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ORIGINAL PAPER

Areas of high diversity for the world's inland-breeding waterbirds

Laura Williamson · Michael Hudson · Mark O'Connell · Nicholas Davidson · Richard Young · Tatsuya Amano · Tamás Székely

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Abstract Waterbirds are a globally-distributed, species-rich group of birds that are critically dependent upon wetland habitats. They can be used as ecosystem sentinels for wetlands, which as well as providing ecosystem services and functions essential to humans, are important habitats for a wide range of plant and animal taxa. Here we carry out the first global analysis of inland-breeding waterbird distributions using data from 471 waterbird species in 28 families to identify global areas of high waterbird diversity. First we identify the primary area of high diversity for all inland-breeding waterbird species to be in Eastern Africa. For globally threatened inland-breeding waterbirds, the area of highest diversity is in Eastern China. Second, we show that the current network of protected areas provides poor coverage for threatened waterbirds in Eastern and Central Asia, and Northern India. In contrast, there is a higher protected area coverage in most of Europe and Brazil. Targeting the specific areas that have the highest numbers of species and the poorest coverage of protected areas is vital for both waterbird and wetland conservation.

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L. Williamson (✉) · M. Hudson · M. O'Connell · T. Székely
Department of Biology and Biochemistry, University of Bath, Bath BA2 7AY, UK
e-mail: lauradwilliamson@gmail.com

M. Hudson · R. Young
Durrell Wildlife Conservation Trust, Trinity, Jersey, Channel Islands JE3 5BP, UK

M. O'Connell
Ecological Research and Training, Stroud GL5 1RT, UK

N. Davidson
Ramsar Convention, 1196 Gland, Switzerland

N. Davidson
Institute of Land, Water & Society, Charles Sturt University, Albury, NSW 2640, Australia

T. Amano
Department of Zoology, University of Cambridge, Cambridge CB2 3EJ, UK

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Abbreviations

CSN	Critical sites network
IBA	Important bird area
IUCN	International Union for Conservation of Nature
UNEP-WCMC	United Nations Environment Programme-World Conservation Monitoring Centre
WOW	Wings over wetlands

Introduction

Waterbirds are a diverse group (878 species in 33 families) that are ecologically dependent upon wetlands (Ramsar 1971; Wetlands International 2006). They make up nearly 10 % of all bird species and are often used to indicate wetland ecosystem health, as well as providing surrogate measures of water quality, chemical contamination, prey availability and vegetation characteristics (Crewe and Timmermans 2005; Hunt and Davis 2006; Mistry et al. 2008). The main threat to waterbirds worldwide is habitat loss or degradation, primarily caused by human activities such as wetland reclamation, agriculture, pollution, land development, transportation corridors and energy production (BirdLife International 2012; Sutherland 2012). Other threats include invasive species, climate change (Wetlands International 2010) and hunting (Kanstrup 2006). Waterbirds are frequently hunted, both for subsistence as well as sport and they provide the primary source of protein in some regions (Kanstrup 2006).

It is important to identify key sites and areas for focusing conservation effort that will support populations of the greatest numbers of species possible. Understanding the drivers and dynamics of waterbird distribution and ecology at a range of scales is essential to underpin actions directed towards their conservation. Biodiversity hotspots have been identified previously, using a variety of criteria including the number of plants, birds and restricted range species (Myers et al. 2000; Orme et al. 2005; Stattersfield et al. 1998); however, a study of areas of high diversity for inland wetland breeding waterbirds has never been performed.

Inland wetlands can have fresh, brackish or saline waters and are primarily fed by rain and/or rivers (Semeniuk and Semeniuk 1995). Some of the common types of inland wetlands include lakes, streams, rivers, ponds, floodplains, springs, alpine tundra and meadows, marshes and swamps (Environment Australia 2001). Inland wetlands are important breeding grounds for waterbirds but have been influenced greatly by human activities. In addition to affecting the quality and size of the wetland, human activities can also cause changes in the wetland's hydrology and salinity which greatly affects the species resident there as well as the environmental processes performed (Muñoz 2009).

