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William Darwall

R Holland

K Smith

D Allen

E Brooks

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Author(s)

William Darwall, R Holland, K Smith, D Allen, E Brooks, V Katarya, C Pollock, Y Shi, Viola Clausnitzer, Neil Cumberlidge, A Cuttelod, K D. Dijkstra, M Diop, N Garcia, M Seddon, P Skelton, J Snoeks, D Twedde, and JC Vie

Implications of bias in conservation research and investment for freshwater species

William R. T. Darwall¹, Robert A. Holland¹, Kevin G. Smith¹, David Allen¹, Emma G. E. Brooks¹, Vineet Katarya¹, Caroline M. Pollock¹, Yichuan Shi¹, Viola Clausnitzer², Neil Cumberlidge³, Annabelle Cuttelod¹, Klaas-Douwe B. Dijkstra⁴, Mame D. Diop⁵, Nieves García¹, Mary B. Seddon⁶, Paul H. Skelton⁷, Jos Snoeks⁸, Denis Tweddle⁷, & Jean-Christophe Vié⁹

¹ Global Species Programme, IUCN (International Union for Conservation of Nature), 219c Huntingdon Road, Cambridge CB3 0DL, UK

² Department of Zoology, Senckenberg Museum for Natural History, P.O. Box 300154, 02806 Görlitz, Germany

³ Department of Biology, Northern Michigan University, Marquette, MI, USA

⁴ Netherlands Centre for Biodiversity Naturalis, P.O. Box 9517, 2300 RA Leiden, The Netherlands

⁵ Wetlands International, Africa Office, Rue 111, Villa No 39, Zone B Dakar, Sénégal

⁶ IUCN SSC Mollusc Specialist Group, Shell Life, Bracken Tor, Saxongate, Okehampton EX20 1QW, UK

⁷ South African Institute for Aquatic Biodiversity, Private Bag 1015, Grahamstown 6140, South Africa

⁸ Royal Museum for Central Africa, Zoology Department, Ichthyology, Leuvensesteenweg 13, B-3080 Tervuren, Belgium and Katholieke Universiteit Leuven, Laboratory of Animal Diversity and Systematics, Charles Deberiotstraat 32, B-3000 Leuven, Belgium

⁹ Global Species Programme, IUCN (International Union for Conservation of Nature), Rue Mauverney 28, 1196 Gland, Switzerland

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Correspondence

Robert Holland, IUCN Global Species Programme, 219c Huntingdon Road, Cambridge, CB3 0DL, UK. Tel: +44(0)1223 814712; Fax: +44(0)1223 277845. E-mail: robert.holland@iucn.org

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Abstract

Human population growth and economic development threaten the integrity of freshwater ecosystems globally, reducing their ability to support biodiversity and provide ecosystem services. However, our knowledge of freshwater biodiversity is fragmented due to bias in conservation research toward primarily terrestrial or charismatic taxonomic groups. Here, we utilize the most comprehensive assessment of freshwater biodiversity for an entire continent to examine the implications of this shortfall. Results indicate that groups that have been the focus of most conservation research are poor surrogates for patterns of both richness and threat for many freshwater groups, and that the existing protected area network underrepresents freshwater species. Areas of highest species richness and threat are congruent with areas where reliance on ecosystem services by humans and pressures placed on freshwater ecosystems are high. These results have implications for targets to reduce biodiversity loss and safeguard associated ecosystem services on which millions of people depend globally.

Introduction

Freshwaters represent one of the most threatened ecosystems globally (Jenkins 2003; Dudgeon *et al.* 2006; Vörösmarty *et al.* 2010) and, despite occupying less than 1% of the Earth's surface, contain 10% of all known species including around a third of all vertebrates (Strayer & Dudgeon 2010). Associated with this rich diversity, the world's freshwaters provide ecosystem goods and services valued at several trillion USD/year globally (Postel & Carpenter 1997) that form a vital component of the

livelihoods of many people (Neiland & Bene 2008; Rebelo *et al.* 2009; Dugan *et al.* 2010). Exploitation of these resources for food, energy, transport, and water supply (Dudgeon *et al.* 2006) together with the emerging threat from climate change (Woodward *et al.* 2010) have led to an estimated extinction risk among freshwater species that is significantly higher than found terrestrially (Ricciardi & Rasmussen 1999; Darwall *et al.* 2009; WWF 2010).

