

## A review of recent ecological changes in the Sahel, with particular reference to land-use change, plants, birds and mammals

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### Abstract

This review focuses on recent ecological changes in the Sahel. While other recent reviews focused mainly on agricultural changes, remote sensing, and the evolution and distribution of biodiversity, no review focused on ecological changes over time although these changes needed to be summarized to better understand the recent and often dramatic species declines across the Sahel during the last half century. Therefore, I conducted a literature review to summarize these changes, in particular changes to (i) land-use and land-cover, (ii) wetlands, (iii) plants, (iv) birds, especially large and migratory birds and (v) large mammals. The main conclusion is that the exceptionally severe Sahel drought in the late 20th century was extremely detrimental to both human society and nature, but thereafter, rainfall, agricultural productivity and human welfare increased again. As human populations and their ecological footprint increased dramatically, the Sahel's biodiversity continued to become more and more impoverished, whereby woody vegetation, migratory birds, and large birds and mammals suffered particularly severe declines. Besides the agricultural expansion, the other main reasons for these declines are wetland conversions, increased fire frequency, overharvesting, persecution, poisoning and death caused by human artefacts and disturbance. More effective protected areas are urgently needed, which could also generate much needed tourism revenue.

*Key words:* biodiversity, biological impoverishment, desertification, ecological degradation, land degradation, Sahel

### Résumé

Cette étude s'intéresse aux changements écologiques récents dans le Sahel. Alors que d'autres études récentes se concentraient principalement sur les changements agricoles, la télédétection ainsi que l'évolution et la distribution de la biodiversité, aucune ne s'est penchée sur les changements écologiques dans le temps, et pourtant il faut récapituler tous ces changements pour mieux comprendre les déclinés récents et souvent spectaculaires des espèces dans le Sahel au cours de cette dernière moitié de siècle. C'est pourquoi j'ai réalisé une revue de la littérature pour résumer ces changements, en particulier ceux qui touchent (i) l'utilisation et la couverture des sols, (ii) les zones humides, (iii) les plantes, (iv) les oiseaux, et surtout les plus grands et les migrateurs et (v) les grands mammifères. La conclusion principale, c'est que la sécheresse exceptionnellement grave qui a affecté le Sahel à la fin du 20<sup>ème</sup> siècle fut extrêmement dommageable tant pour la société humaine que pour la nature, mais qu'après, les chutes de pluies, la productivité agricole et le bien-être humain se sont améliorés. Alors que les populations humaines et leur empreinte écologique ont augmenté de façon spectaculaire, la biodiversité du Sahel s'est appauvrie de plus en plus, et la végétation ligneuse, les oiseaux migrateurs, les grands oiseaux et les grands mammifères ont connu un déclin particulièrement sévère. À part l'expansion agricole, les autres raisons majeures de ces déclinés sont : la conversion des zones humides, la plus grande fréquence des feux, la surexploitation, les persécutions, les empoisonnements, et les morts causées par les artefacts et les perturbations humains. Il faut d'urgence créer des aires protégées plus efficaces qui pourraient aussi générer des revenus touristiques très attendus.

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## Introduction

Peter Jones, who worked and lived in the Sahel for many years, once said to me in a rather resigned voice: 'This one will be the best documented mass extinction'. As ornithologists prepare to meet at the 14th Pan-African Ornithological Congress (PAOC 14) under the title of 'Global changes/Threats and opportunities for birds in Africa', it is a sure bet that many of their presentations will add further detailed documentation of the ongoing sixth mass extinction (Ceballos *et al.*, 2015). Human-driven environmental change has now accelerated to such a degree that humans must be considered the dominant force shaping the earth's biosphere, with all driving forces of biodiversity change accelerating (Vitousek *et al.*, 1997; Pereira *et al.*, 2010; McGill *et al.*, 2015). The drivers are as follows: overexploitation; habitat destruction, modification and fragmentation; invasive species; and pollution which includes the increasing threats of climate change and ocean acidification (Millennium Ecosystem Assessment, 2005; Jackson, 2008).