In response to the on-going degradation of wetlands and to prevent further destruction, the Ramsar Convention on Wetlands was established in 1971 (Ramsar 1971). The convention recognised that wetlands need to be protected due to their important economic, cultural, scientific, biodiversity and recreational values. Key areas must also be designated and protected as Wetlands of International Importance ('Ramsar Sites') where they meet at

least one of nine qualifying criteria (including regularly supporting over 1 % of a waterbird biogeographic population or regularly supporting >20K waterbird individuals). Under criteria developed by Birdlife International, wetlands are also recognised as Important Bird Areas (IBAs) if they support significant numbers of globally threatened species, hold restricted-range species, or have a high proportion of migratory species (BirdLife International 2012). While IBAs and Ramsar sites identify important conservation locations, the protection they offer is often site or region-specific. Another tool for identifying important sites is the Critical Sites Network (CSN) tool, developed by the Wings Over Wetlands (WOW) project, which combines data from many sources to identify important locations for 294 species of waterbirds in Africa and Western Eurasia (http://csntool.wingsoverwetlands.org/csn/default.html).

In recent decades, there has been an international focus to conserve waterbirds on a flyway scale, through a number of statutory and voluntary initiatives along the largely North–South migratory waterbird flyways (Global Interflyway Network 2012). However, this conservation approach focuses assessment and conservation on migratory species only, and there is a need to also assess and conserve non-migratory waterbird species (Green 1996). Over 70 % of threatened migratory Anatidae (ducks, geese and swans) are recorded in Ramsar sites, however only 10 % of threatened non-migratory Anatidae are protected at the same level (Green 1996).

The objectives of this study were to use inland-breeding waterbird distribution data, first, to determine global areas of high diversity for all inland-breeding waterbirds and threatened inland-breeding waterbirds, and second, to examine the overlap of these areas with current protected areas. The overall aim of our research is to highlight areas in which concentrated conservation effort would most benefit inland-breeding waterbird species.

Methods

Data

Spatial distribution data of waterbirds (and all other bird species) were provided by BirdLife International (BirdLife International and NatureServe 2011). The data included the breeding, non-breeding, migratory and resident ranges of all populations of each species for which such data exists. The dataset included 31 families and 866 species of waterbirds. Two families that are identified as separate families by Wetlands International (Rynchopidae and Sternidae) were included in the waterbird family Laridae in the BirdLife International data. Categories within the IUCN Red List of Threatened Species (BirdLife International 2012, downloaded on 16 March 2012) were used to quantify the 'threat level' for each waterbird species. Threatened refers to species in the IUCN global categories of Vulnerable, Endangered and Critically Endangered. The threat status of each order of inland-breeding waterbirds was analysed and can be seen in Fig. 1.

Using the data presented on the IUCN website, each waterbird species was categorised based on its primary breeding habitat and also if it was primarily migratory or year-round resident. Categories for breeding habitat included inland, coastal, both inland and coastal, as well as terrestrial. The inland-breeding category was defined as including all inland wetlands including freshwater, brackish and saline environments. Only species classified as breeding in inland wetland environments were included in this analysis, which gave a total of 471 species. Waterbird species were also determined to be majority migratory, resident or 'both'. For a species to be considered migratory it had to have populations spending the breeding season and non-breeding season in different areas.

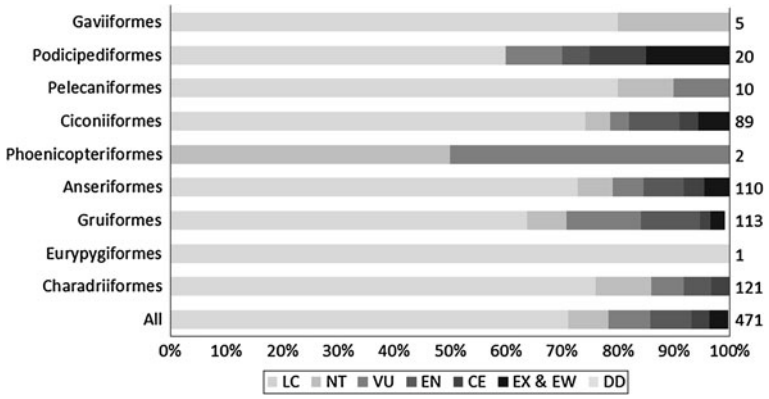

Fig. 1 Threat status of inland-breeding species in each waterbird order. The *numbers* on the *right* represent the number of species included in this study from each order

The spatial extents of protected areas were obtained from the World Database on Protected Areas, created by IUCN and UNEP-WCMC (http://www.wdpa.org/). Country borders for use in the maps were obtained from http://thematicmapping.org, and land use maps were downloaded from POSTEL Service Centre (http://toyo.mediasfrance.org).