Despite the important contribution of freshwater ecosystems to global biodiversity, conservation research

is skewed toward more charismatic species groups, predominantly birds and mammals (Clark & May 2002). Data on the distribution and conservation status of these groups, and more recently amphibians, have provided important insights into broad-scale ecological patterns and form the basis of strategies for investment to reduce the rate of global biodiversity loss (Brooks *et al.* 2004, 2006; Rodrigues *et al.* 2004; Ricketts *et al.* 2005; Grenyer *et al.* 2006). A key limiting factor for the incorporation of freshwater species as explicit targets has been a lack of data on their distribution and conservation status. Given this lack of data, it is assumed that the better-known groups will act as surrogates for conservation planning purposes (Grenyer *et al.* 2006; Rodrigues & Brooks 2007). Although spatial patterns of freshwater and terrestrial species show agreement at coarse scales (i.e., ecoregions (Abell *et al.* 2010)), concordance of patterns between groups has not been examined at scales practical for conservation. The taxonomic bias therefore raises the question of whether conservation priorities based on the better-known groups will provide cobenefits for freshwater species, or whether the balance of research and investment should be shifted to more fully reflect the importance of the world's freshwater ecosystems and the level of threat they face.

Here, we examine the impact of this bias utilizing a recently published broad assessment of freshwater biodiversity at the species level for an entire continent (Darwall *et al.* 2011). Included for the first time are data on all known species of freshwater fish, crabs, molluscs, dragonflies, and damselflies (odonates) found in Africa. We compare patterns of richness and threat for these newly assessed groups with those of birds, mammals, and amphibians, and provide information on the conservation status of freshwater biodiversity across Africa. The effectiveness of birds, mammals, and amphibians as surrogates for the newly assessed freshwater groups is investigated and we examine the representation of freshwater species within the existing protected area (PA) network, as this represents a tangible measure of current priorities for conservation investment. Finally, we consider the practical implications of our findings for the protection of freshwater biodiversity across Africa where impacts to freshwater ecosystems are set to become a major issue in the near future. The African continent is poised to embark on an unprecedented scale of development within its water sector, targeting a 100% increase in irrigated land area and an increase from 7% to 25% of total hydropower potential captured by 2025 (Economic Commission for Africa 2003). With this in mind, we consider the spatial relationship between areas of high value for freshwater biodiversity and areas where investment in infrastructure and land use change is required to alleviate

poverty. The identification of such sites of potential conflict of interests is essential to establish conservation priorities and guide development actions in Africa's inland waters.

Methods

Analyses were based on range maps of 4,203 freshwater species and 3,521 bird, mammal, and amphibian species. Range maps of bird, mammal, and amphibian species were compiled as polygons derived from a combination of known and expected localities, determined by experts following the IUCN Red Listing process, with areas of unsuitable habitat removed in accordance with the IUCN Red List Guidelines (IUCN Standards and Petitions Subcommittee 2010). Brooks *et al.* (2004) and Rodrigues *et al.* (2004) discuss these data sets in further detail. Freshwater species distributions were based on known or expected presence within 7,079 river catchments across Africa, as delineated by a modified version of the HYDRO1k Elevation Derivative Database that derives catchment boundaries based on a 30 arc-second digital elevation model. Known localities and expert knowledge of expected occurrence within connected catchments was used to map freshwater species. Data on the distribution, abundance, population trends, ecology, habitat preferences, threats, utilization, conservation actions, and conservation status of each of the freshwater species were collated by more than 200 experts through 10 regional workshops held from 2003 to 2009 to assess species extinction risk according to the IUCN Red List Categories and Criteria (IUCN 2001). To allow spatial comparisons between groups, range maps of bird, mammal, and amphibian species were converted into occurrence in river catchments, based on overlaps between ranges and catchments, using the intersect function of ArcGIS 9.3. Subsequent analysis was carried out using both spatial GIS layers and the underlying tabular data that provide a list of all species found within each catchment.