One terrestrial region which for decades has been cited as an example of the potential harbingers to come in terms of ecological destruction is the Sahel region (e.g. Potter, 1974; Zeng, 2003). Hit by one of the fiercest droughts in recorded human history in the late 20th century and home to one of the world's highest growth rates with the human population doubling every 20 years (Zeng, 2003; Thiollay, 2006a) resulting in a population of over 100 million by 2010 and possibly 340 million by 2050 (Potts *et al.*, 2013), the Sahel seemed to be petering on the brink of ecological collapse for a while, with severe worries that ecological regime shift could happen (Foley *et al.*, 2003). The ensuing debate over whether the Sahel is a human-made ecological disaster (or not) is ongoing (Appendix S1). However, since the partial return of rainfall at the beginning of the 21st century and the resulting 're-greening' of the Sahel (Brandt *et al.*, 2015), worries about human disasters have died down somewhat.

However, the ongoing human expansion and the concurrent loss of natural land-cover and biodiversity means that, while agricultural and economic progress is happening to some degree, many species which inhabit the Sahel region are declining, some dramatically, including many species of resident and migratory birds. Two groups are declining particularly rapidly: (i) mostly large raptors, vultures and gamebirds and (ii) migratory birds which

breed in the Palaearctic region but spend part or the entire time of their nonbreeding season in the Sahel.

Besides the loss and degradation of breeding and resting grounds, hunting (especially in the Mediterranean region) and pesticide use, another often cited reason for the migrant bird declines has been the climatic and ecological changes in the overwintering areas in sub-Saharan Africa and especially in the Sahel region. This supposition gathered further support by the detailed mapping of 65 passerine migrant bird species which showed that those species which overwinter in the Sahel have mostly been declining since the 1970s while those bird species which overwinter in other parts of Africa have mostly not been declining (Walther, van Niekerk & Rahbek, 2011). As bird species overwintering in other parts of Africa were not as negatively affected, the question arose what ecological changes brought about by climatic and human drivers may explain this difference. Therefore, I reviewed the literature on climatological and especially ecological changes in the Sahel during the last half century to gain a better understanding of the specific ecological changes that have occurred in the Sahel and in turn have affected bird populations.

## Materials and methods

There are many different definitions about the extent of the 'Sahel region', but, in this review, the 'Sahel' refers to the zone of 250–1100 mm rainfall south of the Sahara and north of the Guinean zone and includes nine countries and parts of several others (Appendix S2). The Sahel's natural vegetation is mainly characterized by semi-desert grassland, thorn shrub and wooded grassland dominated by *Acacia* spp. in the north, but becomes increasingly woody towards the south because of the increasing rainfall (White, 1983; Mcginley, 2008).

I conducted a systematic literature review from August 2009 until March 2016 (Appendix S3). Preliminary results of this review were mentioned in Walther, van Niekerk & Rahbek (2011); Walther *et al.* (2013). From the > 1000 references which I accumulated, I then summarized mainly information which gave detailed information about changes over time, preferably indicating actual time periods, because many references (e.g. Fishpool & Evans, 2001; Zwarts *et al.*, 2009) mention many reasons for and effects of environmental deterioration, but often in general terms and without detailing time periods. The reason for this restriction was that the known population declines of migratory birds took

place over a specific time period (mostly since the early 1970s). Therefore, I focused mainly on information which described changes *over time* which had impacts on the Sahel's *ecology* during the *last half century*. The aim of this review was thus different to the aims of other recent reviews (van Vliet, Reenberg & Rasmussen, 2013; Brito *et al.*, 2014; Knauer *et al.*, 2014; Mbow *et al.*, 2015; Karlson & Ostwald, 2016). Because the recent climatological changes were previously reviewed in detail, I only summarized them briefly, but focussed mainly on the ecological changes resulting from these climatological changes as well as the other drivers of biodiversity change.

This review is organized along three main themes: (i) recent climatological changes, especially rainfall and drought; (ii) land-use and land-cover changes, including wetlands; (iii) biological impoverishment and ecological degradation, particularly of plants, birds and large mammals.