Spatial analysis

ArcGIS 10 (ESRI 2011), Geospatial Modelling Environment (Beyer 2012), IDRISI Selva (Eastman 2012) and MATLAB Release (2010) were used to perform spatial and statistical analysis of the bird distribution data. Distribution maps of all inland-breeding waterbird and threatened inland-breeding waterbird species as well as populations of year-round resident, breeding and non-breeding inland-breeding waterbirds were created using a $0.1° \times 0.1°$ grid. In the analysis of all inland-breeding waterbirds and threatened inland-breeding waterbirds, breeding, non-breeding and resident populations are combined (see Figs. 2, 3 respectively), however these breeding, non-breeding and resident maps can be seen separately in Figs. 4, 5, and 6 respectively. We defined areas of high inland-breeding waterbird diversity to be the ten distinct locations which had the highest number of species, and created these areas manually. In order to do this, the cells with the largest number of species in the raster image were selected, then the cells with the next highest number of species were selected. If several cells were adjacent, they were considered to be a single area. This was repeated until ten separate locations each with an area of at least 15,000 km^2 were highlighted as having the most species.

A correspondence analysis between global waterbird species richness against threatened waterbirds species richness was performed (Fig. 7) using residuals taken from least squared regressions between all global waterbirds (independent variable) and all threatened waterbirds (dependent variable). This analysis was performed for a grid size of $1° \times 1°$. A similar correspondence analysis was also performed between percentage area protected (dependent variable) and one of the following independent variables: (a) the number of waterbird species and (b) the number of threatened species, the results of which can be seen in the Electronic supplementary materials (Fig. OR2).

For additional details on methodology, please see the Electronic supplementary material.