Richness for total species and for threatened species of birds, mammals, and amphibians were calculated for each catchment and used as a baseline to examine the increase in our knowledge of total and threatened species with the addition of the freshwater groups. Correlations between spatial patterns of total species richness and richness of threatened species for each group were examined using Spearman's Rho due to nonnormality of the data, with corrected degrees of freedom calculated using Dutilleul's modified test, implemented in the software SAM (Rangel *et al.* 2010), to account for spatial autocorrelation. Centers of richness for all species and for threatened species

were identified as the 5% most species-rich catchments for each taxonomic group.

The effectiveness of birds, mammals, and amphibians in representing the newly mapped freshwater species was investigated using the Species Accumulation Index of Surrogate Efficiency (SAI) (Rodrigues & Brooks 2007) that determines how comprehensively a network of sites chosen to maximize representation of one taxonomic group captures species in another. To calculate the SAI, a greedy algorithm was used to select the minimum number of catchments that capture all species for each taxonomic group at least once. The selected catchments and the order in which they were selected represent an "optimum" species accumulation curve. The catchments selected for this optimum species accumulation curve for each group were then used to calculate a "surrogate" curve for each of the other groups. Finally, for each group a "random" species accumulation curve was generated by randomly selecting catchments. SAI is calculated as $(S - R/O - R)$ where S is the area under the surrogate curve, R is the area under the random curve, and O is the area under the optimal curve.

PAs, as delineated by The World Database on Protected Areas (WDPA) (IUCN & UNEP-WCMC 2010), were overlaid onto the catchment layer in ArcGIS. All catchments that contained a PA (irrespective of the proportion of catchment area covered) were selected, and the numbers of species within each taxonomic group with ranges intersecting those catchments calculated.

Studies suggest that a value of around 30% of the catchment area under human influence may represent a threshold above which there will be a detrimental effect on freshwater ecosystems diminishing their ability to support biodiversity and provide natural services (Allan 2004). Using this 30% threshold, a subset of 619 catchments was identified where 70% or more of the land within the catchment falls within a PA. These catchments, incorporating 57.8% of the total land area encompassed within the PA network across Africa, are assumed to represent the best protected catchments. Finally, a GIS data layer incorporating spatial data on Ramsar site localities, in both point and polygon format, was created using data extracted from the WDPA. A GIS data layer was then created identifying all catchments containing or intersecting with a Ramsar site, and the overlap between this subset of catchments and species distributions for each taxonomic group calculated.

A GIS layer mapping rural poverty, representing infant mortality rates in the year 2000, was obtained from the United Nations Food and Agriculture Organization (UN FAO) using raster data at a 0.25-degree resolution from the Centre for International Earth Science Information Network. Zonal statistics in the Spatial Analysis toolbox

of ArcGIS 9.3 were used to calculate average infant mortality per catchment. Correlations between rural poverty and total and threatened species richness in catchments were calculated using Spearman's Rho with corrected degrees of freedom calculated using Dutilleul's modified test (Rangel *et al.* 2010).

Finally, large dams (height >30 m or volume > 3 million m³) were utilized as a proxy for the extent of development of inland waters. Present dams were obtained from the FAO Land and Water Digital Media Series #13: "Atlas of Water Resources and Irrigation in Africa" (<http://www.fao.org/geonetwork/srv/en/main.home>). A database of proposed dams was provided by International Rivers in June 2010 (<http://www.internationalrivers.org/node/1785>). Dam locations were plotted in ArcGIS 9.3 and the proportion of catchments within a species range containing present or proposed dams used as a measure of impact.