## Results

### *Rainfall patterns and recent droughts*

The main findings are (Appendix S4):

- 1 The 1968-1997 drought (the 'Sahel drought') was exceptionally severe, being one of the most severe droughts of the 20th century worldwide. Rainfall has increased after the drought, but is still below the long-term average.
- 2 Year-to-year climatic variability was very high in the Sahel and higher than in most of the remainder of sub-Saharan Africa.
- 3 Short-term drivers of the Sahel's climate are sea surface temperature patterns in the oceans, but superimposed upon this natural variability is a long-term regional drying trend due to increasing atmospheric aerosol loading, greenhouse gas concentrations and possibly vegetation changes.
- 4 Models of future climate change in the Sahel do not yet agree, with some predicting a drying and others a moistening trend.

### *Land-use and land-cover changes*

While overall numbers vary between different countries, a clear and almost consistent trend emerged from remote sensing studies whereby natural land-cover have been rapidly replaced by altered land-covers almost all over the Sahel, with the vast majority due to agricultural expansion and some due to the expansion of barren lands

(Appendix S5; Table S1). After the Sahel drought, agricultural productivity rebounded and greatly increased because of (i) increasing rainfall, (ii) improved agricultural practices and (iii) increased conversion of previously natural or semi-natural habitats. Consequently, the Sahel had the fastest loss of natural nonforest vegetation and the fastest agricultural expansion in the entire sub-Saharan region (Brink & Eva, 2009). Thus, the transformation from a natural and semi-natural landscape to human-dominated 'cultural landscape' (Rasmussen, Fog & Madsen, 2001) was especially rapid in the Sahel, in part explaining the biological impoverishment and ecological degradation summarized below.

### *Conversion and degradation of wetlands*

Besides a few larger permanent water bodies and wetlands, the Sahel is sprinkled with thousands of temporary or semi-permanent and often wooded wetlands that occur wherever water from seasonal rains collects in basins or channels, varying in size from tens to thousands of hectares (Brouwer, 2002; Zwarts *et al.*, 2009). The Sahel's wetlands have also experienced widespread conversion and degradation, especially the large and important ones, although some remedial actions have been initiated in recent times. The main findings (Appendix S6) are as follows:

- 1 Almost all wetlands suffered during the Sahel drought simply because much less water was available to maintain ecosystem functions.
- 2 Because of the severe effects of the Sahel drought, but also in the spirit of 'taming' unpredictable natural environments via engineering solutions (Drijver & Marchand, 1986), literally thousands of water control, drainage and irrigation projects of different sizes were built since the 1970s. While these projects produced electricity, increased agricultural productivity in the drained and irrigated areas and prevented flooding in some cases, these projects often severely restricted naturally occurring flood level fluctuations (Zwarts *et al.*, 2005, 2009). These developments together with the Sahel drought decreased floodplain extents to various degrees, but especially in the Sahel's large water systems. Oyebande (2002) estimated that more than 40% of the area of the three dominant river/lake systems (Lake Chad, Niger River, Senegal River) was thus lost. As a result, fish and agricultural production as well as other ecosystem functions and services suffered in the affected floodplain areas, and the socio-economic and

environmental costs of these water management schemes often exceeded the benefits (Drijver & Marchand, 1986; Marchand, 1987; Oyebande, 2002; Schuyt, 2005).

3 Wetlands also suffered from the consequences of increased human impacts, specifically overharvesting of birds, fish, pasture, wood and other natural products; pesticide and other pollution; siltation due to soil erosion; mismanagement; invasive plants; and possibly climate change (Ticheler, 2000; Brouwer, 2002; Oyebande, 2002; BirdLife International, 2010; Adams, 2013; Mitchell, 2013).

4 As these negative effects have become increasingly apparent, some rehabilitation projects, mostly involving re-flooding of dried-up floodplains, have been initiated since the 1990s (Hamerlynck, Ould Baba & Duvail, 1999; Scholte *et al.*, 2000; Loth, 2004).