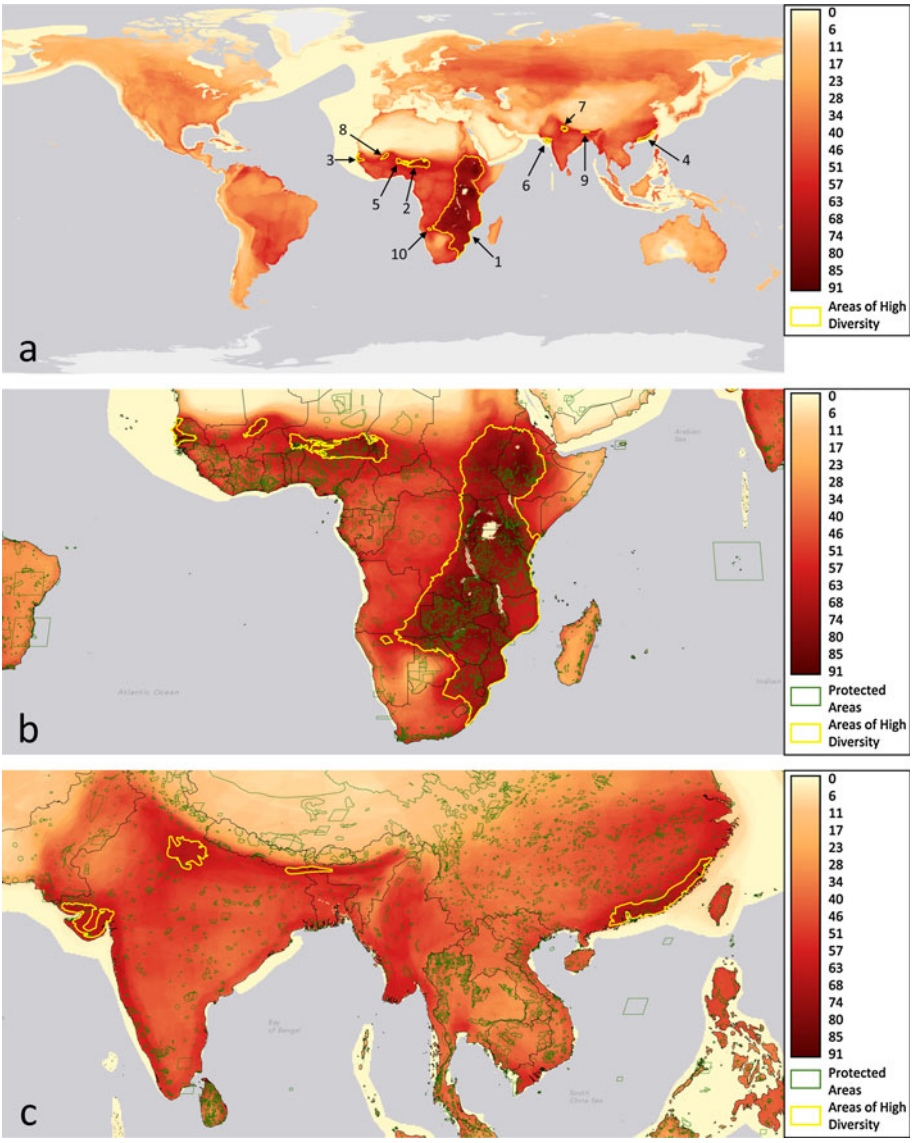

Fig. 2 Areas of high diversity (*yellow outlines*) for inland wetland breeding waterbirds (471 species) showing resident, breeding and non-breeding ranges, **a** globally, **b** in Africa and **c** South Asia. The *numbers* in **a** refer to the area numbers in Table 1. **b**, **c** also show the borders of protected areas. The *colour scale* represents the number of species. (Color figure online)

Results

Areas of high diversity

Of the 471 inland-breeding waterbird species examined, 83 were threatened (18 %) (Fig. 1). Grebes (Podicipediformes), cranes and allies (Gruiformes) and storks and allies (Ciconiiformes) had the highest proportion of threatened species (Fig. 1).

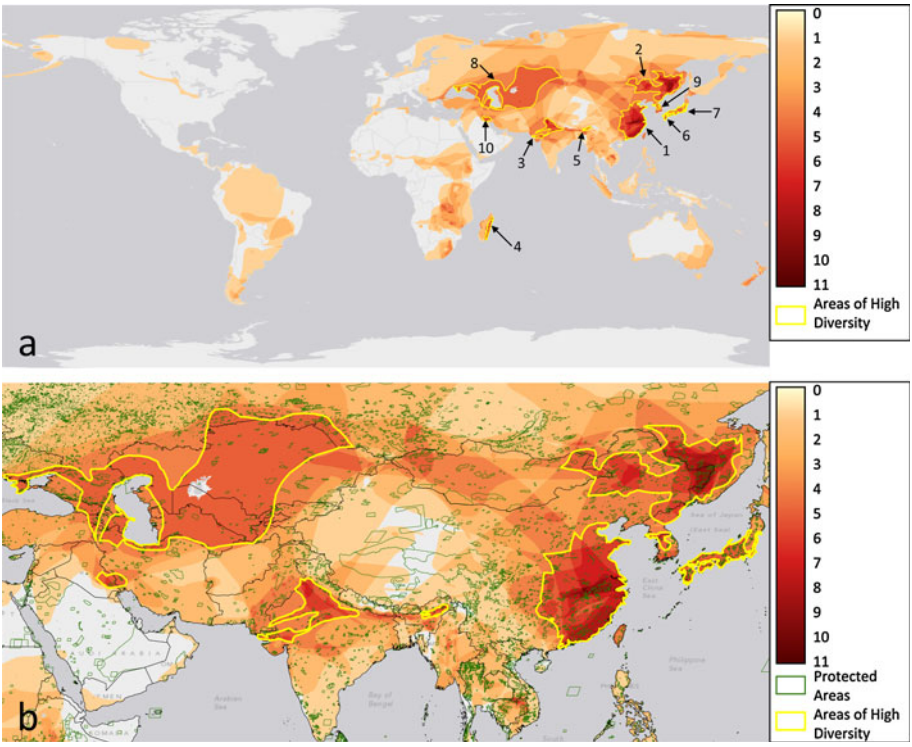

Fig. 3 Areas of high diversity (*yellow outlines*) of threatened inland wetland breeding waterbirds (83 species) showing resident, breeding and non-breeding ranges, **a** globally and **b** in Asia. The *numbers* in **a** refer to the area numbers in Table OR1. The *colour scale* represents the number of species. (Color figure online)

The main area of high waterbird diversity for all inland-breeding waterbirds was in Eastern Africa (Fig. 2; Table 1). The highest number of threatened inland-breeding waterbirds were in Eastern Asia, India, Kazakhstan and Madagascar (Fig. 3; Table OR1). The diversity of resident, breeding and non-breeding populations of inland-breeding waterbirds are shown in Figs. 4, 5, and 6. Eighteen and fifteen percent of inland-breeding waterbird species have year-round resident populations in Eastern Africa and South America respectively (Fig. 4; Table OR2). The majority of migratory species breed at higher latitudes in the northern hemisphere before migrating to the non-breeding ranges closer to the Equator (Figs. 5, 6; Tables OR3, OR4). Kazakhstan and Russia harbour the largest numbers of breeding species (55 species), whereas China (48 species), India and Pakistan (37 species), India and Bangladesh (32 species) and Taiwan (30 species) contain the highest number of non-breeding species.