Results

Correlations of total species richness were stronger between birds, mammals, and amphibians (Spearman's Rho 0.88 to 0.94; Table 1) than between these groups and crabs, fish, and molluscs (Spearman's Rho 0.36 to 0.70; Table 1). For threatened species, there are generally low correlations in richness patterns between all groups (Spearman's Rho 0.12 to 0.33; Table 1). Centers of total bird and mammal richness overlap to some degree (48.5%), however, for all other groups there is little congruence between centers of total species richness or threatened species richness (Table 1).

Results from the SAI analysis indicate significantly higher surrogacy values between birds, mammals, and amphibians than between these taxonomic groups and the freshwater groups (Mann-Whitney U Test $W = 72$, $P < 0.001$; Table 2). Our analysis indicates that individual freshwater groups are significantly better surrogates for birds, mammals, and amphibians (SAI 0.32 to 0.68) than vice versa (SAI -0.44 to 0.34) (Mann-Whitney U Test $W = 142.5$, $P < 0.001$; Table 2). Freshwater groups were found to have significantly lower surrogacy values for each other (SAI -0.14 to 0.71) than birds, mammals, and amphibians for each other (SAI 0.61 to 0.86) (Mann-Whitney U Test $W = 68$, $P < 0.001$; Table 2). An analysis of surrogacy between combined freshwater groups and combined birds, mammals, and amphibians demonstrated that overall the freshwater groups were more effective surrogates for the previously assessed groups (SAI 0.63) than vice versa (SAI 0.49).

There was a significant overlap between PAs and the ranges of all known species of birds, mammals, and

Table 1 Correlations and overlap of centers of species richness between taxonomic groups. Relationships between taxonomic groups based on (a) correlations of total species richness and threatened species richness (b) overlap of catchments identified as centers of total species richness and richness of threatened species, defined as the top 5% of richest sites. For the correlations, significance levels are based on Dutilleul's correction at the * <0.05, ** <0.01, and *** <0.001 level to account for nonindependence arising from spatial autocorrelation. The dashed line indicates division between the traditionally assessed higher vertebrates and the newly assessed freshwater groups.

Taxonomic groups		(a) Correlation richness (Spearman's Rho)		(b) Percentage overlap between centers of richness	
		All species	Threatened species	All species	Threatened species
Amphibians	Birds	0.88**	0.27***	14.1	3.6
Amphibians	Mammals	0.92***	0.33***	20.4	6.6
Birds	Mammals	0.94***	0.31**	48.5	11.8
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Amphibians	Crabs	0.40*	0.24***	7.8	10.5
Amphibians	Fish	0.70**	0.22***	15.6	7.3
Amphibians	Molluscs	0.67**	0.12*	12.5	0
Amphibians	Odonates	0.91***	0.31***	25.1	13.5
Birds	Crabs	0.38*	0.12***	8.4	1.8
Birds	Fish	0.64*	0.17	5.9	2.2
Birds	Molluscs	0.64**	0.16*	4.2	1.2
Birds	Odonates	0.86*	0.16***	13.7	7.6
Mammals	Crabs	0.36*	0.15***	8.8	3.1
Mammals	Fish	0.64*	0.32***	9.3	9.3
Mammals	Molluscs	0.62*	0.13***	8.5	1.2
Mammals	Odonates	0.93***	0.21***	26.5	5.0
Crabs	Fish	0.55***	0.18***	8.4	3.9
Crabs	Molluscs	0.48*	0.12***	15.6	1.5
Crabs	Odonates	0.35	0.19***	11.8	5.7
Fish	Molluscs	0.71***	0.14***	15.7	8.7
Fish	Odonates	0.67***	0.16***	19.2	4.0
Molluscs	Odonates	0.67*	0.13***	14.4	0

Table 2 Species accumulation index of surrogate efficiency (SAI) values indicating the effectiveness of different taxonomic groups as surrogates. SAI values of 1 indicate that the surrogate group fully represents species richness in the focal group, values between 0 and 1 indicate the use of a surrogate is more representative than selecting sites by random, and values between 0 and -1 indicate that the surrogate is less efficient at representing another group than would be achieved through random selection. Values enclosed within the dashed line indicate SAI values for surrogacy between the traditionally studied groups of higher vertebrates.