5 The bird and mammal populations of the wetlands often suffered from the various negative impacts, but also recuperated somewhat due to increasing rainfall and the rehabilitation projects (Shine, 2003; Loth, 2004; Scholte, Adam & Serge, 2007).

#### *Biological impoverishment and ecological degradation*

*Plants and soil.* While remote sensing studies indicated the Sahel's recent re-greening (Epule *et al.*, 2014; Brandt *et al.*, 2015), the concurrent agricultural expansion and increased use of natural resources have nevertheless caused great biological impoverishment and ecological degradation over the last few decades in most areas of the Sahel. The reason for this seeming contradiction is that, while remote sensing studies detected an increase in biological productivity (making the Sahel appear greener from space), this increasing greenness was produced by a decreasing number of plant species and an increasing proportion of economically valuable or alien species, a trend only detectable by *in situ* studies (Wezel & Lykke, 2006; Miehe *et al.*, 2010; Gonzalez, Tucker & Sy, 2012; Herrmann & Tappan, 2013; Mbow *et al.*, 2015; Appendix S7).

Woody vegetation has been particularly severely affected, with steep declines reported for species diversity, abundance and distribution in many locations. The reasons, besides the land-use and land-cover changes summarized above, are as follows: (i) overharvesting for timber, firewood and livestock feed; (ii) overgrazing which negatively impacted both plant communities and soils; (iii) more permanent and intensive agriculture leading to a

decline of rotational agriculture, and thus to a decline of fallows and semi-natural habitats which had been used for grazing and natural resource extraction; (iv) increased fire frequency; (v) replacement with forest monocultures or invasive species (Breman & Kessler, 1995; Lykke, 1998; Wezel & Rath, 2002; Darkoh, 2003; Beudels *et al.*, 2005; Wezel & Lykke, 2006; Cresswell *et al.*, 2007; UNEP, 2007; Aune & Bationo, 2008; Mcginley, 2008; Brandt *et al.*, 2015). These impacts also occurred in many protected areas (only ~ 5% of the Sahel is partially protected and ~ 1% is fully protected) because of mismanagement or the complete or near-complete absence of any funding and personnel so that many of them are mere 'paper parks'.

Soils have been exhausted and exposed to wind and water erosion by (i) livestock overstocking; (ii) inappropriate farming techniques, which includes many forms of permanent agriculture, but also the early abandonment of planted fields, for example due to insufficient rainfall; (iii) the shortening of fallow periods; (iv) the disappearance of protective vegetative cover, for example grassy or woody vegetation; (v) increasing off-road vehicle traffic (Fadul *et al.*, 1999; Wezel & Rath, 2002; Darkoh, 2003; Budde *et al.*, 2004; Mortimore, 2005; Reij, Tappan & Belemvire, 2005; Augusseau, Nikiéma & Torquebiau, 2006; Elhag, 2006; Thiollay, 2006b; UNEP, 2007; Mcginley, 2008; Hiernaux *et al.*, 2009; Brandt *et al.*, 2014).

These damaging trends have been reversed in some areas where land users have applied new or improved farming techniques, such as soil and water conservation techniques, crop diversification, increased fallowing, the natural regeneration of trees and shrubs, and other conservation techniques, such as tree and windbreak planting and agroforestry systems (Tiffen & Mortimore, 2002; Wezel & Rath, 2002; Mortimore, 2005; Reij, Tappan & Belemvire, 2005; Reij, Tappan & Smale, 2009; Alreadaisy & Ali, 2011; Sendzimir, Reij & Magnuszewski, 2011; Brandt *et al.*, 2014). However, these improvements may do relatively little for biodiversity, unless sufficient space is actually given to natural habitats. For example, alien instead of native species was used for some windbreaks and green belts, or only those trees beneficial to farmers were kept and even increased in density which resulted in carefully managed and predominantly agricultural 'parklands' (Tiffen & Mortimore, 2002; Mortimore, 2005; Sendzimir, Reij & Magnuszewski, 2011).

