algeria, Morocco and Mauritania are among the top-40 most highly underfunded countries for biodiversity conservation (Waldron et al. 2013). Greater regional investment is needed via resource allocation from major international funding institutions, such as the World Bank/Global Environment Facility, as well as the development of the resources and capacities, and in some cases the commitment, to make engage in effective protection of natural habitats and the fauna and flora (Brito et al. 2018). Furthermore, regional conservation planning scenarios derived at fine-scales are needed to identify specific wetlands where conservation efforts can be more urgently directed at.

Against this backdrop, there is urgency to build effective knowledge on current land-use systems and socioeconomic processes linked to biodiversity conservation and human development around desert wetlands. Current economic activities exploit smallholder farming and livestock production, with limited opportunities for social development, and the drivers of land-use dynamics are undescribed. Yet, wetlands display high levels of taxonomic diversity and endemic species that can be used for conservation marketing and ecotourism development. The best flagships (species that draw conservation support) have been identified within Sahara-Sahel vertebrates (106 species among 1126 possibilities) for conservation marketing, ecotourism promotion campaigns, and setting CBE programmes (Santarém et al. 2019, 2020b, 2021), and ecotourism potential of some wetlands has been ranked (Santarém et al. 2018). Despite these efforts, detailed socio-economic analyses are needed to evaluate the return-on- investment and resilience factors of current land-use systems and complementary systems (such as CBE) for biodiversity conservation and local human sustainable development (see Saarinen & Gill 2019).

5.2. *Research needs on wetlands*

Research is needed to foster synergies between biodiversity conservation and sustainable community development, while at the same time promoting resilience to global change. The key priority research subjects are: 1) Biodiversity inventory and distribution mapping; 2) Test ecological networks and their environmental dependencies, focusing on species with distinct dispersal abilities and habitat traits; 3) Investigate evolutionary and landscape processes linked to biodiversity distribution; 4) Describe how water- and land-use pressures degrade landscapes and decrease network resilience to global change; and 5) Compare and analyse socioeconomic contexts, livelihood alternatives and scenarios, exploring their sustainability and complementarity to current and future land-use systems. These data need integration to identify priority wetlands for biodiversity conservation while accounting for potential socioeconomic development. The integration of status and trend data on EBV distribution, biodiversity nodes and networks, water and land-condition, and land-use and socioeconomic development scenarios will allow identifying priority wetlands and dispersal corridors for biodiversity conservation and CBE development, and framing local development plans (Brito et al. 2014, 2018; Santarém et al. 2018, 2020b, 2021). The premise is that reducing the negative impact of current land-use systems causing unsustainable pressures over wetlands (e.g. water abstraction for livestock) will contribute to increase water quality and availability under climate change scenarios. Furthermore, this would complement to current land-use systems with CBE, leading to poverty decrease, employment and economic growth, and inequality reduction, thus reducing migratory flow (Brito et al. 2014, 2018; Saarinen & Gill 2019). The most urgent research questions and possible methodological tools are addressed in the following subsections.

5.2.1. Patterns in the distribution of biodiversity. i) How is genetic, species and community diversity spatially structured? ii) Can distinct conservation units (CU: intraspecific groups that need consideration in conservation actions) within selected taxa be identified? iii) Where are biodiversity hotspots located? iv) Can biodiversity in desert wetlands be efficiently monitored using eDNA-based approaches? v) How ecosystem function and structure are spatially distributed and how have they evolved during the last 30 years? Population genetic analyses of flagship taxa are needed to estimate patterns of diversity and population differentiation, spatial genetic structure, migration rates and levels of gene flow (e.g., Velo-Antón et al. 2014). Phylogenetic analyses from environmental metagenomics data are needed to estimate taxonomic diversity (species or higher) (e.g., Egeter et al. 2018), and from tissue-based DNA data to identify CU in all possible vertebrates (e.g., Leite et al. 2015; Metallinou et al. 2015; Tucker et al. 2017; Gonçalves et al. 2018; Velo-Antón et al. 2018). Earth Observation data and remote sensing tools are needed to estimate primary productivity, disturbance regimes, and ecosystem extent and fragmentation (e.g., Udelhoven et al. 2015; Frantz et al. 2016; Schneibel et al. 2017).

5.2.2. Evolutionary and landscape processes linked to biodiversity distribution. i) How are EBV spatially structured in relation to current and changing environmental conditions? ii) Where are historical refugia and suitable areas for taxa dispersal located? iii) Do refugia/corridors predicted by molecular and ecological signatures define the same areas? iv) How will landscape connectivity be affected under global change scenarios? Ecological niche-based models of species/community distribution are needed to relate EBV community composition and environmental variation and global change drivers (e.g., Brito et al. 2011b; Sow et al. 2014; Vale et al. 2014; Gonçalves et al. 2018). Ecological models need to be projected to past climatic conditions to infer areas of climatic stability across time and historical network connectivity. Genetic analyses are needed to infer past events of connectivity and gene flow, and locate wetlands of high genetic diversity (e.g., Gonçalves et al. 2018; Velo-Antón et al. 2018). Network analyses conducted on resistance-to-dispersal maps are needed to model current wetland connectivity. Genetic distances between CU/populations of selected co-distributed taxa need to be compared against estimates of cumulative landscape resistance to estimate current functional connectivity. Connectivity simulations between wetlands under climate and land-use change scenarios are needed to estimate future fragmentation thresholds (e.g., Tarroso et al. 2019).