Focal group	Surrogate group						
	Amphibian	Bird	Mammal	Crab	Fish	Mollusc	Odonate
Amphibian	–	0.69	0.67	0.58	0.51	0.32	0.63
Bird	0.69	–	0.86	0.37	0.35	0.56	0.68
Mammal	0.61	0.75	–	0.48	0.37	0.41	0.57
Crab	0.34	0.15	0.20	–	0.38	0.31	0.35
Fish	0.31	0.28	0.19	0.40	–	0.71	0.58
Mollusc	0.29	0.32	0.22	0.40	0.54	–	0.44
Odonate	–0.35	–0.25	–0.44	–0.14	0.07	0.52	–

amphibians and freshwater groups, as well as those classified as threatened (Table 3). Within catchments where >70% of the area falls within a PA, there is a substantial reduction in the proportion of crab, fish, and mollusc

species captured whereas coverage of birds and mammals remains high (Table 3). Representation of both total and threatened bird and mammal species was substantially higher than for crabs, fish, and molluscs within the

Table 3 Percentage of species within the existing protected area network. The percentage of species from major taxonomic groups (a) captured within PAs based on spatial intersects of catchments with any point within their range, (b) based on presence within catchments where 70% of the area is within a PA, and (c) based on presence within catchments that contain a Ramsar-designated site. The dashed line indicates division between the previously assessed higher vertebrates and newly assessed freshwater groups.

	(a) Intersect PA (<i>n</i> = 2,725)		(b) 70% catchment in PA (<i>n</i> = 619)		(c) Catchment contains a designated Ramsar site (<i>n</i> = 190)	
	% total taxa	% threatened taxa	% total taxa	% threatened taxa	% total taxa	% threatened taxa
Amphibians	95.7	99.4	70.8	49.2	62.2	45.3
Bird	99.1	96.2	95.9	74.2	91.7	61.4
Mammals	97.6	98.4	88.4	98.4	80.1	62.5
Crabs	92.5	88.0	50.0	36.0	44.3	24.0
Fish	87.4	93.9	48.5	31.4	46.6	33.0
Molluscs	80.8	84.1	21.7	33.1	54.8	35.2
Odonates	86.4	100.0	73.7	50.0	82.4	39.7

subset of PAs designated as Wetlands of International Importance by the Ramsar convention (Table 3).

We find a positive spatial relationship between rural poverty and freshwater species richness (Spearman's $Rho = 0.52$, corrected $df = 79.482$, $P < 0.01$), with areas of highest congruence in western Africa and around the Great Lakes of eastern Africa (Figure 1a). The relationship between the richness of threatened species and rural poverty (Figure 1b) is more equivocal (Spearman's $Rho = 0.30$, corrected $df = 222.48$, $P < 0.001$).

Proposed or constructed large dams occurred in 559 catchments across continental Africa with 68% of fish, 57% of crab, 70% of mollusc, and 88% of odonate species coinciding with these developments at some point within their ranges.

Discussion

Patterns of richness and threat for the four freshwater groups assessed during this study represent significant new knowledge about the distribution and status of Africa's biodiversity, particularly in western and central Africa (Figure 2). In some regions, notably the African Great Lakes and parts of western Africa, inclusion of these new data results in a 45% to 96% increase in the number of known threatened species (Figure 2b) above the existing baseline value for birds, mammals, and amphibians. Of the 4,203 freshwater species assessed, 26% are threatened with global extinction. There is insufficient information to assess the status of 741 freshwater species therefore the level of threat could be as high as 37%.