The question arises whether this transition to a more human-dominated landscape increases or decreases the

system's overall resilience. While some authors who mainly focus on agricultural resilience see an increased resilience of the social-ecological system due to improved land management practices (Hiernaux, 1995; Reenberg, 2009; Sendzimir, Reij & Magnuszewski, 2011) and increased agricultural productivity (Mortimore, 2005; Aune & Bationo, 2008; Barbier *et al.*, 2009), other authors more focused on biodiversity and ecosystem functions see a degradation of ecosystem resilience (Poupon & Bille, 1974; Fries, 1990; Schlesinger *et al.*, 1990; Orr, 1995; Küppers, 1998; Batterbury *et al.*, 1999; Diouf & Lambin, 2001; Hein, 2006; Gonzalez, Tucker & Sy, 2012; Mensching, 1985; cited in Leisinger & Schmitt, 1995; Herrmann & Tappan, 2013; Angela Hof, *in litt.* 2009) and ecosystem services (Vetaas, 1993; Lykke, 1998, 2000; Teklehaimanot, 2004; Wood, Tappan & Hadj, 2004; Augusseau, Nikiéma & Torquebiau, 2006; UNEP, 2007; Hiernaux *et al.*, 2009).

*Birds, especially large raptors, vultures and gamebirds.* Among the 1073 bird species listed for the nine Sahelian countries, 2.6% are threatened and 2.8% are near-threatened species (Appendix S8; Table S2). Furthermore, an analysis of the 37 threatened species whose distributions are partial or complete within the Sahel demonstrates that (i) raptors and vultures and (ii) migrant species make up a disproportionate number of the total (Table S3).

The main reasons for the recent and often dramatic declines of large raptors and vultures are as follows: (i) the general trends of biological impoverishment and ecological degradation, which caused a decrease in food and nesting and resting sites; (ii) direct and indirect poisoning; (iii) pesticide use causing direct poisoning or prey decrease; (iv) collisions with or electrocution by power lines; (v) hunting for food and for use in magico-medicinal and superstitious practices. Other less important impacts are (i) measures to prevent bird strikes; (ii) collisions along roads and with wind turbines; (iii) increased rates of nest disturbance and deliberate nest destruction; (iv) defence of livestock; (v) persecution because of irrational fears; (vi) the growing trade in eggs and young (Thiollay, 2006a,b, 2007a,b; Anadón *et al.*, 2010; Buij *et al.*, 2013, 2015; Ogada *et al.*, 2016; Whytock *et al.*, 2016). Smaller or more generalist raptors and vultures are usually less or not at all affected. Large raptors and vultures, but also large game birds, nowadays usually only survive in protected areas (Thiollay, 2007a).

*Migratory birds.* Many migrant bird species which breed in the Palaearctic and overwinter in the Sahel have been declining over recent decades due to ecological changes on the breeding, resting and overwintering grounds. The link between ecological conditions in the Sahel and migrant declines was first made during the Sahel drought when many migrant species declined, some of them precipitously, and later by over 60 studies which demonstrated that adverse ecological conditions in the Sahel affected the phenology, reproduction and survival of Palaearctic migratory birds (summarized in Zwartz *et al.*, 2009; Walther, van Niekerk & Rahbek, 2011; Vickery *et al.*, 2014).

Despite the recent re-greening, many migrant species have not recovered at all, or only recovered very slowly after the Sahel drought. Therefore, it has become increasingly apparent that the more severe long-term impact on migrants has been the steady recent decline of ecological conditions in the Sahel (references above; Cresswell *et al.*, 2007; Ewing, 2008; Kirby *et al.*, 2008; Adams, Small & Vickery, 2014; Appendix S9). Other less important impacts are as follows: (i) pesticide use causing direct poisoning or prey decrease (Keith & Bruggers, 1998; Ewing, 2008; Zwartz *et al.*, 2009); (ii) decrease in those plant species used for resting or fattening up before migration (Wilson & Cresswell, 2006); (iii) hunting (Contesso, 2009); (iv) collisions with human artefacts (Kirby *et al.*, 2008); and (v) climate change (Barbet-Massin *et al.*, 2009). For migratory raptors and vultures, the impacts summarized above also apply.