Eurasia and Northern Africa had more threatened species than expected (Fig. 7) given the total number of species per location, whereas America, some parts of Central and Southern Africa and parts of Australia had fewer threatened species than expected.

Overlap with current protected areas

Brazil, Western China and Greenland contained the largest protected areas (Figs. 1b, c, 2b, OR2), whereas smaller protected areas were scattered throughout the rest of the world.

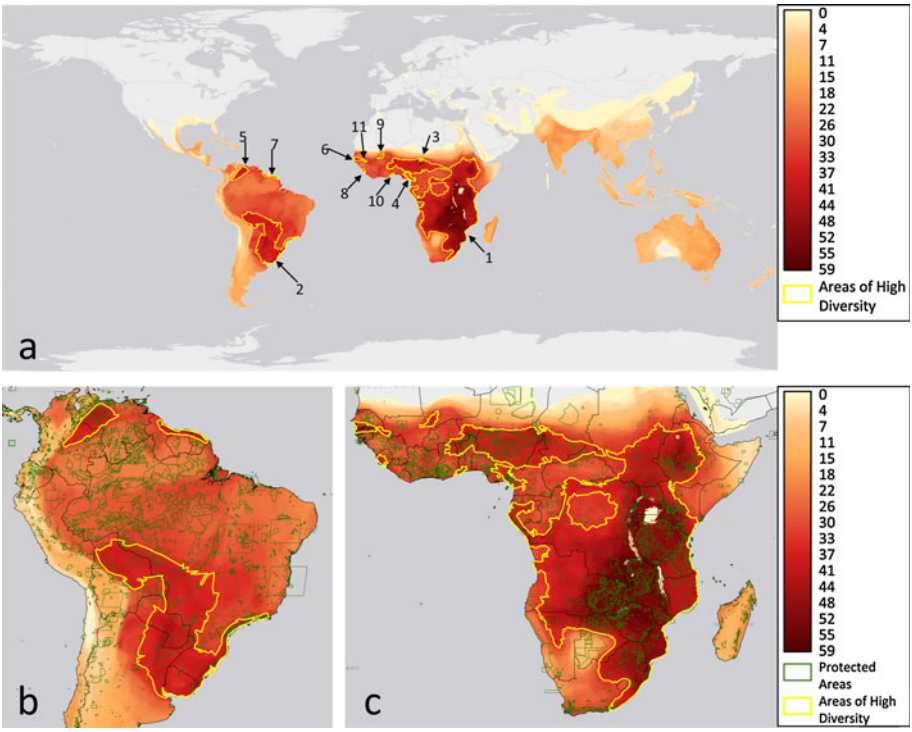

Fig. 4 Inland-breeding year-round resident waterbirds, **a** globally, **b** in South America and **c** Africa. The *numbers* in **a** refer to the area numbers in Table OR2. The *colour scale* represents the number of species. (Color figure online)

Europe appeared to be well-protected, although most of these sites are small (Fig. OR2a). Conversely, most of the rest of the world, especially India, Eastern China, Argentina and Uruguay, Kazakhstan, central USA and Africa had poorer protection than needed (Fig. OR2a).

When protected areas were compared with the number of threatened inland-breeding waterbirds (Fig. OR2b) Asia, the Middle East and Russia (particularly coastal China and northern India) as well as North Western Africa and Argentina were highlighted as having particularly poor coverage of protection.

Discussion

Our study provided three main results. First, we showed that inland-breeding waterbirds have an uneven concentration around the world: the most species rich areas are Eastern Africa and Southern Asia. Second, the highest densities of threatened species are primarily found in Asia. Third, the current network of protected areas appears adequate when compared with the number of inland-breeding waterbird species in Brazil, Greenland and Europe, but under-protected in regions of Asia, Eastern Africa and North and South America.