For birds and mammals, correlation between richness (Spearman's $Rho = 0.94$; Table 1), overlap between centers of richness (48.5%; Table 1), and values of SAI (mammal as surrogates SAI 0.86; birds as surrogates SAI 0.75;

Table 2) indicate similarities in spatial patterns across Africa. However, as demonstrated by Grenyer *et al.* (2006) at a global scale, correlations (Spearman's $Rho = 0.31$; Table 1) and overlaps of hotspots of threatened mammals and birds (11.8%; Table 1) are low emphasizing the importance of primary information as a basis for conservation planning. Our results indicate that the collection of such primary data may be particularly important for freshwater groups as there were generally low correlations between total and threatened species richness and little overlap in centers of richness (Table 1). A comparison of surrogacy between combined freshwater groups and combined birds, mammals, and amphibians suggests that the former represent the most efficient surrogates for overall biodiversity. However, there are generally low surrogacy values between all groups when considered individually (Table 2). For fish, molluscs, and crabs, results suggest that conservation priorities and investment targets based on our knowledge of birds, mammals, and amphibians alone may not adequately represent these freshwater species. Among the freshwater species, odonates are the exception being strongly correlated with bird, mammal, and amphibian distributions; most likely this is a reflection of similarities in both their ecology (being comparatively mobile species largely unrestricted by catchment boundaries), and in habitat selection. Odonates are relatively effective surrogates for birds, mammals, and amphibians (SAI > 0.57 ; Table 2), however, the inverse relationship does not hold (SAI > -0.25 ; Table 2). Odonates' capacity to indicate the state of both terrestrial and aquatic systems (Simaika & Samways 2011) suggests that further work examining their use as surrogates is warranted.

Although driven by a range of differing factors (Joppa *et al.* 2008; Joppa & Pfaff 2009), PAs represent a

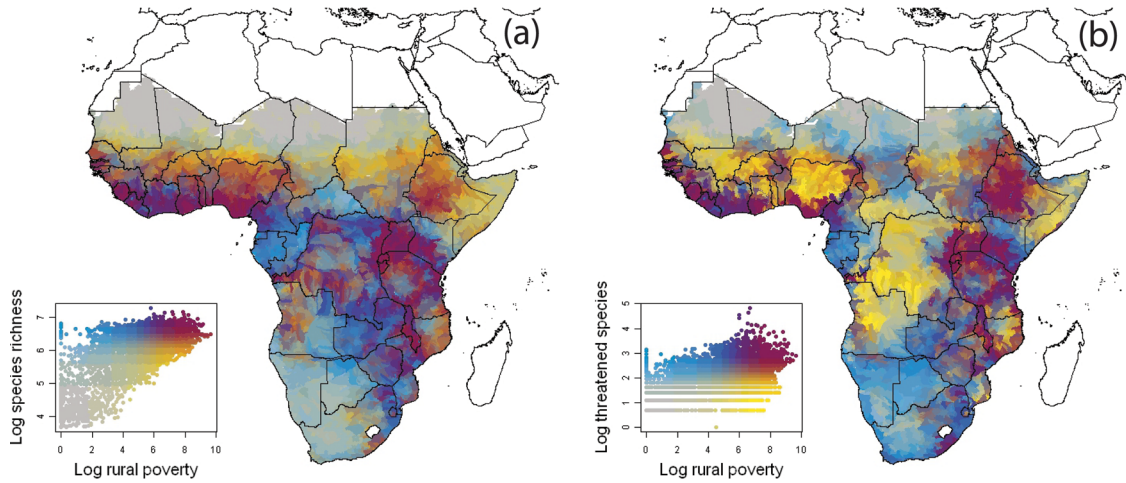


Figure 1 Correlations between rural poverty and biodiversity in sub-Saharan Africa. Relationships are assessed based on infant mortality as an indicator of rural poverty and (a) freshwater species richness (Spearman's Rho = 0.52, corrected df = 79.482, $P < 0.01$) (b) number

of threatened freshwater species (Spearman's Rho = 0.30, corrected df = 222.48, $P < 0.001$). Areas with the darkest shading represent those places where both rural poverty and species richness, or threatened species numbers, are high.