The Sahel drought, although devastating at the time for a number of migrant species, was thus not the only and likely not the most important long-term cause of migrant population losses. Rather, the rapid conversion to a human-dominated landscape and the resulting consequences of the spread of intensive agriculture and the simultaneous decrease of biodiversity, in particular the loss of woody vegetation and wetlands, have likely caused these declines.

*Large mammals.* Large and even medium-sized mammal species have severely declined across the Sahel, many to the point of near extinction or extinction (Appendix S10; Table S4). While these dramatic declines have been mirrored across Africa, they appear to have been especially severe in West Africa, the Sahel and the Sahara (Ray, Hunter & Ziguoris, 2005; Craigie *et al.*, 2010; Brito *et al.*, 2014; Durant *et al.*, 2014). Nowadays, most large

mammals do not survive outside of protected areas (with very few exceptions), and only inside some protected areas, while they are decreasing or extinct in many other protected areas (Caro & Scholte, 2007; Scholte, 2011; Brugière, Chardonnet & Scholte, 2015).

Again, the various threats (habitat decline, human conflict, hunting, etc.) mostly boil down to the intensified human use of the Sahel in combination with the Sahelian countries' legal frameworks and practices which take scant notice of and give very little resources to better ways of humans and large wildlife to coexist (Darkoh, 2003; Ray, Hunter & Ziguoris, 2005; Caro & Scholte, 2007; Scholte, Adam & Serge, 2007; UNEP, 2007; USAID, 2008; IUCN, 2016). However, direct killing, mostly through hunting, but also through poisoning, disturbance and vehicle collisions, appears to have been an even more important cause for the mammalian than for the avian declines (Beudels *et al.*, 2005; Thiollay, 2006b; Brito *et al.*, 2014). Growing wealth around the world has increased the demand for live animals, animal products and hunting tourism, especially among wealthier elites with their increasing desires for status symbols (Chaber *et al.*, 2010; CITES, 2014). Better communication and easier transport have further enhanced wildlife trade (e.g. buying animals and animal products on the Internet) and hunting tourism (e.g. better and more roads and use of off-road vehicles allow hunting almost everywhere in the Sahel, aided by modern firearms) (Beudels *et al.*, 2005; Thiollay, 2006b; Brito *et al.*, 2014; CITES, 2014). As large mammals have thus largely disappeared, there is now some evidence that smaller mammals are also increasingly declining (Thiollay, 2006a,b). Despite a few conservation successes (e.g. reintroduction of the scimitar-horned oryx *Oryx dammah*), the overwhelming trend is therefore one of the rapid and widespread declines of large and even medium-sized mammals, and even within most protected areas.

## Discussion

*"We may have to get used to faunal relaxation in Africa's network of famous reserves leaving a continent containing isolated pockets of large mammal diversity living at low population sizes. Just like Europe."* (Caro & Scholte, 2007)

This stark premonition has already become true for the Sahel as '... much of today's environment and vegetation composition is controlled by humans' (Brandt *et al.*,

2014). The human-driven transformation of a semi-natural and natural landscape used by farmers and pastoralists as well as viable numbers of wildlife into a human-dominated cultural landscape characterized by intensive agriculture and overstocked livestock herds, interspersed with some degraded areas and with barely any large wildlife left, is resulting in the 'green desertification' of the Sahel (Herrmann, Sall & Sy, 2014). The developments outlined in this review mean that the Sahel's ecosystems are rapidly approaching the impoverished biodiversity state of the many other agricultural deserts around the world (Green *et al.*, 2005). Naturally, these recent developments take on a very different and much more positive outlook from the viewpoint of agricultural productivity and resilience [Results (Plants and soil)]. While the recent re-greening and the parallel improvements in agricultural productivity and farming techniques have somewhat improved human welfare, they had little or no positive effect on wild plant and animal populations, as any small gains were more than erased by the widespread losses described in this review.