Areas of key importance for the conservation of threatened populations of inland-breeding waterbirds are coastal and Northern China, India, Madagascar, Japan and

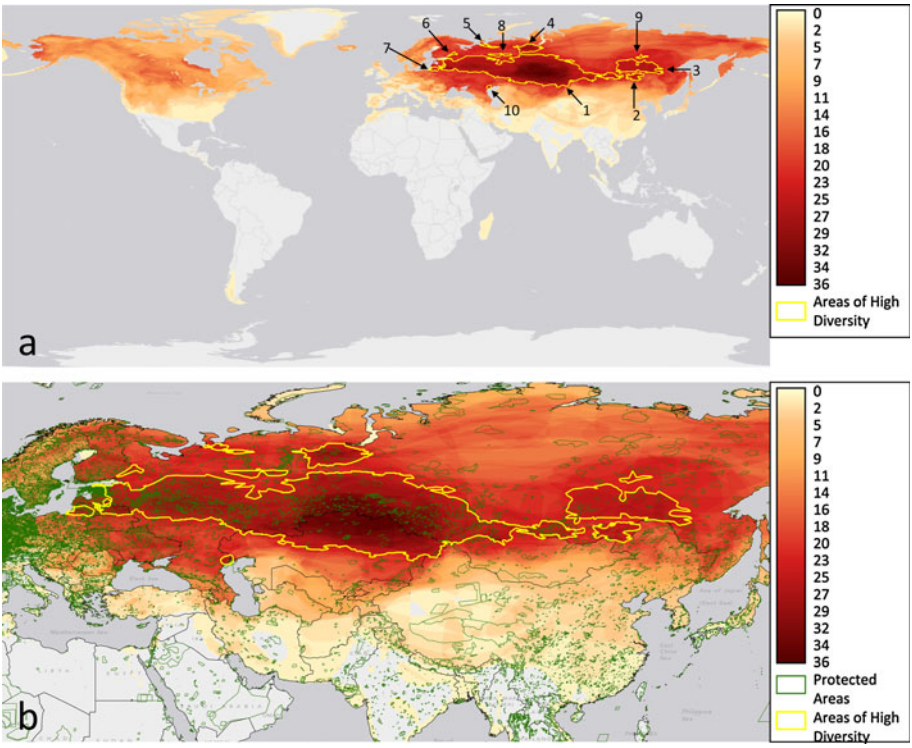

Fig. 5 Inland-breeding migratory waterbird breeding grounds, **a** globally, **b** in Northern Asia and Europe. The *numbers* in **a** refer to the area numbers in Table OR3. The *colour scale* represents the number of species. (Color figure online)

Kazakhstan. Year-round resident populations of inland-breeding waterbirds are primarily located in Eastern Africa and South America. The seasonality of the distributions of non-resident populations is highly apparent as many breed in the Arctic during the northern hemisphere summer before migrating to feed in the tropics.

Our study shows that spatial conservation priorities for inland-breeding waterbirds are not congruent with spatial priorities for other animal and plant taxa. For example, the areas of high diversity for threatened inland-breeding waterbirds are very different than the two primary locations of high diversity found for all threatened bird species; in Bangladesh, India and Bhutan as well as Uruguay and Brazil (Orme et al. 2005; Grenyer et al. 2006). There is an even greater disparity between locations of high inland-breeding waterbird diversity when compared with the global richness of mammals and amphibians (Grenyer et al. 2006), and also hotspots of high plant biodiversity (Mittermeier et al. 1998). These are all areas of extreme importance for the continued survival of waterbirds as a group and are areas that would do well to be targeted as conservation priorities for waterbirds as well as wetlands.

To reduce the threats to waterbirds, we recommend the following actions. First, new protected areas need to be created especially in Eastern Africa, Southern Asia, North and South America and the breeding grounds in the higher latitudes. Existing protected areas need better management effectiveness, in order to improve the status of waterbird