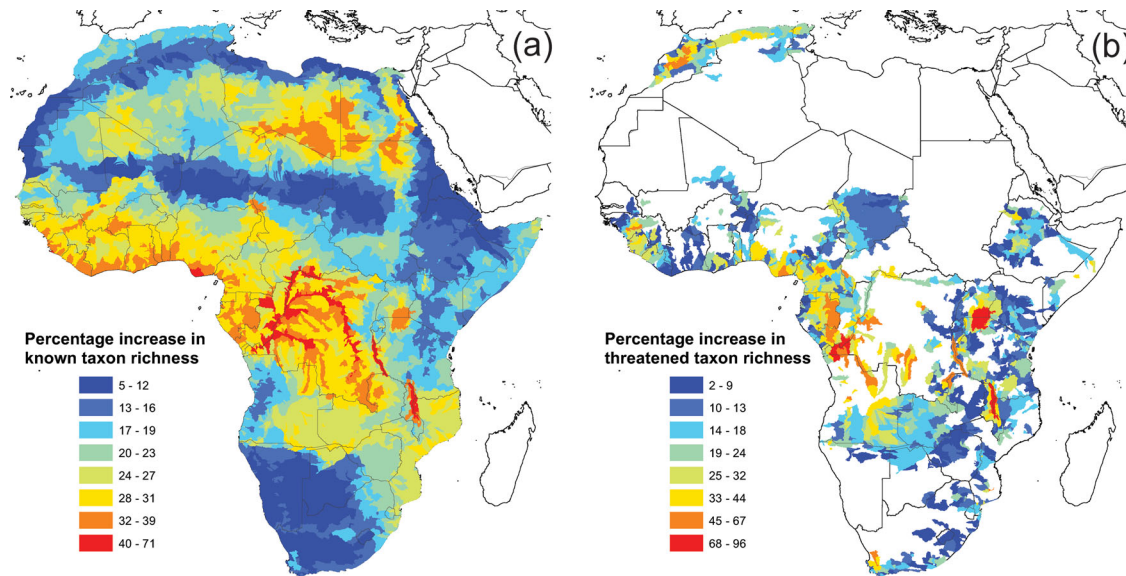


Figure 2 The increase in biodiversity knowledge across continental Africa. Increase in (a) species richness measured as the percentage increase from the baseline level for amphibians, mammals, and birds, and (b) threatened species as the percentage increase above the baseline level for birds, mammals, and amphibians in the number of species classified as threatened according to the IUCN Red List with the addition of the freshwater taxonomic groups.

tangible measure of spatial priorities for conservation and so provide an indication of the level of protection afforded to freshwater species. Overlap between PAs, all species, and threatened species for each taxonomic group was high (Table 3) based solely on intersects between PAs and species ranges. However, the intersect between a species range and a PA will tend to overestimate the effective protection provided by the PA network (Brooks *et al.*

2004). Furthermore, issues specific to freshwater systems will tend to lead to overestimation of the protective coverage of the PA system. For example, many PAs are small and not congruent with freshwater systems where linear features such as rivers are often used as boundary markers (Abell *et al.* 2007) rather than inclusive targets for conservation. Even where freshwater systems fall within a PA, management is often focused on specific aspects

of the terrestrial environment that may not confer benefits for freshwater systems. For example, in southern Africa, only 50% of rivers within PAs are considered to be intact (Nel *et al.* 2007). Effective protection of freshwater species requires appropriate management of the upstream catchment (to control for pollution and sedimentation, and to ensure appropriate water flow) as well as the downstream reaches (to ensure connectivity for migratory species and control of biological invasions), which are rarely considered in the design of terrestrial reserves (Dudgeon *et al.* 2006; Linke *et al.* 2008).