As this model of development spreads around the world, the same process of biological impoverishment is repeated wherever humanity's ecological footprint takes its ever-growing toll on biodiversity (Maurer, 1996; Wackernagel & Rees, 1996; Green *et al.*, 2005; Haberl *et al.*, 2007; Czech, 2013). This transformation usually first affects populations of large animals, such as birds and mammals, which sit on the apex of the food pyramid but are also the prime targets for human hunting and persecution. However, the effects of this transformation later trickle down to smaller and smaller species as more and more resources are human-appropriated. The continuing loss of large-sized keystone species, such as apex predators, should negatively impact the ecological resilience of the Sahel's ecosystems (Hooper *et al.*, 2005). Add to this the widespread losses of plant diversity, natural plant cover, and wetlands, soil degradation and erosion in some areas, and the higher likelihood of climatic fluctuations due to climate change, and we may have the recipe for a perfect ecological storm.

However, the million dollar question remains whether this biological impoverishment will lead to a new and much impoverished but somewhat stable state as in the temperate agricultural deserts of Western Europe and North America, or whether a catastrophic breakdown will happen once the system is pushed beyond certain thresholds. While no ecologist (or economist) has a crystal ball (Stéphenne & Lambin, 2001; Abiodun *et al.*, 2012;

Rasmussen *et al.*, 2012; Mitchell, 2013; Lambin *et al.*, 2014), the Sahel's case may be particularly worrying for the following reasons:

1 One of the world's highest human growth rates causes this transformation to be particularly rapid (Brink & Eva, 2009).

2 The almost complete lack of remedial actions for biodiversity (effective protective areas, hunting restrictions, environmental education and monitoring, etc.) (Monfort *et al.*, 2004; Thiollay, 2006b; USAID, 2008; Reenberg *et al.*, 2009; IUCN, 2016) ensure that the biological impoverishment and ecological degradation will continue unabated for the foreseeable future.

3 The Sahel is a semi-arid ecosystem whose ecological resilience may be especially close to dangerous thresholds because semi-arid ecoregions are inherently more unstable than most other ecoregions (van de Koppel, Rietkerk & Weissing, 1997; Foley *et al.*, 2003; Rietkerk *et al.*, 2004; D'Odorico *et al.*, 2013), and its ecological resilience continues to be eroded rapidly [even if its agricultural resilience is increased, see Results (Plants and soil)].

4 The Sahel drought brought widespread human and ecological disaster, and some authors believe another drought would cause similar havoc again. Brooks (2006) warned that the greater the extent of the re-greening is, the greater any over-extension of agriculture is likely to be, which may thus represent a systematic increase in the vulnerability to future rainfall changes. Therefore, the Sahel drought could be repeated on a massive scale if development trends continue without any attention being paid to longer-term climate variability and ecological resilience.

5 Further warning signs are that the Sahel has recently witnessed an upswing of civil unrest, terrorism and war (Nyong, 2011; Brito *et al.*, 2014) and of the number of environmental refugees (Epule, Peng & Lepage, 2015). Six of the nine Sahelian countries were involved in armed conflicts in 2012, partially because 'unsustainable livelihood systems and poor food security outcomes' increased the risk of protracted crises (Hendrix & Brinkman, 2013). Fjelde & von Uexkull (2012) found that large negative deviations in rainfall and the presence of politically excluded ethno-political groups were associated with a higher risk of communal conflict in sub-Saharan Africa; both these risk factors apply to the Sahel.