5.2.3. Patterns in the distribution of global change drivers and human development constraints. i) What is the status of water quality in desert wetlands? ii) Which wetlands are the most threatened? iii) Is there a relationship between threat status and EBV? iv) What is the level of land degradation in the hinterlands of wetlands, and how is its spatial structure? v) How have drivers of global change evolved during the last 30 years (available time period of EO data)? eDNA data are needed to detect the presence of important bio-indicators and pathogens. Ordination techniques are needed to derive threat indexes for wetlands and regression analyses are needed to estimate relationships with EBV (e.g., Leite et al. 2019). EO time-series data and remote sensing tools are needed to estimate spatially explicit EBVS providing vegetation characteristics at appropriate temporal and spatial scales that might be employed to assess ecological maturity states and trends over time, biomass response to rainfall anomalies and disturbances, and temporal pressures of current land-use systems on biodiversity (e.g., Del Barrio et al. 2010, 2016, 2018; Stellmes et al. 2015; Ruiz et al. 2016; Martinez-Valderrama et al. 2018).

5.2.4. Socioeconomic processes linked to human development. i) Which is the estimated economic return from current land-use systems? ii) What elements could explain community resilience under current and future changes in socio-ecological systems? iii) Which is the willingness of potential tourists to pay to visit wetlands? iv) Which local communities are most motivated to complement current land-use systems with CBE and what contextual factors, if any, explain community differences? v) Which would be the economic return and opportunity cost of including CBE in the current land-use systems array? Detailed demographic and socioeconomic data are needed for profiling current tourist activities, potential tourists, and local communities (and their livelihoods) inhabiting the surroundings of wetlands. Estimates of willingness-to-pay of tourists to see local flagship species are needed to model CBE development scenarios and their socioeconomic and environmental viability. The economic return and wider benefits of CBE against that of current land-use systems needs to be carefully examined and compared (e.g., Kavita & Saarinen 2016; Saarinen 2016).

5.2.5. Priority wetlands for biodiversity conservation and socioeconomic development. i) Which wetlands maximise the concentration of the multiple levels of biodiversity under study? ii) Which corridors are critical to ensure population connectivity and gene flow among wetlands? iii) What is the minimum set of wetlands/corridors that should be simultaneously assigned for conservation, to ensure representation and persistence of EBV under alternative scenarios of climate change, landscape connectivity, and current land-use systems, and for CBE development? iv) Which is the current level of protection of selected wetlands? The results from the previous questions need to be integrated and decision-support tools are needed to simulate distinct cost-target scenarios and to rank wetlands according to suitability for biodiversity conservation and CBE development (e.g., Wintle et al. 2011; Brito et al. 2016; Carvalho et al. 2017).

6. Conclusions

Globally, deserts and arid regions are under increasing threats and further research is needed to foster synergies between local biodiversity conservation and sustainable community development. Addressing the expressed research priorities requires the integration of multiple research fields (e.g. biogeography, population genetics, climate and landscape, social and economic sciences) through cutting-edge technologies in each (e.g. eDNA, population genomics, remote sensing, ecological modelling, network analyses, advanced decision-support tools), and to deal with hierarchical levels of biodiversity (from genes to species, landscapes and ecosystems) under multiple complementary objectives in rather remote regions. Such approach is ambitious but it will provide comparative insights into connectivityfor instance, among wetlands, in desert environments based on combined genetic, spatial and ecological evidence, which will push forward current knowledge boundaries on ecological/anthropogenic mechanisms shaping biodiversity distribution in arid conditions. The analysis framework of such approach, proposing prioritisation solutions that consider multiple biodiversity levels, water- and land condition states, distinct current land-use systems, and alternative actions affording increased socioeconomic return, is scalable and replicable to drylands worldwide, as well as to other taxonomic groups besides vertebrates. It would contribute to the global datasets of all EBV classes (www.geobon.org), and by providing basis for biodiversity conservation and human development it would be aligned with the UN Sustainable Development Goals.

Long-term and efficient conservation of desert biodiversity requires appropriate policy instruments that promote the sustainable use of natural resources, for which local training and capacity building in management of natural resources is basal. Strong commitments for change in global and local attitude towards nature and biodiversity conservation and regional stability are needed to drive sustainable societal change. Developing principles and mechanism to benefit from the sustainable use of deserts and raising environmental alertness and pride within local communities of the value and uniqueness of the desert wildlife is needed to pressure strong policy change.

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