The number of species captured within the PA network was lower when the analysis was restricted to catchments where >70% of each catchment falls within a PA. Although PA coverage for birds and mammals remained high (>88.9% total and >74.2% threatened taxa; Table 3), less than 50% of the total crab, fish, and mollusc diversity was captured and only 33% to 36% of threatened freshwater species (Table 3). Although intensity of activity within a catchment strongly influences the impact on the aquatic environment (Allan 2004), this result indicates a potentially significant shortfall in coverage of freshwater species where PAs might be expected to have the most significant benefits. Perhaps most surprising is the finding that catchments containing Ramsar sites capture a significantly higher proportion of birds and mammals (>80% of all taxa, >60% threatened taxa; Table 3) than crabs, fish, or molluscs (<55% total taxa, <36% threatened taxa; Table 3). This shortfall in taxonomic coverage, which is acknowledged by the Ramsar secretariat, can be addressed through the release of new species data sets such as analyzed here.

Our findings have implications not only for the conservation of freshwater species diversity but also for the protection of a resource upon which many millions of people rely. For example, inland fisheries represent a critically important source of human nutrition in Africa and parts of Asia and provide livelihoods for an estimated 600 million people (Dugan *et al.* 2010). Patterns of spatial overlap between high incidence of rural poverty and high species richness in freshwater ecosystems might therefore indicate both areas of potential conflict of interest and priority areas where the dual benefits to conservation and livelihoods will be greatest (Adams *et al.* 2004). Spatial relationships between rural poverty and both total and threatened freshwater species richness identify western Africa, the Great Lakes of eastern Africa and the Ethiopian highlands as priority areas to protect both centers of freshwater biodiversity and the livelihoods of many of the continent's poorest people (Figure 1).

In conclusion, this study demonstrates that targeting investment at the better-known taxonomic groups

may not confer adequate benefits for other species. Our findings present a strong case for a shift in research and investment to reflect the importance of freshwater ecosystems. The urgency of the situation becomes evident when we observe the spatial scale of current and proposed development actions across Africa. Using large dams as a proxy, we found considerable overlap between development and freshwater species. This may be of particular consequence for the 26% of fish, 9% of crab, 20% of mollusc, and 14% of odonate species considered globally threatened that have ranges contained entirely in catchments with existing or likely future dams.

Results from our study highlight the value of primary information on species distributions and status for making conservation decisions and targeting investment. Given the disproportionate amount of the world's biodiversity found in freshwater systems, information on freshwater species will be essential for implementation of the Conference of the Parties to the Convention on Biological Diversity's Strategic Plan for Biodiversity 2011–2020 (Decision X/2). For example, Target 12 requires that by 2020 "... the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained." Our results suggest that this target is unlikely to be met without targeted protection of threatened freshwater species, as incidental benefits of protection targeted at other groups leave considerable gaps in coverage of freshwater groups. Information from this study can be used to identify priority areas for conservation of freshwater species to support Target 11 that aims to ensure that "... at least 17 per cent of terrestrial and inland water areas, ... especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of PAs and other effective area-based conservation measures, and integrated into the wider landscapes..." The low surrogacy values we report indicate that data on freshwater groups must be used to expand coverage of the existing network of protected sites to reduce the shortfall in coverage of threatened freshwater species.

Most immediately, the freshwater data sets presented here can be utilized to ensure development projects impacting inland waters across Africa are designed to provide a "Net Positive Impact" (TEEB 2010) to society by avoiding, mitigating, and offsetting negative impact on species diversity and people's livelihoods wherever possible. Given the scale of planned development of water resources across Africa (Economic Commission for Africa 2003), the rewards from intervention at this relatively early stage are potentially huge and represent an opportunity for Africa to avoid the significant economic costs of

restoration of inland waters incurred in many other parts of the world (Finlayson *et al.* 2005; Dudgeon *et al.* 2006; Tockner *et al.* 2009). As efforts to expand the information coverage for freshwater species on other continents bear fruit over the next few years (Darwall *et al.* 2009), parallel efforts must be made to ensure effective protection of these species if global diversity of freshwater species and the services they provide to humanity are to be conserved.

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