Consequently, terrorism and war are increasingly threatening research efforts (Sharma, 2011; Brito *et al.*, 2014). That is bad news for the essential tasks of

biodiversity monitoring and research, which are urgently needed but gravely lacking. The dearth of biodiversity information for this region is illustrated by two examples: Ray, Hunter & Zigouris (2005) found that only two of a total of 1716 studies used in their analysis were conducted in the Sahel, and Brito *et al.* (2014) lamented that there is no formal regional red-listing for any taxonomic groups and countries within the Sahel. Therefore, the PAOC 14 could discuss how monitoring and research of birds and conservation assessment efforts could be improved while keeping scientists and staff safe. For example, combining GIS-based information on land-use and land-cover changes with habitat preferences could be used to model population changes without actually having to visit dangerous or inaccessible field sites (Wichmann, Dean & Jeltsch, 2004; Tews *et al.*, 2006; Thuiller *et al.*, 2008; Ash *et al.*, 2009). The increased availability of drones and other emerging technologies could also be very useful (Koh & Wich, 2012; Anderson & Gaston, 2013; Pimm *et al.*, 2015). Brito *et al.* (2014) provided an excellent list of further research needs.

The PAOC 14 should also consider research and outreach about the challenge to better inform decision-makers and the public about the links between biodiversity and human welfare (Walther *et al.*, 2016), for example increased ecological resilience (Durant *et al.*, 2014) or economic benefits of birdwatching (Sekercioglu, 2002). Given the amount of money made from people who enjoy wildlife in other parts of Africa, Sahelian governments and stakeholders should aim to rapidly improve infrastructure and security, both for the benefit of their own people but also for potential tourists. International tourists spend 36 billion US dollars in Africa every year, and 80% of them come for wildlife watching (Findlay, 2016). In Gambia, tourism has become the fastest growing sector of the economy which contributed 12% of the country's GDP and 4% of total employment in 2011 (Nshimyumuremyi, 2014). The governor of Bauchi State, Nigeria, recently emphasized the need for more tourism-based revenue: 'We need to diversify the state revenue base and tourism is a low-hanging fruit', which includes developing assets such as Yankari National Park (Findlay, 2016). The potential for increased tourism revenue is enormous, especially given the Sahel's greater proximity to Europe when compared to traditional tourism destinations, such as Kenya or South Africa.

Githiru (2008) concluded that 'Africa is typically characterized by two intertwined features: rising poverty

levels and a deepening environmental crisis. Generally, human issues, such as poverty, health, education take precedence over environmental issues which are thought of as neither vital nor pressing. The odds are resoundingly cast against conservation'. Unless Sahelian governments and stakeholders recognize the value of biodiversity in general and of wildlife-rich sites in particular because of the various ecosystem functions and services associated with them and consequently enact legislation and provide resources to improve the situation, this review simply adds to the ever-accumulating evidence that, from a biodiversity standpoint, the Sahel is currently a disaster zone. Given the precarious ecological, economic and political state of the Sahel, this conclusion does not bode well for long-term human welfare. However, we also know that nature is resilient, and almost all species are still there. Thus, effective, rapid and significant changes in policy and enforcement can yet reverse this dire situation.

*"The key . . . is to achieve sustainable growth. This calls for replacing the traditional concept of growth based economic output alone with a new approach that stresses development through conservation of Africa's valuable natural resources of soil, water, forests and wildlife."* (Baytas, 1991)

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## Supporting information

Additional Supporting Information may be found in the online version of this article:

**Appendix S1.** The main arguments over whether the Sahel is a human-made ecological disaster (or not).

**Appendix S2.** The definition of the ‘Sahel region’.

**Appendix S3.** Details of the systematic literature review.

**Appendix S4.** Brief review of climatological changes.

**Appendix S5.** Land-use and land-cover changes.

**Appendix S6.** Conversion and degradation of wetlands.

**Appendix S7.** Biological impoverishment and ecological degradation. Plants and soil.

**Appendix S8.** Biological impoverishment and ecological degradation. Birds, especially large raptors, vultures and gamebirds.

**Appendix S9.** Biological impoverishment and ecological degradation. Migratory birds.

**Appendix S10.** Biological impoverishment and ecological degradation. Large mammals.

**Table S1.** Summary of land-use and land-cover changes in the Sahel.

**Table S2.** Number of Sahel bird species in each Red List category.

**Table S3.** Number of threatened and near-threatened bird species whose distributions are  $\geq 30\%$  within the Sahel.

**Table S4.** List of large and medium-sized mammal species ( $\sim 10$  kg or more) of conservation concern.