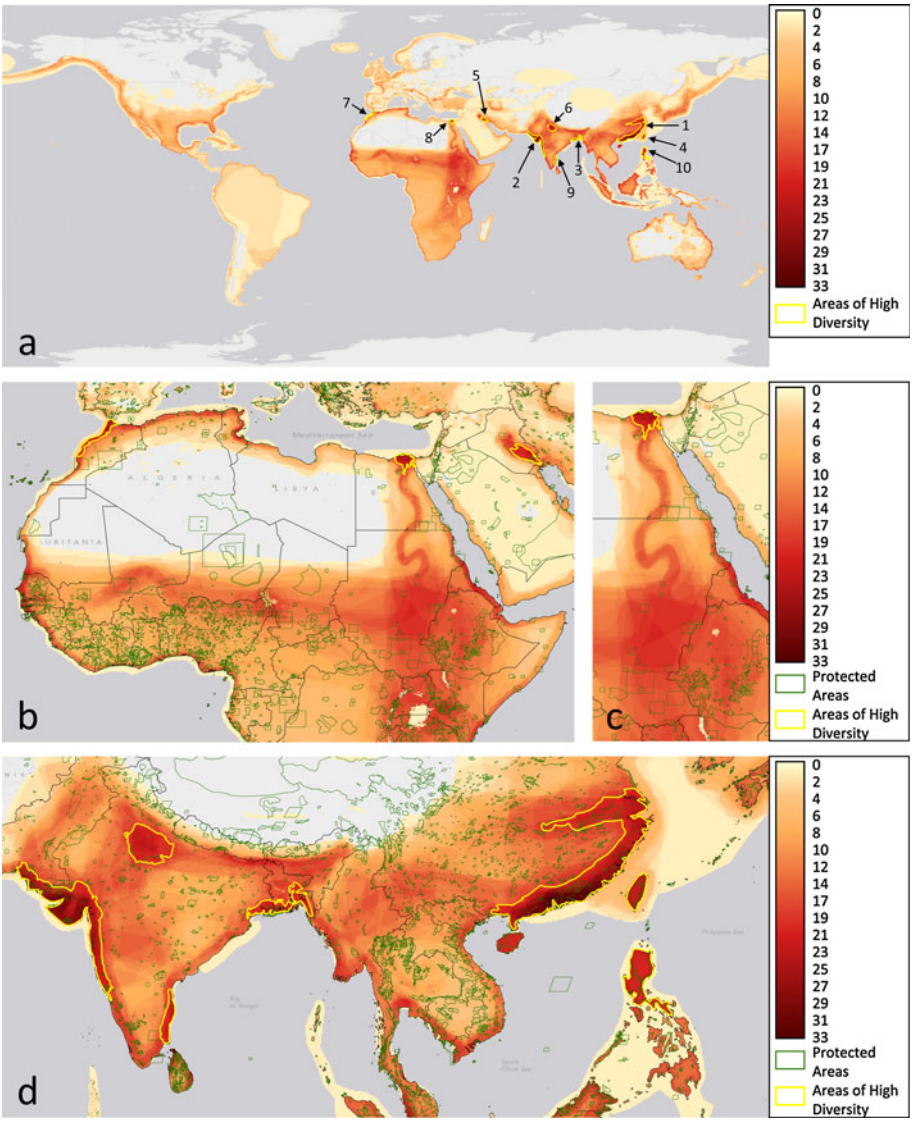

Fig. 6 Inland-breeding migratory waterbird non-breeding areas, **a** globally, **b** in Northern Africa, **c** Nile region, **d** South East Asia. The *numbers* in **a** refer to the area numbers in Table OR4. The *colour scale* represents the number of species. (Color figure online)

populations as well as populations of other species in those areas. More emphasis should be put on protecting wetland habitats in order to benefit waterbirds, other animals and plants, as well as the wetlands themselves for the many other beneficial services they provide to humans. In order to do this, more detailed information is needed about the exact locations of wetlands and their quality and suitability before additional protection can be enacted. There is also a need to enhance the effectiveness of conservation measures and enforcement of protection. For instance, hunting outside the legal period and/or inside protected

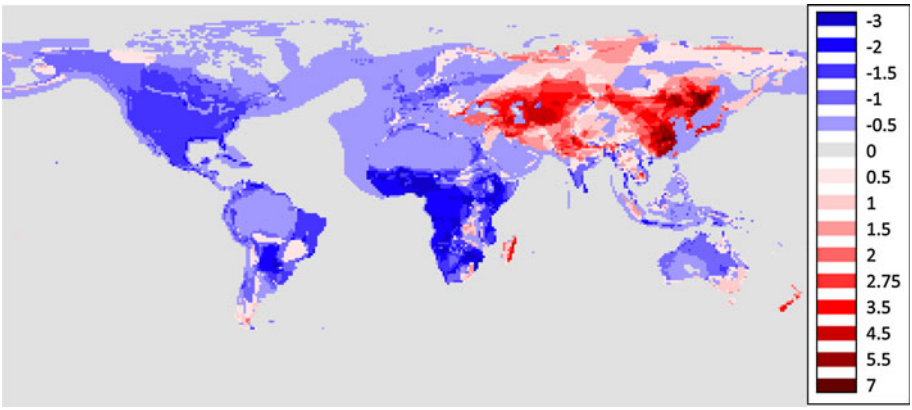

Fig. 7 Spatial distribution of threatened waterbird species in relation to the distribution of all waterbird species. *Positive numbers* represent locations in which there are more threatened waterbirds than expected from all waterbirds whereas *negative numbers* represent areas that have a lower number of threatened waterbirds than expected. This analysis was performed on a grid of 1° × 1°

Table 1 Global areas of high diversity for all inland-breeding waterbirds. Species richness is given as the minimum and maximum number of species per grid cell

#	Total number of species	Countries	Species richness	Area (1000 km^2)
1	138	Sudan, South Sudan, Ethiopia, Kenya, Uganda, Rwanda, Burundi, Democratic Republic of Congo, Tanzania, Zambia, Zimbabwe, Mozambique, Botswana, Swaziland & South Africa	63–91	6,421
2	91	Nigeria, Chad & Cameroon	63–80	335
3	83	Senegal & The Gambia	63–75	66
4	78	China	62–70	95
5	77	Niger & Nigeria	63–67	78
6	76	India	63–69	56
7	76	India	63–68	53
8	73	Mali	63–70	52
9	71	India	63–67	15
10	70	Namibia	63–67	15

areas is a common practice in various countries, and strengthening law enforcement will benefit waterbird populations.

Second, further research is necessary to examine the underlying causes of the observed patterns of waterbird occurrence and to discover exactly which sites in a species' range it makes use of to determine where protected areas should be located. Waterbirds also offer a unique opportunity to monitor the state of wetlands worldwide. We strongly recommend continuing waterbird monitoring programmes and combining them with spatial modelling to analyse different demographic and climatic scenarios. Programs such as Wings over Wetlands could be used to identify areas for comprehensive protection of species; however, it must be expanded to include Asia, Australia and America so that important

stop-over sites can be identified for migratory species and targeted for protection. It is also vital to expand such databases to include non-migratory species.

Third, more awareness of the importance of wetlands habitats and the threats to them is vital for their protection and continued existence. By coordinated training and large-scale monitoring (in programs like Wings Over Wetlands), the awareness of wetlands and wetland birds will likely be enhanced. Therefore, it is important to enhance public knowledge of the situation and involvement in solutions, as well as to gain support from multinational organisations in order to enact international protection measures.

Whilst this was the first analysis of waterbird distributions globally, we recognise two limitations of our study: the limited scope since we were focusing only on inland-breeding species, and the arguable classification of species to inland, coastal or both types of breeding habitats. Focusing only on species that breed in inland wetlands provided an ecologically well-defined group, although this reduced the number of species examined. We did not take into account that these species are not necessarily year-round residents of inland wetlands; many of them are also dependent on coastal wetlands which are also under threat from human encroachment.

Classifying species based solely on their breeding ground was a potential source of error because the IUCN data varied greatly in the amount of detail presented for different species. In order to maintain consistency between species, the IUCN data were the only source considered for this classification. There are potentially quite a few species that belong in the inland-breeding group that were not analysed, because they had to be put in the both inland and coastal category due to insufficient information.

In conclusion, in these global analyses of inland-breeding waterbird distributions, we identified areas of high inland-breeding waterbird diversity: Eastern Africa, Southern Asia and coastal regions throughout the world. Our analyses also show that the majority of threatened inland-breeding waterbirds are found throughout Asia. Since the global human population has now surpassed 7 billion, and far more people live within 100 km of the coast and 200 m of sea level (Small and Cohen 2004), it is anticipated that the pressure will increase even further on the remaining inland and coastal wetland habitats. In Eastern Asia alone, ecological services and fisheries are collapsing while natural disasters are becoming more frequent, which is causing waterbird populations to decline rapidly as well as impacting human livelihoods (MacKinnon et al. 2012). Targeting sites and areas of particular conservation importance, such as those highlighted in this study, is vital for the continued existence of waterbirds and the wetlands upon which they depend.

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